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Evaluation of a No-Clean Soldering Process Designed to Eliminate the Use of Ozone Depleting Chemicals

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November 1992

***GRAM, Inc., Albuquerque, NM**

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Evaluation of a No-Clean Soldering Process Designed to Eliminate the Use of Ozone Depleting Chemicals

IWRP CRADA No. CR91-1026

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INDUSTRIAL WASTE REDUCTION PROGRAM SOLVENT REDUCTION PROGRAM

COOPERATIVE RESEARCH & DEVELOPMENT AGREEMENT
CR91-1026

Motorola Inc., Government Electronics Group
and the Sandia National Laboratories
have entered into a cooperative research & development agreement
to reduce the emission of ozone depleting solvents
through the validation of the reliability of hardware assembled
using a self-cleaning soldering process.

In witness thereof, the parties have caused a CRADA to be signed
by their duly authorized representatives.

27 September 1991

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MOTOROLA INC.

Paul Robinson

Sandia National Laboratories

President-Elect Bill Clinton Receives the First Printed Wiring Board Manufactured with the No-Clean Soldering Process from Sandia President Al Narath and Vice President Paul Robinson During his Visit to Sandia National Laboratories in Albuquerque (September 1992)

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List of Abbreviations

AES	Auger Electron Spectroscopy
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
CFC	Chlorofluorocarbon
CRADA	Cooperative Research and Development Agreement
DOE	Department of Energy
DPA	Destructive Physical Analysis
EMPA	Electron Microprobe Analysis
EMPF	Electronic Manufacturing Product Development Facility, U.S. Navy
EPTB	Electronics Packaging Technology Branch, Naval Weapons Center
FTIR	Fourier Transform Infrared Spectroscopy
GEG	Government Electronics Group, Motorola, Inc.
HPLC	High Pressure Liquid Chromatography
IC	Integrated Circuit
IPC	Integrated Printed Circuit
IR	Infrared
IWRP	Industrial Waste Reduction Program
LANL	Los Alamos National Laboratory
MTB	Motorola Test Board
NC	No-Clean
ODC	Ozone Depleting Chemical
ODP	Ozone Depletion Potential
PWB	Printed Wiring Board
RF	Rosin Flux
RH	Relative Humidity
SAM	Scanning Auger Microscopy
SEM	Scanning Electron Microscopy
SIMS	Secondary Ion Mass Spectroscopy
SIR	Surface Insulation Resistance
SNL	Sandia National Laboratories

Acknowledgements

The authors would like to acknowledge the contributions and support of several organizations and individuals. Department of Energy (DOE) funding provided for this program came from the DOE Industrial Waste Reduction Program under the office of J. Michael Davis, the DOE Assistant Secretary for Conservation and Renewable Energy (CE). Motorola, Inc. provided funding, production facilities, testing, and personnel. The efforts of Bruce Cranford and Don Walter from the CE/Office of Industrial Technologies at DOE, W. Porter Grace from the DOE Albuquerque Operations Office, Robert Cranwell, Dennis Huffman, Leon Chapman, Joan Woodard, G. Gordon Graham, and Dan Arvizu of Sandia National Laboratories, and Richard Benson from Los Alamos National Laboratory were instrumental in putting the program together and making it come to fruition.

John Fischer and personnel at the Product Assurance Division of the Naval Weapons Center at China Lake,

California contributed to our planning of the program and contributed to its performance with FTIR testing of sample hardware. Bill Vuono and personnel from the Navy's Electronic Manufacturing Productivity Facility in Indianapolis assisted by performing ionograph testing on sample boards.

The authors also would like to recognize the following individuals within their organizations that made significant contributions to the program: Frank Potts, Joe Kubas, Robert Reese, Michael Nusser, and Ken Miller at Sandia's Environmental Test Facilities; Ed Weinbrecht and Carol Sumpter of Sandia; Gene Martinez, Kelly Power, Susan Gray, Donna Combs, Kelley Carleno, Shawn Peterson, Maria Frew, Pete Rendek, and Boyd Holmes of Motorola's Government Electronics Group; and J. Doug Farr and W. B. Hutchinson of Los Alamos National Laboratory.

1. Testing Program Overview

The destruction of the Earth's protective ozone layer is one of today's largest environmental concerns. Solvent emissions released during the cleaning of printed wiring boards (PWBs) have been identified as a primary contributor to ozone destruction. The impact of the emission of ozone depleting chemicals (ODCs) on the ozone layer has been well documented. Estimates published in *Electronics*, Jan 1991, indicate that at least 20% of ODC emissions is attributed to cleaning processes of PWBs and other electronic gear. Industry has responded to this environmental problem by:

- Implementing conservation techniques to reduce the emission of ODCs
- Using alternative cleaning solvents that have lower ozone depletion potentials (ODPs)
- Developing new, non-ozone depleting solvents such as terpenes
- Developing no-clean soldering processes

Conservation techniques and the use of lower ODP solvents are only short-term solutions. Environmental legislation and cooperative efforts, such as the Montreal Protocol, are striving to eliminate all ODC usage by the year 2000. Recent findings of the faster-than-expected depletion of the ozone layer over the Northern Hemisphere prompted President Bush to call for the elimination of all chlorofluorocarbons (CFCs) in the U.S. by the end of 1995. In addition, the EPA has proposed legislation in compliance with the Clean Air Act of 1990 that would require warning labels on all products manufactured with Class I chemicals (CFCs, halons, methyl chloroform, and carbon tetrachloride). The effective date for this labeling is May 1993.

Alternative cleaning solvents such as terpenes have environmental and economic limitations, including:

- Environmental impacts of procuring raw materials for cleaning equipment fabrication
- Large amount of energy consumption for conversion of these raw materials into fabrication materials, cleaning machine fabrication, cleaning solvent production, and cleaning equipment operation

- Environmental impacts of disposal or reclamation of the alternative solvents
- Economic impact of equipment purchase and operation and solvent purchase, storage, and handling

Regions such as Florida and Los Angeles will not issue permits for the use of terpenes because of their impact on air quality.

No-clean soldering (sometimes referred to as self-cleaning) processes represent an ideal solution since they eliminate the need for cleaning after soldering. Elimination of solvent cleaning operations significantly reduces the emission of ODCs, reduces energy consumption, and reduces product costs. Several no-clean soldering processes have been developed over the past few years.

The no-clean solder process used by Motorola incorporates a dilute adipic acid flux for a board preparation solution to remove oxidation before soldering and a dilute formic acid vapor in a nitrogen cover blanket to inhibit oxidation during soldering. During soldering, the adipic acid evaporates and the formic acid converts to carbon dioxide (CO_2) and water (H_2O).

Military specifications and standards do not allow use of adipic acid as a fluxing material and mandate that PWBs be cleaned after soldering. Thus, in spite of successes demonstrated by commercial entities, military contractors are prevented from using these new no-clean soldering processes.

The program's purpose was to evaluate the no-clean soldering process and to determine if hardware produced by the process is acceptable for military applications. That is, determine if the no-clean process produces hardware that is as reliable as that soldered with the existing rosin-based flux solvent cleaning process.

The program is a joint effort by Motorola's Government Electronics Group (GEG), Sandia National Laboratories (SNL), and Los Alamos National Laboratory (LANL). The program was funded through a Cooperative Research and Development Agreement (CRADA) under the Department of Energy (DOE) Industrial Waste Reduction Program (IWRP). Specific objectives of the program were to:

- Evaluate the new soldering process
- Manufacture hardware using the new process
- Subject the hardware to environmental conditioning
- Perform appropriate reliability testing and analysis

Test data, findings, and conclusions will be used to support approvals of the process for military hardware applications. This report describes the no-clean soldering process and documents the experimental approach and testing methodologies employed, the results from the experimentation and analysis, and the program conclusions.

1.1 The No-Clean Soldering Process

The no-clean soldering process uses a dilute adipic acid board preparation solution coupled with a formic acid vapor in a nitrogen cover blanket in the soldering zone. Adipic acid is a white crystalline dicarboxylic acid material that is dissolved in anhydrous isopropyl alcohol for use as a flux. The typical concentration of the adipic acid for use as a board preparation material ranges from one to three percent.

Adipic acid has been used as a fluxing material for several years within the commercial electronics industry. The physical and chemical properties of adipic acid have been evaluated by several researchers to characterize the effects of the material after wave soldering. In a large number of applications, the circuit boards have not been cleaned after wave soldering. These uses range from under-hood automotive applications to cellular radio communications.

The adipic acid material used in this program was applied to the PWBs by an ultrasonic spray process. Much of the adipic acid is consumed by the soldering process, with only a small percentage of the original amount of material remaining on the circuit. During the preheat

stage, the adipic acid reacts to reduce the tin and lead oxides on the solder surface, similar to normal rosin fluxes. Small amounts of adipic acid are driven off and condense on the cooler surfaces of the machine during the preheat stage and during the wave soldering operation.

Formic acid vapor is added to the process by bubbling nitrogen through a liquid formic acid solution. The amount of formic acid vapor introduced to the machine is governed by the nitrogen flow rate. Formic acid in the nitrogen cover blanket acts as an oxygen getter, which further reduces oxide formation in the soldering zone. The formic acid decomposes into CO_2 and H_2O due to the heat of the soldering process. An additional benefit of the inert atmosphere is the reduction of dross on the solder pot.

A SEHO wave soldering machine at Motorola GEG (see Figure 1.1) was used to perform all the soldering operations. This machine has independent conveyors for flux, preheat, and solder; a dual wave (turbulent chip and laminar); and an ultrasonic spray head for the board preparation fluid. Thus, this soldering process has many controllable parameters that influence visual solder quality and ionic cleanliness.

1.2 Test Objectives

The purpose of the testing program was to verify that hardware processed on the SEHO wave soldering system using the no-clean soldering process is as reliable as products processed with rosin-based fluxes followed by solvent cleaning. The optimal SEHO machine settings for rosin-based flux soldering have previously been determined and were used to solder the boards with the rosin-based process. On the other hand, the machine settings for the no-clean process were not optimized, rather they were selected to bound the limits of solder joint quality requirements.

Ionograph cleanliness tests were used to establish acceptable levels of contamination on PWBs with respect

to military specifications. Surface insulation resistance (SIR) tests were conducted in environments selected to evaluate hardware reliability degradation over time. In addition, extra PWBs processed at the same time as the study boards were made available for evaluation studies by independent entities.

Every different PWB design requires its own unique settings of soldering process parameters to achieve optimal visual solder quality. However, no attempt was made to optimize the settings for the no-clean soldering process at this early stage of testing. Rather, experiments were conducted using a range of soldering process parameters settings to represent a *broad process window*.

E92-0453

Figure 1.1 SEHO Wave Soldering Machine at Motorola GEG in Scottsdale, AZ

The actual process settings used in the hardware fabrication were based on an experimental design. This approach provides information on how different combinations of process parameters affect solder quality and ionic cleanliness.

Specific test objectives were to demonstrate that the new no-clean soldering process could produce hardware that:

- Is within the military specification limits for ionic cleanliness and surface insulation resistance
- Does not degrade during typical product environmental conditioning
- Does not degrade with long-term storage

To meet these objectives, a series of experiments was designed by the Motorola, SNL, and LANL team. These experiments utilized three different PWBs: a nonfunctional general purpose board, a comb pattern board, and a

functional test board. Each board was selected to perform specific functions in the most cost-effective manner. All three board types were soldered in the no-clean nitrogenous mode with no subsequent cleaning. The processing included several combinations of machine settings designed to bound what is normally experienced in the production environment and encompassing a wide spectrum of product contamination level exposures. The three board types also were soldered in the conventional mode, with rosin flux, and subsequently cleaned in an in-line solvent-based system. These boards provided the baseline to evaluate the cleanliness and reliability of the proposed no-clean soldering approach.

Each test was designed to evaluate a particular failure mode that could be influenced by the wave soldering process. The tests were based on statistically designed factorial experiments so the impact of wave solder machine parameters could be evaluated. A brief overview of each of the PWBs used in the testing is now presented.

1.3 Test PWBs

Motorola Test Board

The Motorola Test Board (MTB) is a nonfunctional PWB that has been previously used by Motorola for soldering process optimization. This board was used for nonfunctional reliability evaluations and experiments that included:

- Visual examination of solder quality
- Cleanliness (ionograph) testing
- Electrical and mechanical solder joint testing after environmental conditioning (temperature-humidity cycling and temperature cycling)
- Surface analysis

The MTB used in these experiments has through-hole components. The MTB has axial, DIP, and TO-99 components. The board also has a connector attached. The MTB was designed to support soldering process optimization studies and contains numerous features, such as various hole-to-lead ratios and different ground plane-to-solder pad combinations.

IPC B-24 Board

The IPC B-24 board was used for surface insulation resistance (SIR) testing. The unsoldered board is bare copper except the gold plated connector fingers. This board contains the IPC standard SIR comb test pattern that was specifically designed for SIR testing. The pattern identifies the effects that solder parameters or materials might have on electrical resistance capabilities, such as residual surface contaminants or reactive products. The IPC B-24 was selected over the IPC B-36 board, which has an IC mounted on its surface, because soldering the IC onto the board could have introduced another contaminant.

Approximately one-half of the IPC boards were pre-cleaned before soldering to remove possible supplier contaminants. The remaining boards were soldered in their as-received condition. The IPC boards were soldered at the same time as the MTBs, with the as-received and pre-cleaned boards soldered for each of the different machine setting combinations specified by the experimental design for the MTBs. Similarly, a group of as-received and pre-cleaned boards were soldered with the rosin-based flux process and underwent solvent cleaning. In addition, some unsoldered boards in the as-received condition went through SIR testing. These boards contained supplier contaminants only. Another group of IPC boards were

conformal coated and subjected to SIR testing to evaluate the effect of the conformal coating on possible residual contaminants or reactive products.

FMU-139 Board

Long-term storage validation required a functional board whose performance could be physically measured and visually inspected after being subjected to simulated long-term storage testing. The FMU-139, a general purpose bomb fuse, was selected for this test. The FMU-139 is a high volume, high reliability, low cost, double-sided board that is 0.093 in thick. It currently is produced with the rosin-based flux solvent cleaning soldering process. The FMU-139 board also was subjected to ionograph and mechanical testing.

Test Matrix

The following test matrix lists each of the tests and indicates which of the three test boards were used as either primary (P) or secondary (S) test vehicles.

Test	FMU-139	MTB	IPC B-24
Visual Solder Defects		P	
Ionograph Cleanliness	S	P	S
SIR			P
Temperature Cycle		P	
Temperature-Humidity	S	P	
Long-Term Storage	P		
Surface Chemical Analysis		P	
Solder Joint Electrical		P	
Solder Joint Mechanical	S	P	

1.4 Experimental Design

The SEHO soldering machine has four zones: the adipic acid fluxing module, the preheat temperature zone, the wave solder zone, and the cool down zone. There are also three independently operated conveyor belts. One of these belts takes the PWB through the adipic acid fluxing module, another takes it through the preheat zone, and the last one takes it over the solder wave and out of the machine. Thus, the SEHO has many settings that can be adjusted to affect the soldering process. These settings include:

- Flux conveyor speed
- Preheat conveyor speed
- Solder conveyor speed
- Solder pot temperature
- Solder wave angle
- Turbulent wave on/off
- Adipic acid concentration
- Formic acid flow rate

Screening experiments were conducted to investigate the impact of these process parameters on solder quality and ionic cleanliness for the FMU-139 and MTBs. This investigation identified the most significant factors (parameters) affecting solder quality and cleanliness. These factors were incorporated into subsequent experimental designs for soldering the boards used with the different tests. The IPC boards were manufactured

at the same time as the MTBs and used the same experimental design factors and levels.

FMU-139

The screening experiment for the FMU-139 boards evaluated the five soldering process factors and levels shown in Table 1.1. The wave angle, solder pot temperature, and turbulent wave status were held constant. Note that time in the solder pot and preheat temperature are controlled by conveyor speeds. A half-fraction of a 2^5 factorial design (five factors at two levels) was utilized, producing a 16 cell experimental design (a cell is a unique combination of soldering process factor levels). One FMU-139 board was manufactured for each of the 16 different cells with the no-clean soldering process and then tested for ionic cleanliness and defects.

Data from these tests were analyzed with analysis of variance (ANOVA), using several statistical software packages. The ANOVA evaluates the significance of factor effects on cleanliness and defects. The most important factors, in order of significance, were:

Ionic Cleanliness:

Preheat Temperature and Time in Solder Pot

Visual Defects:

Time in Solder Pot, Preheat Temperature, and Adipic Acid Concentration

Based on these results and supplemented by further analysis, three factor level combinations for flux conveyor speed, preheat temperature, and time in the solder pot were selected to produce a wide range of cleanliness and solder quality:

1. Good solder quality and ionically clean
2. In-between solder quality and cleanliness
3. Marginal solder quality and ionically dirty (cleanliness $\geq 20 \mu\text{gm/in}^2$ equivalents of NaCl ions)

The parameters used for these three groups of boards provided a broad window of cleanliness and visual solder quality and defined the three experimental cells for the long-term storage test. A group of FMU-139 boards was soldered with the no-clean soldering process for the three different combinations of flux conveyor speed, preheat temperature, and time in the solder pot shown in Table 1.2. The adipic acid concentration and formic acid flow rate were held constant at their high levels.

MTB and IPC B-24

The initial screening experiment for the MTB involved evaluating the effects of the six process factors presented in Table 1.3. A 2^6 completely crossed factorial design was utilized, resulting in 64 different experimental cells. Two MTBs per cell were manufactured using the no-clean soldering process. These boards were visually examined for solder quality and were tested for contaminant levels in an ionograph.

Data from these tests were analyzed with ANOVA using several different software packages to evaluate the significance of factor effects on cleanliness and defects. The most significant effects, in order of significance, were:

Cleanliness

Time in Solder Pot, Preheat, and Flux Conveyor Speed

Visual Defects

Formic Acid Flow Rate and Wave Angle

Factors	Levels	
	Low	High
Flux Conveyor Speed (<i>meters/min</i>)	0.8	1.1
Preheat Temperature ($^{\circ}\text{C}$)	80	120
Time in Solder Pot (<i>sec</i>)	3	6
Adipic Acid Concentration (%)	1	2
Formic Acid Flow Rate (<i>liters/min</i>)	None	7

Table 1.1 Initial Screening Experiment Factors and Levels for the FMU-139 Board

Factors	Solder Quality and Cleanliness (Cell)		
	Good (1)	In-Between (2)	Marginal (3)
Flux Conveyor Speed (<i>meters/min</i>)	0.8	1.1	0.8
Preheat Temperature ($^{\circ}\text{C}$)	120	120	80
Time in Solder Pot (<i>sec</i>)	6	6	3

Table 1.2 No-Clean Soldering Process Settings for the Three FMU-139 Board Experimental Cells

On the basis of this screening experiment, flux conveyor speed, preheat temperature, and time in solder pot were selected as the factors to be incorporated into a 2^3 completely crossed factorial design. Adipic acid concentration, formic acid flow rate, and wave angle were fixed at their high levels. The low levels of these fixed factors did not adversely affect board cleanliness. The selected experimental design factors and the fixed factors formed an eight cell experiment and were determined to best define a broad process window for reliability testing.

Further statistical analysis indicated that a wider range specified by the levels of the three factors in the experi-

mental design should be utilized. The actual levels used for the manufacturing of the MTBs for reliability testing are shown in Table 1.4.

The eight experimental cells in the 2^3 factorial design are formed by these low and high levels of the three factors, hereafter referred to as flux, preheat, and solder. Table 1.5 lists the specific levels of the three factors for each of the eight experimental cells. These eight cells are referred to by number in the MTB and IPC B-24 sections of this report.

The next three sections summarize the test results for each of the test boards used in the experiments.

Factors	Levels	
	Low	High
Flux Conveyor Speed (<i>meters/min</i>)	0.8	1.2
Preheat Temperature ($^{\circ}\text{C}$)	90	130
Time in Solder Pot (<i>sec</i>)	1.5	4
Wave Angle (<i>deg</i>)	5	9
Solder Pot Temperature ($^{\circ}\text{C}$)	245	260
Formic Acid Flow Rate (<i>liters/min</i>)	None	7

Table 1.3 Initial Screening Experiment Factors and Levels for the MTB

Factors	Levels	
	Low	High
Flux Conveyor Speed (<i>meters/min</i>)	0.7	1.4
Preheat Temperature ($^{\circ}\text{C}$)	85	130
Time in Solder Pot (<i>sec</i>)	1	4

Table 1.4 Factors and Levels for the MTB Experimental Design

Cell	Flux	Preheat	Solder
1	Low	Low	Low
2	High	Low	High
3	Low	High	High
4	High	High	High
5	Low	Low	High
6	High	Low	Low
7	High	High	Low
8	Low	High	Low

Table 1.5 Factor Level Combinations for the Eight MTB Experimental Cells

2. MTB Test Results

Pictures of the front and back sides of the MTB appear in Figures 2.1a and 2.1b. A flow diagram of the complete testing sequence of the MTBs is presented in Figure 2.2. This sequence utilized 143 MTBs (see box 1 in Figure 2.2). Of these boards, 128 were manufactured using the no-clean soldering process, with 16 boards per each of the eight experimental cell configurations. The standard rosin-based flux/solvent cleaning process was used to produce the remaining 15 MTBs.

Motorola selected 45 of these boards for ionograph cleanliness testing and visual inspection for defects (see box 2 in Figure 2.2). The testing and inspection were performed at Motorola. These 45 boards consisted of five boards from each of the experimental cell configurations and five rosin flux soldered boards.

The remaining 98 MTBs, 11 per experimental cell and 10 rosin flux boards, underwent electrical reliability testing (box 3). Pre-test joint contact resistances (Rs) and surface leakage resistances (RI) were measured by SNL at five locations on each of the 98 boards. Of these 98 boards, eight (one per cell) were selected for surface cleanliness analysis using small area Fourier transform infrared (FTIR) spectroscopy (box 4) at LANL. The FTIR boards also served as control boards for the electrical reliability tests since they were not subjected to environmental conditioning.

The remaining 90 boards were subjected to environmental conditioning (box 5) at SNL. These boards were split into equal groups of 45 boards (five per experimental cell and five rosin flux boards) for the temperature-humidity test (box 6) and the temperature-cycle test (box 7). After the environmental conditioning, post-test joint contact resistances and surface leakage resistances were measured at the same five locations per board for the 45 temperature-humidity test boards (box 9), the 45 temperature-cycle test boards (box 10), and the eight FTIR control boards (box 8).

The MTBs were manufactured with two steel pins soldered vertically to the board. These pins were added to the board for use in mechanical pull strength testing. Forty-nine boards were selected from the different tests (boxes 2, 8, 9, and 10) for pull strength testing (box 11). These tests were conducted by SNL. The pins were pulled until they separated from the board. In addition, two resistors were selected for pull strength testing. The leads on the resistors were cut and the resistor removed from the board. One of the remaining lead *stubs* for each resistor was pulled until it either separated from the board or broke. The pull strength tests were made on a sample of 18 boards (two per cell and two rosin flux boards) from each of the two groups of boards after they had been exposed to environmental conditioning. The pins and resistors on the FTIR boards also were pulled to serve as a control group for the no-clean boards. The five rosin flux boards from the ionograph/defects testing served as a control group for the pull tests with the rosin flux boards.

A sample of two boards per cell and two rosin flux boards from each of the environmental test groups of boards was selected for post-environmental conditioning surface analysis (box 12). The surface analysis consisted of high pressure liquid chromatography (HPLC) testing and FTIR analysis and was conducted by LANL.

A few other tests conducted on additional MTBs are not shown in Figure 2.2. Eighteen MTBs, two per cell and two rosin flux, were independently evaluated for ionic cleanliness by the Navy's Electronic Manufacturing Productivity Facility (EMPF) in Indianapolis to verify Motorola's ionograph testing. Several MTBs were subjected to preliminary surface analysis at LANL and at the Electronics Packaging Technology Branch (EPTB) of the Product Assurance Division, Naval Weapons Center in China Lake, California.

Figure 2.1a The Front Side of the Motorola Test Board

Figure 2.1b The Back Side of the Motorola Test Board

Figure 2.2 Flow Diagram of the Testing Sequence for the Motorola Test Board

2.1 Ionic Cleanliness and Defects

Test Plan Summary

The ionograph cleanliness of the MTBs was evaluated by Motorola after the completion of wave soldering. This evaluation utilized a standard solvent extract resistivity test. Ionic contamination present on the boards was recorded as microgram equivalents of sodium chloride per square inch of board area, including the surface area of components on the board. An Alpha Metals Model 500 Ionograph was used to evaluate the cleanliness of the MTBs. The acceptance limit for ionic cleanliness, as stated in MIL-STD-2000A, is 20 *micrograms* per square inch equivalents of sodium chloride ions. The three purposes of this test were to:

1. Verify that PWBs soldered on the SEHO wave solder machine are within the required specification limit of 20 $\mu\text{gm}/\text{in}^2$ equivalents of *NaCl* ions.
2. Determine if any significant differences exist in ionic cleanliness between the no-clean process and the typical rosin flux cleaning process.
3. Examine and compare the cleanliness of the MTBs for each of the various wave soldering process parameter settings.

Surface evaluation of the boards also consisted of visual examination and determination of the number of defects per board. Although comparing the number of defects for the two soldering processes is of interest, it should be noted these data are highly dependent on the technician doing the examination and defect counting.

Descriptive Statistics and Data Plots

A listing of the ionograph readings and the number of defects data is given in Table A.1 in the Appendix. Table 2.1 presents descriptive statistics for the ionograph cleanliness measurements on 44 MTBs (5 boards per each of the eight test cells, less one questionable measurement in cell 1, and five rosin flux boards). The individual ionograph measurements are shown in Figure 2.3. The soldering process parameters utilized with the experimental design were set to define a broad window of possible settings. Some of these settings were selected to produce dirty boards. This is apparent in experimental cell 1 (flux, preheat, and solder at their low settings). This is the only cell that produced ionograph readings above the acceptance limit of 20 $\mu\text{gm}/\text{in}^2$ equivalents of *NaCl* ions. Several of the experimental

cells produced ionograph readings similar to those from rosin flux soldering and all five boards in cell 2 (flux and solder high, preheat low) had lower ionograph measurements than the rosin boards.

Table 2.2 gives descriptive statistics for the number of defects per board for the 45 MTBs. The individual observations are shown in Figure 2.4. Rosin boards had the lowest average number of defects. Cell 1 had the next lowest average in contrast to having the highest ionic cleanliness average.

Comparison to EMPF Ionograph Data

To corroborate and verify ionograph cleanliness results, additional ionograph testing was performed by the Navy's EMPF in Indianapolis. Two MTBs per each of the eight experimental cells and two rosin flux soldered MTBs were tested using the facility's Alpha Metals Ionograph Model 500 SM. This ionograph model employs a heated solution that should remove more contaminants and thus produce higher ionic cleanliness measurements.

A listing of the EMPF ionograph data on the MTBs is presented in Table A.2 in the Appendix. The average ionograph measurements made at Motorola and EMPF are given in Table 2.3 for the eight experimental cells and the rosin flux boards. The EMPF ionograph measurements agreed closely with the Motorola measurements and serve to verify the accuracy of the ionograph testing results.

Data Analysis

Figures 2.3 and 2.4 illustrate that the broad range of process parameter settings used with the experimental design produced a wide range of ionograph measurements and the number of defects. These plots show that the results are similar within experimental cells, but some cells are significantly different from other cells.

