Screening Test Results for Developing Guidelines for Conformal Coating Usage and Evaluating Alternative Surface Finishes: A Report from the Circuit Card Assembly and Materials Task Force

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Executive Summary

Circuit Card Assembly and Materials Task Force

The Circuit Card Assembly and Materials Task Force (CCAMTF) was formed in September 1995 to develop and conduct a joint test program for evaluating the reliability of new manufacturing technologies and materials used in producing circuit card assemblies. This program was not a research and development effort. Rather, it focused on both understanding developed and emerging technologies and determining how these technologies apply to state-of-the-art, performance-on-demand military and high-end commercial electronics, from electrical performance, product reliability, and pollution-prevention standpoints. The CCAMTF combines the joint efforts of industry, military, and government and is funded by in-kind contributions of the participating organizations and by the Joint Group on Acquisition Pollution Prevention (JG-APP).. The following organizations are participants in the program:

Southwest Technology Consultants
Texas Instruments Incorporated
Motorola: Automotive & Industrial Electronics Group
GM Hughes Electronics
Electronic Manufacturing Productivity Facility
Contamination Studies Laboratory
AlliedSignal / FM&T- Kansas City
Honeywell
Lucent Technologies
NCMS
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The CCAMTF evaluation has three-phases: Screening, Phase 1, and Phase 2. This report documents the results of the Screening phase.

Goals of the CCAMTF

The CCAMTF developed selection criteria and a ranking methodology for determining the most important technologies to pursue. On-going activities and past consortia work were considered in the selection process. This process identified the following technologies as having greatest impact on environmental pollution source reduction, cost, and yield: (1) guidelines for intelligent use of conformal coating and (2) lead-free organic and metallic printed wiring board surface (PWB) finishes. The CCAMTF then formulated the following goals for its test program: (1) develop guidelines for conformal coating usage and, in particular, determine conditions under which coating can be eliminated and (2) evaluate alternatives to fused tin-lead surface finishes. The diverse membership of the CCAMTF ensured that concerns of industry, military, and government were considered during the planning and execution stages of the program. The CCAMTF also sought input from the electronics community during an open meeting at NEPCON West ‘96.

Background on Conformal Coating. Conformal coating is widely applied to circuit cards to protect against adverse environmental and operating conditions. The application process is costly and time consuming. It is also the source of up to 40% of volatile organic compounds (VOCs) produced in some high-volume manufacturing operations and requires the use of pollution prevention equipment. Many manufacturers believe that conformal coating often adds unneeded cost to their processing that could be eliminated in specific applications without lowering quality or performance.

Background on Alternative Surface Finishes. Surface finishes are applied to PWBs to prevent oxidation of exposed copper conductors on the board, thus ensuring a solderable surface when components are added later. The most widely used processes are hot-air solder leveling (HASL) with solder mask, which is used mainly for commercial applications, and reflowed tin-lead, which is primarily used for military applications. In both processes, tin-lead is fused onto exposed copper surfaces. Besides being a source of lead waste in the environment, a major concern associated with these processes is their inability to provide a level soldering surface. Planarity is extremely important in placing fine pitch components, which are becoming more prevalent in surface mount operations. Wire bonding to plated finishes is also a growing interconnect technology. The fused tin-lead surface finish is a limiting technology with respect to these areas.

Conformal Coating Guidelines

Three screening experiments were conducted to determine the value of conformal coating as a function of spacing between conductors, voltage input, soldering flux, PWB surface finish, and operating environment. Surface insulation resistance (SIR) was measured on test boards with three different surface finishes: (1) HASL with solder mask, (2) reflowed SnPb, and (3) imidazole, an organic solderability preservative (OSP). Half these boards were coated with parylene and the other half were not coated. Half the boards were processed with a halide free low-residue (LR) flux and the remainder were processed with a halide containing water-soluble (WS) flux. Each unique group of processed boards was exposed to different environmental testing conditions.

Results of the screening experiments allow direct comparisons of conformal coated boards with uncoated boards for 24 processing/environmental combinations of interest. These results are very helpful in determining where conformal coating is required and where it can be eliminated as a function of spacing between conductors, voltage input, soldering flux, PWB surface finish, and operating environment. A brief summary of the results for each screening experiment is now given.

Conformal Coating Test Results

The test vehicle for the screening experiments was a modified IPC-B-24 board with the 20-mil spacing between conductors changed on three of its four comb patterns to 16 mils, 12 mils, and 8 mils. SIR measurements were made at three voltages (low — 50V , medium — 100V, and high — 200V) on each of these patterns in one experiment and at 100V in the other two experiments.

The modified SIR test boards were subjected to one of four sets of environmental conditions: (1) 168 *hr* exposure to 85°*C* / 85% RH, (2) 10 cycles of 6.5 *hr* in a condensing atmosphere, (3) exposure to diesel fuel, and (4) exposure to hydraulic fluid.

Overall, voltage had no noticeable affect on SIR and comb pattern spacing did not appear to be an issue other than some bridging problems on 8-mil imidazole and HASL processed boards due to the application of too much solder paste combined with solder mask. A brief summary of the test results is now given for each of the environmental conditions. In addition, exposed copper on the vertical edge of pads or circuit lines did not have a negative effect on SIR.

85/85 Test. Coating applied to boards with a reflowed SnPb surface finish significantly lowered mean SIR during environment and at post-test. Coated and uncoated imidazole boards soldered with LR flux had no significant difference in mean SIR, either during environment or at post-test. The same was true of imidazole boards soldered with WS flux during environment, but coated boards soldered with WS flux had significantly lower mean SIR at post-test. Coated HASL boards soldered with LR flux had significantly higher mean SIR than did uncoated boards both during environment and at post-test. No significant difference in mean SIR was noted during environment for coated and uncoated HASL boards soldered with WS flux. Mean SIR was significantly lower for coated HASL boards soldered with WS flux at post-test.

Condensing Atmosphere Test. Reflowed SnPb boards with coating had a significant increase in mean SIR during environment with either flux. This was a noticeable change from the 85/85 test where coating significantly lowered mean SIR on reflowed SnPb boards. However, there is no significant difference in mean SIR between coated and uncoated reflowed SnPb boards at post-test. Imidazole boards benefited from coating with either flux during environment and at post-test. Mean SIR for coated HASL boards did not differ significantly from mean SIR on uncoated boards, either during environment or at post test. However, coated HASL boards consistently had higher SIR with less variability than uncoated boards.

Fluids Test. Coating, in combination with LR flux, gave significantly higher mean SIR in diesel fuel for all three surface finishes (and for reflowed SnPb with WS flux). However, there were no significant differences in mean SIR on coated and uncoated boards for any experimental combination after the second and final dip in diesel fuel. Mean SIR for coated and uncoated boards was at an acceptable level (10 to 13 log 10 ohms) for all surface finishes after two dips in diesel fuel.

Coating provided significantly higher mean SIR for all boards dipped in hydraulic fluid, but this mean SIR was just above the minimum acceptable level of 8 log 10 ohms.

Alternative Surface Finishes

Two screening experiments were conducted to compare the performance of HASL and six alternative surface finishes (ASFs): two OSPs — benzimidazole and imidazole; immersion Au over Ni plating; immersion Ag plating, electroplated Pd, and immersion Au over electroplated Pd. This evaluation used available industry information to avoid duplication of efforts and built on results of the NCMS 5-year evaluation of PWB surface finishes, and extended those results by:

- Evaluating benzimidazole
- Including immersion Ag
- Expanding the data base on immersion Au
- Evaluating the effect of processing in both open air and nitrogen

The screening experiments evaluated solderability with wetting balance, sequential electrochemical reduction analysis (SERA), and spread tests on readily available test vehicles processed with either LR or WS fluxes. A brief summary of the results of the screening experiments is now given.

ASF Results

Six solderability tests were used on copper coupons having one of the seven surface finishes considered in the evaluation. A comparison of these tests indicated that the commonly used wetting force at 2 *sec* was best for downselecting surface finishes. A spread test was also used to evaluate the width of gaps that were spanned on each surface finish.

Immersion Ag had the best overall performance in the two ASF screening tests. OSPs were competitive with immersion Ag in the non-baking environments. Neither OSP showed adequate wetting when measured by the wetting balance test in the baking environment. Immersion Au/Pd with nitrogen produced results that make it a possible candidate for further evaluation. On the other hand, there appears to be little support for continued evaluation of either immersion Au (cost is also a factor) or immersion Pd.

Phase 1 and 2 Programs

Results of the screening experiments will guide the CCAMTF Phase 1 program. The functional test vehicle developed by the Low-Residue Soldering Task Force (LRSTF) will be used in Phase 1. The LRSTF printed wiring assembly (PWA) will be processed and tested in an experiment shaped by the screening evaluations. Electrical circuit performance data for the LRSTF PWA will be compared with documented data from the LRSTF's evaluation of low-residue soldering.

Benzimidazole and imidazole gave similar results, but benzimidazole was selected over imidazole for Phases 1 and 2. Reasons for selecting benzimidazole were based more on practical considerations than on technical reasons. Specifically, only one OSP was selected to reduce the size and cost of Phases 1 and 2. In addition, benzimidazole is currently being used by CCAMTF military participants.

The LRSTF PWA will also be used in the CCAMTF Phase 2 evaluation to assess the reliability of circuitry processed with and without conformal coating and circuitry processed with the ASFs under study.

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List of Abbreviations

ASF	alternative surface finish
CCAMTF	Circuit Card Assembly and Materials Task Force
CFC	chlorofluorocarbons
CSL	Contamination Studies Laboratories, Inc.
DOD	Department of Defense
DOE	Department of Energy
EMPF	Electronics Manufacturing Productivity Facility
GLM	general linear model
HASL	hot air solder leveling
HCFC	hydrochlorofluorocarbons
IPA	isopropyl alcohol
IPC	Institute on Interconnecting and Packaging of Electronic Circuits
LR	low residue
LRSTF	Low-Residue Soldering Task Force
NCMS	National Center for Manufacturing Sciences
OSP	Organic solderability preservative
PWA	printed wiring assembly
PWB	printed wiring board
RH	relative humidity
SERA	sequential electrochemical reduction analysis
SIR	surface insulation resistance
TI	Texas Instruments
VOC	volatile organic compound
WS	water soluble

1. Introduction

1.1 Background

Conformal Coating. Conformal coating is widely applied to circuit cards for protection against adverse environmental and operating conditions. The application process is costly and time consuming. It is also the source of up to 40% of volatile organic compounds (VOCs) produced in some high volume manufacturing operations, and requires use of pollution prevention equipment. Many manufacturers believe that conformal coating often adds unneeded cost to their processing that could be eliminated in specific applications without affecting quality or performance.

Surface Finishes. Surface finishes are applied to printed wiring boards (PWBs) to prevent oxidation of exposed copper on the board, thus ensuring a solderable surface when components are added later. The most widely used processes for applying surface finishes are hot air solder leveling (HASL) with solder mask, which is used mainly for commercial applications, and reflowed tin-lead, which is used mainly for military applications. In both processes, tin-lead is fused onto exposed copper surfaces. The fused tin-lead surface finish process is a source of lead waste in the environment. Also, a major concern associated with this process is its lack of planarity (i.e., its inability to provide a level soldering surface). Planarity is extremely important in placing fine pitch components, which are becoming more prevalent in surface mount operations. Wire bonding to plating finishes is also a growing interconnect technology. The fused tin-lead surface finish process is a limiting technology with respect to these areas.

1.2 Circuit Card Assembly and Materials Task Force

The Circuit Card Assembly and Materials Task Force (CCAMTF) is a joint industry and military task force formed to provide guidelines on conditions in which coating can be eliminated and to evaluate alternatives to the fused tin-lead surface finish process.

The CCAMTF utilizes the expertise and evaluation resources available from industry and the military to ensure that as many issues of concern as possible are incorporated into the planned program. This effort is supported by in-kind member contributions. The following organizations are participants in the program:

Southwest Technology Consultants
Texas Instruments Incorporated
Motorola: Automotive & Industrial Electronics Group
GM Hughes Electronics
Electronic Manufacturing Productivity Facility
Contamination Studies Laboratory
AlliedSignal / FM&T- Kansas City
Honeywell
Lucent Technologies
NCMS
Alliant Techsystems
GTE
SEHO USA, Inc.
Les Hymes Associates
Wright-Patterson AFB
Hanscom AFB
US Army - MICOM, Huntsville
US Army - Picatinny Arsenal
Naval Air Warfare Center at Indianapolis

This document provides details of the results of the screening phase for two studies involving conformal coating and alternative surface finishes (ASFs). These studies ran in parallel. During Phases 1 and 2, the two studies will be merged to ensure that the results are compatible. Figure 1.1 is a block diagram showing the planned sequence for the project. The CCAMTF plans to issues periodic reports such as this one to document the results of each phase.

1.3 Definition of Need and Planned Technical Solution

The CCAMTF held five meetings in Dallas from September 1995 to March 1996 to determine industry's needs in the areas of circuit card assembly and materials. The primary drivers relative to the CCAMTF in defining these needs were:

Quality, cost, schedule, and environment

The CCAMTF believed the best approach to determining and addressing these needs was a collaborative effort such as that used by the highly successful Low-Residue Soldering Task Force

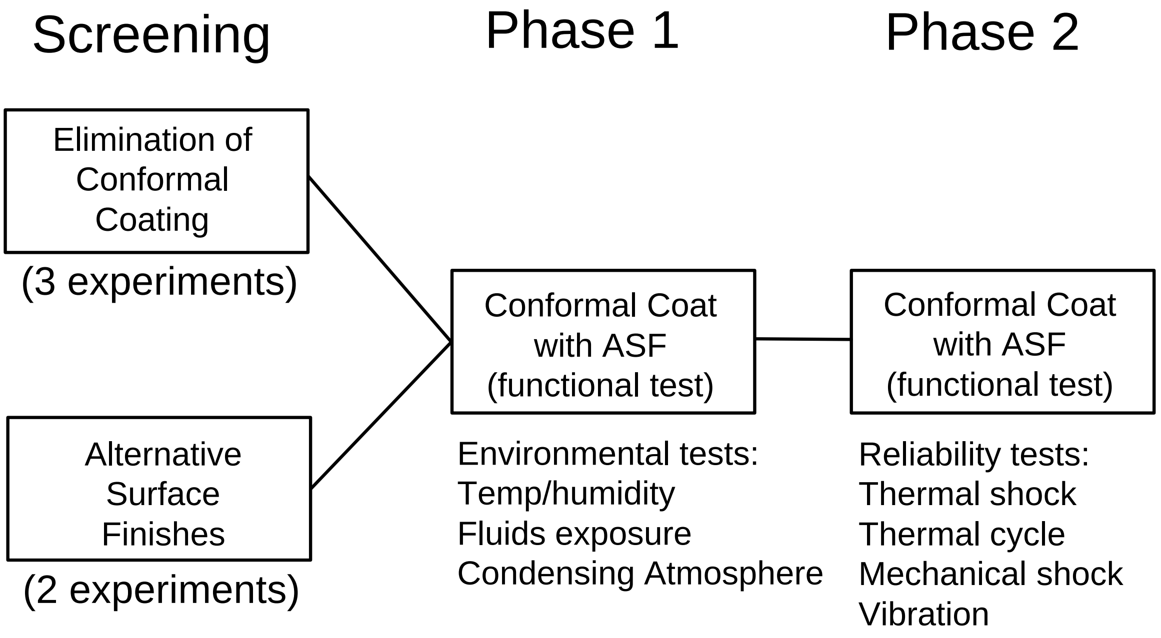

Figure 1.1 Block Diagram Showing the Sequence of the CCAMTF Studies

(LRSTF) in evaluating low-residue soldering for commercial and military applications. The CCAMTF developed a broad list of needs for circuit card assembly and materials, and grouped them into the following three general categories:

Assembly Materials

- Conformal coating
- Lead free solder
- Solder mask
- Conductive adhesive
- Plastic parts
- Green card

Soldering Technologies

- Plasma
- Supercritical fluids
- Vapor phase
- Reduced Oxide Soldering Activation (ROSA)
- Ultrasonic wave
- Conductive reflow

Surface Finishes

- Organic Solderability Preservative (OSP)
- Plating
- Bare Cu

The CCAMTF spent two days during its November 1995 meeting discussing these needs and rating them relative to existing technologies using the following 11 attributes:

- Economics / cost (cycle time, materials)
- Environmental (VOCs, CFCs, HCFCs, Pb)
- Industry wide applicability (DOD, commercial, DOE)
- Reliability impact
- Defect reduction
- Feasibility
- Compatibility with existing materials
- Technology maturity - ratio of (research to be done) to (research done)
- Team resources available
- Increased process options
- Capital investment

Results of this rating process identified specific needs in the areas of conformal coating and alternative surface finishes. In particular, the group believed that use of conformal coating, with and without solder mask, could be greatly reduced and/or eliminated in many specific applications. If so, decreased use of conformal coating would significantly reduce VOC production, decrease costs, and increase throughput without affecting quality or performance. The widely used fused tin-lead surface finish process for covering exposed copper on newly manufactured boards is a limiting technology with respect to the move toward use of fine pitch surface mount components. It is also a source of lead waste in the environment.

1.4 CCAMTF Vision and Mission Statements

The CCAMTF developed the following vision and mission statements to provide clear guidance on group goals and how they would be achieved:

Vision: Facilitate cost effective and timely decision making for adopting new circuit card materials and processes.

Mission: Combine the resources of DOD, industry, and DOE to evaluate the cost, environmental impact, manufacturability, reliability, and performance of printed wiring materials and assembly processes. This evaluation will include alternative PWB surface finishes and conformal coating, which are both enabling technologies.

1.5 Guidelines for Conformal Coating

A three-part evaluation (see Figure 1.1) was planned to determine guidelines for when conformal coating is not required. Screening experiments were conducted to compare the impact of conformal coating as a function of spacing between conductors, voltage input, and PWB surface finish. Surface insulation resistance (SIR) was measured on test boards with three different surface finishes: (1) HASL with solder mask, (2) reflowed tin-lead, and (3) imidazole, an organic solderability preservative (OSP). Half these boards were coated with parylene conformal coating and the other half were not coated. Half the boards were processed with a halide free low-residue flux and the remainder with a halide containing water soluble flux. Each unique group of processed boards was exposed to different environmental testing conditions.

The test vehicle for the screening evaluation was a modified IPC-B-24 board, with the 20-mil spacing between conductors changed on three of its four comb patterns to 16 mils, 12 mils and 8 mils. SIR measurements were made at three voltages (low — 50V, medium — 100V, and high — 200V) on each of these patterns in one screening experiment and at 100V in the two other experiments.

Results of the screening experiments allow direct comparisons of conformal coated boards with uncoated boards for 48 processing / environment combinations of interest. These results are very helpful in determining where conformal coating is required and where it can be eliminated as a function of spacing between conductors, voltage input, and PWB surface finish.

In Phase 1, the functional test vehicle developed by the LRSTF will be processed and tested in an experiment that reflects the results of the screening experiment. Phase 1 electrical circuit performance data for the LRSTF printed wiring assembly (PWA) will be compared with documented data from the LRSTF's evaluation of low-residue soldering. The LRSTF PWA will also be used in the Phase 2 evaluation to assess the reliability of circuitry processed with and without conformal coating.

1.6. Alternative Surface Finishes

A three-part evaluation was also planned to study alternatives to the fused tin-lead surface finish process. Alternative surface finishes (ASFs) are now used in industry in some commercial applications. The planned evaluation made use of available industry information to avoid duplicating efforts and to ensure effectiveness and wide-spread application. A screening experiment was conducted to compare the performance of HASL and four alternative surface finishes: two organic soldering preservatives — benzimidazole and imidazole; immersion Au over Ni plating; immersion Ag plating, electroplated Pd, and immersion Au over electroplated Pd.

This evaluation builds on the results of the NCMS 5-year evaluation of PWB surface finishes and extends those results by:

- Evaluating benzimidazole
- Including immersion Ag
- Expanding the data base on immersion Au
- Evaluating the impact of processing in both open air and nitrogen

The screening phase evaluated solderability with wetting balance, sequential electrochemical reduction analysis (SERA), and spread tests on readily available test vehicles. The screening vehicles were processed with low-residue halide-free and halide containing water soluble fluxes.

In Phase 1, the functional LRSTF PWA will be processed and tested in an experiment shaped by the results of the screening evaluation. Phase 1 electrical circuit performance data for the LRSTF PWA will be compared with documented data from the LRSTF's evaluation of low-residue soldering. The LRSTF PWA will also be used in the Phase 2 evaluation to assess the reliability of circuitry processed with the ASFs being studied.

1.7 Screening Test Results

Section 2 contains the results of the conformal coating evaluation for each of the major test categories: SIR 85NC and 85% relative humidity (RH), condensing atmosphere, and exposure to automotive fluids. The section concludes with a comparison of the results of the three tests. Graphical displays of all the SIR test data for the three screening experiments are given in Appendices A, B, and C.

Section 3 gives the results for the ASF study by two test categories: wetting balance and spread tests. This section also compares wetting balance and SERA tests. Graphical displays of wetting balance and SERA test results are given in Appendix D. Section 3 concludes with a graphical display that combines the results of these two different solderability tests.

Section 4 gives an overview of the plans for the CCAMTF Phase 1 test program.

2. Guidelines for Conformal Coating Usage

2.1 Screening Experiments for Conformal Coating

As shown in Figure 1.1, a three-part evaluation was planned to determine guidelines for when conformal coating is *not* required. The screening phase of this plan was used to determine the value of conformal coating as a function of spacing between conductors, voltage input, soldering flux, PWB surface finish, and operating environment. Surface insulation resistance was measured on 360 test boards with three different surface finishes: (1) reflowed SnPb (120 boards), (2) imidazole — an organic solderability preservative (120 boards), and (3) HASL with solder mask (120 boards) as the baseline. A three-dimensional representation of the test matrix for the screening experiment is shown in Figure 2.1.

Half the test boards in each surface finish group were processed with halide-free low-residue flux and the remainder with halide-containing water soluble flux. Half the boards in each surface finish group were coated with parylene — a vapor deposition process that ensures total and precise coverage of circuitry. The remainder were not coated.

Each surface finish was divided into three groups as specified in a statistically designed experiment for exposure to the following test environments: (1) 85° *C* and 85% relative humidity (180 boards), (2) condensing atmosphere (60 boards), and (3) exposure to automotive fluids (120 boards). SIR was measured at low, medium, and high voltages in the 85° *C* / 85% RH group. The boards used in the fluids test were divided into two groups (60 boards per group). One group was dipped in type 2 diesel fuel and the other group was dipped in Mil-Spec hydraulic fluid.

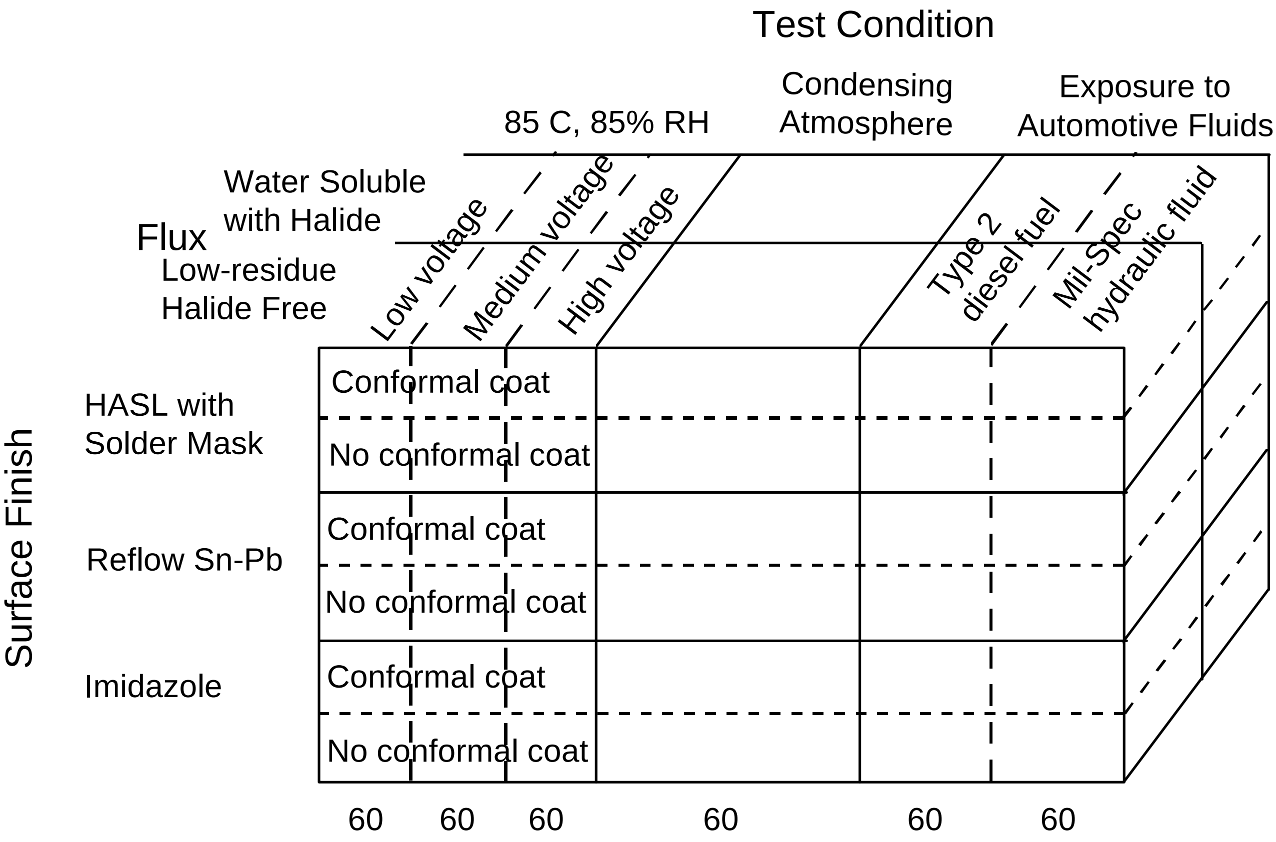

Figure 2.1 Three-Dimensional Representation of the Test Matrix for the Conformal Coating Screening Experiment (5 test boards per cell, 360 total test boards).