Analyses of variance calculations were used to characterize the effect of the three experimental design factors (flux, preheat, and solder) on ionic cleanliness and number of defects. All three main effects and all three second order interactions were significant (at $p = .05$) for the ionograph measurements. The analysis of variance on the number of defects data identified a significant third order interaction. This interaction indicates that the effect of one cell (one combination of the three main effects parameter settings) is significantly different from the other

Cell	n	Mean	Median	Stdev	Min	Max
1	4	24.45	24.7	3.96	20.4	28.0
2	5	3.70	4.0	0.92	2.2	4.5
3	5	8.02	9.3	2.04	5.5	9.6
4	5	6.78	6.8	0.85	5.9	8.1
5	5	8.04	7.8	1.18	6.9	9.6
6	5	11.60	11.3	0.89	10.8	13.1
7	5	7.70	6.6	2.07	5.8	10.5
8	5	13.64	14.2	1.44	12.1	15.4
Rosin	5	5.12	5.0	0.31	4.8	5.5

One questionable measurement value omitted

Table 2.1 Descriptive Statistics for Ionic Cleanliness ($\mu\text{gm}/\text{in}^2$ equivalents of NaCl ions)

Figure 2.3 Ionic Cleanliness Measurements

Cell	n	Mean	Median	Stdev	Min	Max
1	5	11.40	10.0	5.94	5.0	21.0
2	5	43.20	43.0	11.41	31.0	57.0
3	5	27.80	26.0	7.56	20.0	38.0
4	5	22.20	18.0	8.58	15.0	36.0
5	5	75.20	76.0	14.62	52.0	92.0
6	5	51.80	51.0	10.57	37.0	66.0
7	5	102.20	101.0	14.38	80.0	115.0
8	5	102.00	115.0	24.53	75.0	126.0
Rosin	5	4.80	2.0	4.97	1.0	12.0

Table 2.2 Descriptive Statistics for Number of Defects

Figure 2.4 Number of Defects Data

		Experimental Cell								Rosin
	n	1	2	3	4	5	6	7	8	
Motorola	5	24.45	3.70	8.02	6.78	8.04	11.60	7.70	13.64	5.12
EMPF	2	30.91	4.52	7.55	6.97	7.94	11.04	7.95	8.24	3.53

n=4, questionable value omitted

Table 2.3 Comparison of Motorola and EMPF Average Ionograph Measurements ($\mu\text{gm}/\text{in}^2$ equivalents of NaCl ions)

cells. A second set of ANOVA calculations was made after a square root transformation of the ionograph measurements and the number of defects data. These analyses gave similar results. An ANOVA also was performed with the EMPF ionograph data. These results agreed with the analyses of the Motorola ionograph data.

Conclusions

The test results based on experimental design provide useful information on how the soldering process parameter settings affect cleanliness and defects. Only cell 1 (flux, preheat, and solder all low) exceeded the ionograph machine acceptance limit. The average ionograph cleanliness of cell 2 (flux high, preheat low, and solder high) was lower than the average for the existing, optimized rosin flux soldering process. Other cells resulted in average cleanliness that was comparable to the rosin flux average. Results of the additional ionograph testing at the Navy's EMPF facility agreed with those at Motorola.

Visual defects play an important role in the assessment of solder joint quality. Defects are typically identified and counted by technicians. The precision of this count varies from technician to technician though the technicians are highly trained. This problem is well known throughout the industry. Thus, the analysis of count data should always be reviewed closely. However, the analysis of the MTB number of defects data indicated that some no-clean soldering process experimental cells had outcomes almost as good as the rosin flux process.

Statistical analysis undertaken to understand the impact of soldering process parameter settings on cleanliness and defects shows significant parameter combination effects. The results show potential for optimizing parameter settings to produce no-clean boards that are cleaner than the rosin flux boards and as defect-free. Further testing is planned to optimize the no-clean soldering process.

2.2 Contact Integrity

Test Plan Summary

The effects of aging and corrosion on the electrical integrity of the solder joints were evaluated by subjecting the MTBs to temperature-humidity and temperature-cycle testing at SNL. A modified MIL-STD-331B, Table C1-2 single-chamber method was used for the temperature-humidity testing. The temperature-cycle test was custom designed.

The overall goals of the environmental conditioning tests were to accelerate aging and chemical reaction of any corrosive residues on board surfaces and to evaluate the performance of the no-clean soldered boards relative to

the rosin flux soldered boards. Performance was evaluated by taking two electrical measurements: joint contact resistance and surface leakage resistance. Joint contact resistance was expected to increase after the environmental conditioning. Measurements were expected to remain below 1 milliohm and were measured to 10 microhm resolution. Surface leakage resistance was expected to decrease but remain greater than 20 megohms.

Pre- and post-environment electrical measurements were taken on five selected test points per board. Joint contact resistances of five resistors per board were measured using a four-point Kelvin measurement technique with

a calibrated Keithley 580 ohmmeter. Resistance was measured using two probes placed on the component leads on the front of the boards and two probes placed on the respective component solder welds on the back of the boards. The five resistors were designated as R1, R18, R127, R79, and R129 (see Figures 2.1a and 2.1b), with the first three being of the same type. Surface leakage resistance was measured from component leads to adjacent component leads for five paired resistors using a calibrated Keithley 617 programmable electrometer. The five paired resistors were designated R2/R5, R44/R45, R54/R60, R102/R103, and R143/R144. Calibration tests were made throughout the electrical testing periods on three 10 *milliohms* standards for the ohmmeter and three 10 *megohms* standards for the electrometer.

These two electrical measurements were made on 98 MTBs (11 boards from each of the eight experimental cell conditions and 10 rosin flux soldered boards). Five rosin boards and five boards from each cell were used for the temperature-humidity test. A similar group was used for the temperature-cycle test. The remaining eight boards (one per experimental cell) were selected for an FTIR analysis and were later used as a control group for the electrical resistance measurements. Joint contact and surface leakage resistances at the five test points on the 98 boards were measured following the environmental conditioning or the FTIR analysis.

Temperature-Humidity Test

The 45 MTBs chosen for temperature-humidity testing were placed vertically in plastic racks inside a climatic chamber. These boards were exposed to 339 continuous hours of simultaneous temperature and humidity cycling. During the test period, no bias was applied to the MTBs and no testing of the boards occurred. Figures 2.5 and 2.6 present the temperature cycle and relative humidity cycle profile charts for this test.

Temperature-Cycle Test

The 45 MTBs selected for the temperature-cycle test were placed vertically in racks inside a climatic chamber. During the 336-hour continuous test period, the MTBs were not biased or tested. Temperature inside the chamber ranged from -54°C to $+71^{\circ}\text{C}$, with a two-hour dwell time at temperature, two hours for temperature transition, three cycles per day, and 40 total cycles. The temperature cycle profile chart for this test is presented in Figure 2.7.

Descriptive Statistics and Data Plots

Tables containing the pre- and post-environment joint contact resistance data for the MTBs from each of the temperature-humidity, temperature-cycle, and FTIR (control) tests are presented in Tables A.3, A.4, and A.5 in the Appendix. All surface leakage resistance measurements were greater than 200 *megohms* before and after the environmental conditioning and FTIR analysis. The maximum *ohms* range of the electrometer is 200 *megohms* without using its built-in additional voltage source. However, use of the additional voltage source requires elaborate test fixturing. Since the requirement that surface leakage resistance remain greater than 20 *megohms* was met in all cases both before and after testing, the additional test fixturing needed to capture the actual measurements was not pursued. It was concluded that the environmental conditioning and the FTIR analysis had no adverse effects on surface leakage resistance. Thus, neither these data nor their descriptive statistics are included in this report.

Table 2.4 presents descriptive statistics for the joint contact resistance pre-environment measurements for the no-clean (NC) boards and the rosin flux (RF) boards. As stated previously, resistors designated R1, R18, and R127 are the same type and size. The pre-environment joint contact resistance measurements for these resistors, on both the no-clean boards and the rosin flux boards, formed data distributions not significantly different from each other. These data were thus combined to form one no-clean distribution and one rosin flux distribution. The post-environment measurements for these resistors were not significantly different and also were combined.

Dotplots of the pre-environment joint contact resistance data distributions for the three resistor types for both the no-clean boards and the rosin flux boards are presented in Figure 2.8. Each data value in a dotplot is represented by a dot placed above a horizontal line that has been scaled to the unit of measure.

The pre-environment joint contact resistance of the no-clean boards and the rosin flux boards are similar within each resistor type in Figure 2.8. Descriptive statistics for pre- and post-environment joint contact resistance measurements of the three resistor types for both the no-clean and rosin flux boards are presented in Table 2.5. The pre-environment data include all the boards prior to environmental conditioning. The post-environment data are summarized by test type. Dotplots of the pre- and post-environment data for the three resistor types are presented in Figures 2.9 through 2.11.

Figure 2.5 Temperature Cycle Profile for Temperature-Humidity Test

Figure 2.6 Relative Humidity Cycle Profile for Temperature-Humidity Test

Figure 2.7 Temperature Cycle Profile for Temperature-Cycle Test

	Board	n	Mean	Median	Stdev	Min	Max
R1, R18, R127	NC	264	192.35	190.0	19.10	150.0	240.0
	RF	30	190.33	190.0	16.50	160.0	220.0
R79	NC	88	76.02	80.0	11.60	50.0	110.0
	RF	10	80.00	80.0	8.16	70.0	90.0
R129	NC	88	102.61	100.0	15.42	70.0	130.0
	RF	10	97.00	95.0	10.59	80.0	110.0

Table 2.4 Descriptive Statistics for Pre-Environment Joint Contact Resistance (μ ohms) for the Three Resistor Types (NC = No-Clean, RF = Rosin Flux)

R1, R18, R127

No-Clean

(n=264)

Rosin Flux

(n=30)

R79

No-Clean

(n=88)

Rosin Flux

(n=10)

R129

No-Clean

(n=88)

Rosin Flux

(n=10)

Figure 2.8 Dotplots of Joint Contact Resistance (μ ohms) Measurements Prior to Environmental Conditioning

R1, R18, R127	Board	n	Mean	Median	Stdev	Min	Max
Pre-Environment	NC	264	192.35	190.0	19.10	150.0	240.0
	RF	30	190.33	190.0	16.50	160.0	220.0
Post-Temperature-Humidity Test	NC	120	192.75	190.0	17.05	150.0	240.0
	RF	15	184.67	180.0	15.52	160.0	210.0
Post-Temperature-Cycle Test	NC	120	179.83	180.0	19.49	130.0	250.0
	RF	15	165.33	160.0	14.57	140.0	190.0
Post-FTIR (Control)	NC	24	177.50	180.0	10.32	160.0	200.0

R79	Board	n	Mean	Median	Stdev	Min	Max
Pre-Environment	NC	88	76.02	80.0	11.60	50.0	110.0
	RF	10	80.00	80.0	8.16	70.0	90.0
Post-Temperature-Humidity Test	NC	40	94.00	90.0	8.71	70.0	110.0
	RF	5	92.00	90.0	8.37	80.0	100.0
Post-Temperature-Cycle Test	NC	40	95.75	95.0	9.84	80.0	120.0
	RF	5	96.00	100.0	5.48	90.0	100.0
Post-FTIR (Control)	NC	8	86.25	90.0	5.18	80.0	90.0

R129	Board	n	Mean	Median	Stdev	Min	Max
Pre-Environment	NC	88	102.61	100.0	15.42	70.0	130.0
	RF	10	97.00	95.0	10.59	80.0	110.0
Post-Temperature-Humidity Test	NC	40	103.50	100.0	10.99	80.0	130.0
	RF	5	98.00	100.0	8.37	90.0	110.0
Post-Temperature-Cycle Test	NC	40	94.50	100.0	13.39	70.0	130.0
	RF	5	88.00	90.0	4.47	80.0	90.0
Post-FTIR (Control)	NC	8	93.75	90.0	7.44	90.0	110.0

Table 2.5 Descriptive Statistics for Pre- and Post-Environment Joint Contact Resistance (μ ohms) for the Three Resistor Types

R1, R18, R127

Figure 2.9 Dotplots of Pre- and Post-Environment Joint Contact Resistance (μ ohms) for R1, R18, R127

R79

Pre-Environment

No-Clean
(n=88)

(2 points per dot)

Rosin Flux
(n=10) Post-Temperature-
Humidity TestNo-Clean
(n=40) Rosin Flux
(n=5) Post-Temperature-
Cycle TestNo-Clean
(n=40) Rosin Flux
(n=5)

Post-FTIR (Control)

No-Clean
(n=8)

Figure 2.10 Dotplots of Pre- and Post-Environment Joint Contact Resistance (μ ohms) for R79

Figure 2.11 Dotplots of Pre- and Post-Environment Joint Contact Resistance (μ ohms) for R129

The descriptive statistics and dotplots of the post-environment joint contact resistance measurements show that the environmental conditioning resulted in some resistance increases and decreases. However, the largest post-environment joint contact resistance measurement was 250 *microohms*. The dotplots show negligible differences between the no-clean and rosin flux post-environment resistances. The post-environment measurements for the three-resistor group (R1, R18, and R127) and the R129 resistor were not significantly different from their pre-environment measurements. On the other hand, the post-environment measurements for the R79 resistor did show a slight increase in resistance.

Descriptive statistics for the differences (deltas) in joint contact resistance from pre- to post-test, defined:

Post-envir resistance - Pre-envir resistance,

for the three resistor types are given in Table 2.6. The results are displayed by test type and by experimental cell. Table 2.7 presents the corresponding descriptive statistics for the FTIR (control) boards.

Tables 2.6 and 2.7 show that only small changes were noted in the average resistance. The largest increase in resistance noted on any single measurement was only 50 *microohms*. Resistance decreases of 40 *microohms* occurred several times for the temperature-cycle test. The largest increase observed for the temperature-humidity test was 30 *microohms*. This value occurred several times. The largest decrease was 30 *microohms*. The resistance deltas for the no-clean boards (in cells 1 -8) did not differ significantly from the rosin flux deltas. Most deltas for the R79 resistor were positive for all tests and all boards. However, these increases are too small to have any impact on the performance of the board. The deltas for the two tests and the three resistor types are plotted in Figures 2.12 through 2.14. The FTIR control points also are plotted in these figures for comparison.

Data Analysis

An analysis of variance was used to analyze the effects of the soldering process parameters on the pre- and post-environment resistances and the resistance deltas of the three resistor types. As previously stated, the experimental design for the MTBs was a 2³ completely crossed factorial with flux conveyor speed, preheat temperature, and time in the solder pot at their respective low and high levels. The analysis indicates which factors and factor

Temperature-Humidity

Temperature-Cycle

FTIR (Control)

Figure 2.12 Dotplots of Post - Pre Resistance Deltas (μ ohms) for R1, R18, and R127

interactions significantly affect resistance prior to environmental conditioning, resistance after environmental conditioning, and the post-pre resistance deltas.

The descriptive statistics and dotplots show little difference in the two environmental conditioning tests and show negligible environmental conditioning effects on resistance. Furthermore, the magnitudes of the resistance measurements and the resistance deltas are small and

R1, R18, R127	n	Temperature-Humidity Test					Temperature-Cycle Test				
		Mean	Median	Stdev	Min	Max	Mean	Median	Stdev	Min	Max
Cell 1	15	0.00	0.0	14.64	-30.0	30.0	-10.67	-20.0	18.70	-40.0	30.0
Cell 2	15	8.00	0.0	14.74	-10.0	30.0	-12.67	-10.0	11.00	-30.0	0.0
Cell 3	15	-4.00	0.0	12.42	-20.0	10.0	-15.33	-10.0	14.07	-40.0	0.0
Cell 4	15	-6.67	-10.0	13.45	-20.0	10.0	-17.33	-20.0	18.31	-40.0	20.0
Cell 5	15	-2.67	0.0	12.23	-30.0	20.0	-8.67	-10.0	19.22	-40.0	20.0
Cell 6	15	1.33	0.0	11.25	-20.0	20.0	-12.00	-10.0	18.59	-40.0	30.0
Cell 7	15	-3.33	-10.0	15.43	-30.0	30.0	-20.00	-20.0	10.69	-40.0	0.0
Cell 8	15	-5.33	0.0	12.46	-30.0	10.0	-10.67	-20.0	21.20	-40.0	40.0
Rosin	15	-3.33	-10.0	12.91	-20.0	30.0	-27.33	-30.0	9.61	-40.0	-10.0
R79	n	Mean	Median	Stdev	Min	Max	Mean	Median	Stdev	Min	Max
Cell 1	5	20.00	20.0	12.25	0.0	30.0	28.00	30.0	4.47	20.0	30.0
Cell 2	5	20.00	20.0	7.07	10.0	30.0	20.00	20.0	7.07	10.0	30.0
Cell 3	5	16.00	20.0	8.94	0.0	20.0	14.00	20.0	13.42	-10.0	20.0
Cell 4	5	8.00	10.0	8.37	0.0	20.0	24.00	20.0	11.40	10.0	40.0
Cell 5	5	18.00	20.0	8.37	10.0	30.0	20.00	20.0	10.00	10.0	30.0
Cell 6	5	12.00	10.0	8.37	0.0	20.0	18.00	10.0	16.43	0.0	40.0
Cell 7	5	16.00	10.0	8.94	10.0	30.0	16.00	20.0	32.10	-30.0	50.0
Cell 8	5	24.00	30.0	8.94	10.0	30.0	16.00	20.0	5.48	10.0	20.0
Rosin	5	6.00	10.0	5.48	0.0	10.0	22.00	20.0	4.47	20.0	30.0
R129	n	Mean	Median	Stdev	Min	Max	Mean	Median	Stdev	Min	Max
Cell 1	5	4.00	10.0	15.17	-20.0	20.0	-2.00	0.0	13.04	-20.0	10.0
Cell 2	5	6.00	0.0	8.94	0.0	20.0	-2.00	0.0	13.04	-20.0	10.0
Cell 3	5	2.00	0.0	13.04	-10.0	20.0	-10.00	-10.0	10.00	-20.0	0.0
Cell 4	5	-6.00	-10.0	11.40	-20.0	10.0	-16.00	-20.0	11.40	-30.0	0.0
Cell 5	5	-4.00	0.0	11.40	-20.0	10.0	-16.00	-20.0	15.17	-30.0	0.0
Cell 6	5	2.00	10.0	10.95	-10.0	10.0	-10.00	-20.0	18.71	-30.0	10.0
Cell 7	5	2.00	0.0	8.37	-10.0	10.0	-26.00	-30.0	5.48	-30.0	-20.0
Cell 8	5	0.00	0.0	12.25	-20.0	10.0	-2.00	-10.0	10.95	-10.0	10.0
Rosin	5	0.00	0.0	14.14	-20.0	10.0	-8.00	-10.0	8.37	-20.0	0.0

Table 2.6 Descriptive Statistics for the Difference in the Post-Environment and Pre-Environment Joint Contact Resistance (μ ohms) for the Three Resistor Types

	n	R1, R18, R127					R79		R129	
		Mean	Median	Stdev	Min	Max	n	Delta	n	Delta
Cell 1	3	16.67	10.0	11.55	10.0	30.0	1	20.0	1	10.0
Cell 2	3	6.67	0.0	11.55	0.0	20.0	1	20.0	1	10.0
Cell 3	3	6.67	10.0	5.77	0.0	10.0	1	30.0	1	20.0
Cell 4	3	3.33	0.0	15.28	-10.0	20.0	1	10.0	1	20.0
Cell 5	3	-23.33	-20.0	5.77	-30.0	-20.0	1	20.0	1	-20.0
Cell 6	3	-23.33	-20.0	5.77	-30.0	-20.0	1	10.0	1	-10.0
Cell 7	3	3.33	10.0	20.80	-20.0	20.0	1	20.0	1	-10.0
Cell 8	3	6.67	10.0	15.28	-10.0	20.0	1	10.0	1	10.0

Table 2.7 Descriptive Statistics for the Difference in the Post-Environment and Pre-Environment Joint Contact Resistance (μ ohms) for the Three Resistor Types on the FTIR (Control) Boards

Temperature-Humidity

Temperature-Cycle

FTIR (Control)

Figure 2.13 Dotplots of Post - Pre Resistance Deltas ($\mu ohms$) for R79

well within acceptable limits. In the presence of such small changes, determining which factors influence those outcomes is of questionable value, so these results are not presented.

Conclusions

The analysis of the test results after environmental conditioning indicated that the conditioning did not appear to impact the reliability of the MTBs. Joint contact

Temperature-Humidity

Temperature-Cycle

FTIR (Control)

Figure 2.14 Dotplots of Post - Pre Resistance Deltas ($\mu ohms$) for R129

resistance measurements on the three resistor types were all small in magnitude, both prior to and following the environmental conditioning. All surface leakage resistance measurements were greater than 200 *megohms*, well above the required 20 *megohms*. The two environmental tests had negligible effect on joint contact resistance. No significant differences were determined among the no-clean MTBs, the rosin flux boards, and the FTIR control boards. In addition, the results from the two environmental tests did not differ significantly.

2.3 Mechanical Pull Strength Test

Test Plan Summary

Some of the no-clean and rosin flux MTBs were subjected to mechanical pull strength tests at SNL. The objective of these tests was to compare the strength of the solder joints for the no-clean soldering process with that of the rosin flux process. Eighteen boards (two from each of the eight no-clean process experimental cells and two rosin flux boards) were selected for testing. The

selection was made from those MTBs that had been subjected to each of the temperature-humidity and temperature-cycle environmental tests. The eight MTBs used for FTIR testing (one per each of the eight experimental cells) and the five rosin flux MTBs used for ionograph testing were used as control boards for the comparison. These latter MTBs were not subjected to environmental conditioning.

Figure 2.15 Testing Machine Used in the Mechanical Pull Strength Test for Pulling Pins and Resistors from MTBs

Two pins .0505 *in* in diameter were soldered to the MTBs (opposite of the connector) specifically for this test. In addition, resistors R36 and R38 shown in Figure 2.1a were tested. The .0420 *in* diameter leads of these resistors were clipped and one of the remaining lead stubs was pulled. A hydraulically operated, 22,000 *lb* Material Test System Model 880 testing machine was used to exert increasing pulling force on the test pins and the resistor leads until they either separated from the board or broke. Figure 2.15 shows a MTB in the pull testing machine. Force was applied by the hydraulic actuator at the rate of 0.002 *in/sec* with the board mounted on a platen and the machine connected to a pin or component. The force, or load, (in *lbs*) at the point of failure was measured by a load cell and recorded by computer.

Descriptive Statistics and Data Plots

A listing of the pull strength data on test pins and resistors is presented in Table 3 of Appendix A. Pull strength data on the two different pins were not significantly different from each other. For the purposes of data description, plotting, and analysis, pull strength data

on the two pins are not differentiated by pin. Similarly, pull test data on the two different resistors did not differ significantly. A dotplot and descriptive statistics of the pull strength (*lbs*) of pins are presented in Figure 2.16. The dotplot and descriptive statistics of the pull strength of resistors are presented in the same figure. For comparison, the dotplots for pins and resistors in this figure are presented using the same scale and the pull strengths of pins and resistors on the rosin flux soldered boards are indicated by an asterisk (*).

The pull strength tests resulted in two modes of failure: joint separation from the board and lead breakage. The entire solder joint separated from the board socket for all pins and two-thirds of the resistors. On the remaining resistors the lead broke. *In no case did the lead pull out of the solder.* Since no solder joints failed, the pull strength data for both pins and resistors represent minimum solder joint strengths.

All pin and resistor mechanical pull strengths tests exceeded 40 *lbs*. The average pull strength was 57.28 *lbs* for test pins and 64.19 *lbs* for resistors. In addition to being larger than pin pull strengths, resistor pull

strengths were less variable. As can be seen in the figure, pull strengths for the no-clean boards were essentially the same as those of the rosin flux boards for both pins and resistors.

Figure 2.17 presents dotplots and descriptive statistics of pin pull strengths for the different boards and the different environmental tests and control boards. The pull strength of pins on the rosin flux boards are indicated by an asterisk. Average pin pull strength for the different boards and tests ranged from 53.62 *lbs* (rosin flux boards after the temperature-cycle test) to 59.35 *lbs* (the ionographed rosin flux control boards). The same types of dotplots and statistics for resistor pull strength are presented in Figure 2.18. The resistor pull strength data can be seen to be less variable than the pin data. Average resistor pull strength ranged from 62.5 *lbs* (rosin flux boards after the temperature-humidity test) to 65.03 *lbs* (no-clean boards after the temperature-cycle test).

Data Analysis and Conclusions

Mechanical pull strength testing did not produce a single solder joint failure. Every pin solder joint separated from the MTB with the joint intact. Pull tests of resistor leads either separated the solder joint from the board intact or

broke the lead without pulling the lead from the solder joint.

The lowest pull strength observed for pins and resistors was 44.3 *lbs*. This value far exceeds any minimum mechanical performance specifications. The dotplots and descriptive statistics indicate very little difference in pull strength for any experimental condition. That is, the pull strengths were very uniform for the MTBs subjected to environmental testing, the non-conditioned control MTBs, and the no-clean and rosin flux MTBs.

An analysis of variance identified soldering process parameters that had a significant impact on the pull strength test values. However, these results are not presented since the pull strengths for all combinations of soldering parameters far exceeded minimum specifications.

The mechanical testing of the MTBs determined that solder joints on the no-clean soldering process boards performed equally well as the solder joints on the rosin flux boards. No significant effects of environmental conditioning were determined for the no-clean boards of the rosin flux boards.

2.4 Surface Chemical Analysis

Surface chemical analysis procedures were performed on the MTB by LANL and by the Electronics Packaging Technology Branch (EPTB) of the Product Assurance Division at the Naval Weapons Center at China Lake, California.

LANL Analysis

Motorola test boards were surveyed at LANL for free and complexed chemical residues using several techniques. These techniques included:

- High pressure liquid chromatography (HPLC) analysis for conventional solder flux residues and free adipic acid
- A 1,1,2 Trichlorotrifluoroethane board rinse followed by an infrared (IR) examination of the CH region of the eluant for total hydrocarbon and grease determination
- Small area (10^2 - 10^4 *micron*²) optical microscopy and FTIR examination of deposits atop solder pads

The purpose of these examinations was to determine if any residues of the adipic and formic acid materials were present on the boards after soldering. The analytic determinations, using both qualitative and quantitative analysis procedures, provide information that can relate to functional electrical performance when the information is sufficient to make this association. Any degradation in electrical performance or observed performance parameters may be attributable to the effects of the different no-clean solder process parameter setting combinations (experimental cells).

It is not unusual to find trace amounts of unreacted adipic and formic acid materials present on the surface of some of the boards as a result of board design or soldering process parameters. Salts of *Pb* and *Sn* adipates and formates also might be present, as well as cyclic anhydrides of adipic acid. These tests also verified that the materials used in the rosin flux soldering process were effectively removed from the boards by the solvent cleaning.

Pin Pull Strength (lbs)

○=Rosin Flux

Sample	n	Mean	Median	Stdev	Min	Max
Total	96	57.28	57.95	6.08	44.3	74.8
No-Clean	78†	57.29	57.95	6.35	44.3	74.8
Rosin Flux	18	57.27	58.10	4.87	49.3	66.1

†Two missing data points due to pin breakage

Resistor Pull Strength (lbs)

○=Rosin Flux

Sample	n	Mean	Median	Stdev	Min	Max
Total	98	64.19	64.40	2.05	57.2	68.9
No-Clean	80	64.27	64.55	2.17	57.2	68.9
Rosin Flux	18	63.86	64.25	1.40	60.1	65.3

Figure 2.16 Dotplots and Descriptive Statistics for Pull Strength (lbs) of Pins and Resistors

Pin Pull Strength (lbs)

○=Rosin Flux

Test	Board Type	n	Mean	Median	Stdev	Min	Max
Total Sample	Both	96	57.28	57.95	6.08	44.3	74.8
Temperature-Humidity	NC	32	57.55	57.15	5.79	48.2	71.7
	RF	4	55.28	55.05	4.99	49.4	61.6
Temperature-Cycle	NC	31†	56.01	58.10	7.02	44.3	74.8
	RF	4	53.62	51.90	5.65	49.3	61.4
FTIR	NC	15†	59.35	59.10	5.80	48.9	67.0
Ionograph	RF	10	59.53	59.45	3.54	53.7	66.1

NC=No-Clean, RF=Rosin Flux

†One missing data point due to pin breakage

Figure 2.17 Dotplots and Descriptive Statistics of Pin Pull Strength (lbs) for the Different Tests

Resistor Pull Strength (lbs)

Test	Board Type	n	Mean	Median	Stdev	Min	Max
Total Sample	Both	98	64.19	64.40	2.05	57.2	68.9
Temperature-Humidity	NC	32	64.11	64.25	1.98	59.4	67.4
	RF	4	62.50	62.40	2.34	60.1	65.1
Temperature-Cycle	NC	32	65.03	65.30	1.72	60.9	68.9
	RF	4	64.08	64.35	1.03	62.6	65.0
FTIR	NC	16	63.06	64.30	2.76	57.2	66.6
Ionograph	RF	10	64.32	64.25	0.66	63.5	65.3

NC=No-Clean, RF=Rosin Flux

Figure 2.18 Dotplots and Descriptive Statistics of Resistor Pull Strength (lbs) for the Different Tests

The HPLC analysis procedure was closely based on the IPC Honeywell 355 method for conventional solder residue determinations (e.g., abietic and neoabietic acids). Though this procedure works well for conventional rosin based solder fluxes, the uncomplexed formic and adipic acids are only sparingly soluble in the acetonitrile elution solvent. Even with the limited solubility of the adipic and formic acids in the acetonitrile solvent, the procedure could very effectively determine free (uncomplexed) adipic acid concentrations down to 40 mg cm^{-2} . Eighteen boards were examined prior to environmental testing. This examination showed that the free adipic acid levels were below detection limits on all boards.

Total hydrocarbon and grease contamination levels were determined following an American Society for Testing and Materials (ASTM) method that entailed washing the solder side of the MTBs with 1,1,2 Trichlorotrifluoroethane and monitoring the absorbance of the CH stretch region in a long (0.5 - 2.0 mm) path length liquid IR cell. Only two of the 18 boards examined exhibited any detectable hydrocarbon contamination and these levels were below 2 mg cm^{-2} .

However, optical microscopy and small area FTIR examination confirmed the presence of small amounts of nonmetallic residues on the surface of the MTBs. A representative IR spectrum with an optical micrograph from a small area of a MTB processed using the no-clean method is shown in Figure 2.19.

The conventional rosin flux soldered/solvent cleaned boards generally possess bright, clean solder joints, as expected using a well refined technology. The boards soldered using the no-clean process exhibited some white deposits around the edges of the solder pads and occasionally in the center of depressed, solder-filled, plated through holes. Although a detailed discussion of this representative spectrum is beyond the scope of this report, several distinct IR features are worthy of mention. Most of the deposits examined exhibited a broad featureless vibrational band from $3000\text{-}3600 \text{ cm}^{-1}$ identified with the O-H stretch of adsorbed water, sharper bands in the $2900\text{-}3000 \text{ cm}^{-1}$ region consistent with C-H stretches, and a strong band at $1620\pm 20 \text{ cm}^{-1}$ assigned to a C=O stretch. All of these spectral features are consistent with the presence of surface functionalities that arose from carboxylic acids present in the no-clean process (e.g., formic and adipic acids).

Small area FTIR examination of the conventional rosin flux/solvent cleaned boards revealed no measurable

organic residue present. Infrared spectra recorded from residues present on the no-clean boards were noticeably different from reference spectra derived from free adipic and formic acid. This observation, coupled with the inability to remove these crystalline deposits using the 1,1,2 Trichlorotrifluoroethane wash procedure described above, suggests that the deposits arise from partial thermal degradation products of the adipic/formic acid vapor as the board moves from the no-clean process stream.

Naval Weapons Center EPTB Analysis

Several MTBs underwent an additional FTIR analysis performed by the EPTB Materials Laboratory of the Product Assurance Division at the Naval Weapons Center. Slight amounts of materials were observed on some board surfaces, but the amounts were not quantifiable. These slight residues were determined to be adipic and formic acid materials, confirming the LANL analysis. The EPTB Materials Laboratory concluded that, although minute amounts of residue were present on the boards, the materials were not present to an extent that would be considered significant and the circuits were generally considered as acceptably clean.

Conclusions

Although the surface analysis procedures were not able to quantify the amounts of residue materials present on the circuits, the materials were verified to consist of adipates and formates. Quantification of the amount of residues present would have provided additional information useful to develop a data base for further work, but at this point it was not mandatory. The extraction procedure and HPLC processes are not meant to serve as on-line process verification methods for cleanliness. Currently, there are no known limits that pertain to amounts of specific organic residue materials on PWBs after wave soldering.

Based on experiences at Motorola and elsewhere, the presence of small amounts of residue materials on the MTBs after wave soldering is not surprising. However, in the absence of any defined limits for residue materials arising from the newly emerging soldering processes, residue findings on the MTBs must be coupled with the solder quality, ionic cleanliness, SIR, and reliability testing results. The no-clean soldered boards performed excellently throughout this entire testing program. The adipic and formic acid materials appear safe for broader use as materials for the no-clean solder process.

Figure 2.19 A Representative IR Spectrum with An Optical Micrograph of the Small Area of the No-Clean MTB Indicated in the Photograph

3. IPC B-24 Test Results

A picture of the IPC B-24 board, with its four comb patterns, appears in Figure 3.1. The IPC boards were soldered at the same time as the MTBs. A flow diagram of the complete testing sequence of the IPC boards is presented in Figure 3.2. This sequence utilized 223 IPC boards (see box number 1 in Figure 3.2). One hundred and seven of these boards were cleaned prior to soldering to remove contaminants remaining from the supplier's manufacturing process. The remaining boards were soldered in their as-received condition. One hundred eighty-seven cleaned or as-received boards were manufactured using the no-clean soldering process with the eight experimental design cell soldering process parameter configurations. These 187 boards consisted of 24 boards per each of the eight experimental cells, except for two cells with 23 boards and one with 21. A group of 12 pre-cleaned and 12 as-received boards were soldered with the rosin flux process followed by a solvent cleaning. In addition, 12 unsoldered IPC boards in the as-received condition were included in the testing sequence to represent boards with supplier contaminants only.

Ninety-five boards were selected for ionograph cleanliness testing (see box 2 in Figure 3.2) at Motorola. These 95 boards consisted of five cleaned and five as-received boards from each of the eight experimental cells, five cleaned and five as-received rosin flux soldered boards, and five unsoldered boards in their as-received condition.

A similar set of 95 boards (see box 3 in Figure 3.2) underwent environmental conditioning and surface insulation resistance (SIR) testing at SNL. Surface insulation resistance measurements were made prior to environmental conditioning for each of the four comb patterns (designated *A*, *B*, *C*, and *D*) on the boards.

After pre-testing, the group of 95 boards for SIR testing was divided into two groups for two different environmental conditioning tests (see boxes 4 and 5 in Figure 3.2). The first group consisted of 18 cleaned boards (two per experimental cell and two rosin flux) and 30 as-received boards (three per experimental cell, three rosin flux, and three unsoldered). This group was subjected to environmental conditioning in a climatic chamber set at constant 85°C and 85% relative humidity (chamber *H* - high temperature). The second group, consisting of 27 cleaned boards (three per experimental cell and three rosin flux) and 20 as-received boards (two per experimental cell, two rosin flux, and two unsoldered), was

subjected to constant 50°C and 90% relative humidity (chamber *L* - low temperature). A second set of pre-test SIR measurements was made, on comb pattern *A* only, after the boards were placed in the chambers but before the start of the environmental conditioning.

The 33 remaining IPC boards were set aside as spares for additional testing (see box 6 in Figure 3.2). Based on preliminary test findings on the other boards, this spare group was conformal coated and subjected to SIR testing to evaluate the effect of the conformal coating on possible residual contaminants or reactive products. These 33 boards consisted of two pre-cleaned, no-clean boards per experimental cell, except for one cell with only one board; two as-received no-clean boards per experimental cell, except for two cells with only one board and one cell with no boards; two pre-cleaned and two as-received rosin flux boards; and two as-received unsoldered boards.

This group of 33 conformal coated boards was subjected to environmental conditioning at constant 65°C and 90% relative humidity (chamber *M* - medium temperature). This group also was pre-tested inside the chamber for comb pattern *A*. The conformal coated boards were not pre-tested outside the chamber.

The 48 boards in chamber *H* and the 47 boards in chamber *L* were subjected to 21 days of continuous conditioning at their respective temperatures and humidities (boxes 7 and 8). During the environmental conditioning, a 49.5 direct current voltage bias was applied to comb patterns *A*, *B*, and *C*. This electrical bias was continuously applied except during intermittent SIR measurements on comb pattern *A*. Patterns *B*, *C*, and *D* were not intermittently measured. Intermittent SIR measurements were taken on the following days during environmental conditioning: 1, 4, 7, 14, and 21.

The 33 conformal coated boards were subjected to 14 days of continuous environmental conditioning (box 9) with the same electrical bias used in chambers *H* and *L*. Intermittent SIR measurements were taken on comb pattern *A* on the following days during environmental conditioning: 1/3 (8 hours), 1, 2, 4, 7, and 14.

After the climatic chambers were shut off and the environment stabilized, post-test SIR measurements were taken on pattern *A* while the boards remained in the chambers (boxes 10, 11, and 12). The boards in test chambers *H* and *L* were removed from the chambers and

Figure 3.1 The IPC B-24 Board Used for Surface Insulation Resistance Testing

post-tested (box 13). This post-test included SIR measurements on all four comb patterns. The conformal coated boards were not post-tested outside the chamber.

A sample of boards from the three tests was selected for post-environmental conditioning surface failure analysis (box 14) at LANL. This sample consisted of all 18 cleaned boards and 20 of the 30 as-received boards (two of the three from each of the experimental cells and

the rosin and unsoldered boards) from chamber *H*, 18 of the 27 cleaned boards (two of the three from each of the experimental cells and the rosin boards) and all 20 of the as-received boards from chamber *L*, and all 33 conformal coated boards from chamber *M*. The surface analysis utilized electron microprobe analysis (EMPA), scanning Auger microscopy (SAM), and secondary ion mass spectroscopy (SIMS) to evaluate IPC board surface residues.

* Number of Boards

** Intermittent SIR Testing/Constant 49.5V Bias Applied

Figure 3.2 Flow Diagram of the Testing Sequence for the IPC B-24 Boards

3.1 Ionic Cleanliness

Test Plan Summary

The ionograph cleanliness of the cleaned and as-received IPC boards was evaluated by Motorola after the completion of wave soldering. This evaluation utilized the same standard solvent extract resistivity test and the same ionograph machine as used for the MTBs. Ionic contamination present on the boards was recorded as microgram equivalents of sodium chloride per square inch of board area. The same acceptance limit for ionic cleanliness of $20 \mu\text{gm/in}^2$ equivalents of sodium chloride ions was used for the IPC boards. The four purposes of this test were to:

1. Verify that the IPC boards soldered on the SEHO wave solder machine are within the required specification limit of $20 \mu\text{gm/in}^2$ equivalents of *NaCl* ions.
2. Determine if any significant differences exist in ionic cleanliness between the pre-cleaned and as-received boards and among the no-clean soldered boards, the rosin flux soldered boards, and the unsoldered boards.
3. Examine and compare the cleanliness of the IPC boards for each of the various wave soldering process parameter settings.
4. In conjunction with SIR testing, evaluate the effects of residual ionic contaminants on electrical degradation.

Descriptive Statistics and Data Plots

Listings of the ionograph readings for the cleaned and as-received IPC boards are given in Tables A.7 and A.8 in the Appendix. Table 3.1 presents descriptive statistics for the ionograph cleanliness measurements on the 45 cleaned IPC boards (five boards per each of the eight experimental cells and five rosin flux boards). A plot of the square root of the ionograph measurements for the cleaned IPC boards is shown in Figure 3.3. The square root transformation of the measurements was used to provide better separation of the lower readings and thus better indicate the grouping of readings within experimental cells. The ionograph acceptance limit is indicated in the plot by the dashed line. Descriptive statistics for the ionograph measurements of the as-received IPC boards are presented in Table 3.2. A plot of the square root of the ionograph measurements for the as-received boards is shown in Figure 3.4.

The IPC boards were manufactured according to the same experimental design as the MTBs. As stated previously, the soldering process parameters utilized with the experimental design defined a broad window of possible settings. Some of these settings were expected to produce dirty boards. For the cleaned IPC boards, all the boards in experimental cell 1 (flux, preheat, and solder at their low settings) and two of the boards in cell 6 (flux at high, preheat and solder low) had ionic cleanliness measurements that exceeded the acceptance limit of $20 \mu\text{gm/in}^2$ equivalents of *NaCl* ions. Cleaned boards in the remaining cells had cleanliness measurements well below the acceptance limit. Boards in cells 2 and 4 had the lowest measurements and were comparable to the rosin flux boards.

Ionic cleanliness measurements for the as-received IPC boards generally agreed with the results of the cleaned boards but were slightly lower. One of the as-received boards in cell 1 clearly exceeded the acceptance limit. Two other as-received boards in cell 1 and three in cell 6 were very close to the limit. As-received boards in cells 2 and 4 were again comparable to the rosin flux boards. The four (one questionable measurement was excluded) as-received boards in cell 5 (flux and preheat low, solder high) also had low readings comparable to the rosin boards. The five as-received unsoldered boards had ionic cleanliness measurements very similar to the rosin boards.

Comparison to MTB and EMPF Ionograph Data

To corroborate and verify the IPC board ionograph cleanliness results, additional cleaned and as-received IPC boards were tested by the Navy's EMPF in Indianapolis. Two cleaned and two as-received boards per each of the eight experimental cells, two cleaned and two as-received rosin flux boards, and two as-received unsoldered boards were tested at the Navy's facility. As stated previously, the EMPF uses an Alpha Metals Ionograph Model 500 SM, which employs a heated solution that should remove more contaminants.

The EMPF cleanliness data for the cleaned and as-received IPC boards are listed in Tables A.9 and A.10 in the Appendix. Table 3.3 displays average cell ionograph measurements for the cleaned and as-received IPC boards tested at the EMPF and the averages of the ionograph testing performed by Motorola. Average cell ionograph readings for the MTBs from both test sites also are presented for comparison.

Cell	n	Mean	Median	Stdev	Min	Max
1	5	28.28	30.1	5.63	20.7	34.8
2	5	0.46	0.5	0.27	0.0	0.7
3	5	2.96	2.4	1.44	1.2	4.6
4	5	0.30	0.4	0.30	0.0	0.7
5	5	3.14	3.6	2.06	0.9	5.9
6	5	19.30	17.1	5.40	12.8	25.5
7	5	1.78	2.3	0.95	0.7	2.7
8	5	3.80	3.6	2.03	1.1	6.8
Rosin	5	0.40	0.1	0.41	0.1	0.9

Table 3.1 Descriptive Statistics for Ionic Cleanliness ($\mu\text{gm}/\text{in}^2$ equivalents of NaCl ions) for Cleaned IPC B-24 Boards

Figure 3.3 Square Root of Ionic Cleanliness Measurements for Cleaned IPC B-24 Boards

Cell	n	Mean	Median	Stdev	Min	Max
1	5	20.40	20.2	6.03	14.1	29.8
2	5	0.60	0.7	0.38	0.0	1.0
3	5	2.82	2.7	1.60	1.2	5.1
4	5	0.36	0.2	0.37	0.0	0.8
5	4*	0.40	0.3	0.49	0.0	1.0
6	5	15.76	18.4	5.15	8.8	20.4
7	5	1.58	1.8	0.58	0.7	2.1
8	5	3.74	3.6	2.68	0.9	8.0
Rosin	5	0.34	0.4	0.33	0.0	0.7
Unsoldered	5	0.56	0.8	0.54	0.0	1.2

*One questionable value omitted

Table 3.2 Descriptive Statistics for Ionic Cleanliness ($\mu\text{gm}/\text{in}^2$ equivalents of NaCl ions) for As-Received IPC B-24 Boards

Figure 3.4 Square Root of Ionic Cleanliness Measurements for As-Received IPC B-24 Boards

Board	Test Site	n	Experimental Cell								R	U
			1	2	3	4	5	6	7	8		
MTB	MOT	5	24.45	3.70	8.02	6.78	8.04	11.60	7.70	13.64	5.12	
	EMPF	2	30.91	4.52	7.55	6.97	7.94	11.04	7.95	8.24	3.53	
IPC (C)	MOT	5	28.28	0.46	2.96	0.30	3.14	19.30	1.78	3.80	0.40	
	EMPF	2	29.78	0.09	2.96	0.65	0.45	18.52	1.01	2.05	0.05	
IPC (A/R)	MOT	5	20.40	0.60	2.82	0.36	0.40	15.76	1.58	3.74	0.34	0.56
	EMPF	2	39.18	0.04	3.94	0.30	0.28	19.75	2.41	10.25	0.05	0.10

C=Cleaned, A/R=As-Received, R=Rosin Flux, U=Unsoldered

n=4, questionable value omitted

Table 3.3 Comparison of Motorola and EMPF Average Ionograph Measurements ($\mu\text{gm}/\text{in}^2$ equivalents of NaCl ions) for MTBs and IPC Cleaned and As-Received Boards

The EMPF ionograph measurements agree closely with the Motorola measurements for all three board types tested and further verify the accuracy of ionograph testing results. Ionograph results for the cleaned and as-received IPC boards are quite similar to each other and both the IPC cleaned and as-received results are close to the MTB results.

Figures 3.5 and 3.6 present the MTB cell average ionograph values plotted versus the IPC cleaned and the IPC as-received cell average ionograph values. Figure 3.7 contains a plot of the IPC cleaned cell average ionograph values versus the IPC as-received cell averages. These plots contain dashed lines indicating the cleanliness acceptance limit and a 45 degree line. Cell average values that are close to each other fall close to this 45 degree line. In addition, the correlation of the two sets of average values is indicated in each plot.

The plots indicate good agreement between the average ionograph values of the MTBs and both the IPC cleaned and as-received boards. The plot of the IPC cleaned versus as-received boards shows very close agreement, with a correlation of .992. This plot also indicates that the IPC cleaned board average ionograph values are slightly higher than the as-received average values, implying that the pre-cleaning of the IPC boards resulted in ionically dirtier boards.

Data Analysis and Conclusions

Similar to the MTB ionograph results, the broad range of soldering process parameter settings used with the experimental design produced a wide range of ionograph measurements. Analysis of variance was utilized to characterize the effects of the three experimental design factors (flux, preheat, and solder) on ionic cleanliness. All three main factor effects and one second order interaction were significant for both cleaned and as-received IPC board ionograph measurements. Similar results occurred with the EMPF ionograph data. These ANOVA results were also similar to the ANOVA results on the MTB ionograph measurements.

The soldering process parameter settings clearly affect the ionograph cleanliness of the IPC boards, both cleaned and as-received, and the MTBs. Ionograph measurements for cell 1 exceeded the machine acceptance limit for the MTBs and both the cleaned and as-received IPC boards. Some measurements for cell 6 exceeded the limit for the IPC boards. None of the cell 6 measurements for the MTBs exceeded the limit. The average ionograph cleanliness of cell 2 (flux high, preheat low, and solder high) was comparable to or better than the average for the existing, optimized rosin flux soldering process for the MTBs and both the cleaned and as-received IPC boards. The average ionograph cleanliness of the

Figure 3.5 Average Cell Ionograph Readings for MTBs versus IPC Cleaned Boards

Figure 3.6 Average Cell Ionograph Readings for MTBs versus IPC As-Received Boards

Figure 3.7 Average Cell Ionograph Readings for IPC Cleaned versus As-Received Boards

unsoldered, as-received IPC boards is slightly higher than the as-received rosin flux soldered board. Cell 4 (flux, preheat, and solder all high) also produced boards with ionograph cleanliness comparable to the rosin flux boards in all cases and comparable to the unsoldered boards for the as-received IPC boards. The significant para-

meter combination effects on ionic cleanliness demonstrate potential for optimization of the no-clean soldering process. Certain parameter setting combinations result in no-clean soldered boards that are currently comparable to the rosin flux/solvent cleaning process.

3.2 Surface Insulation Resistance

Test Plan Summary

The effects of aging and corrosion on the electrical resistivity of no-clean soldered boards were evaluated through SIR testing of the IPC B-24 test pattern. Chemical reactions of contaminants and any corrosive residues remaining on the boards were accelerated through environmental conditioning inside a climatic chamber. Surface insulation resistance testing took place prior to, during, and following the environmental conditioning. A constant direct current bias of 49.5 volts was applied continuously throughout the environmental conditioning.

Surface insulation resistance testing followed procedure IPC T-650, 2.6.3.3, which defines two different test conditions for SIR testing: 85°C, 85% relative humidity (RH) and 50°C, 90% RH. The standard test period is seven days, with measurements at four and seven days to be evaluated. Figure 3.8 shows IPC B-24 boards mounted on a rack inside one of the climatic chambers.

The goals of the SIR testing and environmental conditioning were to accelerate aging and corrosion of the IPC boards and to evaluate the performance of the no-clean soldered boards relative to the rosin flux soldered boards. In addition, the effects of the two different test conditions

Figure 3.8 IPC B-24 Boards Mounted in Climatic Chamber for SIR Testing

and the pre-cleaning of supplier contaminants on electrical resistivity were to be evaluated. Performance was evaluated by taking pre- and post-test SIR measurements (outside the chamber) at the four different comb patterns on the IPC B-24 boards (patterns designated A, B, C, and D). Comb pattern A was intermittently tested throughout the environmental conditioning at time = 0 (pre-test inside the chamber), 1, 4, 7, 14, 21, and 22 (post-test inside chamber) days. A Keithley 617 programmable electrometer was used to measure the in-between finger resistance of the four printed circuit comb patterns on the IPC board. Surface insulation

resistance was expected to decrease during the environmental conditioning but remain above a MIL-STD acceptance limit of 100 *megohms*.

A group of 95 IPC B-24 boards was subjected to SIR testing and environmental conditioning. These 95 boards consisted of five cleaned and five as-received boards from each of the eight experimental cells defining the no-clean soldering process parameter settings, five cleaned and five as-received rosin flux soldered boards, and five as-received unsoldered boards. After pre-environment SIR measurement outside the chamber at the four comb

patterns, the 95 boards were divided into two groups for the two environmental test conditions. The first group of 48 boards (18 cleaned and 30 as-received) were vertically inserted into test racks placed inside climatic chamber *H* (constant 85°C, 85% RH). The second group of 47 boards (27 cleaned and 20 as-received) were placed in chamber *L* (constant 50°C, 90% RH). Pre-environment SIR was again measured at comb pattern *A* on the boards inside the chambers at ambient environment.

Surface insulation resistance was measured intermittently on comb pattern *A* throughout the 21 days of continuous environmental conditioning. Comb patterns *A*, *B*, and *C* were continuously electrically biased with 49.5 direct current *volts* during the environmental conditioning, except during SIR measurements. Post-environment SIR was measured at comb pattern *A* with the boards remaining inside the chambers and at all four comb patterns on the boards after removal from the chambers.

Preliminary results from the SIR testing of these boards identified a few from both chambers that developed a mossy film during the environmental conditioning. An additional test was planned using 33 spare, already soldered, IPC boards. These boards, consisting of 17 cleaned and 16 as-received boards, were conformal coated to evaluate the effect of the coating on residual reactive products that might have contributed to the film development on the boards. The conformal coated boards were subjected to 14 days of continuous environmental conditioning in climatic chamber *M* (constant 65°C, 90% RH). This additional environmental condition is defined by MIL-I-46058C, as referenced in Appendix A to MIL-STD-2000A. Comb pattern *A* was intermittently SIR tested at time = 0 (pre-test inside chamber), 8 hours, 1, 2, 4, 7, 14, and 15 (post-test inside chamber) days. No pre- or post-environment measurements were taken outside the chamber and comb patterns *B*, *C*, and *D* were not tested. The electrical bias of 49.5 direct current *volts* also was applied continuously during this environmental conditioning.

Descriptive Statistics

Listings of the SIR measurements ($\times 1\text{E}12\text{ ohms}$) for each of the chambers *H*, *L*, and *M* are given in Tables A.11, A.12, and A.13, respectively, in the Appendix. Descriptive statistics for the SIR measurements ($\times 1\text{E}12\text{ ohms}$) for the 18 cleaned IPC boards undergoing the environmental conditioning in chamber *H* (85°C, 85% RH) are presented in Table 3.4. The statistics are for the outside-the-chamber pre- and post-test SIR measure-

ments taken on all four comb patterns per board and for the pre-test, intermittent SIR testing (days 1, 4, 7, 14, and 21), and post-test measurements taken only on comb pattern *A* with the boards inside the chamber. The statistics are broken down by no-clean or rosin flux board type. In addition, statistics for the outside-the-chamber post-test--pre-test SIR differences (deltas) are included in the table.

Similarly, descriptive statistics for the SIR measurements ($\times 1\text{E}12\text{ ohms}$) on the 30 as-received boards environmentally conditioned in chamber *H* are presented in Table 3.5. Three of these as-received boards were unsoldered and their descriptive statistics are included in the table. Tables 3.6 and 3.7 contain the same statistics for the 27 cleaned and 20 as-received IPC boards going through chamber *L* (50°C, 90% RH).

Descriptive statistics for the 17 cleaned and 16 as-received conformal coated IPC boards environmentally conditioned in chamber *M* (65°C, 90% relative humidity) are presented in Tables 3.8 and 3.9. These statistics are for the inside chamber pre- and post-test SIR measurements ($\times 1\text{E}12\text{ ohms}$) and the intermittent measurements taken during the environmental conditioning (days 1/3, 1, 2, 4, 7, and 14). Measurements taken on the conformal coated boards were on comb pattern *A* only. The post-pre delta statistics for the conformal coated boards are based on the inside chamber post- and pre-test measurements. It should be noted that the post-test measurements on the conformal coated boards were taken after 14 days of environmental conditioning, in contrast to the 21 days of conditioning of the other boards. Therefore, the post-test and post-pre delta values and statistics for the conformal coated boards in chamber *M* represent somewhat different measures than those on the other boards in chambers *H* and *L*.

Pre-test SIR measurements for the no-clean soldered boards range from a minimum 0.072 *teraohms* to a maximum 183.248 *teraohms*. Average pre-test values for the no-clean soldered cleaned and as-received boards and the different chambers (at pre-test, different chambers are meaningless) range from 2.346 to 26.851 *teraohms*. For the rosin flux soldered boards, pre-test measurements ranged from 3.892 to 88.330 *teraohms* and the average pre-test ranged from 12.618 to 39.365 *teraohms*. The pre-test SIR measurements on the as-received unsoldered boards ranged from 12.497 to 58.780 *teraohms*, with averages ranging from 14.513 to 39.365 *teraohms*.