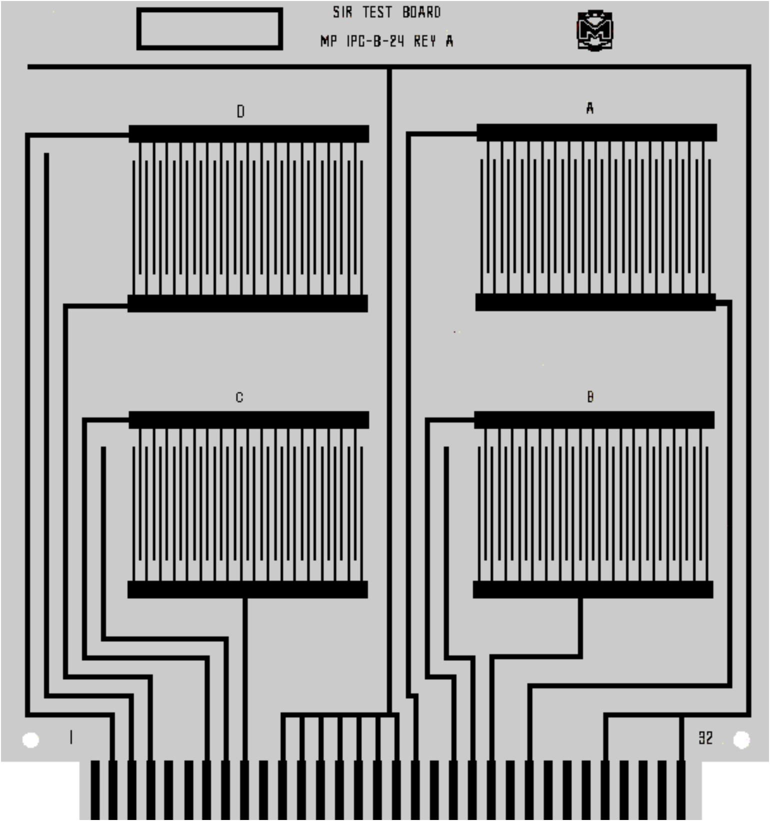

Figure 2.2 The IPC-B-24 Test Board

2.2 Test Vehicle

The IPC-B-24 board shown in Figure 2.2 has four comb patterns with 20-mil spacing between the 16-mil lines forming the comb patterns. The current trend in the electronics industry is to use finer pitch surface mount components. This feature is included in the evaluation by changing the spacings between the conductors in comb patterns *A*, *C*, and *D* on the IPC-B-24 board as follows: 8 mils on *A*, 12 mils on *C*, and 16 mils on *D*. Changing the spacing between the conductors in the comb patterns is a unique characteristic of the screening experiment, as is the use of three different test voltages.

2.3 Board Fabrication

The modified B-24 board was fabricated at Texas Instruments Printed Circuits Resources board fabrication shop in Austin, TX. The base material for this board is 1*oz*/1*oz* copper clad FR4, 0.062 *in* thick. The reflowed SnPb finish was applied by the TI fab shop. The imidazole and HASL surface finishes were applied by Lucent Technologies. In addition to the 360 boards specified in the test matrix in Figure 2.1, 24 modified B-24 boards were produced to serve as controls. These boards were fabricated with the three surface finishes shown in Figure 2.1, in addition to a bare Cu finish. None of the control boards was soldered, but half of each finish group were coated with parylene.

2.4 Board Processing

After fabrication, all 360 boards specified in the test matrix in Figure 2.1 were shipped to the Electronic Manufacturing Productivity Facility (EMPF) in Indianapolis for processing. The modified B-24 boards were soldered with the comb pattern up in an Electrovert Omniflow seven zone, nitrogen purged reflow oven. Oxygen content was kept under 20 parts per million. Solder paste was printed on the comb pattern using a laser cut 5-mil thick stainless steel stencil made by Alpha Metals. Pastes used for half the boards contained a halide-free low-residue flux. A halide-containing water soluble flux was used on the remainder of the boards. The low-residue paste was Multicore NC40 (ANSI/J-STD-004 flux designation ROL0). The water soluble paste was Multicore WS12 (ANSI/J-STD-004 flux designation ORM1).

The pastes were stored in a refrigerator until about 24 *hr* before use. The pastes were printed on an MPM Ultraprint stencil printer. The squeegees were stainless steel and a double print was used to eliminate variations caused by printing direction. The print speed varied from 0.9 to 1.2 *in*/*sec*, and the total force on the squeegee was 12 pounds. The typical print speed for the low-residue paste was 1.1 *in*/*sec*. The print speed for the water soluble paste varied as its viscosity changed. The print speed started at 0.9 *in*/*sec* and was increased to 1.2 as the paste became thinner.

The boards soldered with low-residue flux were not cleaned after soldering. The boards soldered with water soluble flux were cleaned after soldering using an aqueous process.

2.5 Conformal Coating

After processing, the boards were shipped to AlliedSignal in Kansas City where half the boards in each experimental grouping were conformally coated with Parylene C (MIL-I-46058 Type XY coating) supplied by Specialty Coating Systems. This coating was selected for the screening study because it provides total and precise coverage of circuitry. Other coating types will be addressed in Phase 1 (see Section 4).

Boards were handled with gloves prior to coating to eliminate any handling induced contamination. Boards were not cleaned prior to coating (i.e., boards were coated in the as solder processed condition). A latex backed platers tape was used to mask the gold plated board connector tabs. Adhesion promoting primer was not used in the parylene coating application process. The final coating thickness ranged from 0.001 *in* to 0.0015 *in*.

Coating Adhesion. No peel testing per standard was performed to evaluate coating adhesion. This will be addressed in Phase 1. However, the coated PWBs did receive visual and pseudo peel testing before test exposure. Visual examination under 1X to 10X revealed no evidence of delaminations, voids, discolorations, texturing, chalking or tackiness before or after test exposure. To remove the masking tape, the parylene was scored at the tape and the tape peeled from the PWB. Pulling the tape did not cause the parylene to peel from the PWBs.

2.6. Screening Experiment 1: SIR Testing for the 85° *C* and 85% RH Test Environment

The 180 test boards specified in Figure 2.1 for exposure to the 85° *C* / 85% RH environment were shipped to Contamination Studies Laboratory, Inc. (CSL) in Kokomo, IN for environmental conditioning and SIR testing. These boards were exposed to this environment for 168 *hr*. A staggered ramp was used to prevent condensation (during ramp up, the temperature is raised to test conditions before the humidity is increased and the procedure is reversed during ramp down). SIR measurements were made on all four comb patterns at pre-test (prior to exposure to environment); at 24, 96, and 168 *hr* during test exposure; and at 2 and 24 *hr* after environmental exposure (post-test). The control boards were also exposed to the same environmental conditions as the 180 test boards.

Figure 2.1 shows the 85/85 test boards divided into three groups of 60. Each group was to be tested at one of three voltages: low (50V), medium (100V), and high (200V). However, due to a misunderstanding, all 180 boards were tested at each of the three voltages, creating 15 measurements in each experimental cell. The SIR measurements exhibited a high degree of agreement among the different voltage levels (that is, they were very highly correlated from one voltage group to the next), which implies that voltage was not a major factor in this experiment (see Section 2.9).

2.7 SIR Cell Means for 85° *C* / 85% RH

When the modified B-24 boards were processed, bridges formed on 106 of the 180 8-mil patterns and on 5 of the 180 12-mil patterns. These bridges resulted from applying too much solder paste, combined with the solder mask on the imidazole and HASL boards. This circumstance forced solder to bridge adjacent joints. These bridges were not related to the design of the experiment. No rework was done to remove the bridges. Bridges create shorts, which lower SIR measurements to an unacceptable level (less that 8 log 10 ohms).

Table 2.1 gives means for initial, 168 *hr*, and post-test SIR measurements at medium voltage for each experimental cell (15 observations per cell) for boards without bridges. Eliminating bridged boards creates some empty cells in Table 2.1 (denoted by an asterisk) for 8-mil spacing with imidazole and HASL. Table 2.2 gives means with the bridged boards included. Table 2.1 also includes the means for half the control boards (the other half were inadvertently used with the fluids tests — thus, a complete set of controls was not available for the 85/85 screening experiment). For ease of comparison, means are also given in Table 2.1 for sample boards from the alternative surface finish (ASF) study that were subjected to testing after completion of solderability tests detailed in Section 3.

2.8 Boxplot Displays for SIR Measurements

SIR measurements are frequently displayed in a U-shaped line graph that connects the means over time. While such plots are helpful in interpreting the results, they have two shortcomings. First, the sample mean is heavily influenced by outlying or unusual observations and, as such, can be misleading. For example, the mean for {2, 3, 5, 6, 99} is 23, which is not representative of the bulk of the data. The median (middle observation) of this set of numbers is 5, which is more representative of the bulk of the data. Another way to express this phenomenon is that the mean is not a robust measure of location. A second problem with a plot of the means is that all the information about the variability in the data is lost.

These problems can be overcome by using boxplots to display SIR measurements. A boxplot is shown in Figure 2.3. The left-hand side of the box portion of the plot represents the lower quartile ($X_{.25}$), or lower 25% of the sample data. The right-hand side of the box represents the upper quartile ($X_{.75}$), or upper 25% of the sample data (or lower 75%). Thus, the box contains the middle 50% of the sample data. The vertical line in the middle of the box represents the sample median ($X_{.50}$).

The interquartile range (IQR) is the difference between the upper quartile and the lower quartile. The horizontal line on the right-hand side of the box in Figure 2.3 extends to the maximum observation in the interval from $X_{.75}$ to $X_{.75}$ + 1.5 IQR. This line never extends beyond $X_{.75}$ + 1.5 IQR. The line on the left hand side extends to the smallest observation between $X_{.25}$ and $X_{.25}$ - 1.5 IQR. This line never extends below $X_{.25}$ - 1.5 IQR. Any observations outside of these limits are regarded as outliers and are marked with an asterisk. Figure 2.3 shows the presence of one outlier. Coated and uncoated boards are shown simultaneously in boxplots in the graphs in this section. To avoid confusion, outliers for coated boards are marked with an asterisk, and outliers for uncoated boards are marked with an open square symbol "•." Boxplots can be constructed either horizontally or vertically.

2.9 Boxplots for SIR 85° *C* / 85% RH Test Measurements

Boxplots are used in Figures 2.4 to 2.23 to show selected effects of the experimental factors used in the SIR 85/85 testing: surface finish, flux, pattern spacing, voltage, and coating. Each boxplot represents 15 observations for one experimental cell (unless data are missing). The shaded boxplots in these figures represent conformally coated boards; the unshaded boxplots represent boards without conformal coating. The width of the boxplots for coated boards is slightly less than those for boards without conformal coating to increase readability when boxes overlap.

SIR Versus Test Time. Figures 2.4 to 2.9 display SIR measurements versus test time for reflowed SnPb, imidazole, and HASL. The boards in this experiment were processed with either low-residue (LR) or water-soluble (WS) flux and were tested with medium voltage on the 16-mil comb pattern. The lines in each figure connect the medians and exhibit a U-shaped appearance, which is analogous to the commonly used plot of the means.

Figures 2.4 and 2.5 demonstrate there is no advantage to using conformal coating with reflowed SnPb either during test exposure or at the end of the test. The boxplots in these figures indicate that uncoated boards perform as good as or better than coated boards at all test times. In Figure 2.5, SIR on coated SnPb boards processed with WS flux is noticeably lower than that of coated boards processed with LR flux. Boxplots in Figures 2.6 overlap and show no advantage to using conformal coating at any test time for imidazole with LR flux. As shown in Figure 2.7, there is a slight advantage to using coating on imidazole boards processed with WS flux during test exposure, but there is a big decrease in SIR for coated boards after completion of test exposure.

As shown in Figure 2.8, coating gives a slight increase in SIR for HASL finished boards with LR flux at the 96 and 168 *hr* tests and gives approximately a two-order magnitude increase on the post-test measurement. Results in Figure 2.9 for WS flux and HASL show a very narrow edge to using coating during test exposure and a decrease after exposure. Additional comparisons of coating and not coating in the 85/85 environment are made in Sections 2.11 and 2.15.

SIR Versus Comb Pattern Spacing. Figures 2.10 to 2.15 show SIR at 168 *hr* and post 24 *hr* plotted against the width of the spacing on the comb patterns on the test board. The plots on the left-hand side of these graphs represent LR flux and the plots on the right-hand side represent WS flux. Note that the width of the spacing is not a factor, as the behavior is approximately the same for all spacings for a given surface finish and flux combination.

Figures 2.10 and 2.11 show that reflowed SnPb performs better without coating, both during test exposure and at post 24 hours for all spacings. The most striking feature of these graphs is the significantly lower SIR at post 24 hours with WS flux and coating. Coated and uncoated boards perform at the same level for imidazole boards processed with LR flux, as shown in Figures 2.12 and 2.13, but as with reflowed SnPb, WS lowers post-test SIR on coated boards. Figures 2.14 and 2.15 show that HASL boards with coating and LR flux have higher SIR at all spacings, both during test exposure and at post 24 hours. There is no advantage during test exposure to using conformal coating on HASL boards processed with WS flux. Also, coating lowers post-test SIR on HASL boards with WS flux.

SIR Versus Surface Finish. Figures 2.16 and 2.17 provide side-by-side comparisons of surface finishes for the 168-hr and post-24 *hr* SIR measurements on 16-mil spacing, using medium voltage. These figures demonstrate that reflowed SnPb does not benefit from conformal coating either during test exposure or at the post 24 *hr* test. Coated and uncoated boards with imidazole give the same performance in all cases, except for the post 24 *hr* measurement with WS flux, where coated boards have significantly lower SIR (about three orders of magnitude). HASL boards benefit (about an order of magnitude) from coating when LR flux is used. HASL coated and uncoated boards perform at the same level during test exposure with WS flux, but coating lowers the post 24 *hr* SIR (about two orders of magnitude) when WS flux is used. The right-hand side of Figure 2.17 shows the negative impact that the combination of conformal coating and WS flux have on SIR for all surface finishes.

SIR Versus Voltage. SIR measurements have been plotted against voltage in Figures 2.18 to 2.23 by surface finish for SIR at 168 *hr* and post 24 *hr* test. The horizontal alignment of the boxplots indicates that voltage did not influence SIR either during test exposure or at post 24 *hr*. The only indication of voltage influence in the 12 sets of graphs in these figures occurs in the left-hand side of Figure 2.23 where SIR at medium voltage on coated boards is higher than on uncoated boards (approximately 13.5 log 10 ohms to 12 log 10 ohms).

Other Displays. Pairing the experimental factors produces a large number of displays similar to those shown in Figures 2.4 to 2.23. These displays have been placed in Appendix A for ready reference. Appendix A contains 72 displays similar to Figures 2.4 to 2.9; 54 displays with SIR results plotted against comb pattern spacing, as shown in Figures 2.10 to 2.15; 72 displays with SIR results plotted against surface finish spacing, as shown in Figures 2.16 and 2.17; and 72 displays similar to Figures 2.18 to 2.23, with SIR results plotted against voltage.

The reader is encouraged to study these displays. In particular, note that uncoated boards with a reflowed SnPb surface finish give higher SIR during test exposure and at post 24 *hr* than do boards with coating. Imidazole boards with LR flux appear to be invariant to coating either during test exposure or at post 24 *hr* test. Imidazole boards with WS flux benefit slightly during the early stages of environmental exposure (24 and 96 *hr*), but are negatively impacted by coating after environmental exposure.

HASL boards benefit slightly from coating (less than an order of magnitude) during test exposure. HASL boards with LR flux also benefit from coating at the post 24 *hr* test, but WS flux has a negative impact when used with coating. (In Section 3, it is shown that WS flux also performed poorly in the alternative surface finish study.) Figures in Appendix A also show that different voltages and spacings give similar results.

The performance of coated and uncoated boards is compared in three other test environments later in this section.

Table 2.1 SIR Means (log 10 ohms) with Bridged Boards Eliminated (100V)

					8-Mil Spacing			12-Mil Spacing		
	Surface	**Coating**	**Flux**	**n**	**Initial**	**168 hr**	**PostTest**	**Initial**	**168 hr**	**PostTest**
SIR 85/85	**SnPb**	**No**	**LR**	15	10.00	7.86	11.46	9.96	8.60	11.98
			WS	15	11.64	7.46	12.33	11.81	7.69	12.56
		Yes	**LR**	15	10.34	7.63	10.81	10.56	7.92	11.03
			WS	15	12.54	6.17	7.66	12.85	6.04	7.96
	Imid	**No**	**LR**	15	13.11	7.76	12.26	13.02	7.74	12.41
			WS	15	12.04	7.97	12.34	12.30	7.30	11.75
		Yes	**LR**	15	*	*	*	13.04	7.83	12.11
			WS	15	12.40	8.36	9.61	13.03	7.24	8.95
	HASL	**No**	**LR**	15	12.59	7.65	8.85	12.02	7.46	11.80
			WS	15	*	*	*	12.23	7.24	10.90
		Yes	**LR**	15	*	*	11.11	11.65	8.37	13.75
			WS	15	*	*	*	13.08	7.17	8.98
Controls	**Bare Cu**	**Yes**	**None**	3	12.85	6.65	10.16	13.45	7.08	10.41
	SnPb	**No**	**None**	3	9.62	9.36	12.86	9.31	9.37	13.06
	Imid	**No**	**None**	3	12.44	7.17	11.38	12.62	7.17	11.27
	HASL	**No**	**None**	3	9.16	8.96	12.82	9.01	8.93	13.28
ASF	**Benzi**	**No**	**None**	2	11.96	8.16	11.66	11.24	7.91	10.79
	Au	**No**	**None**	2	12.11	8.18	12.00	12.15	7.67	11.03
	Ag	**No**	**None**	2	11.04	7.91	11.84	11.11	8.54	12.50
	Pd	**No**	**None**	2	8.78	6.51	11.37	8.18	6.52	10.73
	Au/Pd	**No**	**None**	2	11.75	8.79	12.73	11.39	8.59	12.66

					16-Mil Spacing			20-Mil Spacing		
	Surface	**Coating**	**Flux**	**n**	**Initial**	**168 hr**	**PostTest**	**Initial**	**168 hr**	**PostTest**
SIR 85/85	**SnPb**	**No**	**LR**	15	10.05	8.58	11.94	10.19	8.85	12.28
			WS	15	11.89	7.68	12.58	12.22	8.17	12.58
		Yes	**LR**	15	10.68	7.83	10.74	10.80	8.21	11.03
			WS	15	12.82	6.51	7.99	13.33	6.93	8.74
	Imid	**No**	**LR**	15	12.87	7.62	12.27	12.11	7.75	12.30
			WS	15	12.44	7.19	11.40	12.39	7.39	11.35
		Yes	**LR**	15	12.52	7.83	12.29	13.29	7.99	12.52
			WS	15	13.02	7.45	8.92	12.83	7.75	9.23
	HASL	**No**	**LR**	15	11.83	7.38	11.74	12.57	7.60	12.03
			WS	15	12.57	6.99	10.55	12.60	7.15	10.87
		Yes	**LR**	15	11.93	8.67	13.55	12.20	8.70	13.79
			WS	15	13.20	7.22	8.95	12.64	7.51	9.10
Controls	**Bare Cu**	**Yes**	**None**	3	13.70	7.95	11.00	13.49	8.45	12.90
	SnPb	**No**	**None**	3	9.72	9.14	13.11	9.70	9.44	13.38
	Imid	**No**	**None**	3	12.61	7.35	11.71	12.77	7.25	11.43
	HASL	**No**	**None**	3	8.85	7.64	13.49	8.86	8.98	13.51
ASF	**Benzi**	**No**	**None**	2	11.24	7.94	10.56	10.31	7.99	11.46
	Au	**No**	**None**	2	11.45	7.61	10.17	11.63	8.16	10.84
	Ag	**No**	**None**	2	9.99	7.79	11.08	11.30	9.51	12.39
	Pd	**No**	**None**	2	8.54	6.55	12.11	9.22	6.57	10.85
	Au/Pd	**No**	**None**	2	11.17	9.27	12.74	11.48	8.96	12.87

Table 2.2 SIR Means (log 10 ohms) for All Measurements (100V)

					8-Mil Spacing			12-Mil Spacing		
	Surface	**Coating**	**Flux**	**n**	**Initial**	**168 hr**	**PostTest**	**Initial**	**168 hr**	**PostTest**
SIR 85/85	**SnPb**	**No**	**LR**	15	10.00	7.86	11.46	9.96	8.60	11.98
			WS	15	11.26	7.36	11.90	11.81	7.69	12.56
		Yes	**LR**	15	10.34	7.63	10.81	10.56	7.92	11.03
			WS	15	12.54	6.06	7.55	12.85	6.01	7.43
	Imid	**No**	**LR**	15	7.90	6.47	7.67	13.02	7.74	12.41
			WS	15	6.40	6.13	6.42	11.46	7.12	10.99
		Yes	**LR**	15	6.00	6.00	6.00	13.04	7.83	12.11
			WS	15	6.43	6.16	6.24	13.03	7.24	8.95
	HASL	**No**	**LR**	15	6.44	6.11	6.19	12.02	7.46	11.80
			WS	15	6.00	6.00	6.00	11.40	7.08	10.24
		Yes	**LR**	15	6.00	6.00	11.11	11.65	8.37	13.75
			WS	15	6.00	6.00	6.00	12.61	7.09	8.78

					16-Mil Spacing			20-Mil Spacing		
	Surface	**Coating**	**Flux**	**n**	**Initial**	**168 hr**	**PostTest**	**Initial**	**168 hr**	**PostTest**
SIR 85/85	**SnPb**	**No**	**LR**	15	10.05	8.58	11.94	10.19	8.85	12.28
			WS	15	11.89	7.68	12.58	12.22	8.17	12.58
		Yes	**LR**	15	10.68	7.83	10.74	10.80	8.21	11.03
			WS	15	12.82	6.17	7.85	13.33	6.80	8.74
	Imid	**No**	**LR**	15	12.87	7.62	12.27	12.11	7.75	12.30
			WS	15	12.44	7.19	11.40	12.39	7.39	11.35
		Yes	**LR**	15	12.52	7.83	12.29	13.29	7.99	12.52
			WS	15	13.02	7.45	8.92	12.83	7.75	9.23
	HASL	**No**	**LR**	15	11.83	7.38	11.74	12.57	7.60	12.03
			WS	15	12.57	6.99	10.55	12.60	7.15	10.87
		Yes	**LR**	15	11.93	8.67	13.55	12.20	8.70	13.79
			WS	15	13.20	7.22	8.95	12.64	7.51	9.10

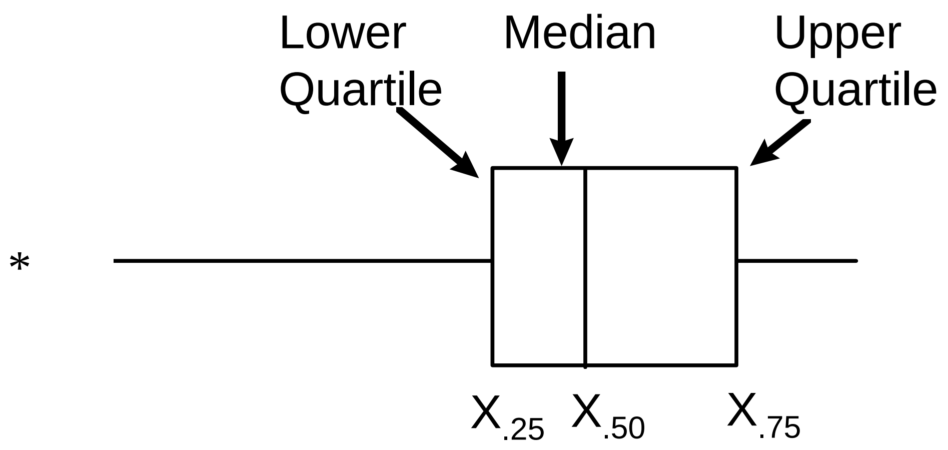

Figure 2.3 A Boxplot Used to Display SIR Measurements

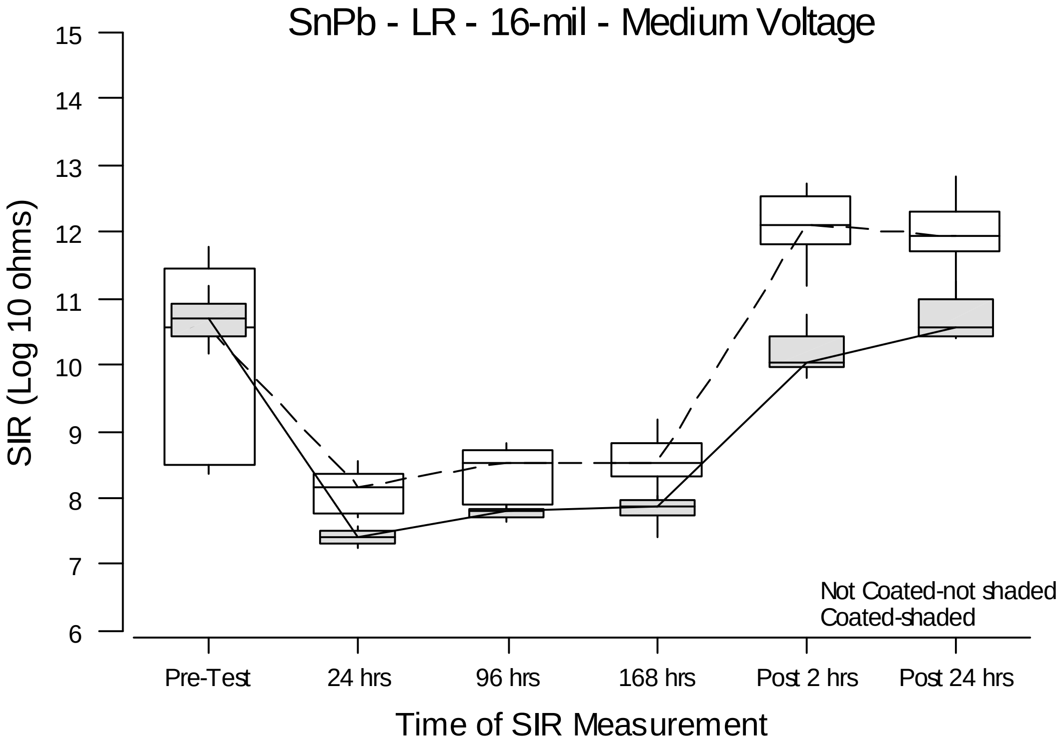

Figure 2.4 SIR 85/85 Boxplots: Medium Voltage, SnPb, LR Flux by Coating versus Time for 16-Mil Spacing

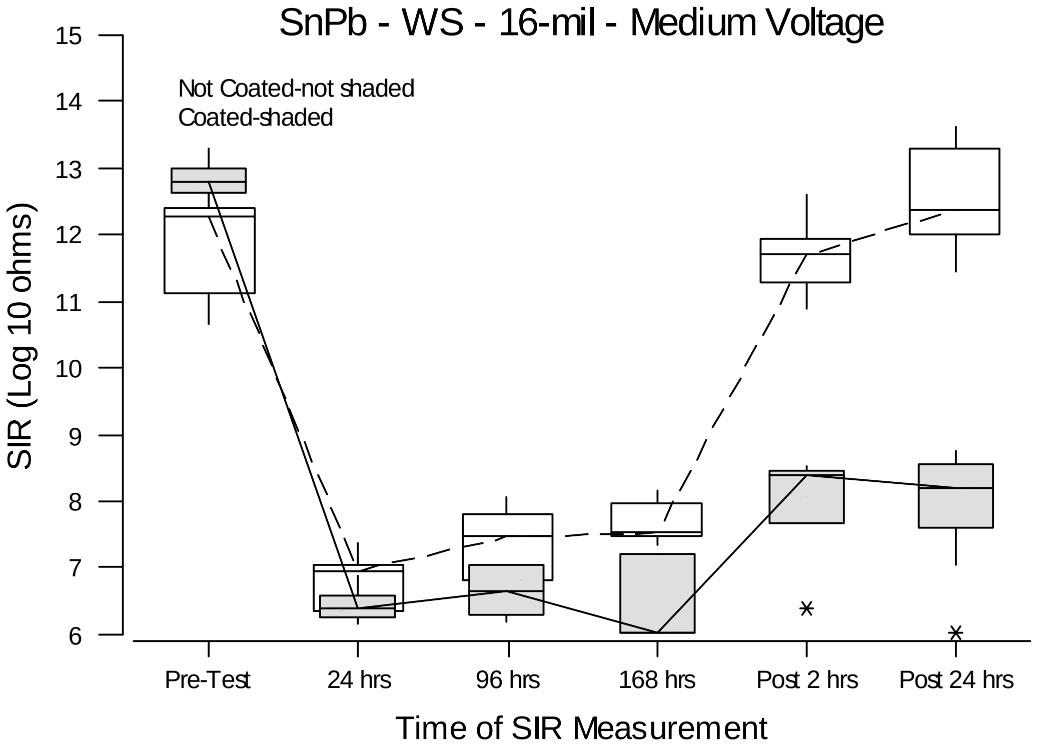

Figure 2.5 SIR 85/85 Boxplots: Medium Voltage, SnPb, WS Flux by Coating versus Time for 16-Mil Spacing

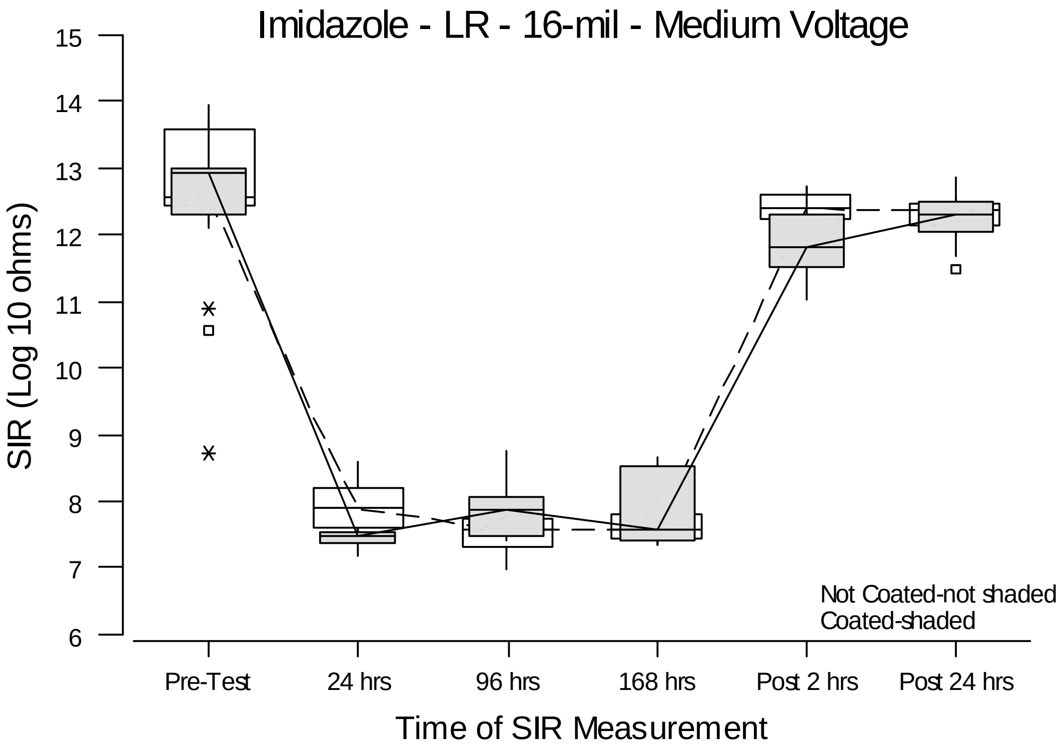

Figure 2.6 SIR 85/85 Boxplots: Medium Voltage, Imidazole, LR Flux by Coating versus Time for 16-Mil Spacing

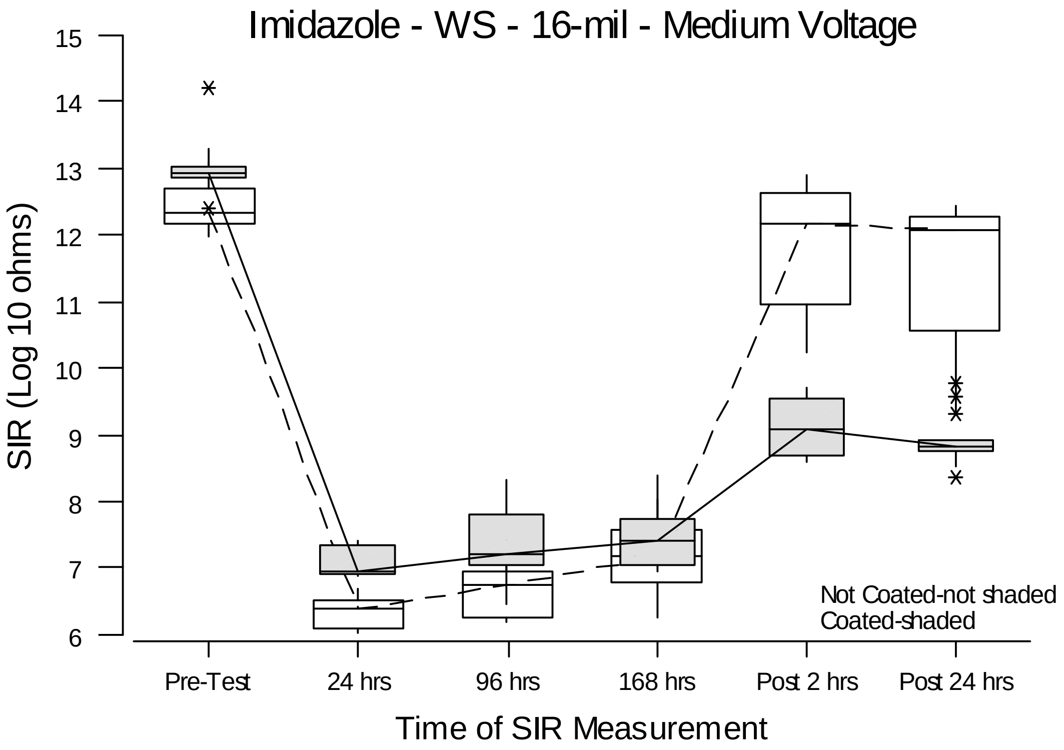

Figure 2.7 SIR 85/85 Boxplots: Medium Voltage, Imidazole, WS Flux by Coating versus Time for 16-Mil Spacing

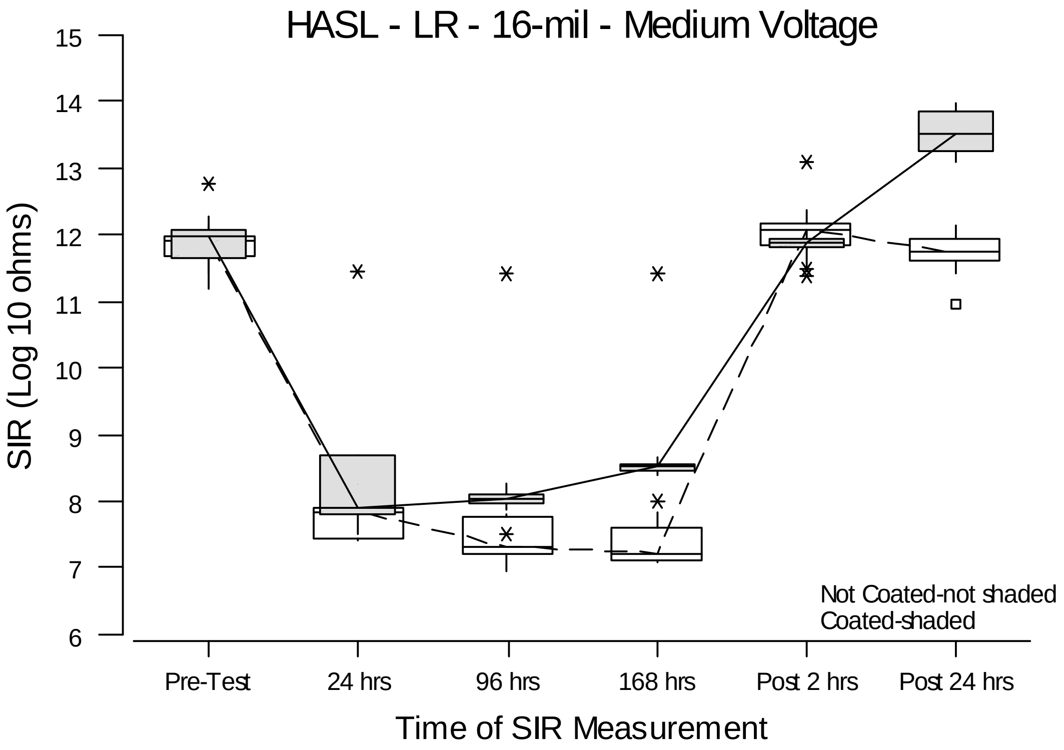

Figure 2.8 SIR 85/85 Boxplots: Medium Voltage, HASL, LR Flux by Coating versus Time for 16-Mil Spacing

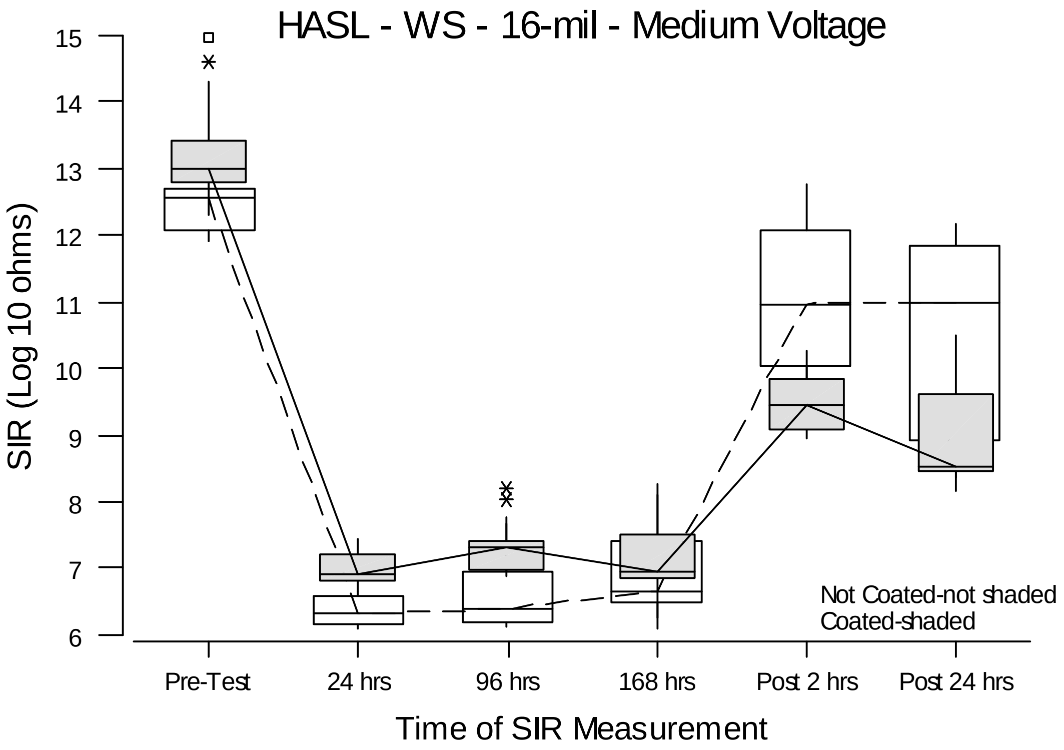

Figure 2.9 SIR 85/85 Boxplots: Medium Voltage, HASL, WS Flux by Coating versus Time for 16-Mil Spacing

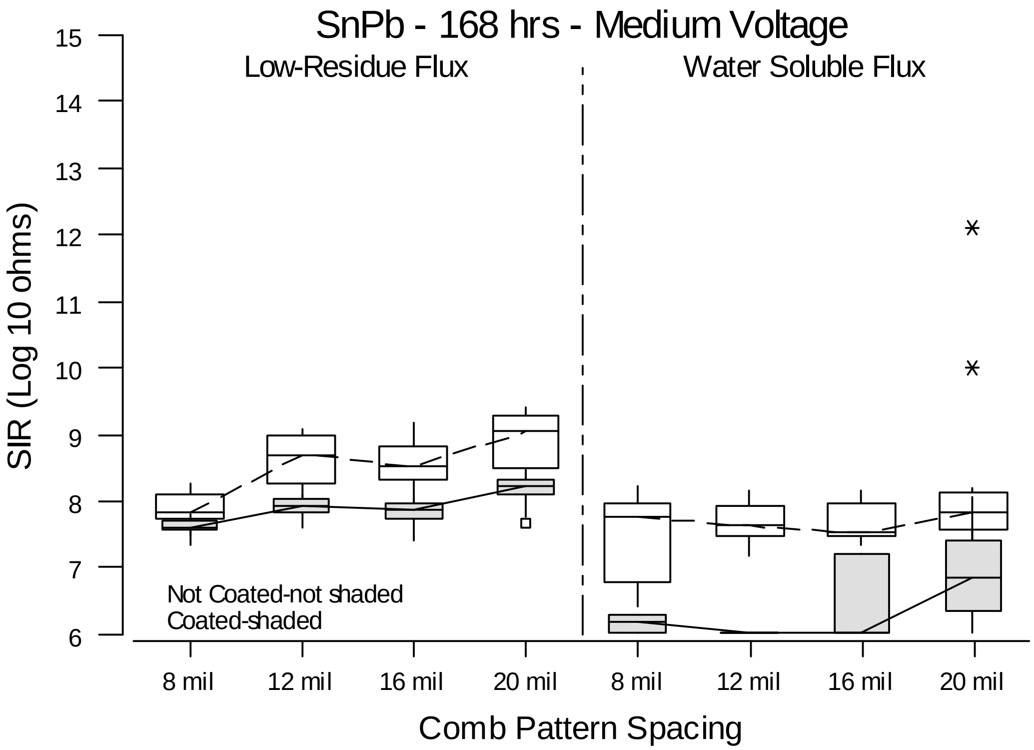

Figure 2.10 SIR 85/85 Boxplots: Medium Voltage, SnPb, 168 hr by Coating versus Spacing

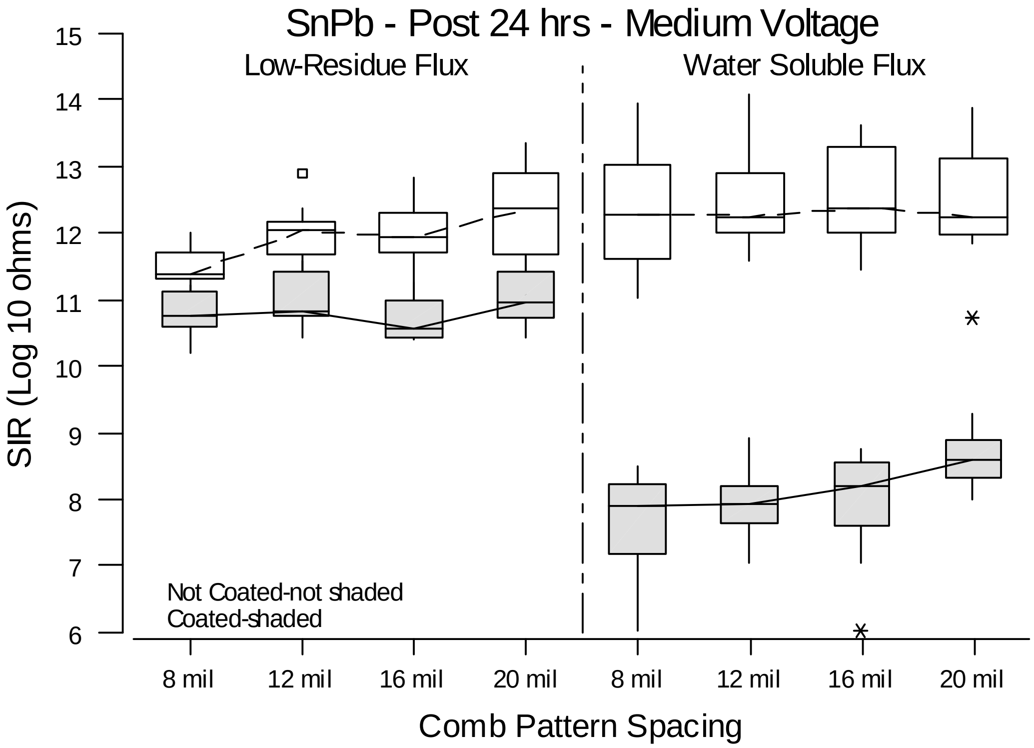

Figure 2.11 SIR 85/85 Boxplots: Medium Voltage, SnPb, Post 24 hr by Coating versus Spacing

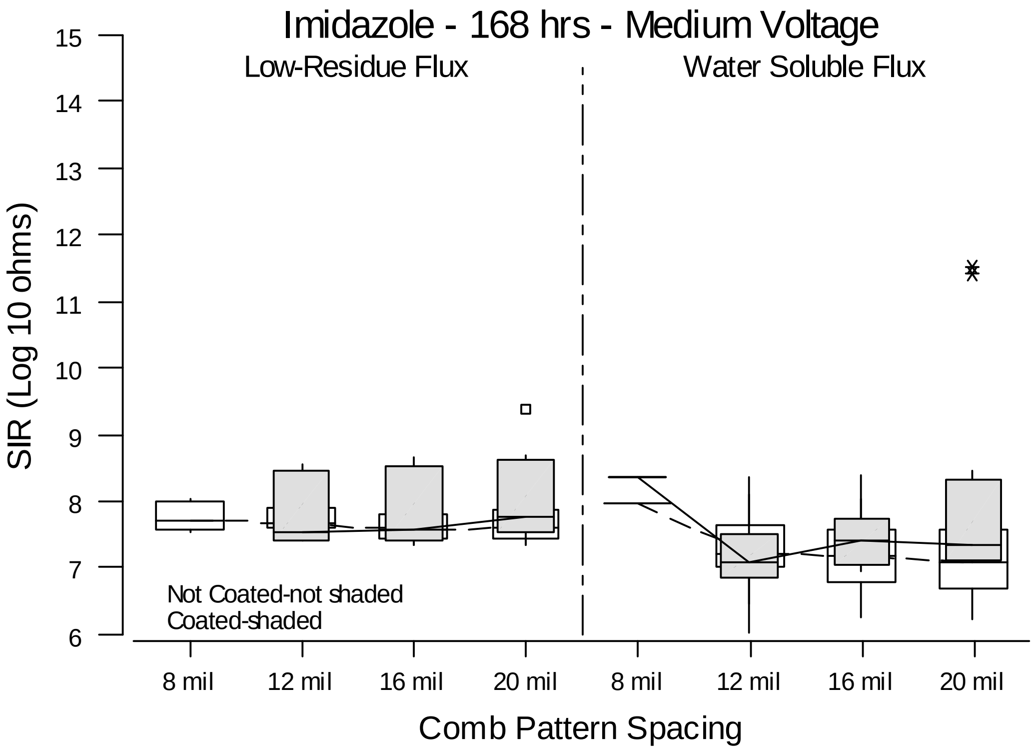

Figure 2.12 SIR 85/85 Boxplots: Medium Voltage, Imidazole, 168 hr by Coating versus Spacing

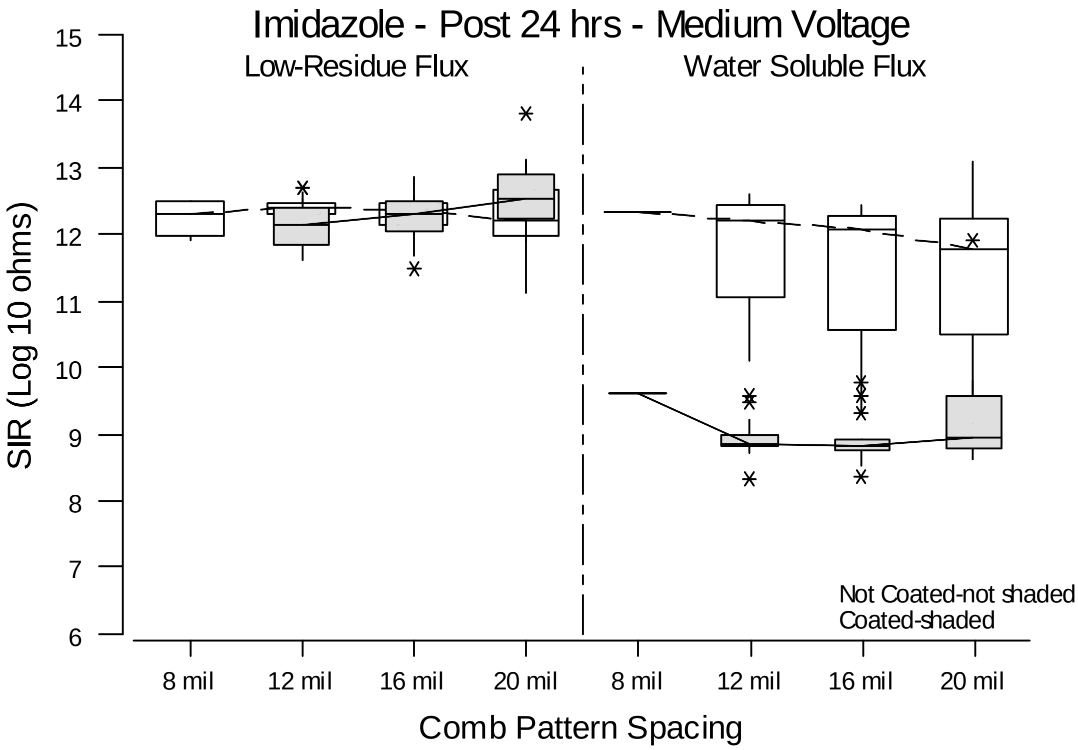

Figure 2.13 SIR 85/85 Boxplots: Medium Voltage, Imidazole, Post 24 hr by Coating versus Spacing