During the environmental testing, some SIR measurements decreased by several orders of magnitude. For no-clean soldered boards, the SIR measurements at the different

Pattern	Test	Board	n	Mean	Median	Stdev	Min	Max
A	Pre-Test	NC	16	4.450	3.465	3.931	1.022	17.782
	Outside	RF	2	49.710	49.710	54.617	11.090	88.330
	Pre-Test	NC	16	4.818	2.767	5.974	1.096	25.890
	Inside	RF	2	21.297	21.297	2.762	19.344	23.250
	Day 1	NC	16	.002	9.5E-5	.003	7.9E-6	.010
		RF	2	.006	.006	4.1E-4	.006	.006
	Day 4	NC	16	.001	.001	.001	1.6E-5	.004
		RF	2	.003	.003	3.1E-4	.003	.004
	Day 7	NC	16	.001	.001	6.8E-4	2.4E-5	.002
		RF	2	.002	.002	1.9E-4	.002	.002
	Day 14	NC	16	.001	.001	3.4E-4	3.8E-4	.001
		RF	2	.002	.002	1.4E-4	.001	.002
	Day 21	NC	16	.001	.001	2.3E-4	.001	.001
		RF	2	.002	.002	1.6E-4	.001	.002
	Post-Test	NC	16	.873	1.006	.328	1.2E-4	1.175
	Inside	RF	2	1.199	1.199	.099	1.129	1.269
B	Post-Test	NC	16	2.384	2.153	1.754	2.1E-4	7.980
	Outside	RF	2	2.695	2.695	.562	2.297	3.092
	Post-Pre	NC	16	-2.067	-1.329	4.406	-17.584	.849
	Delta	RF	2	-47.016	-47.016	54.055	-85.238	-8.793
	Pre-Test	NC	16	10.968	7.874	10.146	1.456	32.400
	Outside	RF	2	37.995	37.995	30.116	16.699	59.290
C	Post-Test	NC	16	2.079	2.069	.283	1.493	2.862
	Outside	RF	2	2.296	2.296	.434	1.989	2.603
	Post-Pre	NC	16	-8.889	-5.840	10.205	-30.329	1.019
	Delta	RF	2	-35.698	-35.698	29.682	-56.687	-14.710
	Pre-Test	NC	16	6.878	4.638	6.572	.702	22.460
	Outside	RF	2	47.146	47.146	45.558	14.931	79.360
D	Post-Test	NC	16	1.982	1.982	.260	1.487	2.435
	Outside	RF	2	2.008	2.008	.140	1.910	2.107
	Post-Pre	NC	16	-4.896	-2.677	6.423	-20.082	.995
	Delta	RF	2	-45.137	-45.137	45.419	-77.253	-13.021
	Pre-Test	NC	16	2.630	1.695	2.420	.443	8.402
	Outside	RF	2	15.310	15.310	7.168	10.241	20.378
D	Post-Test	NC	16	1.325	1.350	.229	.851	1.684
	Outside	RF	2	1.206	1.206	.215	1.054	1.358
	Post-Pre	NC	16	-1.305	-.416	2.401	-7.073	.985
	Delta	RF	2	-14.104	-14.104	6.953	-19.020	-9.187

Table 3.4 Descriptive Statistics for SIR (x1E12 ohms) for IPC Cleaned Boards, 85°C, 85% RH (Chamber H) (NC=No-Clean, RF=Rosin Flux)

Pattern	Test	Board	n	Mean	Median	Stdev	Min	Max
A	Pre-Test Outside	NC	24	16.605	12.086	13.934	1.128	59.929
		RF	3	20.200	14.145	13.779	10.485	35.970
		U	3	21.297	17.957	8.284	15.205	30.730
	Pre-Test Inside	NC	24	13.410	15.507	9.986	.379	36.424
		RF	3	17.030	19.632	4.534	11.794	19.664
		U	3	23.424	19.300	9.696	16.471	34.500
	Day 1	NC	24	.001	3.0E-4	.002	1.1E-6	.008
		RF	3	.005	.005	.001	.005	.006
		U	3	.012	.001	.002	.010	.014
	Day 4	NC	24	.001	.001	.001	1.6E-6	.003
		RF	3	.003	.003	2.0E-4	.003	.004
		U	3	.004	.004	.001	.003	.005
	Day 7	NC	24	.001	.001	4.9E-4	6.6E-5	.002
		RF	3	.002	.002	8.0E-5	.002	.002
		U	3	.002	.002	2.8E-4	.002	.003
	Day 14	NC	24	.001	.001	2.5E-4	2.3E-4	.001
		RF	3	.001	.001	5.6E-5	.001	.002
		U	3	.002	.001	1.7E-4	.001	.002
	Day 21	NC	24	.001	.001	1.9E-4	4.3E-4	.001
		RF	3	.001	.001	7.0E-5	.001	.001
		U	3	.002	.001	1.4E-4	.001	.002
	Post-Test Inside	NC	24	.900	.939	.240	.021	1.123
		RF	3	1.134	1.133	.049	1.086	1.183
		U	3	1.028	.998	.082	.965	1.121
	Post-Test Outside	NC	24	2.160	2.014	.890	.019	3.582
		RF	3	2.398	2.534	.371	1.978	2.681
		U	3	2.390	2.178	.567	1.959	3.032
	Post-Pre Delta	NC	24	-14.445	-9.865	13.822	-56.908	1.874
		RF	3	-17.802	-11.464	13.620	-33.436	-8.507
		U	3	-18.908	-15.998	8.568	-28.552	-12.173

Table 3.5 Descriptive Statistics for SIR (x1E12 ohms) for IPC As-Received Boards, 85°C, 85% RH (Chamber H) (NC=No-Clean, RF=Rosin Flux, U=Unsoldered)

Pattern	Test	Board	n	Mean	Median	Stdev	Min	Max
B	Pre-Test Outside	NC	24	24.724	18.030	35.087	1.273	183.248
		RF	3	30.650	27.930	7.756	24.620	39.400
		U	3	32.363	22.350	19.379	20.040	54.700
	Post-Test Outside	NC	24	1.933	1.936	.175	1.567	2.203
		RF	3	2.082	2.095	.043	2.034	2.118
		U	3	1.906	1.938	.088	1.807	1.974
	Post-Pre Delta	NC	24	-22.791	-16.038	35.154	-181.682	.602
		RF	3	-28.568	-25.896	7.755	-37.305	-22.502
		U	3	-30.457	-20.412	19.316	-52.726	-18.233
C	Pre-Test Outside	NC	24	11.008	9.169	6.434	.414	27.960
		RF	3	15.706	18.782	6.439	8.305	20.030
		U	3	20.594	21.610	3.758	16.433	23.740
	Post-Test Outside	NC	24	2.056	2.017	.370	1.610	3.378
		RF	3	1.877	1.878	.032	1.844	1.909
		U	3	1.738	1.718	.149	1.599	1.896
	Post-Pre Delta	NC	24	-8.952	-6.899	6.420	-25.793	1.473
		RF	3	-13.829	-16.904	6.410	-18.122	-6.461
		U	3	-18.857	-19.892	3.906	-22.141	-14.538
D	Pre-Test Outside	NC	24	8.060	5.499	7.956	.392	30.710
		RF	3	12.618	12.618	1.935	10.684	14.553
		U	3	14.513	12.551	3.445	12.497	18.490
	Post-Test Outside	NC	24	1.163	1.285	.492	.001	2.469
		RF	3	1.120	1.147	.058	1.053	1.159
		U	3	1.038	1.026	.142	.904	1.186
	Post-Pre Delta	NC	24	-6.897	-4.430	7.845	-29.401	.593
		RF	3	-11.498	-11.459	1.888	-13.406	-9.631
		U	3	-13.474	-11.593	3.317	-17.304	-11.525

Table 3.5 (continued)

Pattern	Test	Board	n	Mean	Median	Stdev	Min	Max
A	Pre-Test	NC	24	2.474	1.108	3.428	.072	14.382
	Outside	RF	3	24.997	26.950	6.425	17.822	30.220
	Pre-Test	NC	24	2.907	2.120	2.691	.288	11.459
	Inside	RF	3	20.214	17.320	6.732	15.413	27.910
	Day 1	NC	24	.217	.056	.310	7.1E-6	1.126
		RF	3	.339	.310	.355	2.5E-4	.709
	Day 4	NC	24	.261	.148	.290	8.2E-6	.841
		RF	3	.575	.663	.537	4.0E-4	1.063
	Day 7	NC	24	.237	.135	.255	6.3E-6	.703
		RF	3	.327	.372	.306	9.5E-5	.608
	Day 14	NC	24	.161	.062	.189	6.3E-6	.545
		RF	3	.219	.156	.255	4.1E-5	.499
	Day 21	NC	24	.108	.022	.138	5.8E-6	.364
		RF	3	.300	.410	.263	4.1E-5	.490
	Post-Test	NC	24	4.804	4.054	3.375	3.6E-5	9.810
	Inside	RF	3	9.252	10.825	8.575	1.9E-4	16.932
B	Post-Test	NC	24	7.617	7.647	4.130	.003	20.150
	Outside	RF	3	7.904	6.753	8.537	.001	16.957
	Post-Pre	NC	24	5.143	5.933	5.819	-7.590	20.078
	Delta	RF	3	-17.094	-17.821	6.766	-23.467	-9.993
C	Pre-Test	NC	24	7.474	4.732	8.071	.468	28.900
	Outside	RF	3	23.216	19.203	8.830	17.105	33.340
	Post-Test	NC	24	8.161	7.533	3.711	1.2E-4	16.345
	Outside	RF	3	8.999	7.191	3.412	6.872	12.934
D	Post-Pre	NC	24	.687	3.248	9.068	-28.900	10.862
	Delta	RF	3	-14.217	-9.914	10.765	-26.468	-6.269
	Pre-Test	NC	24	3.799	1.982	4.144	.221	14.762
	Outside	RF	3	21.428	21.840	4.023	17.215	25.230
E	Post-Test	NC	24	7.175	7.089	2.288	3.511	12.536
	Outside	RF	3	8.328	7.643	1.589	7.196	10.144
	Post-Pre	NC	24	3.376	3.622	4.255	-6.955	9.377
	Delta	RF	3	-13.101	-14.197	2.706	-15.086	-10.019
F	Pre-Test	NC	24	2.346	1.476	2.556	.072	8.600
	Outside	RF	3	16.915	18.596	3.486	12.907	19.242
	Post-Test	NC	24	6.719	6.572	2.434	2.963	13.603
	Outside	RF	3	9.742	10.393	1.759	7.750	11.083
G	Post-Pre	NC	24	4.373	4.574	3.316	-1.433	13.036
	Delta	RF	3	-7.173	-8.159	4.253	-10.846	-2.514

Table 3.6 Descriptive Statistics for SIR (x1E12 ohms) for IPC Cleaned Boards, 50°C, 90% RH (Chamber L)
(NC=No-Clean, RF=Rosin Flux)

Pattern	Test	Board	n	Mean	Median	Stdev	Min	Max
A	Pre-Test Outside	NC	16	10.572	7.759	8.756	1.105	28.380
		RF	2	24.043	24.043	17.150	11.916	36.170
		U	2	39.065	39.065	7.361	33.860	44.270
	Pre-Test Inside	NC	16	10.499	7.557	8.540	.965	28.640
		RF	2	18.999	18.999	6.437	14.447	23.550
		U	2	13.408	13.408	.127	13.318	13.498
	Day 1	NC	16	.868	.066	2.343	4.3E-6	9.530
		RF	2	.287	.287	.230	.124	.449
		U	2	1.069	1.069	.065	1.023	1.114
	Day 4	NC	16	1.026	.101	2.960	5.9E-6	12.052
		RF	2	.678	.678	.331	.444	.913
		U	2	1.024	1.024	.014	1.014	1.034
	Day 7	NC	16	.904	.181	2.577	4.7E-6	10.512
		RF	2	.629	.629	.171	.508	.750
		U	2	.764	.764	.005	.761	.767
	Day 14	NC	16	.797	.154	2.471	2.2E-5	10.035
		RF	2	.567	.567	.024	.550	.584
		U	2	.525	.525	.002	.523	.526
	Day 21	NC	16	.747	.068	2.447	6.9E-6	9.907
		RF	2	.454	.454	.013	.445	.463
		U	2	.432	.432	.009	.426	.439
	Post-Test Inside	NC	16	6.475	6.849	6.007	1.0E-4	25.500
		RF	2	11.449	11.449	.131	11.356	11.541
		U	2	10.073	10.073	2.389	8.384	11.762
	Post-Test Outside	NC	16	6.181	6.137	3.745	.001	12.809
		RF	2	8.390	8.390	.779	7.839	8.940
		U	2	6.823	6.823	1.445	5.801	7.844
	Post-Pre Delta	NC	16	-4.391	-4.345	9.703	-21.991	9.728
		RF	2	-15.654	-15.654	17.929	-28.331	-2.976
		U	2	-32.243	-32.243	8.805	-38.469	-26.016

Table 3.7 Descriptive Statistics for SIR (x1E12 ohms) for IPC As-Received Boards, 50°C, 90% RH (Chamber L) (NC=No-Clean, RF=Rosin Flux, U=Unsoldered)

Pattern	Test	Board	n	Mean	Median	Stdev	Min	Max
B	Pre-Test Outside	NC	16	26.851	19.648	25.381	1.715	79.480
		RF	2	25.762	25.762	12.202	17.134	34.390
		U	2	39.365	39.365	27.458	19.949	58.780
	Post-Test Outside	NC	16	6.704	7.293	3.073	.161	12.528
		RF	2	8.044	8.044	2.338	6.390	9.697
		U	2	6.735	6.735	1.278	5.831	7.639
	Post-Pre Delta	NC	16	-20.146	-12.087	25.027	-71.179	6.577
		RF	2	-17.719	-17.719	14.540	-28.000	-7.437
		U	2	-32.630	-32.630	28.736	-52.949	-12.310
C	Pre-Test Outside	NC	16	8.530	8.668	5.871	.414	20.620
		RF	2	40.915	40.915	8.846	34.660	47.170
		U	2	16.409	16.409	3.531	13.912	18.906
	Post-Test Outside	NC	16	6.502	7.294	3.223	1.3E-5	10.615
		RF	2	7.850	7.850	2.834	5.846	9.854
		U	2	6.416	6.416	1.442	5.396	7.435
	Post-Pre Delta	NC	16	-2.028	-2.530	5.724	-10.262	8.087
		RF	2	-33.065	-33.065	6.012	-37.316	-28.814
		U	2	-9.994	-9.994	2.090	-11.471	-8.516
D	Pre-Test Outside	NC	16	5.179	4.453	3.157	.359	11.003
		RF	2	11.971	11.971	11.425	3.892	20.050
		U	2	20.334	20.334	1.933	18.967	21.700
	Post-Test Outside	NC	16	8.240	6.956	4.985	3.537	24.630
		RF	2	8.822	8.822	1.339	7.875	9.769
		U	2	6.889	6.889	1.640	5.729	8.048
	Post-Pre Delta	NC	16	3.061	1.662	6.753	-4.267	24.271
		RF	2	-3.149	-3.149	10.086	-10.281	3.983
		U	2	-13.445	-13.445	3.572	-15.971	-10.919

Table 3.7 (continued)

Pattern	Test	Board	n	Mean	Median	Stdev	Min	Max
A	Pre-Test Inside	NC	15	15.084	14.718	3.847	8.694	22.020
		RF	2	8.174	8.174	2.736	6.239	10.108
	8 Hours	NC	15	.002	.003	.001	.001	.004
		RF	2	.002	.002	8.3E-5	.002	.003
	Day 1	NC	15	.003	.003	.001	.001	.005
		RF	2	.003	.003	3.6E-4	.003	.004
	Day 2	NC	15	.003	.004	.002	.001	.006
		RF	2	.004	.004	.001	.004	.005
	Day 4	NC	15	.004	.003	.002	.002	.006
		RF	2	.005	.005	.001	.004	.006
	Day 7	NC	15	.004	.003	.002	.001	.007
		RF	2	.005	.005	.001	.004	.006
	Day 14	NC	15	.004	.004	.001	.002	.006
		RF	2	.005	.005	.001	.004	.006
	Post-Test Inside	NC	15	13.117	13.845	4.131	.265	16.620
		RF	2	12.330	12.330	.515	11.966	12.694
	Post-Pre Delta	NC	15	-1.967	-1.813	4.700	-13.411	4.557
		RF	2	4.157	4.157	3.251	1.858	6.455

Table 3.8 Descriptive Statistics for SIR (x1E12 ohms) for IPC Conformal Coated, Cleaned Boards, 65°C, 90% RH (Chamber M) (NC=No-Clean, RF=Rosin Flux)

Pattern	Test	Board	n	Mean	Median	Stdev	Min	Max
A	Pre-Test Inside	NC	12	13.246	13.465	4.017	6.991	20.001
		RF	2	11.851	11.851	4.022	9.007	14.695
		U	2	16.095	16.095	.241	15.924	16.265
	8 Hours	NC	12	.002	.002	.001	3.0E-4	.003
		RF	2	.003	.003	1.5E-4	.003	.003
		U	2	.003	.003	2.6E-4	.003	.003
	Day 1	NC	12	.002	.002	.001	.001	.005
		RF	2	.004	.004	2.8E-5	.004	.004
		U	2	.005	.005	.001	.004	.005
	Day 2	NC	12	.003	.003	.002	.001	.006
		RF	2	.004	.004	.001	.004	.005
		U	2	.006	.006	.001	.006	.006
	Day 4	NC	12	.004	.003	.002	.001	.006
		RF	2	.005	.005	4.7E-4	.004	.005
		U	2	.006	.006	.001	.006	.007
	Day 7	NC	12	.004	.003	.002	.002	.006
		RF	2	.005	.005	.001	.005	.006
		U	2	.006	.006	.001	.006	.007
	Day 14	NC	12	.004	.003	.001	.002	.006
		RF	2	.005	.005	4.6E-4	.005	.005
		U	2	.006	.006	.001	.005	.006
	Post-Test Inside	NC	12	14.888	15.143	1.800	11.604	17.818
		RF	2	10.044	10.044	1.737	8.815	11.272
		U	2	14.039	14.039	1.336	13.094	14.983
	Post-Pre Delta	NC	12	1.642	1.690	2.909	-3.309	6.727
		RF	2	-1.808	-1.808	2.285	-3.423	-.192
		U	2	-2.056	-2.056	1.095	-2.830	-1.282

Table 3.9 Descriptive Statistics for SIR (x1E12 ohms) for IPC Conformal Coated, As-Received Boards, 65°C, 90% RH (Chamber M) (NC=No-Clean, RF=Rosin Flux, U=Unsoldered)

days ranged from 0.0000011 to 12.052 *teraohms* and averages ranged from 0.001 to 1.026 *teraohms*. The rosin flux boards had SIR readings that ranged from 0.000041 to 1.063 *teraohms* and averages from 0.001 to 0.678 *teraohms* during testing. The SIR measurements during the testing of unsoldered boards ranged from 0.001 to 1.114 *teraohms* and averaged 0.002 to 1.069 *teraohms*.

After the environment in the chambers was discontinued, almost all of the SIR measurements increased, some by several orders of magnitude, to close to pre-test levels. Some post-test SIR measurements increased to higher values than at pre-test. However, a few SIR readings remained low. The post-test SIR range for no-clean soldered boards was 0.000013 to 24.63 *teraohms* and the averages ranged from 1.163 to 8.240 *teraohms*. For rosin flux boards, the post-test range was 0.001 to 16.957 *teraohms* and the averages ranged from 1.120 to 9.74 *teraohms*. Post-test measurements of the unsoldered boards ranged from 0.904 to 8.048 *teraohms* and averaged 1.038 to 6.889 *teraohms*.

Data Plots

The actual SIR measurements ($\times 1E12$ *ohms*), by experimental cell, for the cleaned and as-received boards for each of the three chambers are presented in a series of plots from pre-test through post-test in Figures 3.9 through 3.18. Due to the large order-of-magnitude differences of the measurements over time, the SIR data are plotted on log scale. Data points for the no-clean boards are plotted using experimental cell symbols. The rosin and unsoldered board measurements are denoted by R and U. Each of the plots contains a dashed line indicating the MIL-STD acceptance limit of 100 *megohms*.

Figure 3.9 contains nine plots (pre-test outside and inside; days 1, 4, 7, 14, and 21; and post-test inside and outside) of the individual SIR measurements on comb pattern A for the cleaned boards in chamber H. Pre- and post-test measurements outside the chamber on comb patterns B, C, and D for the cleaned boards in chamber H are presented in the six plots in Figure 3.10. Plots of the measurements from the as-received boards in chamber H are presented in Figures 3.11 and 3.12. Figures 3.13 through 3.16 contain plots of the measurements for the cleaned and as-received boards in chamber L. The cleaned and as-received conformal coated board SIR measurements are presented in eight plots (pre-test inside chamber; days 1/3, 1, 2, 4, 7, and 14; and post-test inside chamber on comb pattern A only) in each of Figures 3.17 and 3.18.

The data plots and descriptive statistics show that, for given measurement times and within the same chambers and cleaned or as-received groups, the SIR measurements on the no-clean boards, rosin flux boards, and unsoldered (as-received) boards are relatively similar. In general, the outside chamber pre-test measurements agreed closely with the inside chamber measurements. However, once the climatic chambers were turned on, the SIR values declined, in some cases severely. Most of the lowest SIR measurements were observed at the first day of environmental conditioning. By the fourth day, most of these low readings had already started to increase. These lower readings continued to increase gradually over the course of the testing. However, the higher SIR measurements at day 1 of testing tended to remain at approximately the same value or to decrease slightly over the remainder of the testing.

The 8-hour test time on the conformal coated boards in chamber M was included in this later test to provide some information on when the SIR readings reach their lowest values. As can be seen in the 8-hour plots in Figures 3.17 and 3.18, the measurements appear to be at their lowest values in comparison to the other test times. It appears that SIR readings are most adversely affected during the first 24 hours of environmental conditioning.

A clear effect of test chamber is evident in the SIR data plots. All boards in the high temperature chamber H had lower and less variable readings than the boards in the low temperature chamber L from day 1 through post-test. In fact, all but a few SIR measurements on the boards in chamber H converged as the testing progressed. Boards in chamber L had day 1 through day 21 readings that, for the most part, were not nearly as low as those from chamber H. The chamber L measurements were also more variable and did not converge over time as in chamber H. However, just as in chamber H, there were a few readings on days 1, 4, and 7 from chamber L that were below the MIL-STD limit of 100 *megohms*.

Conformal coated boards in chamber M had SIR measurements that also decreased once the environmental conditioning started, but to values higher than those from chamber H and lower than those from chamber L. Most of the chamber M SIR readings remained close to their initial lowest readings at the 8-hour test time, with slight increases over the testing duration. The SIR measurements from this chamber were less variable than the other two chambers, except for when the chamber H values converged. None of the chamber M measurements on the conformal coated boards were below the 100 *megohm* limit.

IPC Cleaned, Test Conditions 85°C, 85% RH

Figure 3.9 Pattern A SIR Measurements (x1E12 ohms) by Experimental Cell for IPC Cleaned Boards, 85°C, 85% RH (dashed line = MIL-STD limit)

IPC Cleaned, Test Conditions 85°C, 85% RH

Figure 3.9 (continued)

IPC Cleaned, Test Conditions 85°C, 85% RH

Figure 3.10 Patterns B, C, and D SIR Measurements (x1E12 ohms) by Experimental Cell for IPC Cleaned Boards, 85°C, 85% RH (dashed line = MIL-STD limit)

IPC As-Received, Test Conditions 85°C, 85% RH

Figure 3.11 Pattern A SIR Measurements (x1E12 ohms) by Experimental Cell for IPC As-Received Boards, 85°C, 85% RH (dashed line = MIL-STD limit)

IPC As-Received, Test Conditions 85°C, 85% RH

Figure 3.11 (continued)

IPC As-Received, Test Conditions 85°C, 85% RH

Figure 3.12 Patterns B, C, and D SIR Measurements (x1E12 ohms) by Experimental Cell for IPC As-Received Boards, 85°C, 85% RH (dashed line = MIL-STD limit)

IPC Cleaned, Test Conditions 50°C, 90% RH

Figure 3.13 Pattern A SIR Measurements (x1E12 ohms) by Experimental Cell for IPC Cleaned Boards, 50°C, 90% RH (dashed line = MIL-STD limit)

IPC Cleaned, Test Conditions 50°C, 90% RH

Figure 3.13 (continued)

IPC Cleaned, Test Conditions 50°C, 90% RH

Figure 3.14 Patterns B, C, and D SIR Measurements (x1E12 ohms) by Experimental Cell for IPC Cleaned Boards, 50°C, 90% RH (dashed line = MIL-STD limit)

IPC As-Received, Test Conditions 50°C, 90% RH

Figure 3.15 Pattern A SIR Measurements (x1E12 ohms) by Experimental Cell for IPC As-Received Boards, 50°C, 90% RH (dashed line = MIL-STD limit)

IPC As-Received, Test Conditions 50°C, 90% RH

Figure 3.15 (continued)

IPC As-Received, Test Conditions 50°C, 90% RH

Figure 3.16 Patterns B, C, and D SIR Measurements (x1E12 ohms) by Experimental Cell for IPC As-Received Boards, 50°C, 90% RH (dashed line = MIL-STD limit)

IPC Conformal Coated, Cleaned, Test Conditions 65°C, 90% RH

Figure 3.17 Pattern A SIR Measurements (x1E12 ohms) by Experimental Cell for IPC Conformal Coated, Cleaned Boards, 65°C, 90% RH (dashed line = MIL-STD limit)

IPC Conformal Coated, Cleaned, Test Conditions 65°C, 90% RH

Figure 3.17 (continued)

IPC Conformal Coated, As-Received, Test Conditions 65°C, 90% RH

Figure 3.18 Pattern A SIR Measurements (x1E12 ohms) by Experimental Cell for IPC Conformal Coated, As-Received Boards, 65°C, 90% RH (dashed line=MIL-STD limit)

IPC Conformal Coated, As-Received, Test Conditions 65°C, 90% RH

Figure 3.18 (continued)

The day 4 and day 7 SIR measurements are the particular days to be evaluated with the 100 *megohm* limit according to the test procedure IPC T-650, 2.6.3.3. The most measurements falling below the 100 *megohm* limit was nine of the 18 cleaned boards in chamber *H* on day 1 (see day 1 in Figure 3.9). By day 4, all but two measurements were above the limit. Only one reading was below the limit at day 7 and all were above the limit at day 14 and following. However, one post-test measurement did not increase to the pre-test range and remained just above the limit. The as-received boards in chamber *H* displayed almost the same number of measurements below the limit on these days as the cleaned boards in chamber *H*.

Results from chamber *L* were quite different from those in chamber *H*. Measurements throughout this test have a wide range and have more variability. The cleaned boards had two measurements below the limit at day 4 and three at day 7, including one *rosin flux board* (see Figure 3.13). These three measurements remained below or near the limit throughout the testing. The outside chamber post-test plot in this figure shows that two of the measurements did not recover to the pre-test range, but were above the limit. One of these boards was the *rosin flux board*. Measurements on the as-received boards in chamber *L* were similar to the cleaned

boards, with one measurement below the limit at both day 4 and day 7 (see Figure 3.15). This one measurement remained below the limit until the outside post-test.

Chamber *M* SIR board measurements displayed the least amount of variability (see Figures 3.17 and 3.18), which may have been partially due to the conformal coating of the boards. None of the cleaned or as-received conformal coated boards in chamber *M* had any measurements that decreased below the 100 *megohm* limit.

The plots of the post-test outside chamber *H* measurements for patterns *A*, *B*, *C*, and *D* (see Figures 3.9 through 3.12) exhibit the convergence of the SIR readings after undergoing the high-temperature conditioning, except for a few poor performing boards. After the low-temperature conditioning in chamber *L*, post-test SIR measurements had less variability than the pre-test measurements and did converge, but not as uniformly as with chamber *H*. Again, there were a few poor performing boards at the outside post-test. The post-test (inside chamber) plots of the medium-temperature conditioning in chamber *M* (see Figures 3.17 and 3.18) also exhibit the convergence of the SIR readings for both the cleaned and as-received boards. One of the cleaned conformal coated boards performed worse than the others at the post-test, but was well above the limit.

Cleaned versus As-Received

Boards soldered with the no-clean process in their as-received condition had higher pre-test SIR measurements than the no-clean soldered boards that were pre-cleaned prior to soldering. Figure 3.19 contains a plot of the outside chamber pre-test SIR measurements, by experimental cell, for the 95 boards (not conformal coated) before being placed in chambers *H* or *L*. Measurements are plotted in this figure with symbols indicating whether the boards were cleaned (C) or as-received (A). The horizontal line in the plot across the eight no-clean process experimental cell columns represents the median pre-test SIR value for these boards. The numbers of cleaned and as-received pre-test measurements above and below the median form a 2 x 2 contingency table that can be used to test the significance of the association of higher SIR measurements with no pre-cleaning of the boards.

	Cleaned	As-Received	
Above Median	7	33	40
Below Median	33	7	40
	40	40	80

The chi square value for this table is 33.8, which is significant at $< .0001$, indicating significantly higher pre-test SIR values associated with not cleaning the boards before soldering.

This relationship does not appear to exist for the rosin flux soldered boards (see Figure 3.19). If pre-cleaning the boards somehow introduces other contaminants onto the boards, the solvent cleaning of the rosin flux soldering process probably removes them. Thus, the pre-cleaned and as-received rosin flux boards perform similarly at pre-test. The unsoldered boards (as-received only) had pre-test measurements similar to the other as-received board measurements.

Dotplots of the pre-test SIR measurements for the cleaned and as-received boards are presented in Figure 3.20. The dotplots show the two different distributions of pre-test values, with the higher distribution of measurements for the as-received boards.

Once the environmental conditioning began, the primary factor influencing SIR was test chamber. The effect of

cleaned versus as-received, as experienced with the pre-test SIR, disappeared at day 1 and was not present thereafter. That is, there was negligible difference between the cleaned and as-received boards after the start of environmental testing.

Conformal Coating

Conformal coating of boards had an effect on pre-test SIR and eliminated any differences between the cleaned and as-received boards. Figure 3.21 presents a plot of inside pre-test SIR measurements, by experimental cell, for the entire set of 127 IPC boards tested. Measurements are plotted in this figure with a symbol denoting the conformal coated boards (C) and the boards not conformal coated (M). As can be seen in the figure and in the pre-test SIR measurement dotplots for the two groups of boards in Figure 3.22, conformal coating resulted in somewhat higher and less variable pre-test SIR.

Again, once the environmental conditioning began, the primary factor influencing SIR was test chamber. Conformal coating did not appear to have an effect on SIR after the start of environmental testing.