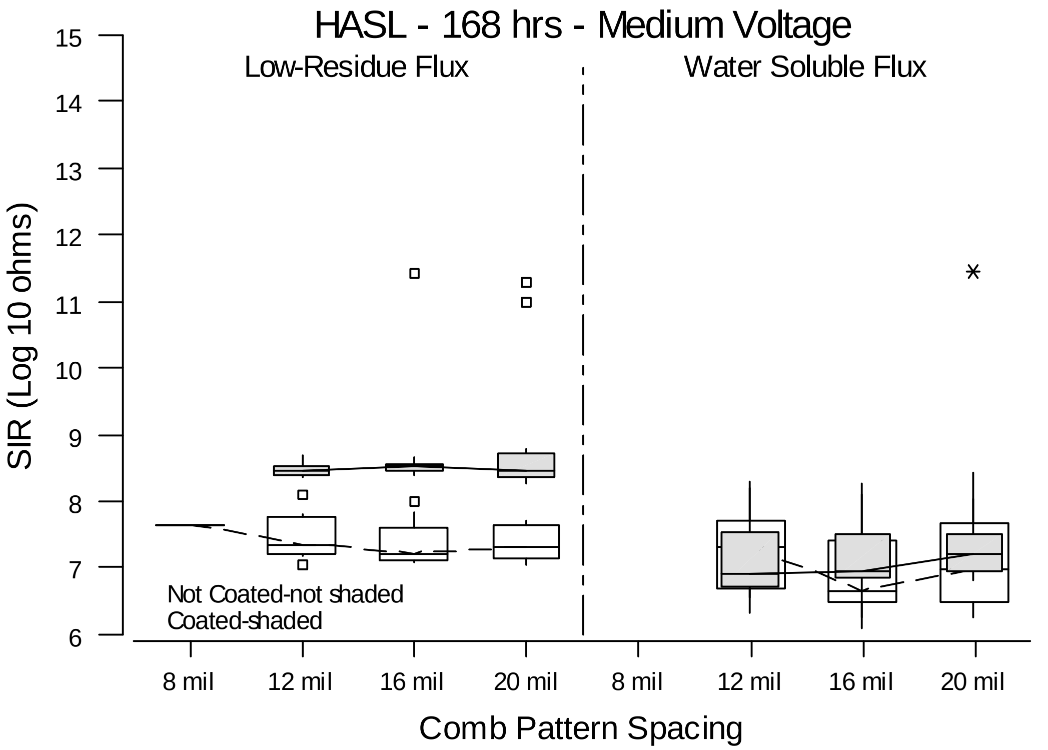

Figure 2.14 SIR 85/85 Boxplots: Medium Voltage, HASL, 168 hr by Coating versus Spacing

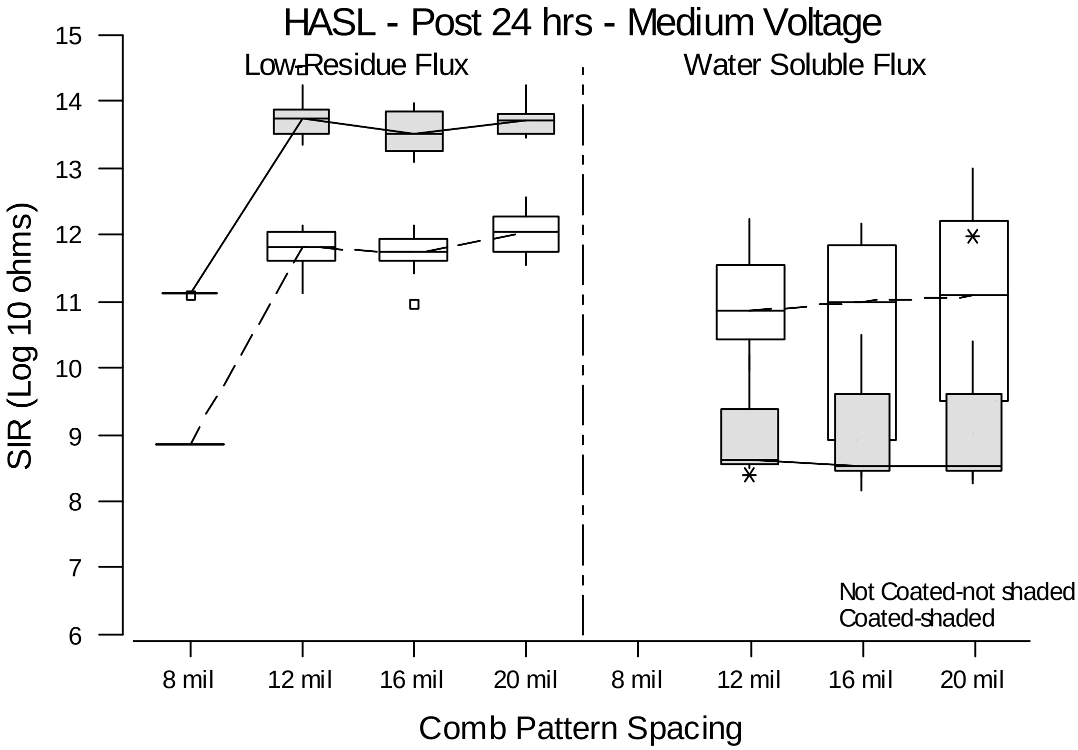

Figure 2.15 SIR 85/85 Boxplots: Medium Voltage, HASL, Post 24 hr by Coating versus Spacing

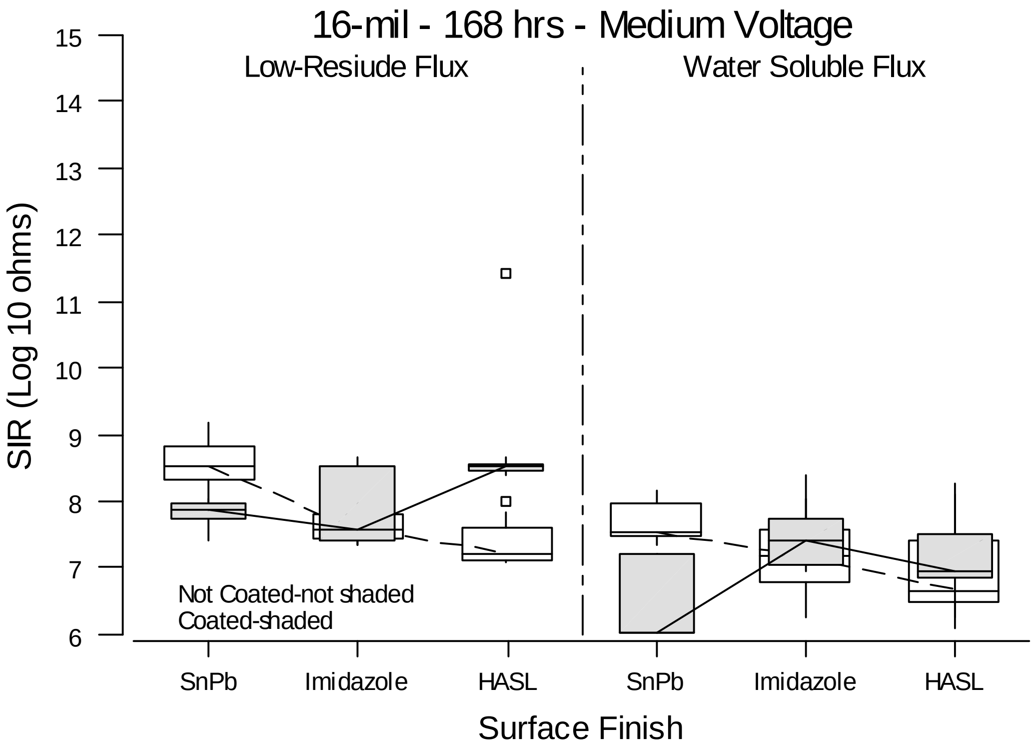

Figure 2.16 SIR 85/85 Boxplots: Medium Voltage, 16-Mil Spacing, 168 24 hr by Coating versus Surface Finish

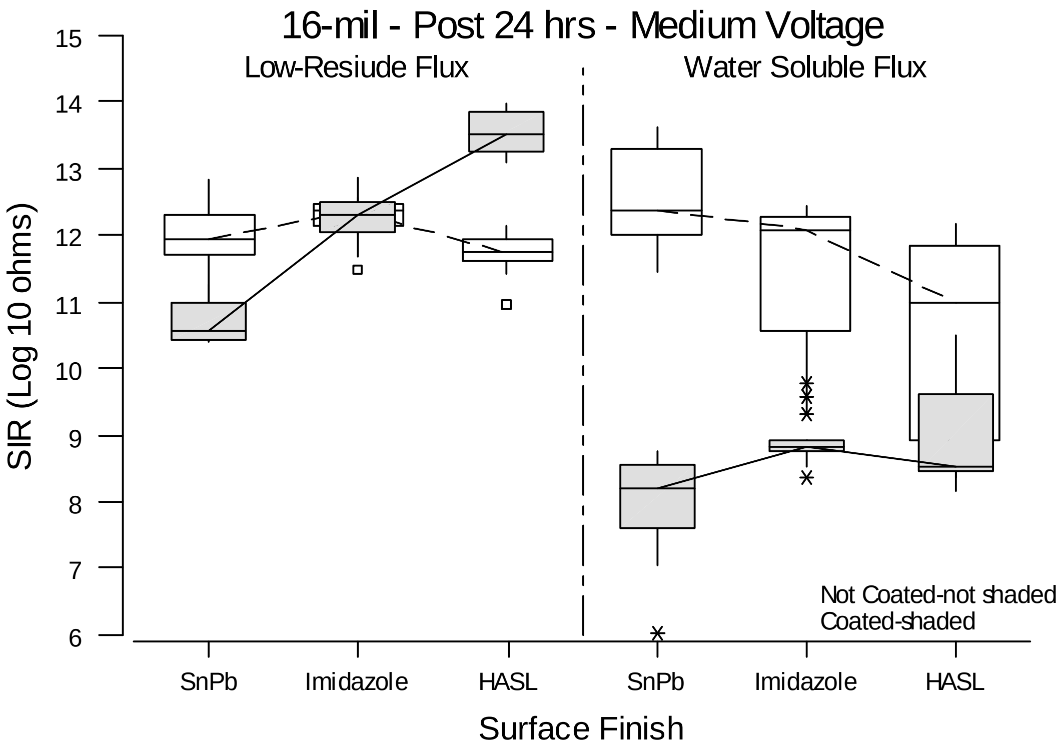

Figure 2.17 SIR 85/85 Boxplots: Medium Voltage, 16-Mil Spacing, Post 24 hr by Coating versus Surface Finish

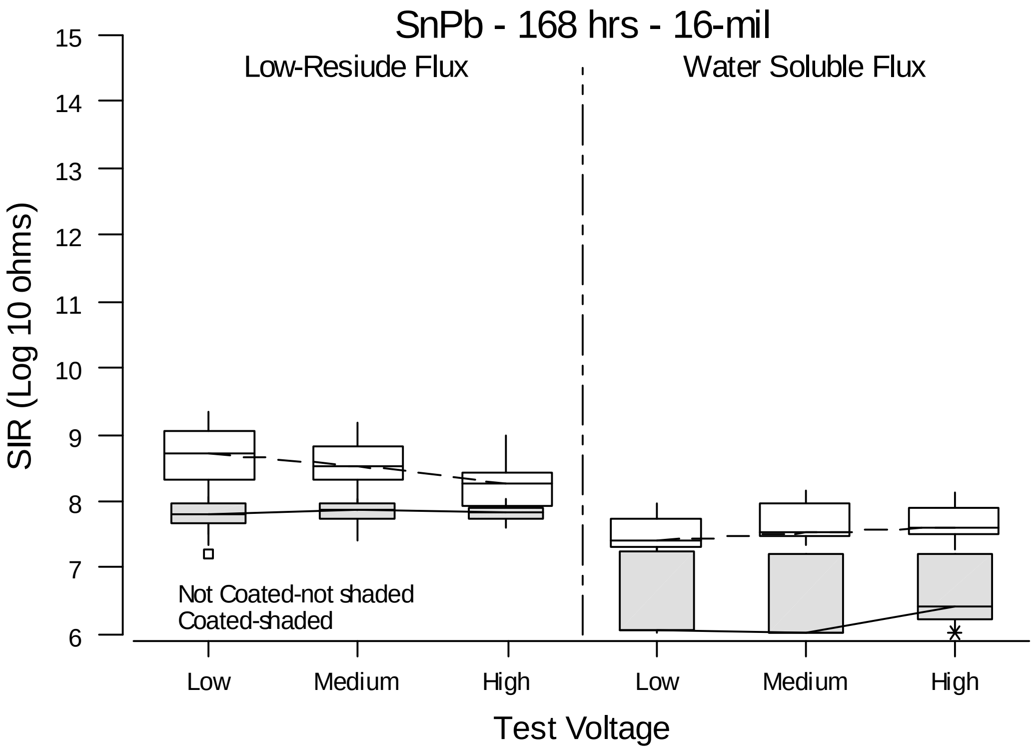

Figure 2.18 SIR 85/85 Boxplots: SnPb, 16-Mil Spacing, 168 hr by Coating versus Voltage

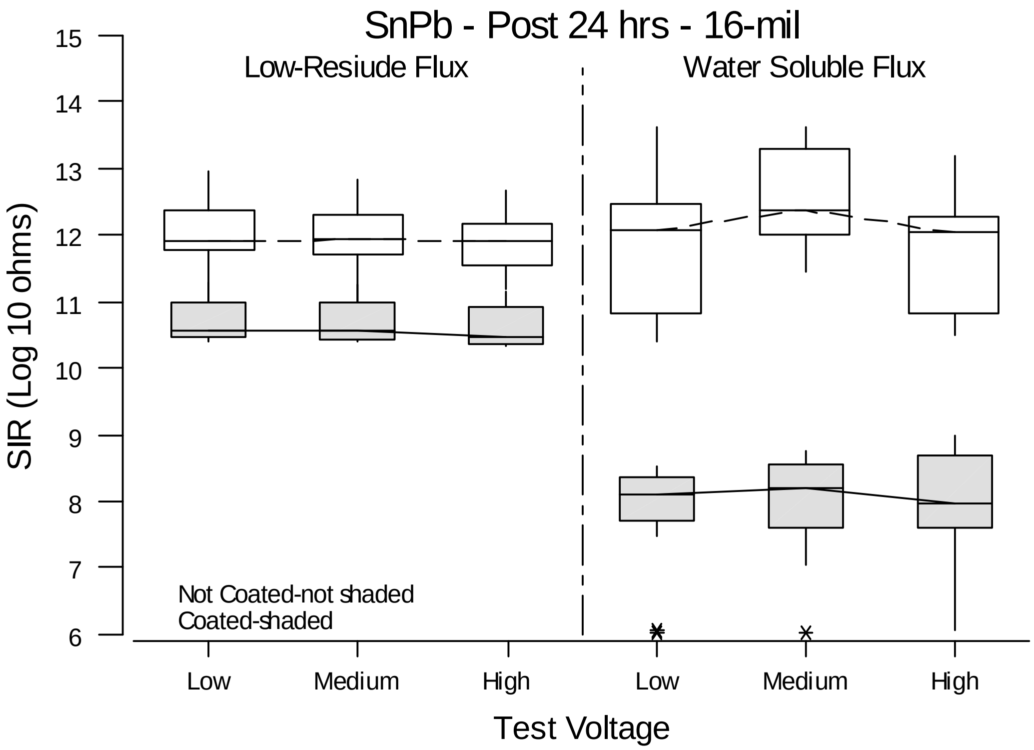

Figure 2.19 SIR 85/85 Boxplots: SnPb, 16-Mil Spacing, Post 24 hr by Coating versus Voltage

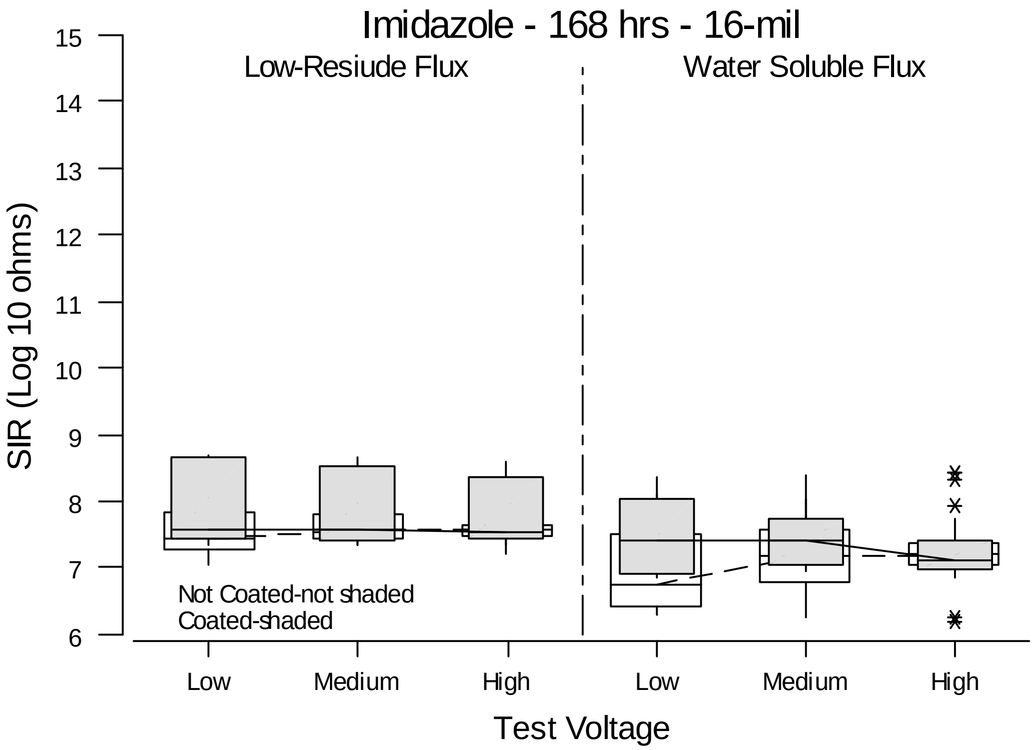

Figure 2.20 SIR 85/85 Boxplots: Imidazole, 16-Mil Spacing, Post 24 hr by Coating versus Voltage

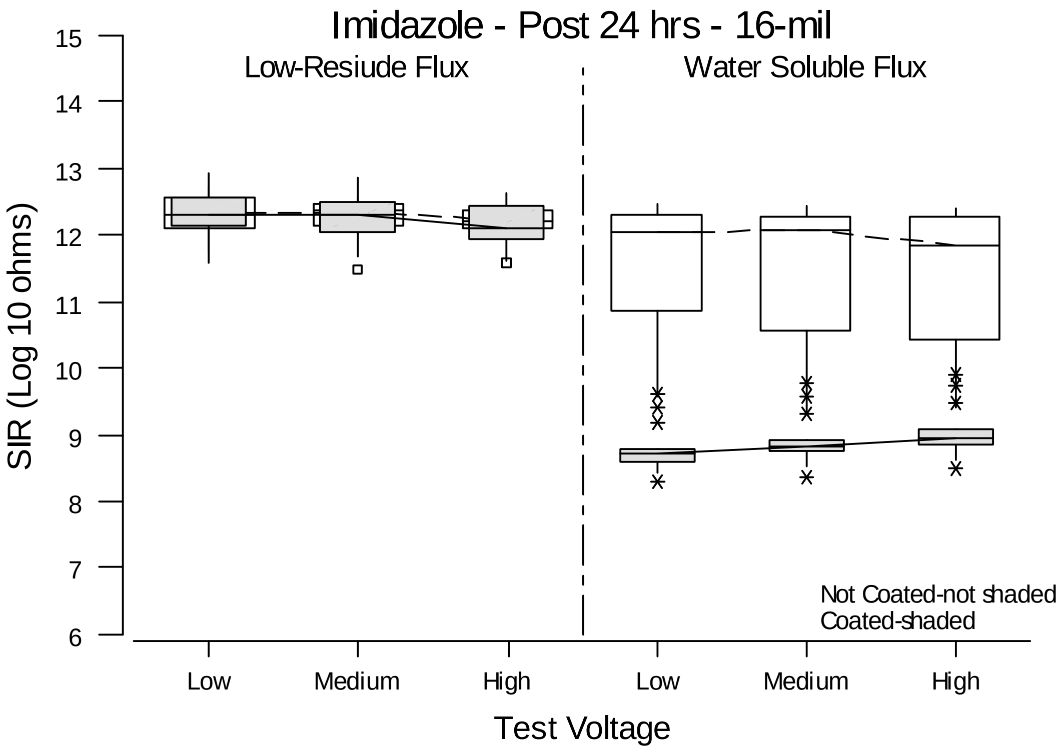

Figure 2.21 SIR 85/85 Boxplots: Imidazole, 16-Mil Spacing, Post 24 hr by Coating versus Voltage

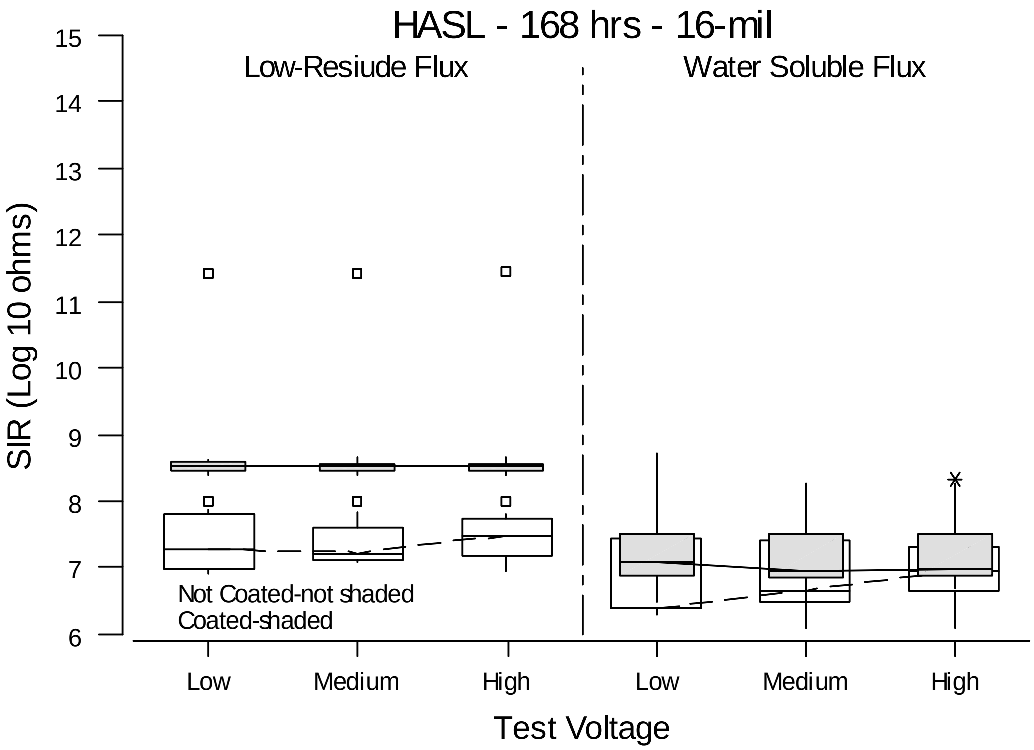

Figure 2.22 SIR 85/85 Boxplots: HASL, 16-Mil Spacing, 168 hr by Coating versus Voltage

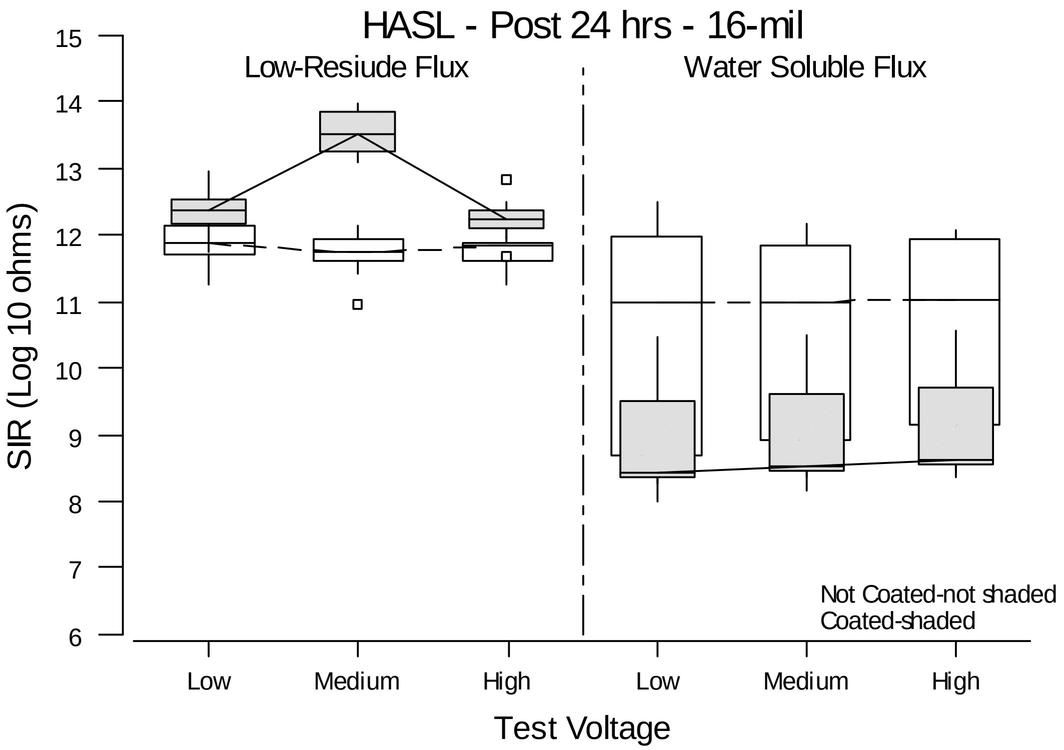

Figure 2.23 SIR 85/85 Boxplots: HASL, 16-Mil Spacing, Post 24 hr by Coating versus Voltage

2.10 General Linear Modeling for SIR 85° *C* / 85% RH Test Measurements

In addition to serving as sanity checks, the graphical displays in Appendix A are very useful aids for interpreting test results. However, formal statistical analyses are required to determine which experimental factors or combinations of factors have a statistically significant impact on the SIR test results. This determination is accomplished by using general linear models (GLMs) to analyze the experimental data.

A GLM can be expressed as an equation of the following form:

$$Y = \beta_0 + \beta_1 D_1 + \beta_2 D_2 + \beta_3 D_3 + \beta_4 D_4 + \beta_5 D_5 + \beta_6 D_6 + \beta_7 D_1 D_3 + \beta_8 D_1 D_4 + \beta_9 D_1 D_5 + \beta_{10} D_1 D_6 + \ldots \quad (2.1)$$

The coefficients in the GLM ($\beta_0, \ldots, \beta_{10}$) are estimated using ordinary least squares regression techniques. The dummy variables, $D_1, \ldots, D_6$, are set equal to 1 to identify particular experimental variables such as: type of surface finish, conformal coating, type of flux, level of test voltage, etc., that are associated with individual test results. Otherwise, the dummy variables are set to 0. The following dummy variables can be used to represent the experimental variables in the test matrix in Figure 2.1 for individual SIR 85/85 test results.

D_1 = 0 if surface finish is not reflowed SnPb
= 1 if surface finish is reflowed SnPb
D_2 = 0 if surface finish is not imidazole
= 1 if surface finish is imidazole
D_3 = 0 if board is not conformally coated
= 1 if board is conformally coated
D_4 = 0 if flux is not water soluble with halide
= 1 if flux is water soluble with halide
D_5 = 0 if medium voltage is not used
= 1 if medium voltage is used
D_6 = 0 if high voltage is not used
= 1 if high voltage is used

Note that the surface finish is HASL if $D_1 = 0$ and $D_2 = 0$. Likewise, if $D_5 = 0$ and $D_6 = 0$, the voltage is low. The "base case" occurs when all $D_i = 0$. Thus, the base is HASL, with LR flux, no conformal coating, and low voltage. The GLM approach provides a tool for identifying the statistically significant experimental variables and their interactions. That is, all terms in the model that are significantly different from the base case are identified. These analyses also provide direct comparisons at each test time of conformal coated boards with uncoated boards for surface finishes, fluxes, and voltage shown in the test matrix in Figure 2.1.

2.11 General Linear Model Results for SIR 85° *C* / 85% RH

Tables 2.3 to 2.6 contain results of the GLM analyses for SIR 85/85 testing on the 8-, 12-, 16-, and 20-mil comb patterns, respectively. The last row in each table shows the number of missing and/or omitted observations. That is, test results for comb patterns with bridges were omitted from the analyses, and SIR measurements were not recorded for several combinations of voltage and time for some boards. GLM results are given by test time within each table. The values in the row labeled as "Constant" are the estimates of β_0 in the respective GLM. The estimate of β_0 represents the base case — HASL with LR flux, coating, and tested at low voltage. For example, the base case estimate for 168 *hr* in Table 2.5 is 7.61 log 10 ohms.

The shaded cells in each column designate experimental factors, or combinations thereof, that do not differ significantly from the base case. Cells that are not shaded identify those terms in the GLM that deviate significantly from the base case. For example, the first non-shaded cell under 168 *hr* in Table 2.5 contains the value 0.89 and is on the row headed by SnPb. This value indicates that reflowed SnPb surface finish has an increase in mean SIR of 0.89 log ohms over that of the base case. The next non-shaded cell in this column shows an increase over the base case of 0.80 when using coating. The other terms have similar interpretations. However, the terms within each column must be viewed collectively to properly gauge the contribution of any experimental factor.

Using the coefficients in the fourth column of Table 2.5, the estimated GLM for 16-mil spacing at 168 *hr* is:

$$Y = 7.61 + 0.89\, D_1 + 0.80\, D_3 - 0.91\, D_4 - 1.48\, D_1 D_3 - 0.56\, D_2 D_3 + 0.45\, D_2 D_4 - 0.34\, D_1 D_3 D_4 \quad (2.2)$$

The model R^2 at the bottom of the column gives the percentage of the variability in the SIR measurements that is explained by the model. For the model in Equation 2.2, this value is 50.5%. The maximum for this value is 100%, but 50.5% is statistically significant and will likely do a good job of predicting mean SIR for various combinations of experimental factors. The estimate of the standard deviation for the model is

Table 2.3 GLM Results for SIR 85/85 Tests with 8-Mil Spacing

Experimental Variables	Pre-Test	24 *hr*	96 *hr*	168 *hr*	Post 2 *hr*	Post 24 *hr*
Constant	11.06	7.62	7.51	7.86	9.48	9.02
SnPb					1.59	2.39
Imidazole					2.95	3.24
Conformal Coating		0.74	0.21		-2.88	2.09
Flux		-1.01				
Medium Voltage			0.15			
High Voltage		0.35				
SnPb*Coating		-0.92		-0.21	1.94	-2.72
Imidazole*Coating						-4.73
SnPb*Flux	0.64		-0.51	-0.41		
Imidazole*Flux						
SnPb*Medium Voltage	-0.91				0.24	
Imidazole*Medium Voltage						
Coating*Medium Voltage						
Flux*Medium Voltage	0.90					
SnPb*High Voltage	-1.06		0.44		0.39	
Imidazole*High Voltage						
Coating*High Voltage			-0.23	-0.89		
Flux*High Voltage	1.07	-0.28	-0.63			
SnPb*Coating*Flux	0.83	-0.20	-1.07	-1.08	-2.30	-3.01
Imidazole*Coating*Flux						
SnPb*Coating*Medium						
Imid*Coating*Medium Voltage						
SnPb*Coating*High Voltage				0.97		
Imid*Coating*HIgh Voltage						
SnPb*Flux *Medium Voltage						0.91
Imid*Flux *Medium Voltage						
SnPb*Flux *High Voltage						
Imid*Flux *HIgh Voltage						
SnPb*Coating*Med Volt*Flux						-1.02
Imid*Coating*Med Volt*Flux						
SnPb*Coating*High Volt*Flux						
Imid*Coating*High Volt*Flux						
Model R^2	54.5%	84.7%	78.2%	53.1%	81.4%	89.5%
Standard Deviation	0.89	0.27	0.29	0.39	0.44	0.54
Missing Observations Out of 540	354	355	383	376	381	330

Table 2.4 GLM Results for SIR 85/85Tests with 12-Mil Spacing

Experimental Variables	**Pre-Test**	**24 *hr***	**96 *hr***	**168 *hr***	**Post 2 *hr***	**Post 24 *hr***
Constant	10.60	7.64	7.50	7.72	11.86	12.47
SnPb		0.34	0.63	0.85		-0.52
Imidazole	2.20	0.39			0.74	
Conformal Coating	0.41	0.43	0.43	0.46		-0.82
Flux	2.19	-1.27	-0.76	-0.80	-0.23	-2.10
Medium Voltage	1.03				0.22	
High Voltage	1.07					
SnPb*Coating		-0.96	-0.74	-1.03	-1.43	
Imidazole*Coating		-0.90		-0.38	-1.17	0.44
SnPb*Flux	-0.73		-0.28			2.09
Imidazole*Flux	-2.26	-0.47		0.28		1.42
SnPb*Medium Voltage	-1.57					
Imidazole*Medium Voltage	-1.01					
Coating*Medium Voltage					-0.61	1.11
Flux*Medium Voltage	-1.36	0.11			-0.93	-0.62
SnPb*High Voltage	-1.85			-0.26	0.30	
Imidazole*High Voltage	-1.32	0.32				
Coating*High Voltage						
Flux*High Voltage	-1.49	0.28				
SnPb*Coating*Flux	0.50		-0.84	-1.27	-2.09	-3.31
Imidazole*Coating*Flux		1.17			-1.91	-2.46
SnPb*Coating*Medium					0.53	-1.32
Imid*Coating*Medium Voltage					0.58	-1.09
SnPb*Coating*High Voltage		0.30				
Imid*Coating*HIgh Voltage						
SnPb*Flux *Medium Voltage	1.72		0.27		0.78	1.13
Imid*Flux *Medium Voltage	1.08				0.55	0.59
SnPb*Flux *High Voltage	2.07			0.74		
Imid*Flux *HIgh Voltage	1.60	-0.37				
SnPb*Coating*Med Volt*Flux						
Imid*Coating*Med Volt*Flux						
SnPb*Coating*High Volt*Flux		-0.52				
Imid*Coating*High Volt*Flux						
Model R^2	68.6%	81.8%	60.9%	41.8%	71.8%	82.2%
Standard Deviation	0.72	0.30	0.40	0.56	0.52	0.69
Missing Observations Out of 540	112	112	150	54	139	21

Table 2.5 GLM Results for SIR 85/85 Tests with 16-Mil Spacing

Experimental Variables	**Pre-Test**	**24** ***hr***	**96** ***hr***	**168** ***hr***	**Post 2** ***hr***	**Post 24** ***hr***
Constant	11.56	7.68	7.50	7.61	12.05	12.36
SnPb	-0.83	0.35	0.82	0.89	-0.42	-0.42
Imidazole	1.30				0.39	
Conformal Coating	0.35	0.55	0.71	0.80		-0.52
Flux	1.24	-1.40	-0.90	-0.91	-1.00	-2.43
Medium Voltage		0.12				
High Voltage		0.25				
SnPb*Coating		-1.35	-1.22	-1.48	-1.63	-0.66
Imidazole*Coating	-0.67	-0.79	-0.29	-0.56	-0.70	0.43
SnPb*Flux			-0.38		0.85	2.38
Imidazole*Flux	-1.67			0.45	0.59	1.49
SnPb*Medium Voltage	-0.55				0.52	
Imidazole*Medium Voltage						
Coating*Medium Voltage					-0.40	0.62
Flux*Medium Voltage					-0.32	
SnPb*High Voltage	-0.82				0.48	
Imidazole*High Voltage						
Coating*High Voltage						
Flux*High Voltage	-0.29					
SnPb*Coating*Flux	0.52	0.52		-0.34	-1.61	-2.94
Imidazole*Coating*Flux	0.97	0.91	0.31		-2.08	-2.42
SnPb*Coating*Medium						-0.80
Imid*Coating*Medium Voltage					0.58	-0.62
SnPb*Coating*High Voltage		0.28				
Imid*Coating*HIgh Voltage						
SnPb*Flux *Medium Voltage	0.49		0.26			0.54
Imid*Flux *Medium Voltage						
SnPb*Flux *High Voltage	1.05					
Imid*Flux *HIgh Voltage						
SnPb*Coating*Med Volt*Flux						
Imid*Coating*Med Volt*Flux						
SnPb*Coating*High Volt*Flux		-0.46				
Imid*Coating*High Volt*Flux						
Model R^2	62.3%	74.9%	58.4%	50.5%	63.8%	77.7%
Standard Deviation	0.75	0.39	0.48	0.51	0.65	0.79
Missing Observations Out of 540	100	100	123	30	130	2

Table 2.6 GLM Results for SIR 85/85 Tests with 20-Mil Spacing

Experimental Variables	**Pre-Test**	**24 *hr***	**96 *hr***	**168 *hr***	**Post 2 *hr***	**Post 24 *hr***
Constant	11.17	8.06	7.63	7.73	12.53	12.77
SnPb			0.96	1.10	-0.27	-0.46
Imidazole	1.10					-0.40
Conformal Coating		0.41	0.58	0.73	-0.38	-0.72
Flux	1.50	-1.51	-0.74	-0.72	-1.28	-2.50
Medium Voltage	1.21					
High Voltage	1.36	0.21				
SnPb*Coating		-1.02	-1.34	-1.39	-1.23	-0.59
Imidazole*Coating	1.18	-0.84		-0.41		0.88
SnPb*Flux		0.73				2.43
Imidazole*Flux	-1.36			0.33	0.81	1.53
SnPb*Medium Voltage	-2.15				0.35	
Imidazole*Medium Voltage	-1.38					
Coating*Medium Voltage						0.64
Flux*Medium Voltage	-1.26					
SnPb*High Voltage	-2.26					
Imidazole*High Voltage	-1.63					
Coating*High Voltage						
Flux*High Voltage	-1.40				0.44	
SnPb*Coating*Flux	0.70			-0.50	-1.49	-2.20
Imidazole*Coating*Flux	-0.74	1.15			-1.45	-2.33
SnPb*Coating*Medium	0.51					-0.62
Imid*Coating*Medium Voltage						-0.64
SnPb*Coating*High Voltage						
Imid*Coating*HIgh Voltage						
SnPb*Flux *Medium Voltage	1.70					
Imid*Flux *Medium Voltage	1.41					
SnPb*Flux *High Voltage	2.03					
Imid*Flux *HIgh Voltage	1.76					
SnPb*Coating*Med Volt*Flux						
Imid*Coating*Med Volt*Flux						
SnPb*Coating*High Volt*Flux						
Imid*Coating*High Volt*Flux						
Model R^2	66.6%	34.2%	27.1%	27.8%	50.4%	69.8%
Standard Deviation	0.69	0.84	0.84	0.86	0.75	0.90
Missing Observations Out of 540	100	101	107	7	130	0

given beneath the model R^2. This value is 0.51 (about 0.5 log ohm).

Using the values in the last column of Table 2.5, the estimated GLM for 16-mil spacing at Post 24 *hr* is:

$$\begin{aligned} Y = {} & 12.36 - 0.42\,D_1 - 0.52\,D_3 - 2.43\,D_4 - 0.66\,D_1D_3 \\ & + 0.43\,D_2D_3 + 2.38\,D_1D_4 + 1.49\,D_2D_4 \\ & + 0.62\,D_3D_5 - 2.94\,D_1D_3D_4 - 2.42\,D_2D_3D_4 \\ & - 0.80\,D_1D_3D_5 - 0.62\,D_2D_3D_5 \\ & + 0.54\,D_1D_4D_5 \end{aligned} \tag{2.3}$$

The model R^2 is 77.7% with standard deviation, 0.79.

Mean Prediction. GLMs can be used to estimate mean SIR for each combination of experimental factors by summing the constant term and all significant effects that *apply to the particular combination* of interest. To illustrate, consider a prediction for SIR at 168 *hr* on the 16-mil comb pattern for a board with SnPb surface finish, conformal coating, LR flux, and tested at medium voltage. This value is found from Table 2.5 by summing 7.61 (the constant term) + 0.89 (SnPb) + 0.80 (Coating) - 1.48 (SnPb*Coating) = 7.82. This value can be found in Table 2.8, where predicted means are given for each combination of experimental factors. Table 2.1 shows the actual observed mean is 7.83. Note that several coefficients in the 168 hr column were not used since these experimental factors do not apply to this prediction.

The predicted mean for the same combination of factors for the Post 24 *hr* model (see Table 2.9) for 16-mils is found as 12.36 (the constant term) - 0.42 (SnPb) - 0.52 (Coating) - 0.66 (SnPb*Coating) + 0.62 (Coating*Medium Voltage) - 0.80 (SnPb*Coating* Medium Voltage) = 10.59. The observed value is 10.74, as given in Table 2.1.

Conformal Coating Versus No Coating. Tables 2.7 to 2.9 give predicted means from the GLM analyses for initial (pre-test), 168 *hr* (during environmental exposure), and post 24 *hr* SIR tests for 8-, 12-, 16-, and 20-mil comb pattern spacing. These predictions agree closely with the observed means in Table 2.1. Such agreements are important since they provide assurance the GLM analyses have correctly identified the significant experimental factors.

The boxplots in Figures 2.4 to 2.9 and GLM analyses are supplemented with statistical analyses, comparing the mean SIR for conformally coated boards with mean SIR for uncoated boards for each combination of experimental factors. Two-sample t-tests were used to determine if the respective population means were significantly different at a 5% level of significance. Table 2.10 contains t-test results for each pair of boxplots in Figures 2.4 to 2.9. The entries in the body of Table 2.10 have the following interpretations: a positive value denotes a significant increase in mean SIR (log 10 ohms) when conformal coating is used; “0” denotes no significant difference in mean SIR for coated and uncoated boards, and a negative value denotes a significant decrease in mean SIR when coating is used.

Table 2.10 contains t-test results for each combination of surface finish, flux, and test time for 16-mil spacing and medium voltage. Similar tables could be created for each combination of spacing and voltage, but previous results in this section indicate that neither of these factors has a significant impact on the test results.

As shown in Table 2.10, mean SIR is significantly higher at Pre-Test for all conformally coated boards soldered with WS flux than the mean SIR for uncoated boards soldered with WS flux. There is no difference in mean SIR for coated and uncoated boards soldered with LR flux at Pre-Test. Coated reflowed SnPb boards with either flux have significantly lower mean SIR during test exposure and at Post-Test. Imidazole boards with either flux have approximately 0.5 log ohm higher mean SIR at 24 and 96 *hr*, but show no difference at either 168 *hr*. At Post-Test, imidazole with either flux have significantly lower mean SIR with coating in all but one case where there is no difference. HASL boards with LR benefit from coating during test exposure and at Post 24 *hr*. HASL boards with WS flux behave similar to imidazole boards with WS flux.

2.12 Screening Experiment 2: SIR Testing for the Condensing Atmosphere Environment

The test matrix in Figure 2.1 specifies 60 test boards for use in the condensing atmosphere test. After processing, these boards were shipped to AlliedSignal in Kansas City for exposure to a condensing atmosphere environment and SIR testing. These boards were subjected to 10 cycles of approximately 6.5 hr each. Figure 2.24 shows the temperature and humidity profiles for one cycle in a Terry Benchmaster chamber, which is summarized as follows:

1. Apply electrical bias to the boards and begin monitoring electrical performance.
2. Begin with boards at 25°*C* and 60% RH.

Table 2.7 Predicted Means Based on the GLM Analyses of Initial SIR Responses at 85° *C* / 85% RH

8-Mil Spacing

		Low Voltage		Medium Voltage		High Voltage	
	Coating	**LR**	**WS**	**LR**	**WS**	**LR**	**WS**
SnPb	**No**	11.06	11.70	10.15	11.69	10.00	11.72
	Yes	11.06	12.53	10.15	12.52	10.00	12.54
Imidazole	**No**	11.06	11.06	11.06	11.96	11.06	12.13
	Yes	11.06	11.06	11.06	11.96	11.06	12.13
HASL	**No**	11.06	11.06	11.06	11.96	11.06	12.13
	Yes	11.06	11.06	11.06	11.96	11.06	12.13

12-Mil Spacing

		Low Voltage		Medium Voltage		High Voltage	
	Coating	**LR**	**WS**	**LR**	**WS**	**LR**	**WS**
SnPb	**No**	10.60	12.06	10.05	11.87	9.82	11.86
	Yes	11.01	12.98	10.47	12.79	10.23	12.77
Imidazole	**No**	12.81	12.73	12.82	12.47	12.56	12.59
	Yes	13.22	13.14	13.24	12.88	12.97	13.01
HASL	**No**	10.60	12.79	11.63	12.46	11.67	12.37
	Yes	11.01	13.20	12.04	12.87	12.09	12.78

16-Mil Spacing

		Low Voltage		Medium Voltage		High Voltage	
	Coating	**LR**	**WS**	**LR**	**WS**	**LR**	**WS**
SnPb	**No**	10.73	11.98	10.18	11.92	9.91	11.92
	Yes	11.08	12.84	10.54	12.79	10.26	12.79
Imidazole	**No**	12.87	12.44	12.87	12.44	12.87	12.15
	Yes	12.55	13.08	12.55	13.08	12.55	12.79
HASL	**No**	11.56	12.81	11.56	12.81	11.56	12.52
	Yes	11.92	13.16	11.92	13.16	11.92	12.87

20-Mil Spacing

		Low Voltage		Medium Voltage		High Voltage	
	Coating	**LR**	**WS**	**LR**	**WS**	**LR**	**WS**
SnPb	**No**	11.17	12.66	10.24	12.17	10.26	12.39
	Yes	11.17	13.37	10.75	13.38	10.26	13.10
Imidazole	**No**	12.27	12.40	12.11	12.39	12.00	12.49
	Yes	13.45	12.84	13.29	12.83	13.18	12.93
HASL	**No**	11.17	12.66	12.38	12.62	12.53	12.62
	Yes	11.17	12.66	12.38	12.62	12.53	12.62

Table 2.8 Predicted Means based on the GLM Analyses of 168 *hr* SIR Responses at 85° C / 85% RH

8-Mil Spacing

		Low Voltage		Medium Voltage		High Voltage	
	Coating	**LR**	**WS**	**LR**	**WS**	**LR**	**WS**
SnPb	**No**	7.86	7.45	7.86	7.45	7.86	7.45
	Yes	7.65	6.17	7.65	6.17	7.74	6.25
Imidazole	**No**	7.86	7.86	7.86	7.86	7.86	7.86
	Yes	7.86	7.86	7.86	7.86	6.97	6.97
HASL	**No**	7.86	7.86	7.86	7.86	7.86	7.86
	Yes	7.86	7.86	7.86	7.86	6.97	6.97

12-Mil Spacing

		Low Voltage		Medium Voltage		High Voltage	
	Coating	**LR**	**WS**	**LR**	**WS**	**LR**	**WS**
SnPb	**No**	8.57	7.76	8.57	7.76	8.31	8.24
	Yes	8.00	5.93	8.00	5.93	7.74	6.41
Imidazole	**No**	7.72	7.20	7.72	7.20	7.72	7.20
	Yes	7.80	7.28	7.80	7.28	7.80	7.28
HASL	**No**	7.72	6.92	7.72	6.92	7.72	6.92
	Yes	8.18	7.38	8.18	7.38	8.18	7.38

16-Mil Spacing

		Low Voltage		Medium Voltage		High Voltage	
	Coating	**LR**	**WS**	**LR**	**WS**	**LR**	**WS**
SnPb	**No**	8.50	7.59	8.50	7.59	8.50	7.59
	Yes	7.82	6.57	7.82	6.57	7.82	6.57
Imidazole	**No**	7.61	7.15	7.61	7.15	7.61	7.15
	Yes	7.85	7.39	7.85	7.39	7.85	7.39
HASL	**No**	7.61	6.71	7.61	6.71	7.61	6.71
	Yes	8.41	7.50	8.41	7.50	8.41	7.50

20-Mil Spacing

		Low Voltage		Medium Voltage		High Voltage	
	Coating	**LR**	**WS**	**LR**	**WS**	**LR**	**WS**
SnPb	**No**	8.84	8.11	8.84	8.11	8.84	8.11
	Yes	8.18	6.95	8.18	6.95	8.18	6.95
Imidazole	**No**	7.73	7.34	7.73	7.34	7.73	7.34
	Yes	8.05	7.66	8.05	7.66	8.05	7.66
HASL	**No**	7.73	7.01	7.73	7.01	7.73	7.01
	Yes	8.46	7.74	8.46	7.74	8.46	7.74