Comparison of Chambers

Figures 3.23 through 3.32 present plots of SIR, by experimental cell, with measurements differentiated by test chamber symbols *L*, *M*, and *H*, and SIR dotplots by chamber for test times at days 1, 4, 7, 14, and 21. As can be seen in the figures, SIR is inversely proportional to test chamber temperature throughout the environmental conditioning. In addition, the plots demonstrate the convergence, or smoothing, of the measurements over time, especially for the chamber *H* and *M* measurements, and display the higher variability of the chamber *L* measurements. The few poor performing boards can also be seen in the plots. Note that Figures 3.31 and 3.32 contain plots of the *L* and *H* chamber measurements only, since the conformal coated boards were not tested at day 21.

A similar plot and dotplots of inside chamber post-test SIR for all three chambers are presented in Figures 3.33 and 3.34. The return of SIR to close to pre-test levels is displayed in these figures. Post-test measurements of the conformal coated boards in chamber *M* were mostly higher than those from the other chambers, but the conformal coated boards were environmentally conditioned for only 14 days. Boards in chambers *L* and *H* were tested for 21 days.

Pattern A Pre-Test Outside Chamber

Figure 3.19 Pattern A Pre-Test Outside Chamber SIR (x1E12 ohms) by Experimental Cell (C=Cleaned, A=As-Received)

Cleaned

As-Received

Figure 3.20 Dotplots of Log of Pattern A Pre-test Outside Chamber SIR (x1E12 ohms) for Cleaned and As-Received Boards

Figure 3.21 Pre-Test Inside Chamber SIR (x1E12 ohms) by Experimental Cell (C=Conformal Coated, N=Not Conformal Coated)

Figure 3.22 Dotplots of Log of Pre-Test Inside Chamber SIR (x1E12 ohms) for Not Conformal Coated and Conformal Coated Boards

Figure 3.23 Day 1 SIR (x1E12 ohms) by Experimental Cell

Figure 3.24 Dotplots of Log of Day 1 SIR (x1E12 ohms) for Chambers L, M, and H

Figure 3.25 Day 4 SIR (x1E12 ohms) by Experimental Cell

Figure 3.26 Dotplots of Log of Day 4 SIR (x1E12 ohms) for Chambers L, M, and H

Figure 3.27 Day 7 SIR (x1E12 ohms) by Experimental Cell

Figure 3.28 Dotplots of Log of Day 7 SIR (x1E12 ohms) for Chambers L, M, and H

Figure 3.29 Day 14 SIR (x1E12 ohms) by Experimental Cell

Figure 3.30 Dotplots of Log of Day 14 SIR (x1E12 ohms) for Chambers L, M, and H

Day 21

Figure 3.31 Day 21 SIR (x1E12 ohms) by Experimental Cell

Chamber L

Chamber H

Figure 3.32 Dotplots of Log of Day 21 SIR (x1E12 ohms) for Chambers L and H

Figure 3.33 Post-Test Inside Chamber SIR (x1E12 ohms) by Experimental Cell

Figure 3.34 Dotplots of Log of Post-Test Inside Chamber SIR ($\times 1E12$ ohms) for Chambers *L*, *M*, and *H*

Outside chamber post-test SIR measurements on comb pattern A only, for chambers *L* and *H* are plotted in Figures 3.35 and 3.36 and clearly demonstrate the difference between the effects of the low and high temperature testing on SIR. Post-test measurements from chamber *L* were higher and more variable than those from chamber *H* and still displayed some experimental cell influence. The high test temperature of chamber *H* appears to have stressed the boards to the point that most of them performed almost exactly alike at post-test.

Figures 3.37 and 3.38 contain a plot and dotplots showing the chamber effect on the inside post-pre delta SIR for all three chambers. Again, higher chamber temperatures produced larger (negative) delta SIR. The same chamber effect is displayed in the pattern A outside chamber post-pre delta SIR plots, for chambers *L* and *H*, shown in Figures 3.39 and 3.40.

Outside chamber pre-test and post-test SIR measurements on comb patterns *B*, *C*, and *D* were mostly similar

to the measurements on comb pattern A. The same effect of higher pre-test SIR with as-received boards, on the combined set of all four comb patterns, is shown in the dotplots in Figure 3.41. Outside chamber post-test SIR measurements of the combined patterns are displayed in the total sample dotplot in Figure 3.42. The two spikes in the distribution of post-test measurements are attributable to the two chambers, with chamber *H* resulting in lower SIR.

Dotplots of the outside chamber post-pre delta SIR for the set of combined comb patterns are presented in Figure 3.43. The first dotplot in the figure is of the deltas of the logs of post- and pre-test SIR and displays the deltas in terms of orders of magnitude. Actual post- and pre-test measurement deltas are shown in the second dotplot. The deltas ranged from -181.7 *teraohms* to 24.3 *teraohms*. Only thirteen of the deltas were decreases of more than two orders of magnitude. The highest decrease was by more than five orders of magnitude. As can be seen in the figure, several boards actually had higher post-test readings than at pre-test.

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Figure 3.35 Pattern A Post-Test Outside Chamber SIR (x1E12 ohms) by Experimental Cell

Figure 3.36 Dotplots of Log of Pattern A Post-Test Outside Chamber SIR (x1E12 ohms) for Chambers L and H

Figure 3.37 Post-Pre Inside Chamber Delta SIR (x1E12 ohms) by Experimental Cell

Figure 3.38 Dotplots of Post-Pre Inside Chamber Delta SIR (x1E12 ohms) for Chambers L and H

Figure 3.39 Pattern A Post-Pre Outside Chamber Delta SIR (x1E12 ohms) by Experimental Cell

Figure 3.40 Dotplots of Pattern A Post-Pre Outside Chamber Delta SIR (x1E12 ohms) for Chambers L and H

Pre-Test Outside Chamber - Patterns A, B, C, and D Combined

Total Sample

Cleaned

As-Received

Figure 3.41 Dotplots of Log of Pre-Test Outside Chamber SIR (x1E12 ohms) for Patterns A, B, C, and D Combined

Post-Test Outside Chamber - Patterns A, B, C, and D Combined **Figure 3.42 Dotplot of Log of Post-Test Outside Chamber SIR (x1E12 ohms) for Patterns A, B, C, and D Combined**

Post-Pre Outside Chamber Delta - Patterns A, B, C, and D Combined

Figure 3.43 Dotplots of Log Post-Log Pre and Post-Pre Outside Chamber Delta SIR ($\times 10^{12}$ ohms) for Patterns A, B, C, and D Combined

Relationship of Ionic Cleanliness to SIR

The relationship of ionic cleanliness to SIR was evaluated by calculating the correlation of average ionic cleanliness with average SIR per each of the eight no-clean soldering process experimental cells and the rosin flux group of boards. Plots of average ionic cleanliness versus average SIR were also produced to display the relationship.

As stated previously, the eight experimental cells defined a broad process window of levels of board cleanliness for the no-clean process. Some of the no-clean process parameter combinations that define the cells were known to produce dirty boards. The ionic cleanliness testing of the MTBs and IPC B-24 boards demonstrated the wide range of cleanliness of the boards. Ionic cleanliness results were found to be consistent for the MTBs and the cleaned and as-received IPC boards. Because the MTBs are test boards designed for this kind of testing, their ionic cleanliness results were used to examine the relationship to SIR.

Some of the ionic cleanliness results were significantly higher than the majority of the others and the square roots of the MTB ionograph measurements were used to provide better separation of the lower measurements. Similarly, because the SIR measurements spanned several orders of magnitude, the log of cell average SIR was utilized. Nonparametric rank correlations were used to eliminate possible effects of differences in the units of measure of ionic cleanliness and SIR.

Figures 3.44 through 3.49 present plots of the average square root of the MTB ionograph measurements versus the log of the average of the SIR measurements ($\times 10^{12}$ ohms) per each of the experimental cells and the rosin flux group of boards. The symbol used in the plots is the experimental cell number (R denotes rosin flux). Each of these figures contains six plots, one for each of the six common testing times across the three test chambers *L*, *M*, and *H* (pre-test inside; days 1, 4, 7, and 14; and post-test inside). The six figures containing the six plots are for the cleaned and as-received boards within chambers *H*, *L*, and *M*, respectively.

Within each plot, the rank correlation of the average cleanliness measure with the average SIR measure is identified. It was anticipated that dirtier boards (higher ionograph measurements) would result in lower SIR measurements. Correlations approaching -1.0 indicate this relationship exists and closer to 0.0 indicate no relationship. Correlations in the plots identified with an

asterisk (*) are significant (at a level of significance of $p = .05$).

Some surprising and inconsistent results are displayed in the figures. Pre- and post-test SIR are not affected by ionic cleanliness. Only one post-test (as-received boards in chamber *L*, Figure 3.47) and no pre-test correlations of cleanliness with SIR are significant. However, ionic cleanliness has a strong inverse relationship with SIR once the environmental conditioning begins, especially at day 1 and day 4. Five of the six plots show significantly correlated (inversely) measures at both day 1 and day 4. Four of the day 7 and three of the day 14 plots display significant relationships.

As expected, correlations that involve the SIR measurements that converge over time for the high temperature chamber *H* decrease with the convergence. The boards in the low temperature chamber *L*, with higher and more variable SIR readings than the other chambers, have higher correlations and have more significant correlations at days 7 and 14 than chambers *M* and *H*.

Analysis and Conclusions

Several analyses of variance were performed to investigate any significant factor effects on SIR. In most cases, the ANOVA results confirmed the influence of factors identified in the previous plots. Whether boards are pre-cleaned before soldering is the most influential factor affecting pre-test SIR. After the environmental conditioning begins, this factor effect is no longer present and chamber is the most significant factor. Chamber is the only significant factor effect on post-test SIR.

Attempting to determine significant factor effects on SIR measurements during the environmental conditioning led to inconsistent results. This inconsistency is not surprising given the relationship of ionic cleanliness to the SIR measurements during the environmental testing. All three experimental design factors strongly influenced ionic cleanliness, which in turn influences most of these SIR measurements.

Analysis of the correlations between sequential SIR measurement times indicated that the pre-test outside was highly correlated with pre-test inside the chamber, which was expected. However, there is no correlation between pre-test measurements and day 1 measurements. From day 1 through the last day of testing (day 21, or day 14 for conformal coated boards), the SIR measurements are strongly correlated. Correlations between the last day of testing and the post-test measurements are

IPC Cleaned, Test Conditions 85°C, 85% RH

Figure 3.44 Average Square Root of MTB Ionograph ($\mu\text{gm}/\text{in}^2$) versus Average IPC SIR (x1E12 ohms) for Cleaned Boards, 85°C, 85% RH (Chamber H) (*=significant rank correlation at .05 significance level)

IPC As-Received, Test Conditions 85°C, 85% RH

Figure 3.45 Average Square Root of MTB Ionograph ($\mu\text{gm}/\text{in}^2$) versus Average IPC SIR ($\times 1\text{E}12$ ohms) for As-Received Boards, 85°C, 85% RH (Chamber H) (*=significant rank correlation at .05 significance level)

IPC Cleaned, Test Conditions 50°C, 90% RH

Figure 3.46 Average Square Root of MTB Ionograph ($\mu\text{gm}/\text{in}^2$) versus Average IPC SIR ($\times 1\text{E}12$ ohms) for Cleaned Boards, 50°C, 90% RH (Chamber L) (*=significant rank correlation at .05 significance level)

IPC As-Received, Test Conditions 50°C, 90% RH

Figure 3.47 Average Square Root of MTB Ionograph ($\mu\text{gm}/\text{in}^2$) versus Average IPC SIR (x1E12 ohms) for As-Received Boards, 50°C, 90% RH (Chamber L) (*=significant rank correlation at .05 significance level)

IPC Conformal Coated, Cleaned, Test Conditions 65°C, 90% RH

Figure 3.48 Average Square Root of MTB Ionograph ($\mu\text{gm}/\text{in}^2$) versus Average IPC SIR (x1E12 ohms) for Conformal Coated, Cleaned Boards, 65°C, 90% RH (Chamber M) (*=significant rank correlation at .05 significance level)

IPC Conformal Coated, As-Received, Test Conditions 65°C, 90% RH

Figure 3.49 Average Square Root of MTB Ionograph ($\mu\text{gm}/\text{in}^2$) versus Average SIR ($\times 1\text{E}12$ ohms) for Conformal Coated, As-Received Boards, 65°C, 90% RH (Chamber M) (n=0 for Cell 5) (*=significant rank correlation at .05 significance level)

insignificant. Further, there is no correlation between pre-test and post-test SIR measurements. Even though the post-test readings increase to approximately the same range as their pre-test readings, the post-test values are not dependent on what the pre-test values were.

Several conclusions were reached through SIR testing and analysis of the IPC B-24 cleaned and as-received boards with the three test chamber conditions:

- The average SIR within any experimental cell for each of the cleaned or as-received boards and for each chamber exceeded the MIL-STD limit of 100 megohms at each testing time.
- There were a few poor performing boards that fell below this limit, including one rosin flux soldered board.
- All of the boards had acceptable SIR readings at the end of the test.
- The poor performing boards appeared to be independent of the soldering process, process parameter combinations, pre-cleaned or as-received boards, and the test chamber conditions.
- As-received no-clean soldered boards had higher initial SIR measurements than the no-clean boards that were cleaned before soldering.
- During and following the environmental conditioning, test chamber temperature had the largest influence on SIR, with higher temperatures resulting in lower SIR, and there was no difference between the pre-cleaned and as-received boards.
- Most of the high temperature test chamber SIR measurements converged to about the same value over time during the testing and at the post-test.
- The low temperature test chamber SIR measurements, in addition to being mostly higher than the high temperature measurements, were much more variable.
- Ionic cleanliness does not affect pre- or post-test SIR.
- Average ionic cleanliness is strongly correlated with average SIR measurements during the environmental conditioning.
- Pre-test SIR measurements are not correlated with SIR measurements taken during the environmental conditioning, the SIR measurements during the testing are not correlated with post-test measurements, and the pre-test measurements are not correlated with the post-test measurements.
- Conformal coated boards had higher average initial SIR readings with less variability than the pre-test SIR measurements on the other boards and had no poor performing boards with SIR measurements below the 100 megohm limit.

In summary, the no-clean soldered boards were within military specifications for SIR testing and compared favorably to the rosin flux soldered boards for all stages of the SIR testing and analysis. With SIR test results from no-clean boards equivalent to the results from rosin flux boards and considering that the rosin flux/solvent cleaning soldering process has been fine-tuned and optimized, the no-clean soldering process achieved a high level of performance.

3.3 Surface Chemical Analysis

LANL Analysis

A set of six IPC B-24 PWBs were examined by LANL following SIR testing to determine the presence of chemical residues and to assess whether these residues reflected differences between SIR test cell results. The IPC boards examined were those that displayed lowered resistance values during and at the end of the temperature-humidity environmental testing program. Figure 3.11 displays the SIR measurements for two of these boards, the cell 3 and cell 8 as-received boards in chamber *H* that had SIR among the lowest at days 1, 4, and 7 and lowest at post-test. Three of the six boards were the cell

3, cell 8, and rosin flux cleaned boards in chamber *L*, shown in Figure 3.13, that had the lowest SIR throughout the testing. The remaining board examined was the cell 1 as-received board in chamber *L*, shown in Figure 3.15, that had the lowest SIR throughout the testing.

The analytical procedure began with an optical micrograph examination, followed by electron microprobe analysis (EMPA), secondary ion mass spectroscopy (SIMS), and scanning Auger electron spectroscopy (AES) of selected target areas of the less desirable IPC boards. Only a representative case will be discussed but, in general, the

Figure 3.50 Magnified View of Suspect SIR Board (a) 7x, (b) 40x, (c) Ion-induced Secondary Electron Image of Corrosion Deposit

set of six less desirable IPC boards all had regions of similar surface corrosion and contamination.

Shown in Figure 3.50 are optical micrographs and a secondary electron image of a typical corrosion deposit. Figure 3.51 shows a composite photograph containing SIMS elemental maps of the elemental contaminants of

one of the corrosion deposits. The elemental image maps clearly show the inhomogeneous presence of *Pb* and *Sn*. Copper and potassium are evident as well as a number of common impurities (*Na*, *Ca*-not shown) that are typically found following water evaporation. Of note, is the increase in the *Pb* ion yield over a specific region of the solder runner and a decrease in the *Sn* ion yield in the same region.

Figure 3.51 SIMS Elemental Maps of Corrosion Deposit Shown in Figure 3.50c

In general, the SIR PWBs that displayed these corrosion deposits always had some level of *Cu* underneath or mixed in with a rather thick (many microns deep) mixed *Pb* and *Sn* oxide layer. Frequently the *Pb* and *Sn* oxide regions were found between the comb runners, with the *Pb* in greater chemical abundance than found in the source solder. Any realistic moisture content would lead to noticeably lower resistance values or even a potential eventual electrical short. Assuming that the SIR boards did not possess any observable gross initial defects, the

source of the deposits was most likely the process water contamination level at the *end* of the test and the environmental chamber surfaces with which the water came into contact during the testing.

Visual examination of the six affected SIR PWBs clearly indicated that comb pattern A of the IPC B-24 board had the highest density of corrosion defects. The fact that this portion of the test board was typically run with an applied potential suggests that the predominant mode

of corrosion deposits was driven by an electrochemical process. The no-clean soldering process IPC boards and the conventional rosin flux/solvent cleaned boards were simultaneously run in the environmental test chamber. Unfortunately, this makes it impossible to assess whether the observed corrosion deposits were influenced by adipic and formic acid residues being picked up in the humidity in the chamber, or if the corrosion was solely due to electrochemical migration caused by the presence of a thin film of water on the board surface.

Electrochemical Migration in SIR Testing

Data on the effects of electrochemical migration in SIR testing has been published by Dr. Jack Brous of Alpha Metals. These results indicate that SIR testing is very sensitive to the presence of small amounts of water. The electrochemical migration is thought to be a direct result of water droplets condensing from the humid chamber environment onto the comb pattern surfaces. The droplets form the solute in which any ionizable material may dissolve, forming the electrolyte necessary for current flow between opposing electrode pairs. The resulting electrical path provides the vehicle for the electrical force to form metal dendrites, which develop quickly when under bias voltage.

The level of bias voltage to use with SIR testing has recently been under debate. Higher voltages usually cause the dendrites to be blown off and reformed several

times during the course of a "wet" SIR test. This phenomenon has been documented by other researchers through observation and recording with strip chart recorders, which plot current spikes throughout the SIR test process. As the dendrites grow across the free space to the conductors, they eventually blow apart like a small fuse, causing a small current spike. Data gathered on electrochemical migration indicate that it may occur repeatedly during the course of any SIR test.

Conclusions

Corrosion and residues observed on the six poor performing IPC boards appear consistent with electrochemical migration and other SIR testing experiences. The average SIR values of the no-clean soldered IPC boards in the different parameter setting combinations were all within military specifications, though these boards contained small amounts of residues. It is strongly emphasized that one of the rosin flux/solvent cleaned SIR boards displayed a prominent corrosion short of similar chemical composition to that shown in Figure 3.50. The 21-day SIR test used in this testing program was extensive, especially in comparison to the normal 7-day SIR test, and contributed to the corrosion development. Results from this extensive SIR testing show that the no-clean soldered IPC boards compared favorably to the optimized rosin flux boards. The no-clean process boards were also found to have ionic cleanliness comparable to the rosin flux boards.

4. FMU-139 Test Results

One of the major goals of the evaluation of the no-clean process was to determine if the adipic and formic acid materials affected the electrical function of PWBs during a simulated long-term storage test. It was of interest to determine if the elimination of cleaning the circuit boards after the no-clean wave soldering process had any impact on the performance of the PWB. This issue needs to be addressed before the no-clean process can be considered for widespread application.

The FMU-139 PWB, an electrically functional bomb fuse, was selected as the test vehicle for long-term storage testing. This PWB is a high volume product that has been produced by Motorola for over eight years. There is a significant amount of environmental test data available for the FMU-139 based on evaluations during its life history. These data were based on the standard rosin flux soldering process and can serve as a reference to determine the effects of the adipic and formic acid process.

The wave solder processing parameters for the FMU-139 test boards were based on the results of previous screening experiments conducted for the evaluation of the no-clean process. The no-clean soldering process used adipic and formic acids as the fluxing agents, with *no cleaning* of the boards after wave soldering. The soldering process parameters and settings were defined by the three experimental cells given in Table 1.2. These three combinations of solder process parameters were selected to produce boards with good, in-between, and marginal solder quality and ionic contamination.

Ten FMU-139 boards were selected for ionograph testing at Motorola. These boards consisted of four boards from experimental cell 1 (good solder quality and ionically

clean) and two boards from each of experimental cells 2 (in-between) and 3 (marginal). The remaining two boards were soldered with the traditional rosin flux process and solvent cleaned.

Two groups of FMU-139 bomb fuse boards were subjected to long-term storage testing. One group of 40 boards was in its as-soldered condition. These 40 boards consisted of ten boards from each of three different no-clean soldering process parameter combinations. The other ten boards in the group of 40 were soldered with rosin flux and solvent cleaned with methyl chloroform. The second group consisted of eight boards that were soldered with the no-clean process and then overcoated with a conformal coat. These boards were tested to evaluate the effects of the no-clean process on conformal coated boards.

A set of five FMU-139 boards was selected for post-environmental test surface analysis at LANL. These five boards were from the first set of 40 boards (not conformal coated) and had the poorest visual appearance and electrical performance following the long-term storage test.

Twelve FMU-139 PWBs were tested for solder joint mechanical pull strength. Eight of these boards (two from each of the three no-clean process experimental cells and two rosin flux soldered boards) had been subjected to long-term storage testing. The remaining four boards (one from each experimental cell and one rosin flux board) were from the ten boards that had been ionograph tested. These four boards were not long-term storage tested and served as control boards for the pull strength testing. Two components on each board were mechanically pulled to evaluate the strength of the solder joints and to compare the strength of the joints of the two soldering processes.

4.1 Ionic Cleanliness

Test Plan Summary

The ionic cleanliness of the FMU-139 boards was evaluated by Motorola after the completion of wave soldering. This evaluation utilized the same standard solvent extract resistivity test and the same ionograph machine as used for the MTBs and IPC B-24 boards.

The same ionic contamination acceptance limit of 20 $\mu\text{gm}/\text{in}^2$ equivalents of NaCl ions was used for the FMU boards. The four purposes of this test were to:

1. Verify that the FMU boards soldered on the SEHO wave solder machine are within the required specification limit of 20 $\mu\text{gm}/\text{in}^2$ equivalents of NaCl ions.

2. Determine if any significant differences exist in ionic cleanliness between the no-clean soldered boards and the rosin flux soldered boards.
3. Examine and compare the cleanliness of the FMU boards for each of the three wave soldering process parameter setting combinations.
4. In conjunction with long-term storage testing, evaluate the effects of residual ionic contaminants on electrical functionality over and beyond simulated, typical product shelf-life.

Descriptive Statistics and Data Plots

Ionograph measurements for the FMU boards are listed in Table A.14 in the Appendix. Table 4.1 presents descriptive statistics for the ionograph cleanliness measurements on the ten FMU boards. Four of these boards had been soldered with experimental cell 1 parameter settings (good solder quality and ionically clean). Two boards had been soldered for each of experimental cells 2 (in-between solder quality and cleanliness) and 3 (marginal solder quality and cleanliness). Two rosin flux/solvent cleaned FMU boards also were tested for ionic cleanliness.

A plot of the ionograph measurements for these ten FMU boards is shown in Figure 4.1. The cleanliness acceptance limit of $20 \mu\text{gm}/\text{in}^2$ is indicated by a dashed line in the figure. The wide range of cleanliness produced by the three no-clean experimental cells is displayed in the figure.

As expected, the two cell 3 boards had ionic cleanliness measurements which exceeded the acceptance limit. Ionic cleanliness measurements of the four cell 1 boards were all well within the acceptance limit and almost as low as the measurements on the optimized rosin flux boards. The two cell 2 boards had cleanliness measurements identical to the two middle cell 1 measurements. Since cell 2 was expected to produce boards with solder quality and cleanliness *between* the cell 1 (good) and cell 3 (marginal) solder quality and cleanliness, the cell 2 readings are encouraging.

Conclusions

Ionic cleanliness of the FMU-139 boards was clearly affected by the no-clean soldering process parameter settings. Cell 3 parameter settings produced boards with ionograph measurements that exceeded the acceptance limit. Cells 1 and 2 produced boards with quite low cleanliness readings that were comparable to the cleanliness measurements of the rosin flux/solvent cleaned boards.

Two of the three no-clean soldering process parameter setting combinations produced boards that were well within the ionic cleanliness acceptance limit and nearly as clean as the optimized rosin flux soldered boards. Since the no-clean soldering process parameter settings are easily controlled, optimization of the no-clean process could potentially result in boards as clean or cleaner than the rosin flux/solvent cleaned boards. Further testing is planned to optimize the no-clean process.

Cell	n	Mean	Median	Stdev	Min	Max
1	4	3.85	3.65	1.09	2.8	5.3
2	2	3.65	3.65	0.50	3.3	4.0
3	2	27.05	27.05	4.17	24.1	30.0
Rosin	2	1.25	1.25	0.78	0.7	1.8

Table 4.1 Descriptive Statistics for FMU-139 Ionic Cleanliness ($\mu\text{gm}/\text{in}^2$ equivalents of *NaCl* ions)

Figure 4.1 FMU-139 Ionic Cleanliness Measurements

4.2 Long-Term Storage Test

Test Plan Summary

The long-term storage test conditions of 80°C and 40% relative humidity for the evaluation were developed in a series of consultations with industry experts for accelerated testing. These conditions simulate 20 yrs of storage in a time frame of 2522 hrs (105* days).

The FMU-139 board is designed for 10 yrs of storage. However, the length of the test was extended to simulate 20 yrs of storage. This longer testing period provided an opportunity to examine the process margin. Reliability engineers at Motorola consulted with Nicholas Lycoudes, Motorola Reliability Department of the Integrated Circuit Division, Mesa, AZ to develop the accelerated test program. The technical basis for selecting the test parameters can be found in an article by Mr. Lycoudes in the October 1978 issue of *Solid State Technology*. The test conditions were confirmed with information published in the 1980 *IEEE Proceedings of Reliability & Maintainability Symposium* by E. W. Kimball of Martin

Marietta, Orlando, entitled "Accelerated Vs. Real Time Aging Tests."

The Eyring model for accelerated life testing, based on a modified Arrhenius rate equation, was utilized to calculate the test times. With test conditions of 80°C and 40% relative humidity, test times were calculated using the following equation:

$$t_2 = t_1 \exp \left[\left(\frac{\phi}{K} \right) \left(\frac{1}{T_2} - \frac{1}{T_1} \right) \right] \\ \times \exp \left[\beta \left(\frac{1}{RH_2} - \frac{1}{RH_1} \right) \right] \frac{A Ec_2}{A Ec_1}$$

where

- t_2 = Accelerated Test Time
- t_1 = Simulated Time (20 yrs)
- ϕ = Activation Energy (eV)

K = Boltzmann's Constant ($8.63 \times 10^{-5} \text{ eV/K}$)
 T2 = Accelerated Aging Temperature (K)
 T1 = Normal Temperature (K)
 β = Humidity Acceleration Constant
 RH2 = Accelerated Aging Relative Humidity (%)
 RH1 = Normal Relative Humidity (%)
 A = Voltage Acceleration Constant
 Ec2 = Accelerated Elec. Field in Corrosion Region (V)
 Ec1 = Normal Electric Field in Corrosion Region (V)

The values selected for the test acceleration factors were derived from industry standard accepted values based on work presented by others in the industry.

After wave soldering, the FMU-139 boards were placed in a Dispatch Temperature-Humidity Chamber (Model LEA 1-69). The internal dimensions of the test chamber are 19.5 in high by 20.5 in deep by 23.5 in wide. Eighteen and one-half megohm conductivity reverse osmosis water fed the chamber to provide the humidity for this test. An aluminum support rack was used to hold the boards during the testing. The boards were loaded into the support rack suspended by anodized aluminum rods. The rods were inserted through holes in the PWB's used for board assembly. The boards were separated from each other by anodized aluminum spacers inserted on the rod between boards. This arrangement allowed the boards to be held in an upright position.