Table 2.9 Predicted Means based on the GLM Analyses of Post 24 *hr* SIR Responses at 85° *C* / 85% RH

8-Mil Spacing

		Low Voltage		Medium Voltage		High Voltage	
	Coating	**LR**	**WS**	**LR**	**WS**	**LR**	**WS**
SnPb	**No**	11.42	11.42	11.42	12.33	11.42	11.42
	Yes	10.78	7.77	10.78	7.66	10.78	7.77
Imidazole	**No**	12.27	12.27	12.27	12.27	12.27	12.27
	Yes	9.63	9.63	9.63	9.63	9.63	9.63
HASL	**No**	9.02	9.02	9.02	9.02	9.02	9.02
	Yes	11.11	11.11	11.11	11.11	11.11	11.11

12-Mil Spacing

		Low Voltage		Medium Voltage		High Voltage	
	Coating	**LR**	**WS**	**LR**	**WS**	**LR**	**WS**
SnPb	**No**	11.94	11.93	11.94	12.44	11.94	11.93
	Yes	11.12	7.80	10.92	8.11	11.12	7.80
Imidazole	**No**	12.47	11.79	12.47	11.76	12.47	11.79
	Yes	12.09	8.95	12.12	8.95	12.09	8.95
HASL	**No**	12.47	10.37	12.47	9.75	12.47	10.37
	Yes	11.65	9.55	12.76	10.04	11.65	9.55

16-Mil Spacing

		Low Voltage		Medium Voltage		High Voltage	
	Coating	**LR**	**WS**	**LR**	**WS**	**LR**	**WS**
SnPb	**No**	11.94	11.89	11.94	12.44	11.94	11.89
	Yes	10.77	7.78	10.59	8.14	10.77	7.78
Imidazole	**No**	12.36	11.43	12.36	11.43	12.36	11.43
	Yes	12.28	8.92	12.28	8.93	12.28	8.92
HASL	**No**	12.36	9.93	12.36	9.93	12.36	9.93
	Yes	11.84	9.42	12.47	10.04	11.84	9.42

20-Mil Spacing

		Low Voltage		Medium Voltage		High Voltage	
	Coating	**LR**	**WS**	**LR**	**WS**	**LR**	**WS**
SnPb	**No**	12.31	12.24	12.31	12.24	12.31	12.24
	Yes	11.00	8.73	11.02	8.75	11.00	8.73
Imidazole	**No**	12.36	11.40	12.36	11.40	12.36	11.40
	Yes	12.52	9.23	12.52	9.23	12.52	9.23
HASL	**No**	12.77	10.27	12.77	10.27	12.77	10.27
	Yes	12.05	9.55	12.69	10.19	12.05	9.55

Table 2.10 Two Sample t-Test Comparisons of Mean SIR for Coated and Uncoated Boards for Each Combination of Experimental Factors in the SIR 85/85 Test for 16-Mils at Medium Voltage (positive values denote the magnitude of significant increases in mean SIR (log 10 ohms) with coating, 0 denotes no difference in mean SIR, negative values denote the magnitude of significant decreases in mean SIR with coating)

	Flux	Pre-Test	24 *hr*	96 *hr*	168 *hr*	Post 2 *hr*	Post 24 *hr*
SnPb	**LR**	0	-0.7	-0.6	-0.7	-1.9	-1.2
	WS	0.9	-0.4	-0.7	-1.2	-3.6	-4.6
Imidazole	**LR**	0	0.5	0.4	0	-0.5	0
	WS	0.6	0.8	0.7	0	-2.7	-2.5
HASL	**LR**	0	0.5	0.8	1.3	0	1.8
	WS	0.6	0.6	0.7	0	-1.5	-1.6

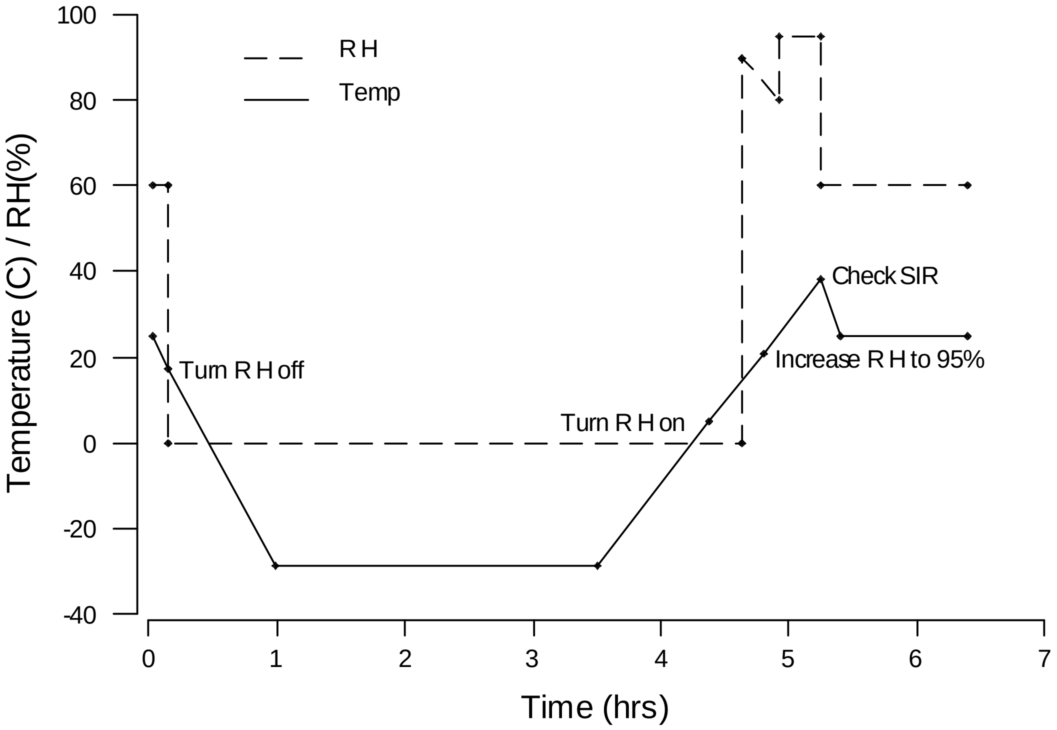

Figure 2.24 Temperature and Humidity Profiles for the Condensing Atmosphere Test

3. Lower the temperature to -29°*C* over a period of 1 *hr*. When the temperature reaches 17°*C*, discontinue the humidity.
4. Stabilize the boards at -29°*C* for 2.5 *hr*.
5. Warm the boards to 38°*C* over a period of 1.75 *hr*
6. At 5°*C*, turn humidity on to 90% to ensure adequate condensing and then lower to 80%.
7. At 21°*C*, turn humidity on to 95%.
8. Check the boards for SIR at 5 *hr* 5 min.
9. Cool the boards to 25°*C* over a period of 15 *min*, with the RH dropped to 60%.
10. Stabilize the boards at 25°*C* and 60% RH for 1 *hr*.

The above steps were repeated 10 times, for a total test time of 65 hr. SIR measurements were made with two Alpha Metals SIROMETERs at Pre-Test, at the end of each of the 10 cycles, and at Post-Test, for a total of 12 SIR measurements on each board. The boards were at a constant 100V bias and tested at 100V (medium voltage in the 85°*C* / 85%RH test). The post-test SIR reading was taken at 25°*C* and 60% RH four *hr* after the completion of cycle 10.

2.13 SIR Cell Means for Condensing Atmosphere

Table 2.11 gives means for initial, Cycle 1, Cycle 10, and post-test SIR measurements for each experimental cell (5 observations per cell) with the bridged boards eliminated. There are 16 empty cells in Table 2.11 (denoted by an asterisk) for 8-mil spacing with imidazole and HASL resulting from eliminating bridged boards.

2.14 Boxplots for SIR Condensing Atmosphere Test Measurements

Boxplots are used in Figures 2.25 to 2.38 to show selected effects of the experimental factors used in the condensing atmosphere test: surface finish, flux, pattern spacing, and coating. Each boxplot represents five observations in one experimental cell (unless data are missing). For the most part, measurements were test equipment limited to a maximum of 12 log 10 ohms, which creates horizontal line effects at 12 log 10 ohms in some figures.

SIR Versus Test Time. Figures 2.25 to 2.30 display SIR measurements versus test time for SnPb, imidazole, and HASL by LR and WS fluxes for the 16-mil comb pattern. The lines in each figure connecting the medians exhibit the U-shaped appearance similar to that in Figures 2.4 to 2.9. Note that Cycle 5 is not shown in these figures. The middle cycles all showed the same behavior; so Cycle 5 was eliminated from the displays and subsequent analyses to avoid congestion.

Figures 2.25 to 2.28 demonstrate a big advantage to using conformal coating on either reflowed SnPb or imidazole boards during test exposure. It is interesting to note that coated and uncoated boards have similar SIR on the post-test measurement except, imidazole with WS flux exhibits greater variability than do the other cases. Boxplots in Figures 2.29 and 2.30 for HASL overlap considerably. The boxplots in Figure 2.30 exhibit great variability throughout the test for both coated and uncoated boards with WS flux.

SIR Versus Comb Pattern Spacing. Figures 2.31 to 2.36 show SIR plotted against comb pattern spacing for both flux types. These graphs display results for Cycle 10 and the post-test measurement. As was the case with the SIR 85/85 tests, the nearly horizontal lines connecting the boxplots indicate that spacing width is not a major factor in the experiment. The greatest variability occurs with imidazole and WS flux.

Figures 2.31 and 2.33 show that coating helps during exposure to test conditions, while Figures 2.32 and 2.34 show that coating adds little value at post-test. Figures 2.35 and 2.36 show that coating is most likely not a valued added process when used with HASL and LR flux. These figures also show that WS flux increased the variability in SIR for both coated and uncoated boards.

SIR Versus Surface Finish. Figures 2.37 and 2.38 show SIR versus surface finish for Cycle 10 and the post-test measurement on 16-mil spacing. Imidazole with coating performs better than the other two finishes during exposure to test conditions. Reflowed SnPb and imidazole both benefit from coating during exposure to test conditions. Coated and uncoated HASL boards perform at approximately the same level with LR flux during exposure to test conditions while WS flux increases the variability in SIR. Post-test SIR is approximately the same for coated and uncoated boards — imidazole without coating and processed with WS flux shows the greatest variability.

Other Displays. Appendix B contains 24 displays similar to Figures 2.25 to 2.30; 15 displays with SIR results plotted against comb pattern spacing, as shown in Figures 2.31 to 2.36; and 20 displays with SIR results plotted against surface finish spacing, as shown in Figures 2.37 and 2.38. The reader is encouraged to study the different comparisons in these displays.

2.15 General Linear Model Results for SIR in Condensing Atmosphere

The following GLM was used to analyze the SIR condensing atmosphere test results:

$$\begin{aligned} Y = {} & \beta_0 + \beta_1 D_1 + \beta_2 D_2 + \beta_3 D_3 + \beta_4 D_4 + \beta_5 D_5 + \beta_6 D_6 \\ & + \beta_7 D_1 D_3 + \beta_8 D_1 D_4 + \beta_9 D_2 D_3 + \beta_{10} D_2 D_4 \\ & + \beta_{11} D_3 D_4 + \beta_{12} D_1 D_3 D_4 + \beta_{13} D_2 D_3 D_4 \end{aligned} \tag{2.4}$$

D_1 = 0 if surface finish is not reflowed SnPb
= 1 if surface finish is reflowed SnPb
D_2 = 0 if surface finish is not imidazole
= 1 if surface finish is imidazole
D_3 = 0 if board is not conformally coated
= 1 if board is conformally coated
D_4 = 0 if flux is not water soluble with halide
= 1 if flux is water soluble with halide

Table 2.11 SIR Means for Condensing Atmosphere (bridged boards eliminated)

				8-Mil Spacing				12-Mil Spacing			
Surface	**Coating**	**Flux**	**n**	**Initial**	**Cycle 1**	**Cycle 10**	**PostTest**	**Initial**	**Cycle 1**	**Cycle 10**	**PostTest**
SnPb	**No**	**LR**	5	11.28	7.30	7.87	11.34	10.84	7.18	7.52	11.01
		WS	5	11.51	7.96	8.76	10.72	11.67	7.52	7.45	11.43
	Yes	**LR**	5	10.38	8.46	9.33	10.29	10.65	8.09	9.05	10.39
		WS	5	12.00	10.47	10.53	11.58	11.98	10.08	10.27	11.42
Imidazole	**No**	**LR**	5	*	*	*	*	12.00	9.94	8.75	11.16
		WS	5	*	*	*	*	11.84	7.62	7.80	11.62
	Yes	**LR**	5	*	*	*	*	12.00	11.09	11.30	12.00
		WS	5	12.00	11.67	11.97	12.00	12.00	11.20	10.52	11.84
HASL	**No**	**LR**	5	9.99	8.35	9.07	11.03	11.53	8.28	9.23	11.25
		WS	5	12.00	12.00	12.00	12.00	11.98	9.25	9.60	11.29
	Yes	**LR**	5	*	*	*	*	12.00	8.92	9.58	11.44
		WS	5	12.00	8.85	9.58	12.00	12.00	10.14	9.91	11.48

				16-Mil Spacing				20-Mil Spacing			
				Initial	**Cycle 1**	**Cycle 10**	**PostTest**	**Initial**	**Cycle 1**	**Cycle. 10**	**PostTest**
SnPb	**No**	**LR**	5	11.04	7.24	7.73	11.05	11.19	7.30	7.91	11.40
		WS	5	11.75	7.49	6.99	11.48	11.93	7.07	7.02	11.65
	Yes	**LR**	5	10.86	8.45	9.17	10.41	10.95	8.35	9.20	10.43
		WS	5	12.00	10.50	10.48	11.50	12.00	10.29	10.38	11.66
Imidazole	**No**	**LR**	5	12.00	9.93	9.22	11.51	12.00	10.22	9.29	11.59
		WS	5	11.66	7.41	7.85	10.48	12.00	7.35	7.88	10.34
	Yes	**LR**	5	11.98	11.85	11.63	12.00	12.00	10.93	11.60	12.00
		WS	5	12.00	11.75	11.38	11.98	12.00	11.34	10.96	11.91
HASL	**No**	**LR**	5	11.54	8.65	9.35	11.20	11.58	8.53	9.28	11.10
		WS	5	12.00	9.62	9.29	11.41	12.00	9.51	9.02	11.26
	Yes	**LR**	5	11.97	9.24	9.78	11.37	12.00	8.68	9.57	11.65
		WS	5	12.00	10.49	10.24	11.75	12.00	10.07	10.72	12.00

D_5 = 0 if testing was not done in week 2
= 1 if testing was done in week 2
D_6 = 0 if testing was not done in week 3
= 1 if testing was done in week 3

This GLM is similar to the one used for the SIR 85/85 analyses, but there are some differences. Voltage is no longer included in the model since only one voltage was used (medium: 100V). The condensing atmosphere test was conducted at three different times over a 3-week period, and an experimental design was developed to maintain balance among the experimental factors each week. Balancing allows terms to be included in the model to account for any possible unwanted effect due to time. (Do not confuse week-to-week test times with cycle times within a given week.) In an ideal testing situation, there should be no effect due to week-to week test times. These terms are included in the model as insurance in case an inadvertent test time effect does occur. The GLM results that follow show that test time was only of minor importance with the 8-mil comb pattern. Since two-thirds of the 8-mil test data were missing, it is doubtful that test time made any significant contribution.

Tables 2.12 to 2.15 contain the results of the GLM analyses for SIR in a condensing atmosphere for 8-, 12-, 16-, and 20-mil comb patterns, respectively. The last row shows the number of missing and/or omitted observations (mostly with 8-mil spacing). That is, results for the comb patterns with bridges were omitted from the analyses. GLM results are given by cycle number within each table.

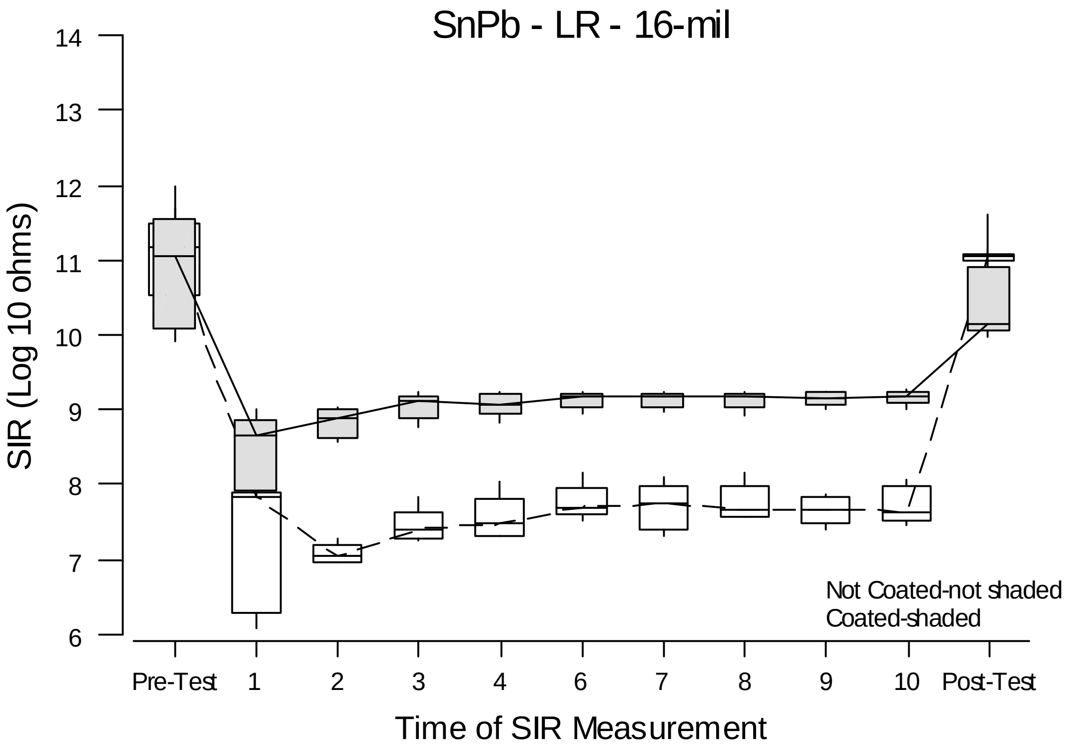

Figure 2.25 SIR Condensing Atmosphere Boxplots: SnPb, LR, 16-Mil versus Time

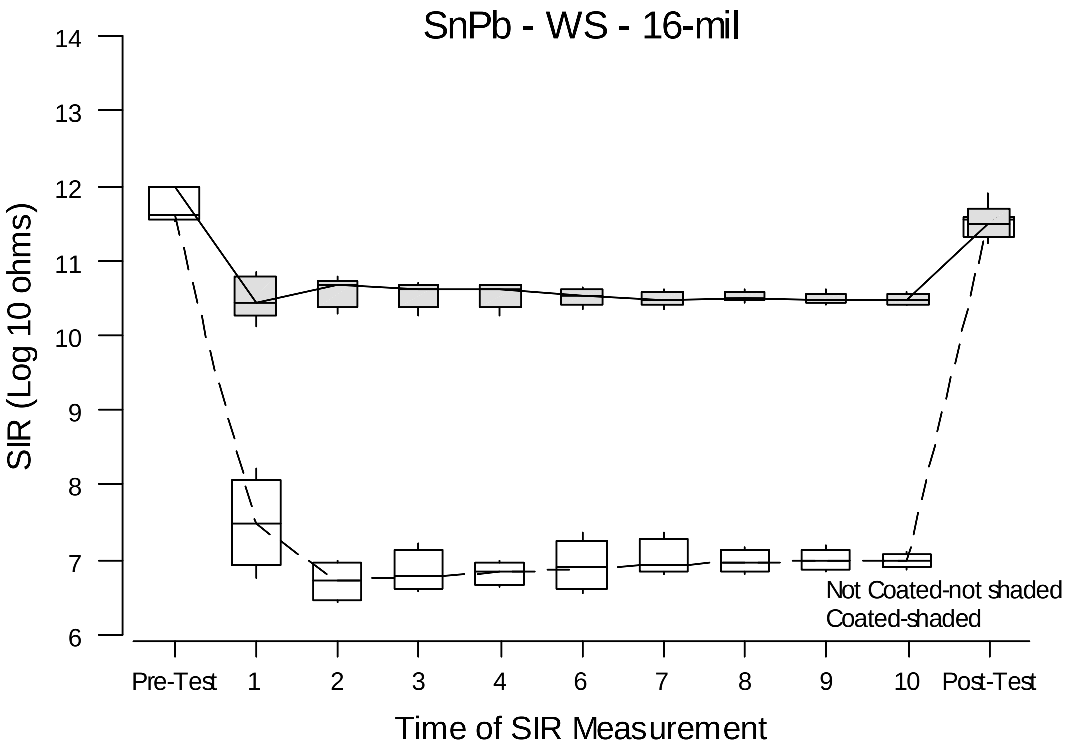

Figure 2.26 SIR Condensing Atmosphere Boxplots: SnPb, WS, 16-Mil versus Time

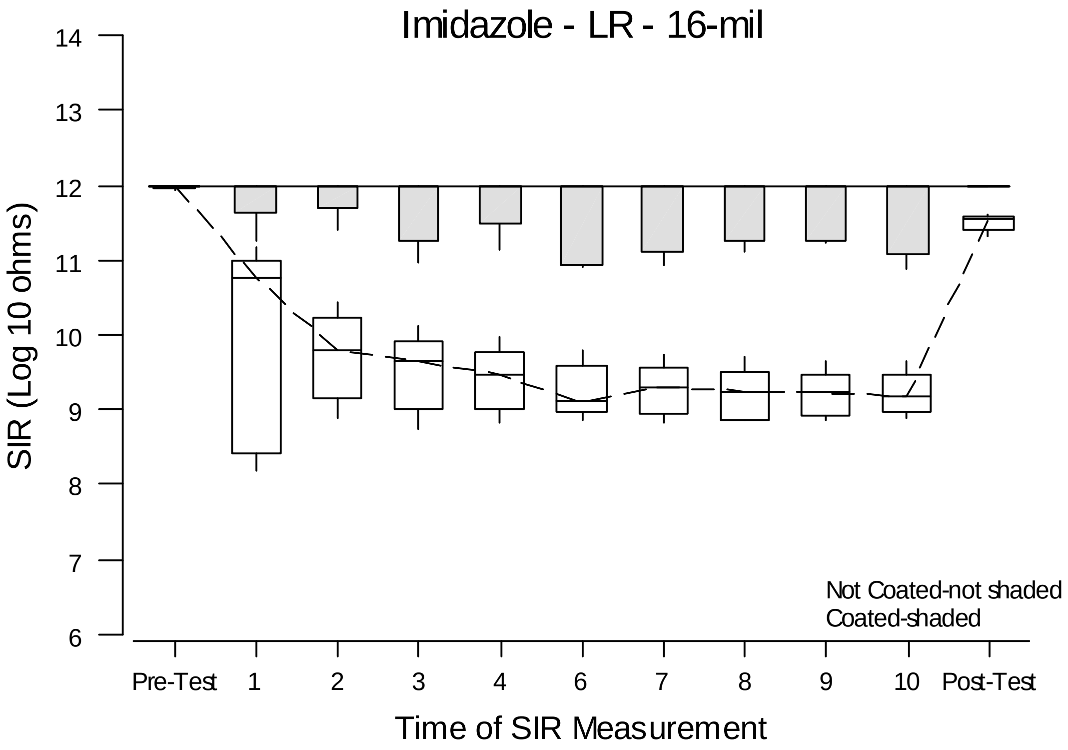

Figure 2.27 SIR Condensing Atmosphere Boxplots: Imidazole, LR, 16-Mil versus Time

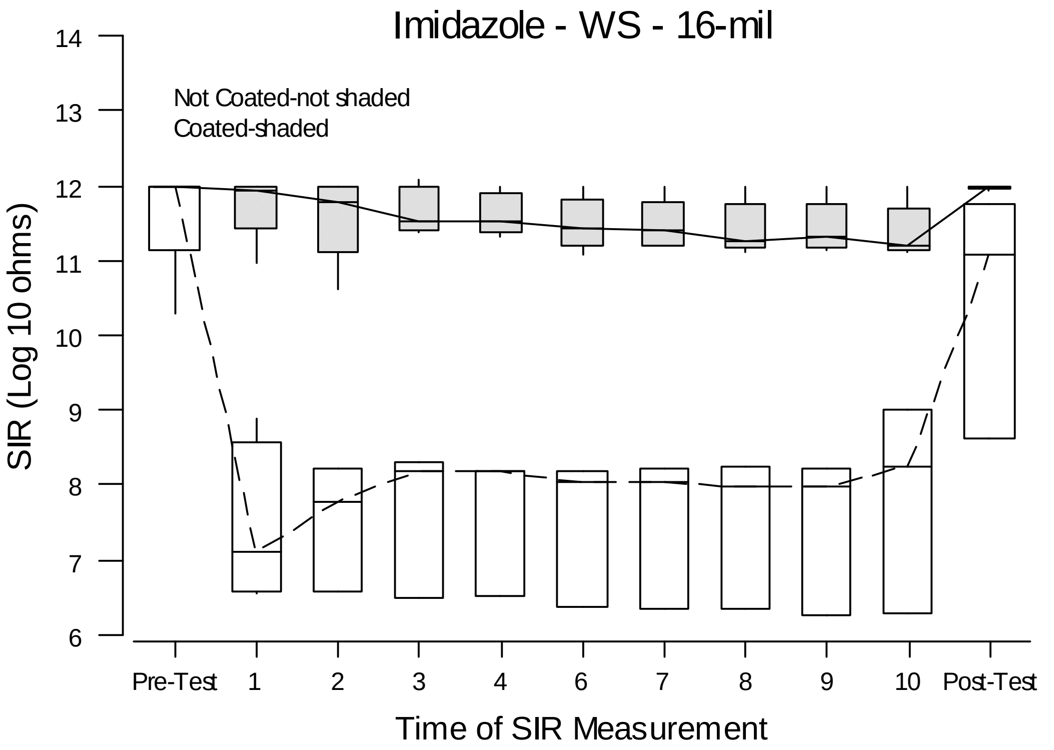

Figure 2.28 SIR Condensing Atmosphere Boxplots: Imidazole, WS, 16-Mil versus Time

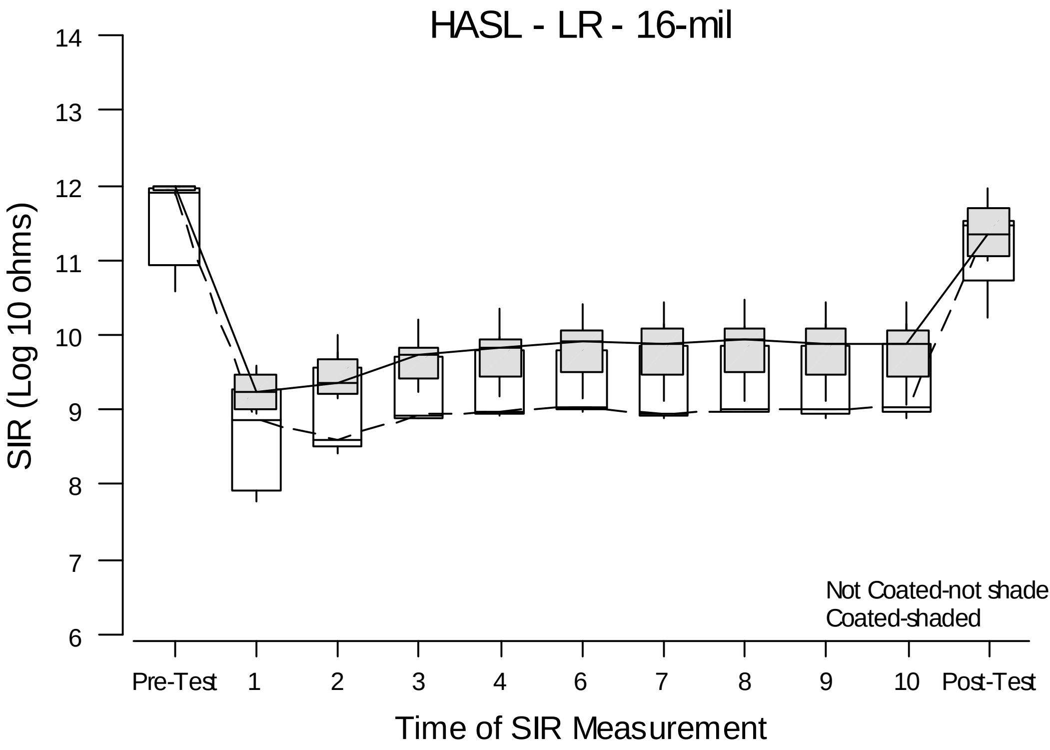

Figure 2.29 SIR Condensing Atmosphere Boxplots: HASL, LR, 16-Mil versus Time

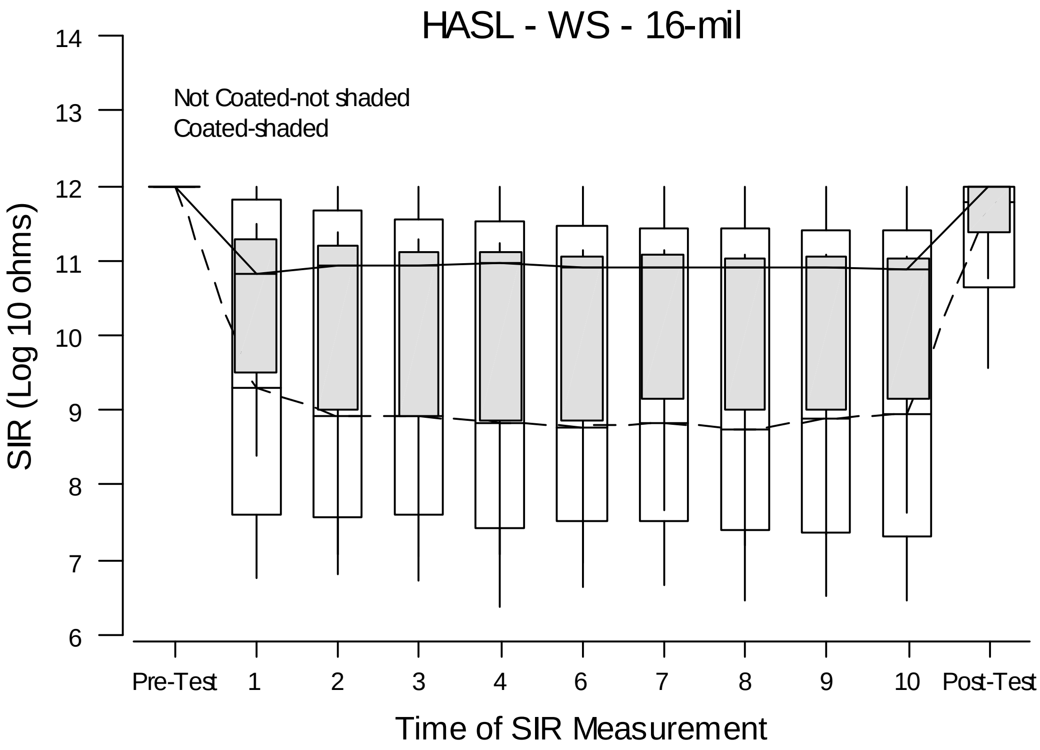

Figure 2.30 SIR Condensing Atmosphere Boxplots: HASL, WS, 16-Mil versus Time

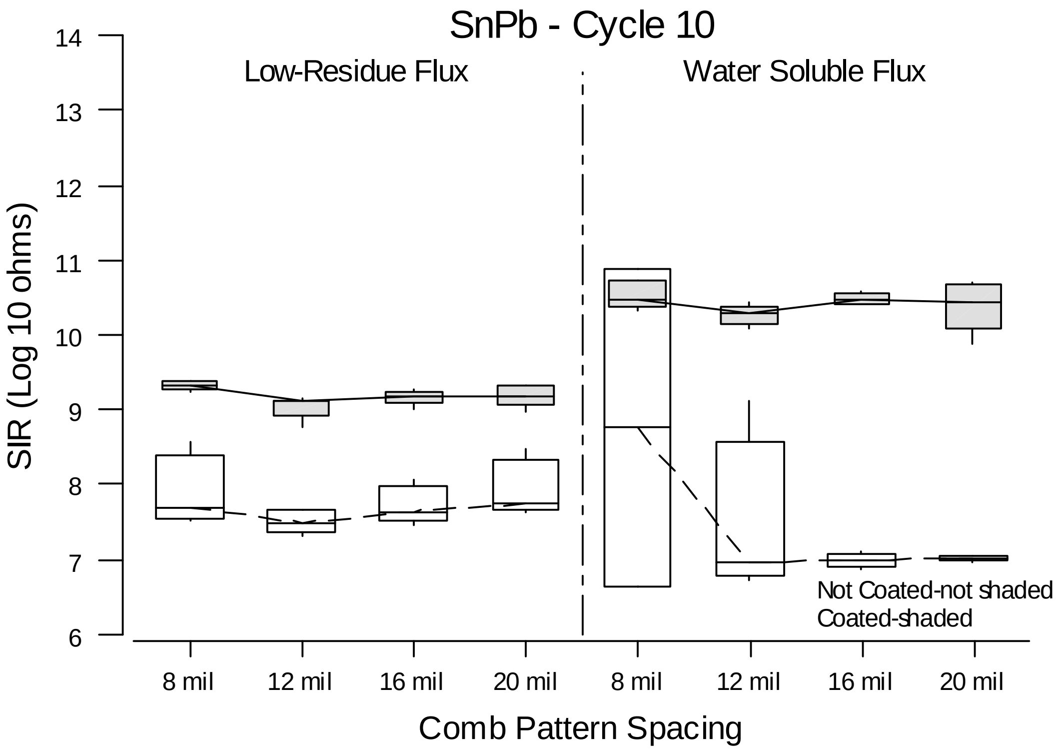

Figure 2.31 SIR Condensing Atmosphere Boxplots: SnPb Cycle 10 versus Comb Pattern Spacing

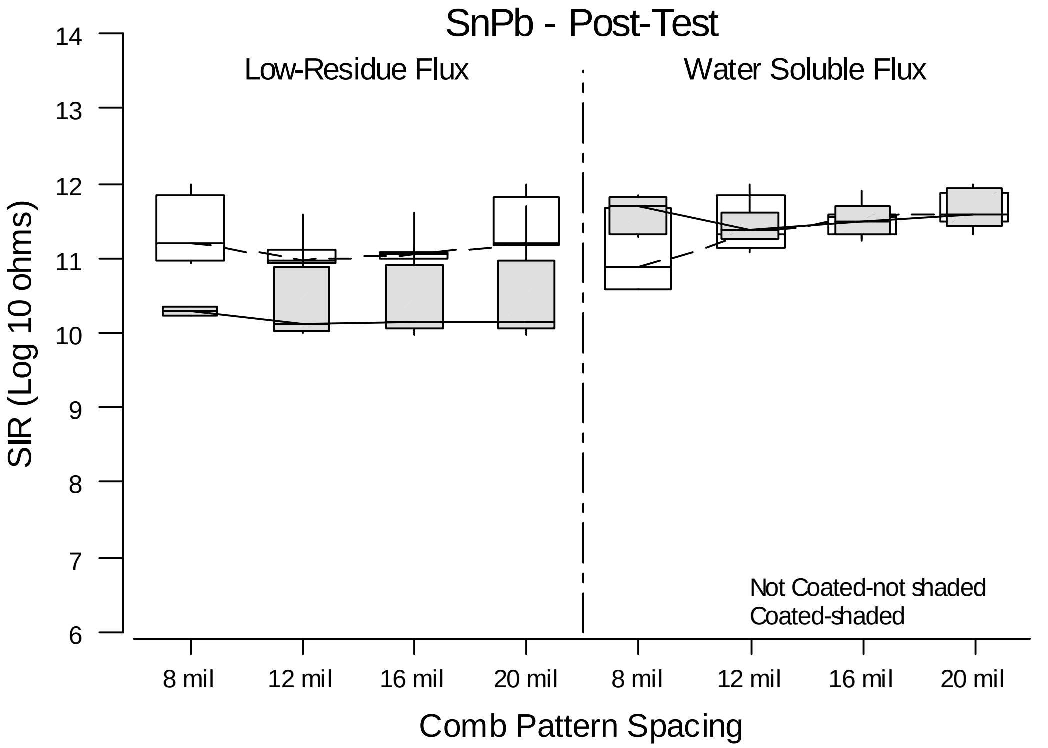

Figure 2.32 SIR Condensing Atmosphere Boxplots: SnPb Post-Test versus Comb Pattern Spacing

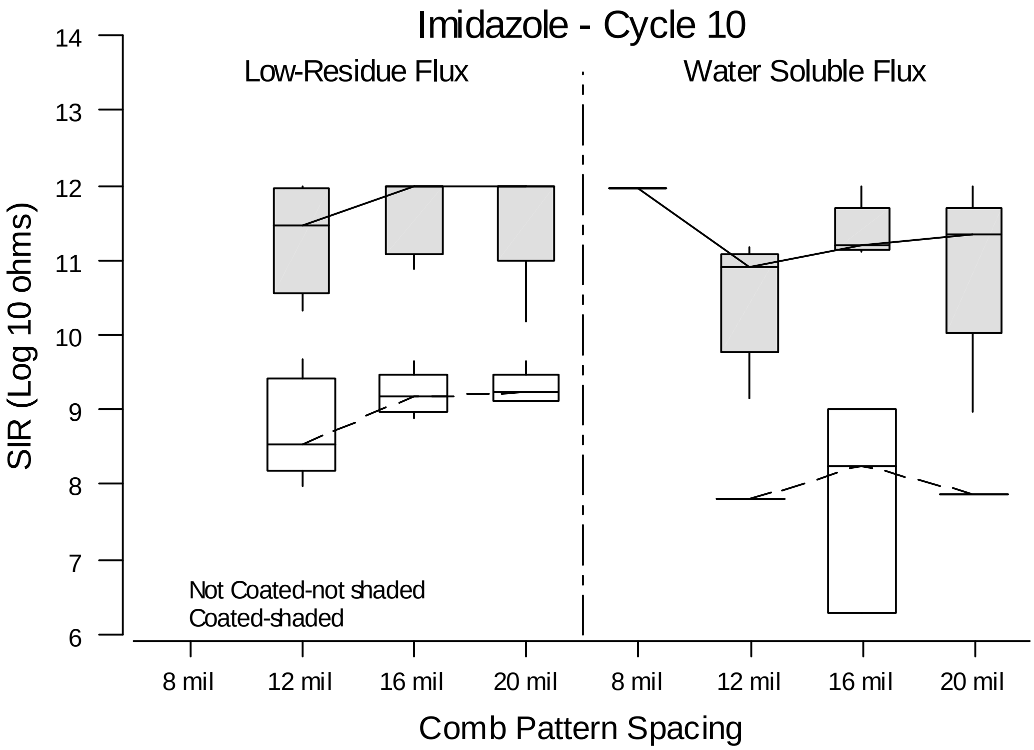

Figure 2.33 SIR Condensing Atmosphere Boxplots: Imidazole Cycle 10 versus Comb Pattern Spacing

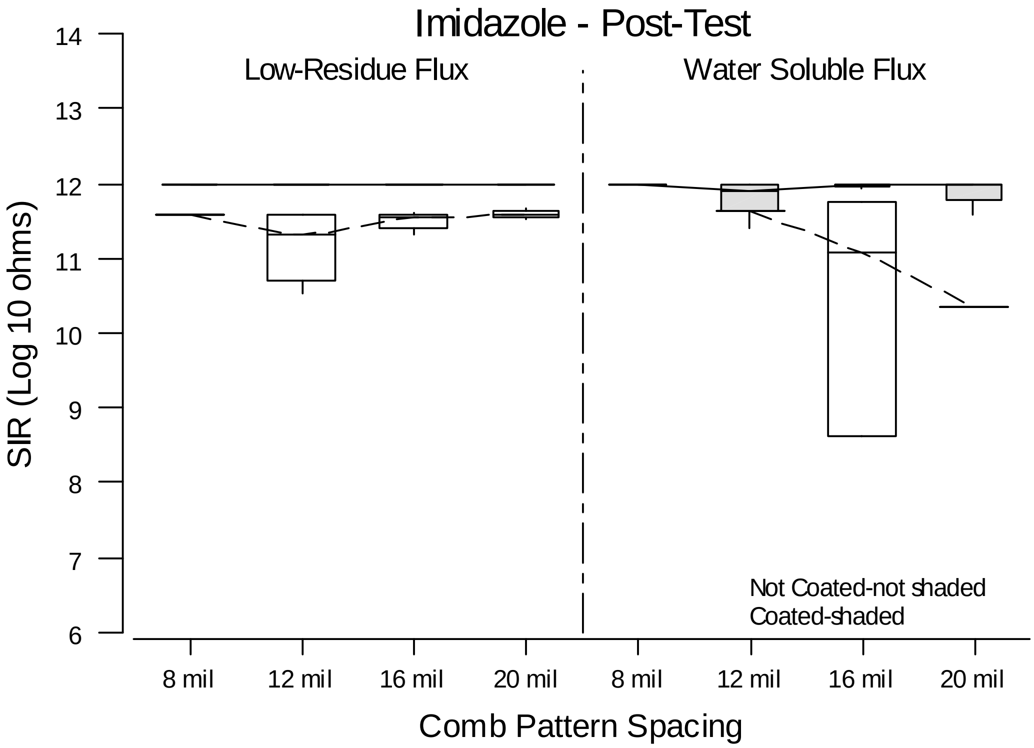

Figure 2.34 SIR Condensing Atmosphere Boxplots: Imidazole Post-Test versus Comb Pattern Spacing

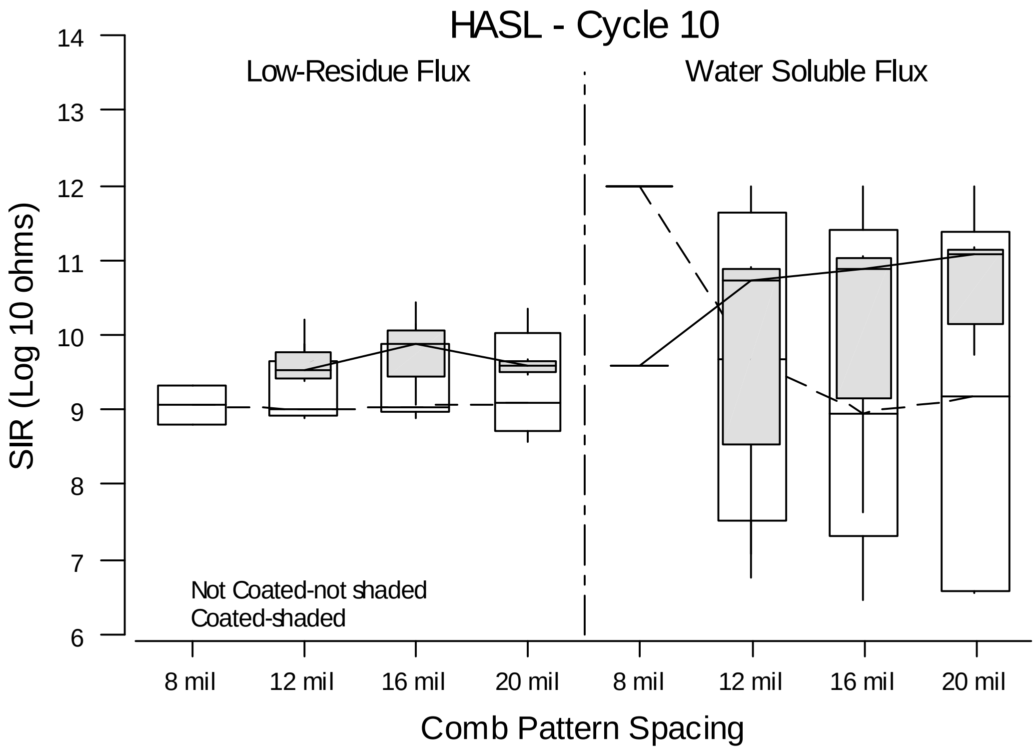

Figure 2.35 SIR Condensing Atmosphere Boxplots: HASL Cycle 10 versus Comb Pattern Spacing

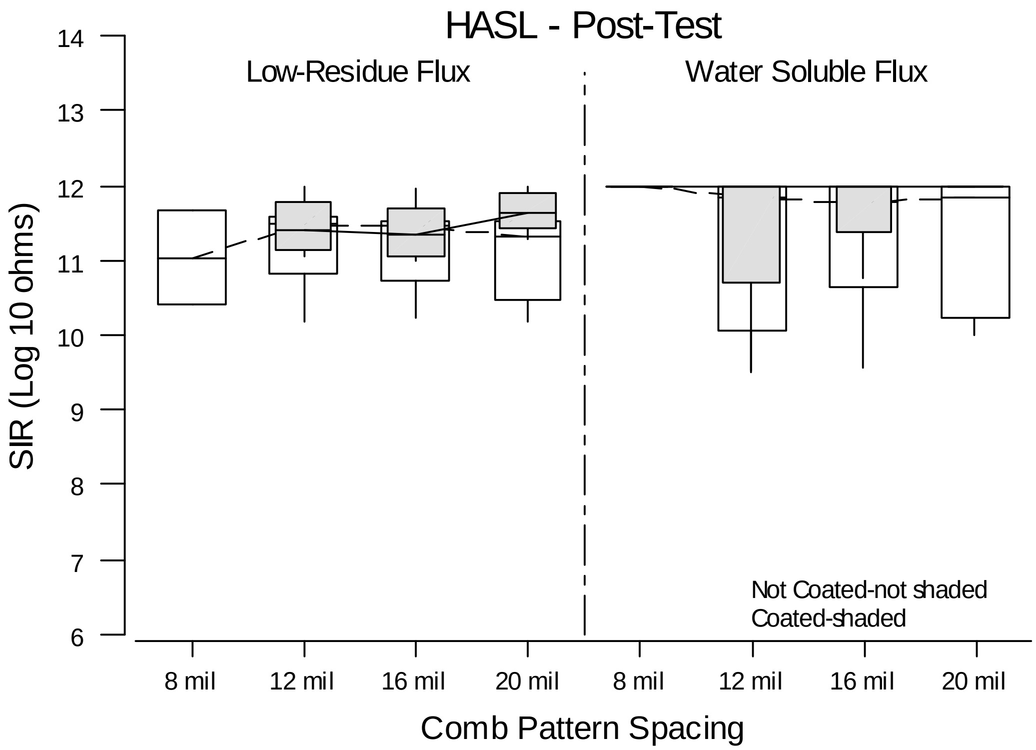

Figure 2.36 SIR Condensing Atmosphere Boxplots: HASL Post-Test versus Comb Pattern Spacing

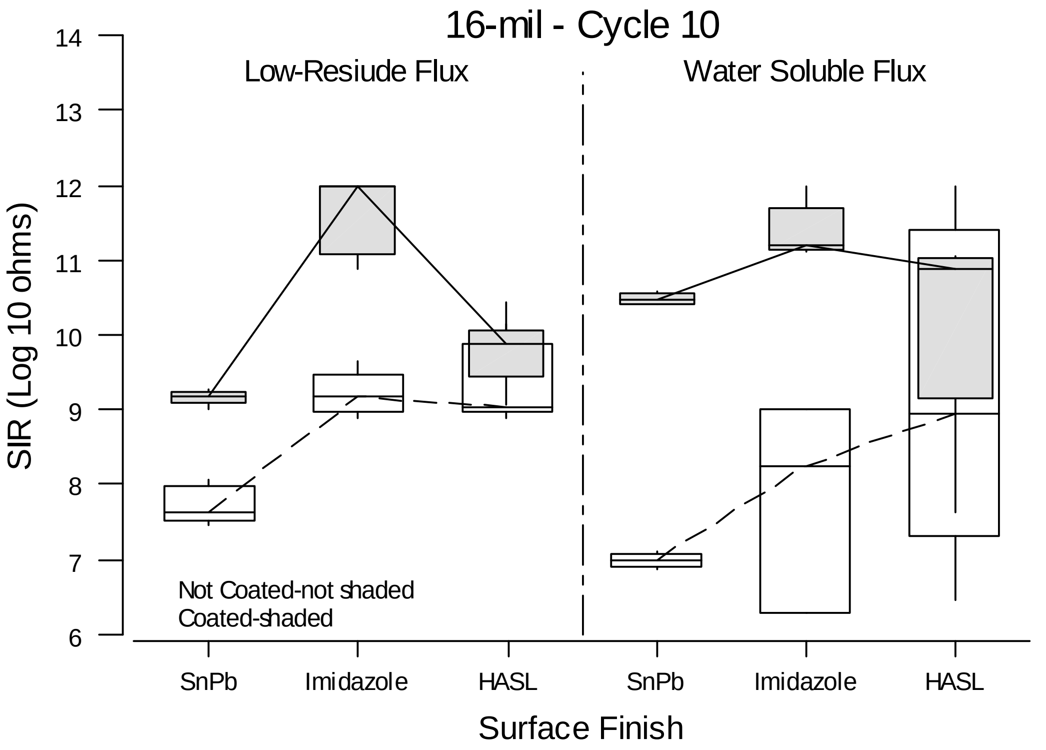

Figure 2.37 SIR Condensing Atmosphere Boxplots: Cycle 10 for 16-Mil versus Surface Finish

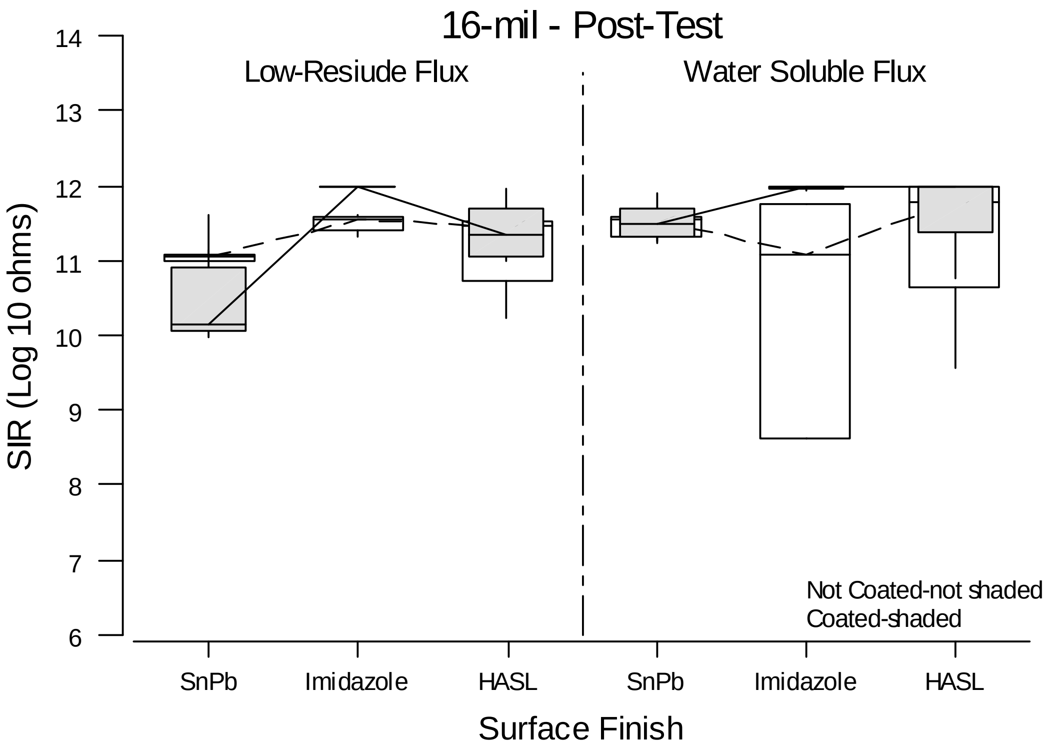

Figure 2.38 SIR Condensing Atmosphere Boxplots: Post-Test for 16-Mil versus Surface Finish

Since the GLM analyses for 8-mil spacing in Table 2.12 are missing two-thirds of the observations, the discussion of the GLM results will center on 12-, 16-, and 20-mil spacing. Figures 2.25 and 2.26 indicated coating was helpful for reflowed SnPb during test exposure, but did not help at post-test. This result is supported by the GLM analyses in Table 2.14. During test exposure, either Coating or SnPb*Coating was always significant — indicating a boost in SIR for reflowed SnPb boards with coating.