Electrical testing was performed on all of the boards at specific intervals during the temperature-humidity testing. The boards were removed from the test chamber for electrical function testing at intervals of 126 hrs, 1260 hrs, 1639 hrs and 2522 hrs. These times correspond to simulated lifetimes of 1 yr, 10 yrs, 13.3 yrs, and 20 yrs, respectively. At each testing time, the boards were removed from the temperature-humidity chamber and allowed to dry for 1 to 2 hrs and then placed in antistat bags until they were electrically tested.

Test Results

All boards were electrically functional after 126 hrs, 1260 hrs, and 1639 hrs of testing. However, sometime after the 1639 hr testing, the environmental chamber float control failed. The float failure caused the top cover of the chamber to fill with water that subsequently dripped onto some of the test boards. This dripping water resulted in increased humidity in the chamber, perhaps as high as 100%, while the temperature remained at 80°C. These increased test conditions increase the simulated life to beyond the intended 20 yrs. Depending

on the exact time of the float control malfunction, the simulated life could easily have exceeded 100 yrs of simulated storage. Since the float control failure was not noted until it was time to make the 2522 hr end of test evaluation, the exact time of failure cannot be determined, nor can the number of simulated years.

The boards were electrically tested per the normal test procedure at the end of 2522 hrs. Three of the adipic and formic acid processed units failed the electrical testing. A visual examination of the boards revealed that a specific diode type (ceramic bodied) failed. This examination also revealed evidence of dripping water on the ceramic bodied diodes. Ceramic bodied diodes on two control boards soldered with the rosin flux also showed significant signs of corrosion around the leads of the diode at the interface with the ceramic body of the component. Both of these boards had white streaks running from the circuit area, indicating these boards had been subjected to a significant presence of water while under test. Similar diodes on other boards in the test chamber not in the drip area did not fail or corrode. Only boards under the dripping water exhibited problems from either corrosion or electrical failure and, of those few boards, the problem was local to one specific component type (a ceramic bodied diode) for all of the failure modes.

This single component type failure indicates that a specific diode type is susceptible to failure when subjected to the conditions that were present when the test chamber controls failed. No other components, such as the resistors, capacitors, glass bodied diodes, ICs, or inductors, exhibited any sign of corrosion or leakage. Generally, the solder joints and components looked good after the 2522 hr test. This is noteworthy considering the significant acceleration of test conditions that occurred during the last phase of the test.

Those ceramic bodied diodes that corroded or failed electrically were subjected to an extensive failure analysis consisting of electrical, visual, and destructive physical analysis (DPA). Photographs of diodes from tested boards are shown in Figures 4.2a, 4.2b, and 4.2c. Figure 4.2a shows one of the diodes that failed at electrical test (from one of the boards under the drip zone). The heavy corrosion products around the diode and the neighboring circuitry provide evidence of the presence of substantial amounts of water in that region. Figure 4.2b shows one of the diodes that was soldered with rosin flux and solvent cleaned. This diode showed signs of corrosion at the end of the component and was on a board that was under the water drip zone. Figure 4.2c shows a diode from one of the boards soldered with the adipic and formic acids

Figure 4.2 (a) Failed No-Clean Diode in the Drip Zone, (b) Rosin Flux Soldered Diode, (c) No-Clean Diode not in the Drip Zone

that was not under the water drip zone. There is no corrosion present on the board or on the diode.

Surface chemical analysis was performed on the failed diodes at LANL. The analysis started with an electron microprobe analysis (EMPA) and secondary ion mass spectroscopy (SIMS) to determine what chemical elements were present in the corroded areas. The DPA of the diodes consisted of evaluation by metallurgical cross section using visual microscopic methodology and EMPA to determine the cause of the failures. The electrical failures were attributable to lead seal failure with moisture penetrating along the axis of the lead/package interface. Corrosion products consistent with this type of failure mode were found along the diode leads in the area where there should be a complete seal of the package around the lead wires.

No other components failed or showed evidence of any type of problem. Even with the significant environmental overstress, the test results provided valuable positive information regarding the benign nature of the adipic/formic acid no-clean soldering process. Those boards that were not under the dripping water functioned perfectly at the end of the 2522 *hr* (simulated 20 *yr*) test.

Repeat of the Long-Term Storage Test

The surface chemical analysis supported the conjecture that water had dripped directly onto the suspect diode during the test. To provide further evidence that the observed failures were due to the malfunction of the test chamber, the long-term storage test was repeated at Motorola and at Sandia. The temperature remained at 80°C for this test, but the relative humidity was increased to 50%. The modified Arrhenius rate equation shows that this change produces 20 *yr*s of simulated storage in approximately 20 days of testing.

The test at Motorola utilized 20 FMU-139 boards comprised of five boards in each of four groups. Three of the groups were soldered with the no-clean process with different process settings. The remaining group was soldered with the traditional rosin-flux solvent cleaning process. Each of these boards had four of the suspect diodes. These boards were tested for 534 *hrs* at 80°C and 50% relative humidity and for 20 *hrs* at 80°C and 62% relative humidity. The increase in relative humidity for 20 *hrs* was due to a minor malfunction of the test chamber. This higher humidity had a net impact of increasing the simulated storage time to 21.8 *yr*s.

The suspect diodes on these boards were electrically tested prior to the start of the long-term storage testing and at 5, 10, 16.8, and 21.8 *yr*s of simulated storage. All of the boards passed each of these tests. The amount of corrosion observed on the diodes was small. Corrosion also was found on conventionally soldered boards and even on diodes on control boards that were not subjected to accelerated aging.

The test at Sandia utilized five FMU-139 boards and 19 MTBs on which several of the suspect diodes were soldered. This test was performed during a 26-day period. The chamber was shut down at various times during this period for testing after 5, 10, 15, and 20 *yr*s of simulated storage. The chamber was set at 80°C and 50% relative humidity throughout the test. Each of the four suspect diodes on the FMU-139 boards were electrically tested. Selected diodes on some of the MTBs also were tested. The results of all of these tests showed no problems with the suspect diode. A microscopic examination of the diode at the end of the test showed the diode to be in excellent condition with only a small amount of corrosion.

These test results support the conclusion that a chamber malfunction was responsible for the failures that occurred during the first long-term storage test.

Conformal Coated FMU-139 PWBs

A group of eight FMU-139 no-clean boards were overcoated with a urethane conformal coat for circuit boards. These boards were coated without cleaning after wave soldering. After curing they were then electrically tested as specified in MIL-I-46058, which chain references back to Method 106 in MIL-STD-202. The test conditions called out in this specification require 240 *hrs* of testing at 65°C and 90% relative humidity.

The boards subjected to this testing did not show any signs of deterioration of conformal coating on the boards or corrosion of any components. All circuits functioned electrically as they should have without problems.

Conclusions

The results from the long-term storage tests demonstrate that adipic and formic acids are materials that are safe and beneficial to the no-clean wave soldering process. Prior to the overtest, the products soldered with the adipic and formic acid materials had substantially exceeded the 10 *yr* product design criteria by a 30% margin. The use of an inert nitrogen atmosphere provides an environment where low solids adipic acid can successfully and safely

serve as a no-clean flux. The solder joints obtained with the adipic/formic acids have the same high quality visual appearance of solder joints formed with rosin fluxes. The

adipic/formic materials do not degrade circuit performance and the residues do not require cleaning.

4.3 Surface Chemical Analysis

A set of five FMU-139 boards were examined by LANL for chemical residues following the long-term storage test at Motorola. These boards were selected on the basis of poor visual characteristics and in some cases poor functional electrical performance following the environmental testing. In all cases the suspect portion of the board was always centered around a particular diode type and from boards that clearly displayed evidence of water dripping down one side of the PWB.

A photomicrograph of the region of the PWB with the suspect diode is shown in Figure 4.2a. Note the obvious chemical residues in the immediate vicinity of the board. These deposits were characterized by EMPA, Auger electron spectroscopy (AES), and SIMS mapping (see Figure 4.3b) and were found to consist of aluminum silicates with high levels of molybdenum oxide. The molybdenum oxide residue is unusual in that it has not been observed in previously analyzed PWBs retrieved from environmental test chambers. The source of this unusual contaminant was traced to the interior of the suspect diode.

A microsection of the questionable diode type was performed from a board that under optical examination displayed initial corrosion attack. The corrosion pathway was traced to water and humidity penetration at the point where the solder cap, the covering ceramic and the diode interior material (*Mo* metal) meet (see Figures 4.3a and 4.3b). A cross section of the suspect diode is shown in Figure 4.3a. This cross section consists of a *T*-shaped *Cu* cup with solder pockets flanking the *T* on both sides. A white region composed of pure *Mo* appears above the

T. A porous *ZnO* ceramic diode body material appears on either side of this component.

The ceramic coating was visually observed to be porous and could, in principle, retain adipic and formic acid residues resulting from the no-clean solder process. In practice only the diodes that clearly displayed water dripping on them had the prominent corrosion attacks. For conformal coated boards the corrosion displayed by this type of board is not evident. The diode clearly was not meant to see this type of service.

A SEM of the region contained in the small dark circle on the middle right hand side of Figure 4.3a is shown with a 1500X magnification in Figure 4.3b. The light region at the top of Figure 4.3b is the solid *Mo* body and the bottom portion is the top right hand *Cu* corner of the *T*-shaped cross section. The mottled center portion is a biphasic *Cu-P* region inherent in the manufacture of the diode. The lighter portion of the mottled region is *P* rich. Note the obvious depletion (corrosion) proceeding from the right (outside) edge. This depleted region further acts as a porous sponge to retain mobile water and other contaminants that are present.

Figure 4.4 shows composite EMPA X-ray maps of the SEM in Figure 4.3b. Note that the images in Figure 4.4 represent a 90° clockwise rotation of the image in Figure 4.3b. The elemental maps included (A) *Cu*, (B) *Mo*, (C) *P*, and (D) *Ag*. Note the decrease in *Cu* concentration in the center portion, consistent with the *Cu-P* band, the dense *Cu* at the left edge and the dense *Mo* band on the right edge.

Figure 4.3 (a) Optical Micrograph of Diode that is Metallographically Mounted on PWB, (b) Secondary Electron Image at 1500X of Circled Region of (a) (Light Area is *P* Rich *Cu* Region, Note Depletion in Outer Edge)

Figure 4.4 Composite EMPA X-ray Maps of the SEM in Figure 4.3b: (a) Cu, (b) Mo, (c) P, and (d) Ag

4.4 Mechanical Pull Strength Test

Test Plan Summary

A sample of no-clean and rosin flux soldered FMU-139 PWBs was subjected to mechanical pull strength tests at SNL. The objective of these tests was to compare the strength of the solder joints for the no-clean soldering process with that of the rosin flux process. A resistor and an impact switch on each of twelve selected boards were mechanically pull tested. Eight of these boards (two from each of the three no-clean process experimental cells and two rosin flux boards) were tested after undergoing the long-term storage testing. The remaining four boards (one from each experimental cell and one rosin flux board) were from the group of boards that were ionograph tested. These four boards were not subjected to long-term storage testing and were used as a control group for the mechanical test.

One of the .014 *in* diameter leads of each resistor and one of the .017 *in* diameter leads of each impact switch were clipped and the remaining lead stubs were pulled. A hydraulically operated, 22,000 *lb* Material Test System Model 880 testing machine was used to exert increasing pulling force on the resistors and switches until the leads broke. Force was applied by the hydraulic actuator at the rate of 0.002 *in/sec* with the board mounted on a platen and the machine connected to a resistor or switch. The force, or load, (in *lbs*) at the point of failure was measured by a load cell and recorded by computer.

Descriptive Statistics and Data Plots

A listing of the pull strength data of the resistors and switches on the FMU-139 boards is presented in Table A.14 in the Appendix. Dotplots and descriptive statistics

of the pull strength (*lbs*) of the resistors and switches are presented in Figure 4.5. The pull strengths of resistors and switches on rosin flux soldered boards are indicated in the dotplots by asterisks (*).

All resistor and switch mechanical failures occurred at pull strengths exceeding 15 *lbs*. The only mode of failure was the lead breaking. In no cases did the lead separate from the solder joint. Therefore, the pull strength data represent minimum solder joint strengths. The average pull strength was 20.25 *lbs* for the impact switch and 15.58 *lbs* for the resistor. As can be seen in Figure 4.5, resistor and switch pull strengths for the no-clean boards were similar to those of the rosin flux boards.

Conclusions

The lowest pull strength observed for the resistors and switches was 15.4 *lbs*. This value exceeds any minimum mechanical performance specifications. Pull strengths for the resistors and switches on the four control boards that were not subjected to long-term storage testing were not significantly different from pull strengths for the eight boards that were long-term storage tested. Since the pull strengths for all three experimental cell soldering parameter combinations exceeded minimum specifications, further analysis to evaluate any effects of these parameters was not necessary.

The mechanical testing of the FMU-139 PWBs determined that solder joints on the no-clean soldering process boards performed equally well as the solder joints on the rosin flux boards. No significant effects of the long-term storage test were determined for the no-clean boards or the rosin flux boards.

	Sample	n	Mean	Median	Stdev	Min	Max
Switch	Total	12	20.25	20.35	.735	18.7	21.2
	No-Clean	9	19.98	20.20	.630	18.7	20.6
	Rosin Flux	3	21.07	21.20	.231	20.8	21.2
Resistor	Total	12	15.58	15.55	.171	15.4	15.9
	No-Clean	9	15.61	15.60	.183	15.4	15.9
	Rosin Flux	3	15.47	15.50	.058	15.4	15.5

Figure 4.5 Dotplots and Descriptive Statistics for Pull Strengths (lbs) of Switches and Resistors on FMU-139 Boards

FMU-139 Test Results

5. Summary and Conclusions

The purpose of this testing program was to compare the no-clean soldering process with existing rosin flux/solvent cleaning soldering. Data were produced that demonstrated that hardware produced with the no-clean process is just as reliable as that from the traditional rosin flux process. Test PWBs used in the testing program were the Motorola test board, the IPC B-24 board, and the FMU-139 board. The following tests were utilized to compare the performance and characteristics of the no-clean and rosin flux/solvent cleaning soldering processes:

- Visual defects in solder quality
- Ionic cleanliness
- Solder joint contact resistance before and after typical product environmental conditioning (temperature-humidity and temperature-cycle)
- Surface insulation resistance
- Solder joint mechanical strength

- Long-term storage solder quality and electrical functionality
- Surface analysis of chemical residues

The following test matrix lists each of the tests and indicates which of the three test boards were used as either primary (P) or secondary (S) test vehicles.

Test	FMU-139	MTB	IPC B-24
Visual Solder Defects		P	
Ionograph Cleanliness	S	P	S
SIR			P
Temperature Cycle		P	
Temperature-Humidity	S	P	
Long-Term Storage	P		
Surface Chemical Analysis		P	
Solder Joint Electrical		P	
Solder Joint Mechanical	S	P	

The conclusions from each of these tests are summarized in the following sub-sections.

5.1 Defects in Solder Quality

Motorola test boards were analyzed for visual defects in solder quality for each of the eight no-clean soldering process parameter setting combinations (experimental cells, described in Section 1.4 and defined in Tables 1.4 and 1.5) and rosin flux soldered boards. The eight experimental cells were planned to span a broad window for the no-clean soldering process, with some cells producing boards with few defects and others producing boards with many defects. The broad process window was utilized to obtain information on the effects of the soldering process parameters on defects. These parameters are easily controlled by settings on the wave soldering machine.

The broad range of process parameter settings produced a wide range of numbers of defects for the eight experi-

mental cells (see Figure 2.4). The process parameters that had the greatest impact on the number of defects were flux conveyor speed, preheat temperature, and time in the solder pot. It should be kept in mind that the precision of these values varies from technician to technician though they are highly trained.

Cell 1 produced the fewest defects and was very similar to the rosin flux process in this respect. However, cells 2, 3, and 4 also were competitive with the rosin flux process. These results indicate that an optimization of the no-clean process parameter control settings will produce boards with an acceptable level of visual defects. Further testing is planned to optimize the no-clean process.

5.2 Ionic Cleanliness

Motorola test boards, IPC B-24 boards (pre-cleaned and as-received), and FMU-139 boards were subjected to

ionograph testing at Motorola. This testing determined the ionic cleanliness of the PWBs from each of the no-

clean soldering process parameter combinations (eight experimental cells for the MTBs and IPC B-24 boards, three experimental cells for the FMU-139 boards) and the rosin flux soldered boards. A group of unsoldered, as-received IPC boards also was tested to determine the cleanliness of boards containing supplier contaminants only. Samples of MTBs and IPC boards were independently ionographed at the Navy's EMPF. The EMPF results corroborated the Motorola results (see Table 3.3).

Ionic cleanliness measurements for the MTBs and the cleaned and as-received IPC boards agreed closely for each of the eight no-clean process parameter setting combinations and the rosin flux boards. The broad range of the no-clean soldering process parameter settings produced a wide range of cleanliness measurements among the eight no-clean experimental cells. Some of the parameter setting combinations were known to produce dirty boards and, as planned, strong effects of the no-clean process experimental design factors on ionic cleanliness were evident.

Cell 1 resulted in ionic cleanliness measurements for the MTBs and cleaned and as-received IPC boards that exceeded the specification limit (see Figures 2.3, 3.3, and 3.4). This is the cell that produced the fewest defects on MTBs, as mentioned above. However, the average ionic cleanliness for cell 2 was comparable to or better than the rosin flux cleanliness average for all three board types. Cells 4, 5, and perhaps 7 produced boards with cleanliness comparable to the rosin flux

boards for all board types and comparable to the unsoldered boards for the as-received IPC board group.

The three experimental cells for the FMU-139 boards also produced a wide range of ionic cleanliness. These three parameter combinations were selected on the basis of preliminary testing to produce three groups of FMU-139 boards: (1) *good* solder quality and ionically clean, (2) *in-between* solder quality and cleanliness, and (3) *marginal* solder quality and ionically dirty (cleanliness exceeding the specification limit).

Average ionic cleanliness for the in-between group of FMU-139 boards was almost identical to that of the good solder quality and cleanliness group (see Figure 4.1). The average ionic contamination for these two groups was almost as low as the average ionic contamination on the rosin flux soldered boards. Since the in-between group was expected to have worse solder quality and ionic contamination than the good group, these results are encouraging. As expected, the ionic contamination on the marginal solder quality and ionically dirty boards exceeded the specification limit.

With some no-clean process parameter setting combinations already producing boards with cleanliness comparable to the optimized rosin flux process, it appears that an optimization of the no-clean soldering process will produce boards that are ionically cleaner than the rosin flux boards. Further testing is planned to optimize the no-clean process.

5.3 Solder Joint Contact Resistance

The electrical integrity of component solder joints on the MTBs was evaluated by accelerating the effects of aging and chemical reaction of any corrosive residues. This acceleration was accomplished through separate temperature-humidity and temperature-cycle environmental conditioning of two samples of MTBs in separate climatic chambers. Both joint contact resistance and surface leakage resistance were measured pre- and post-environmental conditioning.

All pre- and post-test joint contact resistance measurements were consistently small in magnitude and well within acceptable limits (see Figures 2.9 - 2.11). The highest post-test joint contact resistance was 250 *microohms* and the largest increase was 50 *microohms*. There were no significant changes observed between the pre- and post-test joint contact resistance measurements. All pre- and post-test surface leakage resistance

measurements were greater than 200 *megohms*, well above the required 20 *megohms*.

The two environmental tests had negligible impact on both joint contact resistance and surface leakage resistance measurements. No significant differences were determined among the no-clean soldered MTBs, the rosin flux boards, and the control boards (which were not environmentally conditioned). In addition, results from the two environmental conditioning tests did not differ significantly.

Typical product environmental conditioning and electrical testing of the MTBs indicated that the no-clean soldering process produces electrically reliable boards. The no-clean process performed as well as the existing rosin flux process in both the joint contact resistance and surface leakage resistance testing.

5.4 Surface Insulation Resistance

The IPC B-24 boards, containing the IPC standard SIR comb test pattern, were subjected to normal SIR testing. Pre- and post-environmental conditioning SIR was measured on the four comb patterns of the cleaned and as-received IPC boards. Resistance on comb pattern A was measured at specific times throughout the environmental conditioning, including days 4 and 7 as required by SIR testing specifications. Two different test chamber conditions were used for the environmental conditioning, a high temperature chamber H (85°C, 85% RH) and a low temperature chamber L (50°C, 90% RH). An additional set of cleaned and as-received IPC boards was conformal coated and environmentally conditioned in a medium temperature chamber M (65°C, 90% RH).

The average SIR for all eight no-clean parameter setting combinations, for both cleaned and as-received boards and for all three test conditions, exceeded the MIL-STD limit of 100 megohms at each testing time. However, a few individual boards were poor performers during the testing, *including one rosin flux soldered board*. All of the boards had acceptable SIR readings at the end of the test. These poor performing boards appeared to be independent of soldering process, no-clean parameter settings, ionic cleanliness, cleaning prior to soldering, and test conditions. The conformal coated boards had higher average pre-test SIR with less variability than the pre-test SIR on the other boards. None of the cleaned or as-received conformal coated boards, which included no-clean and rosin flux soldered boards, performed poorly in terms of the 100 megohm limit.

Surface chemical analysis techniques were utilized to examine the six poor performing IPC boards, determine the presence of any chemical residues, and assess whether these residues accounted for the low SIR results. The six boards all had developed regions of similar surface corrosion and contamination over the course of the 21-day environmental tests. This corrosion residue, 10 to 50 microns thick, was determined to contain Pb and Sn as well as copper, potassium, and a number of common impurities typically found following water evaporation. The Pb and Sn oxide regions were mostly located between the comb runners, with the Pb in greater chemical abundance than found in the source solder.

Any significant moisture content would lead to noticeably lower resistance values at these regions.

Comb pattern A was observed to contain the highest density of corrosion regions. Since this comb pattern was the one intermittently tested during the environmental conditioning, with the testing necessitating an applied electrical bias, the corrosion was probably driven by an electrochemical process. The fact that one of the six poor performing boards was a rosin flux soldered board and contained a prominent corrosion short of similar chemical composition supports the belief that the development of corrosion was independent of soldering process.

Several additional findings were determined through the SIR testing of the IPC boards. Cleaning of IPC boards led to lower pre-test SIR than the as-received boards (see Figures 3.19 and 3.20). However, once testing was started, there was no difference between the cleaned and as-received boards. These results indicate that the practice of pre-cleaning boards should be reviewed or that these boards contained minimal supplier contaminants.

Test conditions had the largest impact on SIR during the environmental conditioning and at post-test (see Figures 3.23 - 3.36). The high temperature test chamber resulted in lower and less variable SIR measurements which tended to converge over time during the testing and at post-test. The low temperature chamber produced higher and more variable SIR measurements throughout and after the environmental conditioning. Pre- and post-test SIR were not affected by ionic cleanliness, but average SIR during the environmental conditioning had a significant inverse correlation with average ionic cleanliness (see Figures 3.44 - 3.49). Pre-test SIR measurements were not correlated with the SIR measurements taken during the environmental conditioning and neither pre-test or during-test SIR was correlated with post-test SIR.

Environmental conditioning and electrical testing of the cleaned and as-received IPC boards also determined that the no-clean soldering process produces electrically reliable boards. Surface insulation resistance testing produced results showing the no-clean process to perform as well as the existing rosin flux process.

5.5 Solder Joint Mechanical Strength

The mechanical strength of solder joints from both the no-clean and rosin flux soldering processes were tested by mechanically pulling pins and components until separation from the boards occurred. Two pins and two resistors were pulled from each board in a test sample of MTBs and a resistor and an impact switch were pulled from each FMU-139 board in the sample. These pull strength tests occurred after the MTBs and FMU-139 boards had been environmentally conditioned.

Pull strength tests resulted in two modes of failure: joint separation from the board and lead breakage. The entire solder joint separated from the board socket for all pins and two-thirds of the resistors on the MTBs. For the remaining resistors on the MTBs and for all the resistors and switches on the FMU-139 boards, the leads broke. *In no case did the lead pull out of the solder.* Since no solder joints failed, the pull strength data for both pins and components represent minimum solder joint strengths.

The lowest pull strength for pins and resistors on the MTBs was 44.3 *lbs*. The average pull strength was 57.3

lbs for pins and 64.2 *lbs* for resistors. Resistors and switches on the FMU-139 board had a minimum pull strength of 15.4 *lbs*. Pull strengths for the impact switches averaged 20.3 *lbs*. The average pull strength of resistors was 15.6 *lbs*.

The average and lowest pull strengths far exceed any minimum mechanical strength performance specifications. No differences in pin or resistor pull strength were determined for the MTBs after the two different environmental tests, the non-conditioned MTB control boards, and the no-clean and rosin flux MTBs (see Figures 2.18 - 2.20). Similarly, no differences existed between the no-clean and rosin flux solder joint pull strengths of the resistors and switches on the FMU-139 boards (see Figure 4.5).

No-clean soldering process solder joints proved to be mechanically reliable and were not adversely affected by the environmental conditioning. The no-clean solder joints had mechanical pull strengths comparable to the rosin flux solder joints.

5.6 Long-Term Storage

The purpose of the long-term storage test was to compare the no-clean soldering process to the standard rosin flux/solvent cleaning process over 20 *yrs* of simulated storage. The simulated storage was achieved by accelerating chemical reactions according to a modified Arrhenius rate equation (see Section 4.1). The FMU-139 PWB used for this test is a highly reliable and electrically functional board currently in high volume production at Motorola. It should be noted that this product was designed for a 10-year life.

A small climatic chamber was used to simulate the 20 *yrs* of storage using test conditions of 80°C and 40% RH. Using acceleration factors based on the modified Arrhenius rate equation, the FMU boards were subjected to 20 *yrs* of simulated storage through environmental conditioning for 2,522 total *hrs*. Electrical testing was performed on the three no-clean soldering process parameter combination groups of boards (experimental cells, defined in Table 1.2) and the rosin flux boards at specific intervals during the testing. These times corresponded to simulated lifetimes of 1 *yr*, 10 *yrs*, 13.3 *yrs*, and 20 *yrs*. The three no-clean experimental cells, designed to span a range of board cleanliness and solder

quality, represented (1) *good* solder quality and ionically clean, (2) *in-between* solder quality and cleanliness, and (3) *marginal* solder quality and ionically dirty.

All boards were electrically functional after simulated 1 *yr* (126 *hrs*), 10 *yrs* (1,260 *hrs*), and 13.3 *yrs* (1,639 *hrs*) of testing. However, at some point after the 1,639th *hr* of testing, the climatic chamber float control failed. The float failure caused the top chamber cover to fill with water that subsequently dripped onto some of the test boards. The dripping water increased the humidity in the chamber, perhaps to as high as 100%, which would substantially increase the simulated storage to possibly more than 100 *yrs*.

All but three of the no-clean boards remained electrically functional after the 2,522 *hrs* of testing. Visual examination of the three boards revealed that the failures occurred only for a specific diode type (ceramic bodied) and that these failed diodes displayed evidence of dripping water. Two rosin flux boards also contained ceramic bodied diodes that contained significant signs of corrosion. Similar diodes on other boards in the test chamber that were not in the drip area and all other components on

all the boards did not fail or corrode. Electrical functioning of these components after the significantly increased test conditions is noteworthy.

The ceramic bodied diodes that corroded or failed electrically were subjected to an extensive failure analysis and surface chemical analysis. These analyses concluded that the failures were a direct result of the dripping water. Clearly, these diodes were not intended to withstand this type of environment.

To address any uncertainty arising from the float problem and subsequent results, two follow-up long-term storage tests were separately conducted at Motorola and SNL on FMU-139 boards. None of the components, including the suspect diodes, on any of the boards in either of the two tests displayed any corrosion after 5 yrs, 10 yrs, 15 yrs, and 20 yrs of simulated storage.

Another group of no-clean soldered FMU-139 boards were conformal coated. These boards underwent long-

term storage testing to evaluate the effect of the overcoat during simulated storage. None of the conformal coated boards displayed any signs of deterioration of the conformal coating or corrosion of any components. All circuits were electrically functional at the end of testing.

Results from the long-term storage tests demonstrate that the no-clean soldering process produced boards that functioned as well as the existing rosin flux/solvent cleaning process boards during and following simulated storage. The solder joints obtained with the no-clean process have the same high quality visual appearance of solder joints produced by the rosin flux process. These tests also prove that the adipic and formic acid materials used with the no-clean process do not degrade circuit performance and the residues do not require cleaning. The substantial environmental overstress that occurred also provided positive results on the functionality and lack of corrosion of the no-clean boards that withstood far more than 20 yrs of simulated storage.

5.7 Surface Chemical Analysis

No-clean soldered MTBs were examined for free and complexed chemical residues using several surface chemical analysis techniques. The purpose of these examinations was to determine if any residues of the adipic and formic acid materials used by the no-clean soldering process were present on the boards after soldering.

Eighteen MTBs were examined with HPLC analysis prior to environmental conditioning and free adipic acid levels were below detection limits. These boards also were tested for residual hydrocarbon and grease contamination. Free hydrocarbon contamination was barely detected (less than $2 \mu\text{gm}/\text{cm}^2$) on only two of the 18 boards.

Small area FTIR analysis identified the presence of very low levels of adipic and formic acids in certain regions of a few of the MTBs. These results were verified through independent FTIR analysis performed by the Electronics Production Technology Branch of the Product Assurance Division at the Naval Weapons Center in China Lake, California.

No significant residues were found to be present on the MTBs after wave soldering. The adipic and formic acids appear to be effective materials for the no-clean soldering process and the residues from these materials are insignificant and do not need to be cleaned.

5.8 Summary of Findings

Through this testing program, the no-clean soldering process was thoroughly tested and compared to the standard, optimized rosin flux/solvent cleaning soldering process. Major program findings on the no-clean process are:

- Ionic cleanliness equivalent to, and in some cases better than, the rosin flux process was achieved.

- Visual solder quality equivalent to the existing, optimized rosin flux/solvent cleaning process was achieved.
- Strong potential exists for achieving better ionic cleanliness than the rosin flux process by optimizing the no-clean process using its extra control features.

- The no-clean soldered hardware proved electrically and mechanically reliable over a wide range of processing parameters.
 - No-clean soldered boards with ionic cleanliness in excess of the military specification limit still proved reliable.
 - Minimal residues were observed on the no-clean hardware and were determined to have no impact on hardware reliability.
 - Pre-cleaning of PWBs prior to soldering generally resulted in lower initial SIR values.
 - The chemistry of the adipic acid solution, consisting of a simple formulation of adipic acid and isopropyl alcohol, used in the no-clean process is straightforward, which provides a consistent material from lot-to-lot.
 - The new no-clean soldering process is capable of producing quality, reliable hardware over a wide range of processing parameters.
 - The no-clean soldering process did not degrade product shelf life.
 - Since the no-clean process eliminates the need for supplemental cleaning, it will have a positive impact on the depletion of the ozone layer.
 - The elimination of solvent cleaning not only reduces waste (CFC-113) emissions, but also significantly reduces energy requirements and costs for solvent production and reclamation and for production and operation of cleaning equipment.
 - Even without the environmental concerns, use of the no-clean process is preferable since elimination of the cleaning operation significantly reduces time on the production floor.
-

5.9 Projected Energy and Waste Savings

In compliance with President Bush's call for the elimination of all CFCs in the U.S. by 1995, solvent cleaning of PWBs will no longer be allowed. Utilization of the no-clean soldering process within U.S. industry and the elimination of the unnecessary cleaning operation would meet this call and result in substantial reductions in not only CFC emissions but also in energy use and cost.

Projections of waste and energy savings for the no-clean process in the year 2010 were developed for the DOE. Waste savings in the year 2010 are projected to be 18,000 tons of CFC-113. Energy savings from eliminating the production and operation of cleaning equipment and the production and reclamation of solvents are projected to be 1.4×10^{13} BTUs. In addition to benefitting the environment through the elimination of ODCs, industry will profit from the elimination of the cleaning equipment and associated overhead. Current cost estimates for the operation of solvent cleaning systems are between \$100,000 to \$200,000 per year per machine.

This more than offsets the approximate one-time cost of \$25,000 to convert the soldering machine to the no-clean process.

The inert soldering atmosphere produced by the nitrogen cover blanket has reduced a weekly 65 lb buildup of lead-based solder dross in the soldering chamber to *two tablespoons* of carbon-based dross. As a result, weekly preventative maintenance taking five hours has been reduced to quarterly PM.

The no-clean soldering process compared favorably to the rosin flux/solvent cleaning process at every stage of the testing and analysis, especially considering that the rosin flux process has previously been fine-tuned and optimized. Completely eliminating the solvent cleaning step and its associated waste emissions, energy use, and costs, the no-clean soldering process represents an ideal alternative to rosin flux/solvent cleaning soldering.

Appendix. Data Tables

This appendix contains tables of all the test data accumulated from the different tests of the no-clean soldering process using the three PWB types. Some boards were used in more than one test. Therefore,

each case in the data tables is identified by its board serial number (s/n). These eight-character serial numbers uniquely identify each board using the following system.

In addition to the specific test measurements, each data table contains a case (observation number) variable and a variable identifying the corresponding experimental cell. Eight experimental cells were used for the MTBs and IPC B-24 boards, as defined in Tables 1.4 and 1.5. Rosin flux soldered MTBs and IPC boards are indicated by experimental cell 9. Unsoldered, as-received IPC boards are indicated by experimental cell 10. Three experimental cells were used for the FMU-139 boards, defined in

Table 1.2. Rosin flux soldered FMU boards are indicated by experimental cell 4.

The test data presented in these tables are available on floppy diskette. Data from each of the 15 tables are contained in 15 separate ASCII files with file names *TABLEA01.DAT* through *TABLEA15.DAT* corresponding to the table numbers.

MTB Ionic Cleanliness and Defects

Board S/N	Case	Cell	Ionic Cleanliness	Number of Defects
MNS01C01	1	1	20.4	10
MNS01C14	2	1	21.7	5
MNS01C20	3	1	27.7	21
MNS01C21	4	1	28.0	9
MNS01C23	5	1	*	12
MNS02C07	6	2	4.5	57
MNS02C11	7	2	4.0	33
MNS02C15	8	2	3.5	52
MNS02C19	9	2	2.2	43
MNS02C22	10	2	4.3	31
MNS03C07	11	3	9.3	22
MNS03C09	12	3	9.6	26
MNS03C11	13	3	6.1	38
MNS03C14	14	3	5.5	33
MNS03C22	15	3	9.6	20
MNS04C02	16	4	6.2	15
MNS04C03	17	4	5.9	17
MNS04C04	18	4	6.9	18
MNS04C08	19	4	6.8	36
MNS04C10	20	4	8.1	25
MNS05C03	21	5	9.6	76
MNS05C06	22	5	8.9	92
MNS05C13	23	5	6.9	75
MNS05C17	24	5	7.0	81
MNS05C20	25	5	7.8	52
MNS06C07	26	6	13.1	51
MNS06C09	27	6	11.2	56
MNS06C22	28	6	11.6	66
MNS06C23	29	6	10.8	37
MNS06C24	30	6	11.3	49
MNS07C07	31	7	9.3	115
MNS07C08	32	7	10.5	115
MNS07C16	33	7	6.6	101
MNS07C24	34	7	6.3	80
MNS07C26	35	7	5.8	100
MNS08C01	36	8	12.1	126
MNS08C02	37	8	15.4	115
MNS08C09	38	8	14.3	76
MNS08C21	39	8	14.2	118
MNS08C24	40	8	12.2	75
MNR01C04	41	9	4.9	12
MNR01C06	42	9	4.8	1
MNR01C15	43	9	5.4	2
MNR01C20	44	9	5.0	1
MNR01C24	45	9	5.5	6

Table A.1 MTB Ionic Cleanliness ($\mu\text{gm}/\text{in}^2$ equivalent NaCl ions) and Number of Defects Data (Cell 9 = Rosin Flux, * = Missing)

MTB Ionic Cleanliness - EMPF

Board S/N	Case	Cell	Ionic Cleanliness
MNS01C02	1	1	36.17
MNS01C17	2	1	25.65
MNS02C05	3	2	4.40
MNS02C09	4	2	4.63
MNS03C08	5	3	8.71
MNS03C17	6	3	6.38
MNS04C07	7	4	6.77
MNS04C16	8	4	7.16
MNS05C04	9	5	9.19
MNS05C07	10	5	6.69
MNS06C11	11	6	12.27
MNS06C20	12	6	9.81
MNS07C04	13	7	9.23
MNS07C09	14	7	6.67
MNS08C16	15	8	8.99
MNS08C18	16	8	7.49
MNR01C07	17	9	3.86
MNR01C17	18	9	3.19

Table A.2 MTB Ionic Cleanliness ($\mu\text{gm}/\text{in}^2$ equivalent *NaCl* ions) Data from EMPF (Cell 9 = Rosin Flux)

MTB Temperature-Humidity Test

Board S/N	Case	Cell	R1		R18		R79		R129		R127	
			Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
MNS01C06	1	1	170	180	180	200	90	90	100	80	190	160
MNS01C09	2	1	160	160	160	150	60	90	90	100	160	160
MNS01C19	3	1	160	170	200	190	50	70	70	90	180	170
MNS01C25	4	1	190	180	190	190	50	80	70	80	180	180
MNS01C26	5	1	160	190	180	170	70	90	90	90	160	170
MNS02C01	6	2	170	190	180	210	80	100	110	110	210	210
MNS02C10	7	2	160	180	180	180	70	90	80	100	200	200
MNS02C14	8	2	190	180	210	210	70	90	110	110	180	170
MNS02C17	9	2	180	210	180	190	80	90	110	120	200	210
MNS02C26	10	2	170	200	220	210	70	100	100	100	190	190
MNS03C04	11	3	190	200	200	190	60	80	100	110	170	180
MNS03C15	12	3	180	160	210	190	80	100	120	110	180	170
MNS03C20	13	3	190	200	230	210	90	90	120	110	210	200
MNS03C21	14	3	210	210	190	170	70	90	90	110	190	190
MNS03C26	15	3	170	180	200	200	70	90	100	100	190	200
MNS04C12	16	4	230	210	200	210	90	100	120	110	220	200
MNS04C13	17	4	200	190	230	210	90	90	100	110	190	200
MNS04C15	18	4	190	190	220	230	90	100	120	100	190	200
MNS04C17	19	4	200	180	210	190	90	90	130	130	190	180
MNS04C19	20	4	190	200	240	220	80	100	110	100	220	210
MNS05C18	21	5	160	180	170	170	60	90	80	90	180	190
MNS05C21	22	5	230	220	240	230	70	80	100	90	170	170
MNS05C22	23	5	210	190	170	170	70	90	100	80	180	180
MNS05C23	24	5	230	200	190	190	80	90	100	100	200	200
MNS05C26	25	5	200	210	200	200	80	100	110	110	200	190
MNS06C02	26	6	210	190	230	220	90	100	100	110	200	200
MNS06C08	27	6	230	240	190	200	100	100	130	120	180	200
MNS06C12	28	6	220	210	190	190	80	100	90	100	170	170
MNS06C17	29	6	210	210	200	200	90	100	120	110	190	190
MNS06C25	30	6	180	200	200	210	90	110	110	120	200	190
MNS07C02	31	7	160	190	210	180	80	90	110	110	180	170
MNS07C06	32	7	190	200	180	170	80	110	110	110	190	200
MNS07C10	33	7	220	210	210	220	100	110	90	100	180	180
MNS07C15	34	7	200	180	230	220	90	100	90	100	200	180
MNS07C22	35	7	220	210	190	200	80	100	110	100	220	220
MNS08C05	36	8	200	210	200	200	60	80	100	110	190	200
MNS08C08	37	8	210	200	180	160	70	100	100	100	180	180
MNS08C14	38	8	210	210	200	190	80	90	120	100	170	170
MNS08C22	39	8	210	190	200	180	70	100	90	100	190	200
MNS08C23	40	8	190	190	200	200	70	100	110	110	210	180
MNR01C01	41	9	210	210	180	180	90	90	80	90	190	200
MNR01C11	42	9	200	190	170	200	90	100	110	100	220	210
MNR01C12	43	9	190	170	200	190	80	80	100	110	200	180
MNR01C18	44	9	180	170	180	190	90	100	110	90	180	170
MNR01C22	45	9	160	160	190	180	80	90	90	100	170	170

Table A.3 MTB Temperature-Humidity Pre- and Post-Test Resistance (μ ohms) Data for R1, R18, R79, R129, and R127 (Cell 9 = Rosin Flux)

MTB Temperature-Cycle Test

Board S/N	Case	Cell	R1		R18		R79		R129		R127	
			Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
MNS01C10	1	1	180	190	160	160	60	90	70	80	180	150
MNS01C13	2	1	170	170	200	190	70	100	90	80	180	160
MNS01C18	3	1	180	210	210	180	60	90	90	70	220	200
MNS01C22	4	1	170	170	200	160	60	90	110	110	180	160
MNS01C24	5	1	180	160	160	170	60	80	100	110	180	160
MNS02C04	6	2	170	160	190	190	60	90	100	100	180	150
MNS02C06	7	2	190	190	190	180	80	90	90	100	170	160
MNS02C20	8	2	150	150	190	180	70	90	110	100	180	170
MNS02C21	9	2	180	180	200	170	80	100	110	90	210	180
MNS02C23	10	2	160	150	190	170	80	100	90	100	200	180
MNS03C06	11	3	190	180	200	190	80	100	120	100	180	150
MNS03C13	12	3	190	180	220	180	80	100	120	120	190	160
MNS03C18	13	3	190	190	200	200	90	110	120	100	200	180
MNS03C19	14	3	200	200	200	200	90	80	120	120	190	180
MNS03C25	15	3	180	160	190	180	80	100	90	80	220	180
MNS04C09	16	4	160	180	180	170	60	100	100	80	180	150
MNS04C18	17	4	190	170	200	160	80	110	100	90	220	200
MNS04C20	18	4	190	190	200	200	80	90	110	110	190	200
MNS04C21	19	4	200	190	230	200	90	110	120	100	210	170
MNS04C26	20	4	200	170	190	160	70	90	120	90	210	180
MNS05C02	21	5	210	230	220	230	70	100	110	80	210	180
MNS05C08	22	5	190	210	240	200	80	100	80	80	200	190
MNS05C09	23	5	170	170	180	180	80	110	110	90	190	170
MNS05C14	24	5	210	180	200	200	80	90	130	100	170	150
MNS05C19	25	5	160	170	180	170	80	90	80	80	200	170
MNS06C03	26	6	190	200	210	170	70	100	120	90	210	200
MNS06C04	27	6	200	170	190	180	80	90	120	100	200	170
MNS06C14	28	6	190	200	180	160	80	90	90	100	210	200
MNS06C15	29	6	190	190	210	190	70	110	120	100	230	200
MNS06C18	30	6	180	210	190	170	100	100	90	100	170	160
MNS07C03	31	7	210	180	180	180	80	100	120	100	240	200
MNS07C14	32	7	200	170	170	160	90	90	110	80	200	180
MNS07C18	33	7	210	200	180	170	70	120	90	70	210	190
MNS07C20	34	7	200	170	190	170	70	110	120	90	180	150
MNS07C21	35	7	200	180	190	170	110	80	110	80	200	190
MNS08C03	36	8	190	170	170	160	70	90	100	90	230	210
MNS08C04	37	8	200	200	180	170	70	80	90	100	190	180
MNS08C13	38	8	230	190	210	190	70	80	110	100	210	220
MNS08C20	39	8	230	250	180	220	80	100	120	130	210	190
MNS08C17	40	8	190	170	170	150	70	90	100	90	170	130
MNR01C08	41	9	210	190	190	170	80	100	100	90	210	180
MNR01C16	42	9	200	160	210	180	70	90	90	90	200	160
MNR01C19	43	9	160	150	190	180	70	90	110	90	180	150
MNR01C21	44	9	180	150	160	140	70	100	90	90	210	170
MNR01C23	45	9	210	180	190	160	80	100	90	80	190	160

Table A.4 MTB Temperature-Cycle Pre- and Post-Test Resistance (μ ohms) Data for R1, R18, R79, R129, and R127 (Cell 9 = Rosin Flux)

MTB FTIR Control Board Tests

Board S/N	Case	Cell	R1		R18		R79		R129		R127	
			Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
MNS01C12	1	1	160	190	180	190	70	90	80	90	170	180
MNS02C16	2	2	160	180	200	200	60	80	80	90	170	170
MNS03C24	3	3	170	170	160	170	60	90	70	90	160	170
MNS04C24	4	4	170	160	160	180	80	90	70	90	170	170
MNS05C10	5	5	180	160	200	180	70	90	110	90	220	190
MNS06C13	6	6	190	170	180	160	70	80	120	110	210	180
MNS07C19	7	7	170	180	200	180	60	80	110	100	160	180
MNS08C06	8	8	190	180	170	180	80	90	80	90	170	190

Table A.5 MTB FTIR Control Board Pre- and Post-Test Resistance (μ ohms) Data for R1, R18, R79, R129, and R127 (Cell 9 = Rosin Flux)

MTB Pull Strength Test

Board S/N	Case	Test	Cell	Pull Strength			
				Pin 1	Pin 2	Comp 1	Comp 2
MNS01C06	1	1	1	50.9	51.5	66.5	64.3
MNS01C19	2	1	1	53.0	60.0	63.2	64.7
MNS02C10	3	1	2	57.3	63.1	64.2	65.7
MNS02C14	4	1	2	62.3	57.1	65.8	63.2
MNS03C04	5	1	3	56.1	59.1	64.2	62.5
MNS03C20	6	1	3	60.5	57.1	66.4	66.5
MNS04C13	7	1	4	50.8	61.7	62.1	66.6
MNS04C17	8	1	4	51.0	55.6	64.8	63.0
MNS05C18	9	1	5	68.4	65.2	64.8	63.4
MNS05C22	10	1	5	56.7	59.5	66.1	66.7
MNS06C02	11	1	6	48.2	49.7	60.0	61.5
MNS06C08	12	1	6	52.5	50.3	63.1	64.4
MNS07C02	13	1	7	60.9	55.4	64.3	59.4
MNS07C06	14	1	7	61.0	50.8	65.1	61.0
MNS08C05	15	1	8	63.8	57.2	64.1	62.6
MNS08C08	16	1	8	71.7	63.3	63.8	67.4
MNR01C12	17	1	9	55.0	49.4	65.1	63.8
MNR01C18	18	1	9	61.6	55.1	61.0	60.1
MNS01C10	19	2	1	48.9	44.6	63.5	62.2
MNS01C13	20	2	1	51.5	49.3	65.1	62.4
MNS02C04	21	2	2	74.8	53.7	64.9	64.4
MNS02C20	22	2	2	59.4	60.1	65.3	64.3
MNS03C06	23	2	3	60.8	59.4	66.3	60.9
MNS03C18	24	2	3	52.5	63.7	61.7	64.4
MNS04C18	25	2	4	58.1	48.3	65.9	65.8
MNS04C20	26	2	4	59.8	60.6	66.2	65.1
MNS05C02	27	2	5	58.1	*	65.3	64.8
MNS05C08	28	2	5	68.9	56.4	65.6	67.1
MNS06C03	29	2	6	45.6	44.3	62.5	65.5
MNS06C04	30	2	6	59.2	50.1	65.3	67.7
MNS07C14	31	2	7	61.6	54.7	65.6	66.8
MNS07C20	32	2	7	60.0	55.3	65.5	66.8
MNS08C03	33	2	8	50.1	47.6	68.9	65.2
MNS08C13	34	2	8	60.5	58.4	64.6	65.4
MNR01C19	35	2	9	54.2	61.4	62.6	64.3
MNR01C21	36	2	9	49.3	49.6	65.0	64.4
MNS01C12	37	3	1	*	51.3	66.6	64.5
MNS02C16	38	3	2	64.0	64.5	64.5	60.2
MNS03C24	39	3	3	66.5	57.8	64.2	64.3
MNS04C24	40	3	4	65.7	58.9	59.9	65.5
MNS05C10	41	3	5	67.0	63.2	64.3	64.3
MNS06C13	42	3	6	53.5	48.9	59.2	62.6
MNS07C19	43	3	7	59.1	52.9	60.7	66.3
MNS08C06	44	3	8	60.0	57.0	64.6	57.2
MNR01C04	45	4	9	66.1	53.7	64.4	65.1
MNR01C06	46	4	9	57.8	59.5	65.3	63.9
MNR01C15	47	4	9	62.7	58.4	64.2	63.9
MNR01C20	48	4	9	59.4	60.9	64.3	63.5
MNR01C24	49	4	9	61.3	55.5	65.1	63.5

Table A.6 MTB Pull Strength (lbs) Data for Pins and Components (Test 1 = MTBs from Temperature-Humidity Test, Test 2 = Temperature-Cycle Test, Test 3 = FTIR (No-Clean Control Group), Test 4 = Ionograph (Rosin Flux Control Group); Cell 9 = Rosin Flux; * = Missing)

IPC B-24, Cleaned Ionic Cleanliness

Board S/N	Case	Cell	Ionic Cleanliness
BCS01C04	1	1	34.8
BCS01C08	2	1	20.7
BCS01C09	3	1	30.1
BCS01C11	4	1	31.3
BCS01C16	5	1	24.5
BCS02C01	6	2	0.7
BCS02C04	7	2	0.5
BCS02C08	8	2	0.6
BCS02C15	9	2	0.5
BCS02C16	10	2	0.0
BCS03C01	11	3	1.2
BCS03C03	12	3	4.3
BCS03C05	13	3	2.3
BCS03C07	14	3	4.6
BCS03C11	15	3	2.4
BCS04C09	16	4	0.0
BCS04C11	17	4	0.4
BCS04C12	18	4	0.4
BCS04C16	19	4	0.7
BCS04C17	20	4	0.0
BCS05C02	21	5	3.6
BCS05C05	22	5	5.9
BCS05C11	23	5	0.9
BCS05C13	24	5	1.3
BCS05C14	25	5	4.0
BCS06C06	26	6	25.5
BCS06C07	27	6	24.3
BCS06C13	28	6	16.8
BCS06C14	29	6	17.1
BCS06C15	30	6	12.8
BCS07C01	31	7	2.4
BCS07C04	32	7	2.7
BCS07C08	33	7	2.3
BCS07C09	34	7	0.8
BCS07C16	35	7	0.7
BCS08C03	36	8	3.6
BCS08C04	37	8	1.1
BCS08C12	38	8	6.8
BCS08C15	39	8	3.5
BCS08C17	40	8	4.0
BCR01C05	41	9	0.1
BCR01C06	42	9	0.8
BCR01C08	43	9	0.1
BCR01C10	44	9	0.9
BCR01C12	45	9	0.1

Table A.7 IPC B-24, Cleaned Ionic Cleanliness ($\mu\text{gm}/\text{in}^2$ equivalent *NaCl* ions) Data (Cell 9 = Rosin Flux)

IPC B-24, As-Received Ionic Cleanliness

Board S/N	Case	Cell	Ionic Cleanliness
BNS01C01	1	1	29.8
BNS01C05	2	1	16.4
BNS01C09	3	1	20.2
BNS01C12	4	1	21.5
BNS01C13	5	1	14.1
BNS02C04	6	2	1.0
BNS02C05	7	2	0.7
BNS02C06	8	2	0.8
BNS02C11	9	2	0.0
BNS02C15	10	2	0.5
BNS03C03	11	3	1.2
BNS03C08	12	3	5.1
BNS03C09	13	3	3.6
BNS03C10	14	3	2.7
BNS03C11	15	3	1.5
BNS04C09	16	4	0.0
BNS04C13	17	4	0.1
BNS04C14	18	4	0.2
BNS04C15	19	4	0.8
BNS04C17	20	4	0.7
BNS05C03	21	5	*
BNS05C06	22	5	0.0
BNS05C07	23	5	0.0
BNS05C11	24	5	1.0
BNS05C17	25	5	0.6
BNS06C03	26	6	11.8
BNS06C04	27	6	19.4
BNS06C07	28	6	8.8
BNS06C08	29	6	18.4
BNS06C09	30	6	20.4
BNS07C07	31	7	2.0
BNS07C08	32	7	2.1
BNS07C11	33	7	1.3
BNS07C12	34	7	0.7
BNS07C17	35	7	1.8
BNS08C01	36	8	3.6
BNS08C09	37	8	2.2
BNS08C11	38	8	4.0
BNS08C13	39	8	8.0
BNS08C16	40	8	0.9
BNR01C01	41	9	0.4
BNR01C03	42	9	0.0
BNR01C05	43	9	0.7
BNR01C06	44	9	0.0
BNR01C14	45	9	0.6
BNN01C01	46	10	1.2
BNN01C03	47	10	0.8
BNN01C05	48	10	0.8
BNN01C08	49	10	0.0
BNN01C10	50	10	0.0

Table A.8 IPC B-24, As-Received Ionic Cleanliness ($\mu\text{gm}/\text{in}^2$ equivalent NaCl /ions) Data (Cell 9 = Rosin Flux, Cell 10 = Unsoldered, * = Missing)

IPC B-24, Cleaned and As-Received Ionic Cleanliness - EMPF

Board S/N	Case	Cell	Ionic Cleanliness
BCS01C05	1	1	39.20
BCS01C13	2	1	20.36
BCS02C11	3	2	0.00
BCS02C14	4	2	0.17
BCS03C09	5	3	1.48
BCS03C14	6	3	4.44
BCS04C02	7	4	0.73
BCS04C10	8	4	0.56
BCS05C04	9	5	0.70
BCS05C10	10	5	0.20
BCS06C16	11	6	19.60
BCS06C17	12	6	17.44
BCS07C11	13	7	0.41
BCS07C17	14	7	1.61
BCS08C10	15	8	2.30
BCS08C13	16	8	1.80
BCR01C04	17	9	0.06
BCR01C14	18	9	0.03

Table A.9 IPC B-24, Cleaned Ionic Cleanliness ($\mu\text{gm}/\text{in}^2$ equivalent *NaCl* ions) Data from EMPF (Cell 9 = Rosin Flux)

Board S/N	Case	Cell	Ionic Cleanliness
BNS01C03	1	1	41.52
BNS01C10	2	1	36.84
BNS02C14	3	2	0.02
BNS02C17	4	2	0.05
BNS03C01	5	3	3.90
BNS03C06	6	3	3.98
BNS04C02	7	4	0.28
BNS04C10	8	4	0.32
BNS05C12	9	5	0.32
BNS05C13	10	5	0.24
BNS06C02	11	6	22.01
BNS06C15	12	6	17.49
BNS07C01	13	7	4.36
BNS07C09	14	7	0.45
BNS08C03	15	8	15.50
BNS08C15	16	8	4.99
BNR01C09	17	9	0.00
BNR01C12	18	9	0.09
BNN01C11	19	10	0.04
BNN01C13	20	10	0.16

Table A.10 IPC B-24, As-Received Ionic Cleanliness ($\mu\text{gm}/\text{in}^2$ equivalent *NaCl* ions) Data from EMPF (Cell 9 = Rosin Flux, Cell 10 = Unsoldered)

IPC B-24 SIR, Test Conditions 85°C, 85% RH

Board S/N	Pattern A			Pre-Out	Pre-In	Day 1	Day 4
	Case	Clean	Cell				
BCS01C01	1	1	1	1.980	1.945	0.000017726	0.000311600
BCS01C03	2	1	1	3.699	1.702	0.000018349	0.000876200
BCS02C07	3	1	2	3.923	3.766	0.005370000	0.000150120
BCS02C09	4	1	2	2.567	2.080	0.009622000	0.003597000
BCS03C04	5	1	3	4.972	5.250	0.000691900	0.001173200
BCS03C10	6	1	3	4.526	7.902	0.000030470	0.000178270
BCS04C04	7	1	4	8.149	7.639	0.000041220	0.000220900
BCS04C07	8	1	4	1.022	1.096	0.001800400	0.001766500
BCS05C01	9	1	5	4.355	2.252	0.000009163	0.004908000
BCS05C03	10	1	5	5.038	4.852	0.000213400	0.000283900
BCS06C04	11	1	6	3.056	2.897	0.000096590	0.001317200
BCS06C05	12	1	6	17.782	25.890	0.000093250	0.001430400
BCS07C02	13	1	7	2.694	3.042	0.001516500	0.002145000
BCS07C12	14	1	7	2.130	2.146	0.006756000	0.003326000
BCS08C06	15	1	8	2.083	2.638	0.000028090	0.000551900
BCS08C09	16	1	8	3.232	1.992	0.000007939	0.000051850
BCR01C07	17	1	9	88.330	19.344	0.006194000	0.003631000
BCR01C09	18	1	9	11.090	23.250	0.005615000	0.003193000
BNS01C02	19	2	1	5.345	1.877	0.000024980	0.000086520
BNS01C04	20	2	1	19.884	0.379	0.000006643	0.000095830
BNS01C08	21	2	1	59.930	16.344	0.000039030	0.000133940
BNS02C01	22	2	2	1.745	0.930	0.007604000	0.003239000
BNS02C02	23	2	2	30.010	36.424	0.006492000	0.002816000
BNS02C03	24	2	2	1.128	0.543	0.001370200	0.001393000
BNS03C02	25	2	3	22.480	17.255	0.000027600	0.000170890
BNS03C07	26	2	3	3.512	3.081	0.000763400	0.000970300
BNS03C13	27	2	3	18.787	26.240	0.000340200	0.000644800
BNS04C03	28	2	4	10.155	5.624	0.000861100	0.001399800
BNS04C04	29	2	4	14.640	20.134	0.001107400	0.001576200
BNS04C08	30	2	4	11.205	16.135	0.004133000	0.002604000
BNS05C02	31	2	5	12.130	16.632	0.000564800	0.001143700
BNS05C05	32	2	5	11.982	10.836	0.001411200	0.001883600
BNS05C08	33	2	5	22.390	19.245	0.000621000	0.001196800
BNS06C01	34	2	6	9.820	4.376	0.000192660	0.001333900
BNS06C11	35	2	6	5.480	11.082	0.000172050	0.001370800
BNS06C14	36	2	6	8.194	16.379	0.000093170	0.000874000
BNS07C02	37	2	7	23.300	27.240	0.000651100	0.001522300
BNS07C04	38	2	7	47.250	27.350	0.000254900	0.000818500
BNS07C10	39	2	7	12.042	19.356	0.000235400	0.001030700
BNS08C06	40	2	8	26.710	14.879	0.000013279	0.000084650
BNS08C07	41	2	8	13.502	7.164	0.000064870	0.000305500
BNS08C10	42	2	8	6.909	2.334	0.000000107	0.000001637
BNR01C02	43	2	9	14.145	19.632	0.005256000	0.003294000
BNR01C08	44	2	9	10.485	19.664	0.004791000	0.003147000
BNR01C10	45	2	9	35.970	11.794	0.006252000	0.003539000
BNN01C04	46	2	10	17.957	16.471	0.009940000	0.003457000
BNN01C06	47	2	10	30.730	19.300	0.014333000	0.004661000
BNN01C09	48	2	10	15.205	34.500	0.010929000	0.003596000

Table A.11 IPC B-24 SIR (x1E12 ohms) Data for Cleaned and As-Received Boards in Chamber H (Clean 1 = Cleaned, Clean 2 = As-Received, Cell 9 = Rosin Flux, Cell 10 = Unsoldered)

IPC B-24 SIR, Test Conditions 85°C, 85% RH

Pattern A				
Day 7	Day 14	Day 21	Post-In	Post-Out
0.001030900	0.001093900	0.001092100	1.07760000	2.8290000
0.001435700	0.001257700	0.001161800	1.05360000	2.3980000
0.000273200	0.000418900	0.000915800	1.17520000	2.1770000
0.002240000	0.001358100	0.001203800	1.04730000	3.1540000
0.001287100	0.001044600	0.001016600	1.03950000	3.0110000
0.000326400	0.000544200	0.000660700	0.94140000	1.7889000
0.000651300	0.000708500	0.000795700	0.87180000	7.9800000
0.001414900	0.001019400	0.001005900	0.90460000	1.7572000
0.000023560	0.000384700	0.000524600	1.00620000	2.1280000
0.000704800	0.000765900	0.000708200	0.56770000	1.2070000
0.001456500	0.001238700	0.001182400	0.00012281	0.0002099
0.001526600	0.001224700	0.001146200	0.21720000	0.1983420
0.001599300	0.001156300	0.001142200	0.99340000	1.9036000
0.002179000	0.001366200	0.001292900	1.00580000	2.8270000
0.001026800	0.001043200	0.001006500	1.03270000	2.9070000
0.000206800	0.000543400	0.000638900	1.03770000	1.8753000
0.002483000	0.001675900	0.001629600	1.26880000	3.0920000
0.002209000	0.001475100	0.001398400	1.12930000	2.2970000
0.000843100	0.001068200	0.001044500	1.05140000	1.9927000
0.000568800	0.001030800	0.001074900	1.05960000	3.1290000
0.001254900	0.001154900	0.001098300	1.03390000	3.0210000
0.002171000	0.001433200	0.001315200	0.90650000	2.5890000
0.001863700	0.001212700	0.001105800	0.90980000	3.1690000
0.001208000	0.001007600	0.000952800	0.95810000	3.0020000
0.000333600	0.000477500	0.000462100	0.02106000	0.0185910
0.001023700	0.000960300	0.000910700	0.98010000	1.9613000
0.000829200	0.000846700	0.000827900	0.91550000	2.7400000
0.001212400	0.000960800	0.000925400	0.96160000	1.5362000
0.001279800	0.001041500	0.001003700	0.88240000	2.9350000
0.001719400	0.001142900	0.001028300	0.91590000	1.5509000
0.001188600	0.000985700	0.000882600	1.08620000	2.6830000
0.001753400	0.001222400	0.001019200	1.12250000	1.9064000
0.001123800	0.000866300	0.000762400	0.81640000	1.9484000
0.001411600	0.001154300	0.001041500	1.07820000	1.5814000
0.001362700	0.001042100	0.000994800	1.01660000	2.0360000
0.001208300	0.001035500	0.000979100	0.96620000	1.6002000
0.001388000	0.001006900	0.000948300	0.93540000	2.7440000
0.000849700	0.000778300	0.000827900	0.92050000	1.4951000
0.001161500	0.000900800	0.000855500	0.93210000	3.5820000
0.000500600	0.000638400	0.000689600	0.86730000	2.7840000
0.000680100	0.000820700	0.000846700	0.94180000	1.6199000
0.000066300	0.000229200	0.000432400	0.32890000	0.2211000
0.002292000	0.001468300	0.001399500	1.18310000	2.6810000
0.002198000	0.001420600	0.001341500	1.08600000	1.9782000
0.002356000	0.001532300	0.001260400	1.13340000	2.5340000
0.002211000	0.001436100	0.001402600	1.12060000	1.9591000
0.002712000	0.001757800	0.001678600	0.96510000	2.1780000
0.002248000	0.001478400	0.001467300	0.99810000	3.0320000

Table A.11 (continued)

IPC B-24 SIR, Test Conditions 85°C, 85% RH

Pattern B		Pattern C		Pattern D	
Pre	Post	Pre	Post	Pre	Post
1.739	2.0670000	1.969	1.9078000	3.167	1.2454000
1.843	2.8620000	5.732	2.4350000	2.442	1.5708000
8.044	2.1820000	1.100	1.9804000	1.627	1.4428000
2.687	1.8976000	0.702	1.6833000	0.443	1.0776000
31.710	2.0060000	1.687	1.6909000	0.603	1.0908000
4.968	1.8734000	8.093	1.8434000	1.365	1.2404000
16.837	2.1360000	3.544	1.4872000	3.180	0.8507000
3.998	2.0840000	1.777	2.0630000	0.814	1.3808000
12.597	2.3730000	1.092	2.0870000	0.699	1.6841000
20.130	2.1320000	3.517	1.9454000	1.377	1.0710000
8.802	1.9980000	10.282	1.9831000	8.402	1.3287000
32.400	2.0710000	18.956	2.3370000	7.842	1.4972000
3.336	2.0070000	22.460	2.3780000	4.714	1.4752000
7.705	1.8860000	6.491	1.7615000	2.173	1.3711000
1.460	2.1910000	11.946	2.0840000	1.763	1.2379000
17.233	1.4931000	10.694	2.0470000	1.466	1.6371000
59.290	2.6030000	79.360	2.1070000	20.378	1.3583000
16.699	1.9891000	14.931	1.9097000	10.241	1.0537000
5.955	2.1610000	9.265	2.0930000	4.164	2.4690000
9.042	2.0060000	8.555	1.8906000	7.664	1.3218000
17.540	2.0130000	9.161	2.1710000	6.955	1.4225000
1.273	1.8746000	1.273	1.6898000	1.080	1.2884000
33.570	2.1550000	27.960	2.1670000	18.904	1.4703000
2.766	2.0370000	0.414	1.8873000	0.392	0.9855000
32.590	2.2020000	19.432	2.0180000	29.190	1.3768000
30.890	1.9671000	20.980	2.0040000	13.925	1.4148000
18.976	1.8908000	11.382	1.7344000	11.135	1.2809000
183.250	1.5667000	6.253	2.0330000	7.836	1.3444000
18.520	1.9715000	8.353	2.0150000	10.975	1.1672000
10.886	1.7643000	10.044	3.3780000	6.163	1.4087000
23.620	2.1330000	6.261	1.8501000	2.297	1.1863000
24.990	1.9055000	10.772	2.4680000	6.667	1.5995000
27.680	2.2030000	9.178	2.1498000	5.883	1.1668000
14.583	1.7071000	19.732	1.8891000	30.710	1.3094000
13.995	2.0950000	15.199	1.9830000	5.115	0.9709000
18.835	1.8919000	8.193	2.6190000	2.854	1.2897000
11.332	1.8085000	8.205	1.6095000	4.389	0.8579000
14.310	1.7215000	8.900	2.0920000	4.053	1.0819000
7.950	1.9760000	8.077	1.7102000	3.760	0.8614000
35.490	1.7124000	16.612	1.6506000	3.882	0.0006153
20.360	1.8399000	15.571	2.2130000	3.273	0.0011542
14.972	1.7799000	4.416	2.0190000	2.177	0.6479000
27.930	2.0340000	18.782	1.8782000	10.684	1.0534000
39.400	2.0950000	20.030	1.9085000	14.553	1.1471000
24.620	2.1180000	8.305	1.8442000	12.618	1.1592000
22.350	1.9381000	16.433	1.8955000	18.490	1.1859000
54.700	1.9738000	21.610	1.7182000	12.551	1.0257000
20.040	1.8066000	23.740	1.5988000	12.497	0.9036000

Table A.11 (continued)

IPC B-24 SIR, Test Conditions 50°C, 90% RH

Board S/N				Pattern A			
	Case	Clean	Cell	Pre-Out	Pre-In	Day 1	Day 4
BCS01C12	1	1	1	0.226	0.288	0.002933000	0.004260000
BCS01C14	2	1	1	1.383	1.319	0.004517000	0.005887000
BCS01C17	3	1	1	0.751	0.697	0.011548000	0.014306000
BCS02C10	4	1	2	1.459	2.881	0.858500000	0.791500000
BCS02C12	5	1	2	0.452	1.279	0.725900000	0.735400000
BCS02C17	6	1	2	0.478	1.363	0.275300000	0.431600000
BCS03C15	7	1	3	0.072	0.373	0.024240000	0.032020000
BCS03C16	8	1	3	0.573	3.235	0.108660000	0.271500000
BCS03C17	9	1	3	0.474	2.145	0.000007130	0.000008163
BCS04C13	10	1	4	0.255	0.985	0.071120000	0.501900000
BCS04C14	11	1	4	0.898	2.347	0.223600000	0.447300000
BCS04C15	12	1	4	2.035	3.864	0.257600000	0.420300000
BCS05C06	13	1	5	0.561	0.734	0.236500000	0.502200000
BCS05C07	14	1	5	0.418	0.731	0.573200000	0.614700000
BCS05C09	15	1	5	0.730	0.839	0.331800000	0.330900000
BCS06C09	16	1	6	14.382	11.459	0.002443000	0.003237000
BCS06C10	17	1	6	3.435	5.350	0.001744200	0.002547000
BCS06C11	18	1	6	4.771	4.934	0.011363000	0.012559000
BCS07C13	19	1	7	8.334	7.499	1.125600000	0.840600000
BCS07C14	20	1	7	1.783	2.683	0.040620000	0.039170000
BCS07C15	21	1	7	5.440	6.262	0.307800000	0.256500000
BCS08C11	22	1	8	1.561	2.095	0.000891300	0.001394300
BCS08C14	23	1	8	1.319	1.616	0.001155600	0.001962100
BCS08C16	24	1	8	7.593	4.792	0.000283500	0.000010130
BCR01C13	25	1	9	26.950	17.320	0.708600000	1.063100000
BCR01C16	26	1	9	17.822	15.413	0.000248000	0.000401900
BCR01C17	27	1	9	30.220	27.910	0.309600000	0.663000000
BNS01C14	28	2	1	7.056	2.985	0.000004303	0.000005904
BNS01C17	29	2	1	7.573	3.691	0.000026640	0.013218000
BNS02C12	30	2	2	1.491	2.013	0.038870000	0.100002000
BNS02C13	31	2	2	1.105	0.965	0.091640000	0.526900000
BNS03C14	32	2	3	2.035	4.305	0.791900000	0.723100000
BNS03C15	33	2	3	27.790	28.640	0.099860000	0.101910000
BNS04C12	34	2	4	7.460	24.410	9.530000000	12.052000000
BNS04C16	35	2	4	28.380	17.676	0.928900000	0.823800000
BNS05C10	36	2	5	9.156	9.603	1.202600000	1.015300000
BNS05C14	37	2	5	13.368	6.380	0.543000000	0.497200000
BNS06C16	38	2	6	1.606	8.346	0.035480000	0.042360000
BNS06C17	39	2	6	13.246	8.526	0.014030000	0.016438000
BNS07C14	40	2	7	14.358	17.602	0.572100000	0.445900000
BNS07C15	41	2	7	21.260	20.530	0.041190000	0.048020000
BNS08C12	42	2	8	5.331	5.540	0.001025400	0.001764200
BNS08C17	43	2	8	7.945	6.767	0.000415600	0.000734500
BNR01C11	44	2	9	36.170	23.550	0.449400000	0.912600000
BNR01C13	45	2	9	11.916	14.447	0.123630000	0.444200000
BNN01C15	46	2	10	44.270	13.318	1.023000000	1.034100000
BNN01C17	47	2	10	33.860	13.498	1.114500000	1.014300000

Table A.12 IPC B-24 SIR (x1E12 ohms) Data for Cleaned and As-Received Boards in Chamber L (Clean 1 = Cleaned, Clean 2 = As-Received, Cell 9 = Rosin Flux, Cell 10 = Unsoldered)

IPC B-24 SIR, Test Conditions 50°C, 90% RH

Pattern A				
Day 7	Day 14	Day 21	Post-In	Post-Out
0.004928000	0.006048000	0.007231000	3.10800000	9.1730000
0.006611000	0.007341000	0.008459000	3.30400000	5.0790000
0.015672000	0.017359000	0.019394000	4.75900000	10.3370000
0.601900000	0.469300000	0.332100000	7.51400000	5.5100000
0.603900000	0.465700000	0.364300000	9.22100000	9.8060000
0.483600000	0.434800000	0.318100000	8.20500000	7.2680000
0.037020000	0.032030000	0.002386000	5.51000000	20.1500000
0.281500000	0.198960000	0.169660000	8.93200000	11.7140000
0.000006326	0.000006273	0.000005817	0.00003549	1.8771000
0.485300000	0.198890000	0.032950000	1.93380000	5.3310000
0.383200000	0.133260000	0.014699000	1.35350000	4.2640000
0.368100000	0.088170000	0.023990000	1.86780000	9.3160000
0.703400000	0.545000000	0.313500000	9.77600000	8.2370000
0.521600000	0.409600000	0.310000000	9.81000000	9.2660000
0.283400000	0.221100000	0.188970000	8.82700000	8.1050000
0.004004000	0.005174000	0.006746000	3.08300000	8.0260000
0.003037000	0.003960000	0.005081000	2.50700000	5.4400000
0.014048000	0.015518000	0.014291000	3.34800000	12.5770000
0.621500000	0.415700000	0.314600000	7.97000000	6.3790000
0.038030000	0.036250000	0.035450000	5.67500000	10.6630000
0.231400000	0.163540000	0.095920000	7.09500000	6.6010000
0.001802000	0.002443000	0.003088000	1.38940000	6.0290000
0.002504000	0.002876000	0.002913000	0.11738000	1.6687000
0.000014290	0.000010337	0.000014342	0.00032240	0.0026670
0.372100000	0.156480000	0.490300000	16.93200000	16.9570000
0.000095430	0.000040930	0.000040570	0.00018596	0.0006549
0.607500000	0.499300000	0.409500000	10.82500000	6.7530000
0.000004746	0.000021760	0.000006889	0.00010216	0.0009318
0.011265000	0.003802000	0.001136000	0.01709400	0.0280200
0.283900000	0.274400000	0.235100000	7.07900000	6.7410000
0.529500000	0.448300000	0.329800000	9.98300000	9.6460000
0.598000000	0.311800000	0.218300000	6.61800000	5.3760000
0.078260000	0.020830000	0.018820000	7.26500000	5.8850000
10.512000000	10.035000000	9.907000000	25.50000000	12.8090000
0.612500000	0.250300000	0.063910000	3.27700000	6.3890000
0.825700000	0.557800000	0.418000000	7.40600000	6.5190000
0.508600000	0.419700000	0.369400000	8.55000000	9.6110000
0.047220000	0.057920000	0.071490000	8.59100000	11.3340000
0.017782000	0.020170000	0.023040000	4.26700000	3.5260000
0.395400000	0.297400000	0.246100000	7.38600000	9.4240000
0.047420000	0.049960000	0.051560000	5.17900000	5.6730000
0.002205000	0.002871000	0.003628000	1.68340000	3.3980000
0.000954900	0.001290600	0.001572400	0.80560000	2.5360000
0.750100000	0.584100000	0.463300000	11.54100000	7.8390000
0.507600000	0.549700000	0.445200000	11.35600000	8.9400000
0.760800000	0.523100000	0.438600000	11.76200000	5.8010000
0.767600000	0.526400000	0.425900000	8.38400000	7.8440000

Table A.12 (continued)

IPC B-24 SIR, Test Conditions 50°C, 90% RH

Pattern B		Pattern C		Pattern D	
Pre	Post	Pre	Post	Pre	Post
5.610	6.9630000	1.436	5.6970000	0.457	6.1810000
5.908	4.9300000	3.218	4.8530000	1.559	4.9830000
0.738	6.7150000	0.255	5.1240000	1.914	7.8780000
1.499	6.7420000	0.445	6.5320000	0.252	6.3950000
2.003	11.6500000	0.458	9.2010000	0.437	7.1850000
1.408	8.7770000	0.221	7.7830000	0.072	8.4060000
4.733	14.5730000	0.705	7.9060000	0.127	6.8560000
4.467	8.8860000	1.150	6.9190000	0.789	7.6540000
4.730	14.2850000	1.576	8.0310000	0.292	6.7490000
0.515	3.3850000	0.499	3.5110000	0.330	2.9630000
2.058	5.6840000	1.530	5.7080000	0.507	13.6030000
1.464	4.1680000	2.104	3.8130000	1.392	3.1700000
0.468	11.3300000	0.667	8.8520000	0.332	7.0920000
0.939	8.1020000	2.975	5.0710000	2.014	4.8170000
2.203	8.3470000	7.257	8.9240000	1.139	7.5080000
14.732	7.7290000	8.375	4.9710000	5.002	5.9300000
11.043	6.3790000	6.413	7.2770000	4.366	5.1050000
7.176	11.6540000	5.138	7.2410000	2.011	4.1750000
20.710	7.3360000	14.762	10.8210000	7.065	8.6090000
14.488	8.4440000	7.385	5.8670000	5.480	4.5150000
25.410	16.3450000	4.532	12.5360000	8.600	11.6330000
6.755	6.7030000	3.870	6.9360000	2.676	5.2650000
11.430	6.7380000	1.860	11.2370000	2.115	8.7090000
28.900	0.0001217	14.354	7.3990000	7.325	5.8820000
19.203	12.9340000	25.230	10.1440000	19.242	11.0830000
33.340	6.8720000	21.840	7.6430000	12.907	10.3930000
17.105	7.1910000	17.215	7.1960000	18.596	7.7500000
7.376	0.1607700	0.993	0.0000133	2.311	11.2350000
6.701	3.0490000	9.560	7.9810000	5.812	7.7490000
1.715	8.2920000	0.657	7.9950000	0.392	7.8850000
20.890	8.9530000	0.414	8.5010000	0.359	24.6300000
71.930	7.0120000	18.559	9.3040000	8.392	9.4670000
75.480	7.2400000	7.470	0.0001039	7.404	3.5370000
11.039	12.5280000	8.059	9.3070000	4.633	7.1760000
20.940	7.6130000	10.707	10.6150000	10.375	11.3020000
79.480	8.3010000	20.620	10.3580000	3.809	6.3670000
24.210	9.7650000	9.061	6.6060000	4.821	6.2090000
14.832	7.3450000	7.515	4.9110000	3.198	4.0150000
28.460	4.7130000	8.274	5.5700000	4.009	6.2370000
11.333	8.7010000	9.219	4.8420000	4.273	4.7770000
27.060	5.1800000	11.853	6.0910000	11.003	6.7360000
18.405	6.1690000	1.316	8.0310000	3.961	9.9980000
9.758	2.2480000	12.204	3.9150000	8.113	4.5140000
34.390	6.3900000	34.660	5.8460000	3.892	7.8750000
17.134	9.6970000	47.170	9.8540000	20.050	9.7690000
58.780	5.8310000	18.906	7.4350000	18.967	8.0480000
19.949	7.6390000	13.912	5.3960000	21.700	5.7290000

Table A.12 (continued)

IPC B-24 Conformal Coated SIR, Test Conditions 65°C, 90% RH

Board				Pattern A			
S/N	Case	Clean	Cell	Pre-In	8 Hours	Day 1	Day 2
BCS01C06	1	1	1	8.694	0.0008684	0.0013024	0.0017408
BCS01C07	2	1	1	17.021	0.0011447	0.0015076	0.0019678
BCS02C03	3	1	2	22.020	0.0033310	0.0043570	0.0054200
BCS02C06	4	1	2	17.825	0.0033240	0.0036490	0.0041460
BCS03C06	5	1	3	15.743	0.0006678	0.0009334	0.0012559
BCS03C13	6	1	3	13.409	0.0028710	0.0038660	0.0047410
BCS04C06	7	1	4	13.676	0.0030550	0.0039680	0.0044210
BCS04C08	8	1	4	14.718	0.0039560	0.0052260	0.0059270
BCS05C17	9	1	5	18.663	0.0029240	0.0043230	0.0050460
BCS06C03	10	1	6	9.394	0.0011149	0.0015649	0.0020370
BCS06C08	11	1	6	12.637	0.0016262	0.0022260	0.0027340
BCS07C06	12	1	7	13.285	0.0025560	0.0035330	0.0042030
BCS07C07	13	1	7	20.330	0.0025930	0.0032050	0.0038210
BCS08C05	14	1	8	11.359	0.0007033	0.0010372	0.0013915
BCS08C07	15	1	8	17.489	0.0019128	0.0023610	0.0025260
BCR01C03	16	1	9	6.239	0.0024410	0.0035540	0.0046930
BCR01C11	17	1	9	10.108	0.0025580	0.0030410	0.0036450
BNS01C07	18	2	1	8.132	0.0007109	0.0011764	0.0015808
BNS01C16	19	2	1	14.438	0.0011867	0.0014633	0.0018712
BNS02C09	20	2	2	15.903	0.0031810	0.0042240	0.0053200
BNS03C16	21	2	3	13.558	0.0024430	0.0029720	0.0035080
BNS04C06	22	2	4	9.724	0.0027670	0.0034520	0.0040720
BNS04C11	23	2	4	10.140	0.0028560	0.0036460	0.0043870
BNS06C12	24	2	6	12.253	0.0014798	0.0018384	0.0022220
BNS06C13	25	2	6	13.371	0.0008114	0.0011449	0.0014575
BNS07C05	26	2	7	20.001	0.0024420	0.0028080	0.0030750
BNS07C06	27	2	7	15.923	0.0030880	0.0047930	0.0055300
BNS08C05	28	2	8	18.515	0.0008296	0.0011962	0.0015522
BNS08C14	29	2	8	6.991	0.0003002	0.0005371	0.0007731
BNR01C07	30	2	9	9.007	0.0027620	0.0035470	0.0045580
BNR01C17	31	2	9	14.695	0.0029690	0.0035070	0.0037740
BNN01C12	32	2	10	16.265	0.0034580	0.0053100	0.0064620
BNN01C16	33	2	10	15.924	0.0030940	0.0043940	0.0055210

Table A.13 IPC B-24 Conformal Coated SIR (x1E12 ohms) Data for Cleaned and As-Received Boards in Chamber M (Clean 1 = Cleaned, Clean 2 = As-Received, Cell 9 = Rosin Flux, Cell 10 = Unsoldered)

IPC B-24 Conformal Coated SIR, Test Conditions 65°C, 90% RH

Pattern A			
Day 4	Day 7	Day 14	Post-In
0.0023940	0.0029770	0.0035020	13.1210
0.0025210	0.0029580	0.0033350	12.7990
0.0058940	0.0059070	0.0049280	15.8090
0.0048420	0.0047510	0.0040940	16.0120
0.0018625	0.0024810	0.0034410	12.3550
0.0055000	0.0060630	0.0060430	13.8450
0.0018745	0.0009644	0.0018501	0.2649
0.0064320	0.0066340	0.0064140	8.3170
0.0056150	0.0058820	0.0056950	16.0260
0.0026130	0.0030270	0.0033420	13.9510
0.0031350	0.0033080	0.0031760	13.3840
0.0046530	0.0048140	0.0041870	15.2560
0.0042080	0.0043120	0.0037660	15.9070
0.0018384	0.0022650	0.0026540	13.0880
0.0029320	0.0029880	0.0026880	16.6200
0.0056040	0.0062650	0.0060830	12.6940
0.0041980	0.0044990	0.0042970	11.9660
0.0021410	0.0025560	0.0028730	14.8590
0.0024820	0.0028580	0.0030100	15.3260
0.0059060	0.0062820	0.0059380	17.8180
0.0039990	0.0042310	0.0043490	15.6330
0.0049890	0.0053500	0.0049330	13.1420
0.0052820	0.0056690	0.0053900	11.6040
0.0027030	0.0029180	0.0028860	14.9590
0.0018578	0.0021740	0.0024910	14.2360
0.0035970	0.0036090	0.0032150	16.6920
0.0060620	0.0061820	0.0056580	16.4030
0.0020130	0.0023350	0.0026310	15.5540
0.0011724	0.0015965	0.0021380	12.4300
0.0051440	0.0055100	0.0053200	8.8150
0.0044690	0.0047890	0.0046730	11.2720
0.0066510	0.0069150	0.0062240	14.9830
0.0056830	0.0058640	0.0051760	13.0940

Table A.13 (continued)

FMU-139 Ionic Cleanliness

Board S/N	Case	Cell	Ionic Cleanliness
FCS01N02	1	1	5.3
FCS01N05	2	1	4.0
FCS01N11	3	1	3.3
FCS01N15	4	1	2.8
FCS02N05	5	2	3.3
FCS02N10	6	2	4.0
FCS03N01	7	3	30.0
FCS03N06	8	3	24.1
FCR01N14	9	4	1.8
FCR01N16	10	4	0.7

Table A.14 FMU-139 Ionic Cleanliness ($\mu\text{gm}/\text{in}^2$ equivalent NaCl ions) Data (Cells 1-3 = Good, In-Between, and Marginal Solder Quality and Cleanliness as Defined in Table 1.2, Cell 4 = Rosin Flux)

FMU-139 Pull Strength

Board S/N	Case	Cell	Pull Strength	
			Switch	Resistor
FCS01N01	1	1	20.5	15.4
FCS01N05	2	1	19.7	15.5
FCS01N13	3	1	20.2	15.9
FCS02N05	4	2	20.4	15.6
FCS02N06	5	2	20.3	15.4
FCS02N07	6	2	20.6	15.6
FCS03N01	7	3	19.3	15.6
FCS03N03	8	3	20.1	15.6
FCS03N13	9	3	18.7	15.9
FCR01N07	10	4	21.2	15.5
FCR01N12	11	4	21.2	15.5
FCR01N16	12	4	20.8	15.4

Table A.15 FMU-139 Pull Strength (lbs) Test Data (Cells 1-3 = Good, In-Between, and Marginal Solder Quality and Cleanliness as Defined in Table 1.2, Cell 4 = Rosin Flux)

DATE

FILMED

10/18/94

END