However, the post-test reading gives a different interpretation, as coating gives an increase of only 0.39 while SnPb*Coating gives a decrease of 1.30, for a net decrease of 0.91 for coating on reflowed SnPb surface finishes with LR flux. This result is illustrated in the boxplots on the left-hand side of Figure 2.32.

Figure 2.31 shows that coating clearly increases SIR during test exposure for reflowed SnPb, which is supported by the GLM analysis for Cycle 10 in Table 2.14. However, consider the three-way interaction of SnPb, Coating, and Flux in the post-test model for reflowed SnPb. This term has a positive coefficient of 1.09 in Table 2.14, indicating a boost in SIR when conformal coating is used with WS flux. The net effect for this processing combination is 0.39 (Coating) - 1.30 (SnPb*Coating) + 1.09 (Sn*Coating*Flux) = 0.18. However, this brings the performance of coated boards on SnPb with WS flux only up to the performance level of uncoated boards. This is illustrated in the boxplots on the right-hand side of Figure 2.32.

Coating significantly increases SIR for imidazole with both fluxes during test exposure as shown in Figure 2.33. This observation is supported by the GLM analysis for Cycle 10 in Table 2.14. The post-test model for imidazole with LR flux in Table 2.14 shows an increase of 0.39 for coating (see the boxplots on the left-hand side of Figure 2.34). Imidazole with WS flux and coating has a net effect of 0.39 (Coating) - 0.84 (Imidazole*Flux) + 1.11 (Imidazole*Coating *Flux) = 0.66. This effect can be seen on the right-hand side of Figure 2.34 for 16-mil. HASL with LR flux appears to have slightly higher SIR during test exposure as shown in Figure 2.35, but this is not a significant increase since there is no term for Coating in the GLM analyses in Table 2.14. HASL with WS has great variability for both coated and uncoated boards during test exposure. The post-test model for HASL with either flux has an increase of only 0.39 when using coating (see Figure 2.36).

Conformal Coating Versus No Conformal Coating. The predicted means from the GLMs given in Tables 2.16 to 2.19 agree well with the observed means given in Table 2.11. Coating produces higher SIR during test exposure (see Figures 2.25 to 2.30), but post-test predictions for coated and uncoated boards are very close to one another in almost all cases.

Table 2.20 is similar to Table 2.10 and contains t-test results for the condensing atmosphere test. These t-tests compare mean SIR for coated boards with mean SIR for uncoated boards for each combination of surface finish and flux for 16-mil spacing at Pre-Test, Cycle 1, Cycle 10, and Post-Test. Table 2.20 shows that reflowed SnPb and imidazole benefit from coating with either flux during test exposure, but this benefit does not carry over the Post-Test measurement. HASL shows no significant differences in mean SIR for coated and uncoated boards either during test exposure or at Post-Test. There are no significant decreases in mean SIR from using conformal coating, as was true in the 85/85 test environment.

2.16 Screening Experiment 3: SIR Testing for Fluids Exposure

The test matrix in Figure 2.1 specifies 120 boards for exposure to automotive fluids: 60 to Type 2 diesel fuel and 60 to Mil-Spec hydraulic fluid. This test provides an understanding of how the absence of coating affects electrical performance and electromigration of electronic assemblies that are exposed to typical automotive and military fluids. This effect was evaluated by measuring SIR on the modified IPC B-24 boards. The fluids test was conducted at CSL in Kokomo, IN. All SIR measurements were made at medium voltage (100V) and at room temperature conditions on all four test patterns. SIR was recorded before and after fluid exposure for all processing conditions specified in the test matrix. The fluids test used the following test protocol:

1. Visually inspect each board for shorts on patterns and flux residues. Photo document boards prior to exposure to fluids.
2. Separate 120 B-24 boards into two equal groups for diesel fuel and for hydraulic fluid exposure, with each group maintaining balance with respect to surface finish, flux type, and coating.
3. Measure/record initial SIR values on all patterns (test voltage of 100V for 1-*min* electrification on all patterns).
4. Stabilize fluids at room temperature. Dip patterns into fluid and soak for 10 *min*. Record fluid temperature and lab environment.

Table 2.12 GLM Results for SIR Condensing Atmosphere Tests with 8-Mil Spacing

Experimental Variables	Pre-Test	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 6	Cycle 7	Cycle 8	Cycle 9	Cycle 10	Post Test
Constant	9.99	7.32	9.44	9.72	9.72	9.88	9.42	9.92	9.91	9.53	11.32
SnPb	0.89		-1.96	-1.90	-1.88	-1.92	-1.75	-1.89	-1.90	-1.81	
Imidazole											
Conf. Coating											-1.03
Flux	2.01	3.52	1.59	1.39	1.34	1.28	1.34	1.26	1.26	1.34	
SnPb*Coating		1.62	1.86	1.73	1.68	1.61	1.57	1.56	1.56	1.53	
Imid*Coating											
SnPb*Flux	-1.13	-2.39									-0.52
Imidazole*Flu											
Coating*Flux											1.78
SnPb*Coat*Fl											
Imid*Coat*Flu											
Week 2											
Week 3			-0.91	-0.87	-0.85	-0.89		-0.89	-0.86		
Model R^2	53.8%	57.1%	74.9%	72.4%	72.0%	70.9%	63.3%	70.9%	70.8%	62.8%	70.7%
St. Dev.	0.54	1.19	0.93	0.91	0.89	0.90	0.95	0.89	0.89	0.96	0.39
Missing Obs. Out of 60	36	38	40	40	40	40	40	40	40	40	40

Table 2.13 GLM Results for SIR Condensing Atmosphere Tests with 12-Mil Spacing

Experimental Variables	Pre-Test	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 6	Cycle 7	Cycle 8	Cycle 9	Cycle 10	Post Test
Constant	11.92	7.96	8.57	9.14	8.83	9.34	9.54	9.53	9.55	9.58	11.30
SnPb	-1.17	-0.90	-1.33	-1.85	-1.28	-1.88	-2.08	-2.05	-2.09	-2.09	
Imidazole		1.95	1.02				-0.92	-0.96	-0.99	-0.99	
Conf. Coating		1.20	1.17		1.01						
Flux		1.17									
SnPb*Coating				1.84		1.54	1.55	1.54	1.56	1.56	-0.91
Imid*Coating				2.01		1.52	2.30	2.32	2.33	2.32	0.62
SnPb*Flux	1.08										
Imidazole*Flu		-3.47		-1.25	1.07						
Coating*Flux				0.93							
SnPb*Coat*Fl			1.96		1.76	1.30	1.28	1.28	1.26	1.22	1.03
Imid*Coat*Flu		2.39									
Model R^2	57.7%	59.1%	57.3%	59.4%	55.8%	56.4%	60.6%	59.2%	60.0%	60.9%	33.3%
St. Dev.	0.38	1.12	1.07	1.01	1.04	0.98	0.94	0.96	0.95	0.93	0.56
Missing Obs. Out of 60	1	5	5	5	5	6	6	6	6	6	6

Table 2.14 GLM Results for SIR Condensing Atmosphere Tests with 16-Mil Spacing

Experimental Variables	Pre-Test	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 6	Cycle 7	Cycle 8	Cycle 9	Cycle 10	Post Test
Constant	11.89	8.49	9.57	9.34	9.59	9.05	9.06	9.04	9.03	9.35	11.32
SnPb	-0.68	-1.41	-2.65	-2.16	-2.36	-1.44	-1.45	-1.42	-1.44	-1.95	
Imidazole		1.79									
Conf. Coating		1.22				1.13	1.17	1.15	1.16		0.39
Flux		0.80									
SnPb*Coating			1.92	2.04	1.85					1.89	-1.30
Imid*Coating			2.31	2.49	2.20	1.80	1.79	1.85	1.86	2.33	
SnPb*Flux											
Imidazole*Flu		-3.66	-2.04	-1.46	-1.95	-0.86	-0.90	-0.94	-0.97	-1.42	-0.84
Coating*Flux				1.16						1.06	
SnPb*Coat*Fl	0.78	1.39	1.75		1.46	1.77	1.73	1.75	1.74		1.09
Imid*Coat*Flu		3.12	1.76		1.77						1.11
Model R^2	32.4%	72.2%	75.1%	74.2%	72.8%	68.1%	71.0%	69.9%	70.7%	71.2%	38.9%
St. Dev.	0.45	1.00	0.93	0.88	0.91	0.94	0.89	0.91	0.90	0.87	0.57
Missing Obs. Out of 60	0	2	3	3	3	3	3	3	3	3	3

Table 2.15 GLM Results for SIR Condensing Atmosphere Tests with 20-Mil Spacing

Experimental Variables	Pre-Test	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 6	Cycle 7	Cycle 8	Cycle 9	Cycle 10	Post Test
Constant	11.96	8.25	9.23	9.26	9.30	9.25	9.30	9.29	9.32	9.34	11.40
SnPb	-0.88		-2.26	-2.06	-1.99	-1.87	-1.92	-1.84	-1.91	-1.88	
Imidazole		2.33									
Conf. Coating											0.48
Flux		1.54									
SnPb*Coating			2.03	1.88	1.80	1.72	1.76	1.67	1.73	1.69	-1.46
Imid*Coating			2.04	2.10	2.08	2.33	2.20	2.24	2.23	2.20	
SnPb*Flux	0.89	-2.72									
Imidazole*Flu		-4.77	-1.90	-1.78	-1.60	-2.00	-1.75	-1.91	-1.85	-1.79	-1.06
Coating*Flux			1.42	1.43	1.35	1.42	1.33	1.38	1.31	1.27	
SnPb*Coat*Fl		3.22									1.24
Imid*Coat*Flu		3.99									1.09
Model R^2	51.2%	66.8%	73.3%	72.2%	70.0%	69.6%	68.8%	68.7%	69.0%	67.5%	52.4%
St. Dev.	0.33	1.00	0.87	0.87	0.89	0.90	0.90	0.90	0.89	0.91	0.45
Missing Obs. Out of 60	1	4	5	5	6	7	7	7	7	7	7

Table 2.16 Predicted Means for SIR in a Condensing Atmosphere Environment from the GLM for 8-Mil Spacing

Flux	**Finish**	**Coating**	**Initial**	**Cycle 1**	**Cycle 10**	**Post-Test**
LR	**SnPb**	**No**	10.88	7.32	7.72	11.32
		Yes	10.88	8.95	9.25	10.29
	Imidazole	**No**	9.99	7.32	9.53	11.32
		Yes	9.99	7.32	9.53	10.29
	HASL	**No**	9.99	7.32	9.53	11.32
		Yes	9.99	7.32	9.53	10.29
WS	**SnPb**	**No**	11.76	8.45	9.07	10.80
		Yes	11.76	10.08	10.60	11.55
	Imidazole	**No**	12.00	10.84	10.88	11.32
		Yes	12.00	10.84	10.88	12.07
	HASL	**No**	12.00	10.84	10.88	11.32
		Yes	12.00	10.84	10.88	12.07

Table 2.17 Predicted Means for SIR in a Condensing Atmosphere Environment from the GLM for 12-Mil Spacing

			Test Time			
Flux	**Finish**	**Coating**	**Initial**	**Cycle 1**	**Cycle 10**	**Post-Test**
LR	**SnPb**	**No**	10.75	7.06	7.48	11.30
		Yes	10.75	8.26	9.05	10.39
	Imidazole	**No**	11.92	9.91	8.59	11.30
		Yes	11.92	11.12	10.91	11.92
	HASL	**No**	11.92	7.96	9.58	11.30
		Yes	11.92	9.17	9.58	11.30
WS	**SnPb**	**No**	11.83	8.23	7.48	11.30
		Yes	11.83	9.43	10.27	11.42
	Imidazole	**No**	11.92	7.62	8.59	11.30
		Yes	11.92	11.20	10.91	11.92
	HASL	**No**	11.92	9.13	9.58	11.30
		Yes	11.92	10.33	9.58	11.30

5. Remove board from fluid and allow to drip dry for 30 *min*. Wipe off any excess fluid with a lint free cloth.
6. Electrify, measure, and record SIR values on all patterns.
7. Repeat dipping of boards into fresh fluid and a 10 min. soak (Step 4).
8. Remove board from fluid and allow to drip dry for 30 *min*.
9. Wipe off any excess fluid with a lint free cloth.
10. Make SIR measurements on boards and record values.
11. Make visual observations on boards and photo document boards.

Table 2.18 Predicted Means for SIR in a Condensing Atmosphere Environment from the GLM for 16-Mil Spacing

			Test Time			
Flux	**Finish**	**Coating**	**Initial**	**Cycle 1**	**Cycle 10**	**Post-Test**
LR	**SnPb**	**No**	11.22	7.08	7.41	11.32
		Yes	11.22	8.30	9.29	10.41
	Imidazole	**No**	12.00	10.28	9.35	11.32
		Yes	11.89	11.50	11.68	11.71
	HASL	**No**	11.89	8.49	9.35	11.32
		Yes	11.89	9.71	9.35	11.71
WS	**SnPb**	**No**	11.22	7.88	7.41	11.32
		Yes	11.22	10.50	10.36	11.50
	Imidazole	**No**	11.89	7.41	7.93	10.48
		Yes	11.89	11.75	11.33	11.98
	HASL	**No**	11.89	9.29	9.35	11.32
		Yes	11.89	10.51	10.42	11.71

Table 2.19 Predicted Means for SIR in a Condensing Atmosphere Environment from the GLM for 20-Mil Spacing

			Test Time			
Flux	**Finish**	**Coating**	**Initial**	**Cycle 1**	**Cycle 10**	**Post-Test**
LR	**SnPb**	**No**	11.07	8.25	7.46	11.40
		Yes	11.07	8.25	9.15	10.43
	Imidazole	**No**	11.96	10.58	9.34	11.40
		Yes	11.96	10.58	11.54	11.88
	HASL	**No**	11.96	8.25	9.34	11.40
		Yes	11.96	8.25	9.34	11.88
WS	**SnPb**	**No**	11.97	7.07	7.46	11.40
		Yes	11.97	10.29	10.43	11.66
	Imidazole	**No**	11.96	7.35	7.55	10.48
		Yes	11.96	11.34	11.02	11.66
	HASL	**No**	11.96	9.79	9.34	11.40
		Yes	11.96	9.79	10.61	11.40

2.17 SIR Cell Means for Fluids Exposure

Tables 2.21 and 2.22 gives means for initial and post-test SIR measurements for each experimental cell (5 observations per cell) for diesel fuel and hydraulic fluid, respectively. Bridged boards have been eliminated and empty cells are denoted by an asterisk.

2.18 Boxplots for SIR Fluids Exposure Measurements

Boxplots are used in Figures 2.39 to 2.52 to show selected effects of the experimental factors used in the SIR fluids exposure testing: surface finish, flux, pattern spacing, coating, and fluid type. Each boxplot represents five observations for one experimental cell (unless data are missing).

Table 2.20 Two Sample t-Test Comparisons of Mean SIR for Coated versus Uncoated Boards for Each Combination of Experimental Factors in the Condensing Atmosphere Test for 16-Mils (positive values denote the magnitude of significant increases in mean SIR with coating, 0 denotes no difference, negative values denote the magnitude of significant decreases in mean SIR with coating)

	Flux	Initial	Cycle 1	Cycle 10	Post-Test
SnPb	**LR**	0	1.2	1.4	0
	WS	0	3.0	3.5	0
Imidazole	**LR**	0	1.9	2.4	0
	WS	0	4.3	3.5	0
HASL	**LR**	0	0	0	0
	WS	0	0	0	0

SIR Versus Test Time. Figures 2.39 to 2.44 display SIR measurements on the 16-mil comb pattern versus test time for each surface finish and flux combination. Two points are immediately obvious form these figures: (1) diesel fuel has little or no effect on SIR for either coated or uncoated boards and (2) hydraulic fluid has a disastrous effect on both coated and uncoated boards. In regard to point (2), coating clearly gives significantly higher SIR on boards exposed to hydraulic fluid, but SIR values are marginal — just above the minimum acceptable level of 8 log 10 ohms.

Reflowed SnPb, imidazole, and HASL surface finishes all had acceptable levels of SIR in diesel fuel with both fluxes. Coated and uncoated boards had approximately the same level of SIR in diesel fuel for each surface finish and flux combination, with coated boards gaining a slight increase for imidazole and HASL with LR flux. All surface finish and flux combinations are adversely affected by hydraulic fluid (even on the first dip) for both coated and uncoated boards.

SIR Versus Comb Pattern Spacing. Figures 2.45 to 2.50 show SIR plotted against spacing on the comb pattern. Coated and uncoated boards processed with WS flux appear to give approximately the same level of SIR for each spacing with diesel fuel. Coated boards have 2 to 3 log 10 ohms higher SIR for both fluxes in hydraulic fluid and are invariant to spacings. Lines connecting the medians of the boxplots for diesel fuel with LR flux indicate there may be a slight decrease in SIR as spacing increases for all three surface finishes. Spacing was not a factor with either the SIR 85/85 or condensing atmosphere tests.

SIR Versus Surface Finish. Figures 2.51 and 2.52 show SIR versus surface finish by flux type for the post-test measurement on 16-mil spacing. All three surface finishes have approximately the same SIR level in both fluids for a given flux. Coating gives a slight increase in SIR for imidazole and HASL with LR flux in diesel fuel. WS flux gives a slight boost in SIR for boards with a SnPb finish in hydraulic fluid, but the level of SIR is still unacceptable.

Other Displays. Appendix C contains 24 displays similar to Figures 2.39 to 2.44; 18 displays with SIR results plotted against comb pattern spacing, as shown in Figures 2.45 to 2.50; and 24 displays with SIR results plotted against surface finish spacing, as in Figures 2.51 and 2.52. The reader is encouraged to study the different comparisons in these displays.

2.19 General Linear Model Results for SIR Fluids Test

The following GLM was used to analyze the SIR fluids test results:

$$Y = \beta_0 + \beta_1 D_1 + \beta_2 D_2 + \beta_3 D_3 + \beta_4 D_4 + \beta_5 D_1 D_3 + \beta_6 D_1 D_4 + \beta_7 D_2 D_3 + \beta_8 D_2 D_4 + \beta_9 D_1 D_3 D_4 + \beta_{10} D_2 D_3 D_4 \tag{2.5}$$

D_1 = 0 if surface finish is not reflowed SnPb
= 1 if surface finish is reflowed SnPb
D_2 = 0 if surface finish is not imidazole
= 1 if surface finish is imidazole
D_3 = 0 if board is not conformally coated
= 1 if board is conformally coated
D_4 = 0 if flux is not water soluble with halide
= 1 if flux is water soluble with halide

The base case for this GLM is HASL with LR flux and no coating. Tables 2.23 to 2.26 contain results for GLM analyses of SIR tests for 8-, 12-, 16-, and 20-mil

Table 2.21 SIR Means for Diesel Fuel Exposure (bridged boards eliminated)

				Initial SIR				Post-Test SIR			
Surface	**Coating**	**Flux**	**n**	**8**	**12**	**16**	**20**	**8**	**12**	**16**	**20**
SnPb	**No**	**LR**	5	12.29	12.36	12.53	11.94	12.76	12.41	11.49	11.10
		WS	5	12.47	13.47	12.66	12.25	12.48	12.78	12.59	12.20
	Yes	**LR**	5	12.50	12.07	11.87	11.32	12.59	12.49	12.02	11.73
		WS	5	12.51	12.71	12.62	12.20	12.49	13.20	12.62	11.94
Imid	**No**	**LR**	5	*	12.85	12.79	12.18	*	12.50	11.55	11.56
		WS	5	12.59	12.26	12.27	12.23	12.34	12.67	12.62	12.04
	Yes	**LR**	5	*	12.54	13.05	12.10	*	12.74	12.51	12.06
		WS	5	12.23	12.44	12.68	12.10	12.22	12.08	12.44	12.03
HASL	**No**	**LR**	5	12.45	12.14	12.69	11.87	13.05	12.28	11.27	11.05
		WS	5	*	13.11	12.90	11.93	*	12.60	12.77	12.06
	Yes	**LR**	5	*	12.19	12.98	10.83	*	12.64	12.47	10.71
		WS	5	*	13.12	12.62	12.32	*	12.96	12.73	12.08

Table 2.22 SIR Means for Hydraulic Fluid Exposure (bridged boards eliminated)

				Initial SIR				Post-Test SIR			
Surface	**Coating**	**Flux**	**n**	**8**	**12**	**16**	**20**	**8**	**12**	**16**	**20**
SnPb	**No**	**LR**	5	11.77	12.67	11.99	12.17	6.19	6.49	6.29	6.28
		WS	5	12.84	12.65	12.84	13.07	6.65	6.54	7.10	7.13
	Yes	**LR**	5	10.64	11.57	11.04	11.23	8.91	9.30	8.50	8.45
		WS	5	12.88	12.88	13.33	12.85	9.22	9.22	8.71	8.73
Imid	**No**	**LR**	5	10.73	12.75	12.88	12.92	6.05	6.09	6.05	6.11
		WS	5	*	12.25	13.41	13.11	*	6.31	6.15	6.22
	Yes	**LR**	5	*	12.30	13.21	12.82	*	9.20	9.01	9.05
		WS	5	13.03	12.25	12.79	13.11	6.92	8.48	8.98	9.46
HASL	**No**	**LR**	5	12.19	12.31	12.89	12.47	6.03	6.91	6.03	6.08
		WS	5	*	12.23	13.01	13.11	*	6.94	6.10	6.15
	Yes	**LR**	5	*	12.43	12.51	12.26	*	8.95	8.64	8.53
		WS	5	*	12.19	13.03	12.82	*	8.83	8.63	8.50

comb patterns, respectively. Each table contains results for both diesel fuel and hydraulic fluid. The last row in each table shows the number of missing and/or omitted observations (mostly with 8-mil spacing).

Models for Pre-Test with diesel fuel are all quite poor (the 8-mil model in Table 2.23 has no significant variables). Pre-Test models for hydraulic fluid at 8- and 12-mil are also poor, while models at 16- and 20-mil are good. These models should agree, as nothing has been done to the boards at this point.

Models for 12-, 16-, and 20-mil at 1st dip with diesel fuel all select several significant variables and have corresponding high R^2 values. On the other hand, diesel fuel models at 2nd dip (post-test) have low R^2 values similar to Pre-Test models.

The last two sets of boxplots on the right-hand side of Figures 2.39 to 2.44 show nearly constant responses for coated boards and uncoated boards at the 1st and 2nd dips in hydraulic fluid, with the SIR of coated boards being approximately 2.5 orders of magnitude higher. The models for 1st and 2nd dips in hydraulic fluid reflect this phenomenon by identifying conformal coating variables plus variables accounting for variation in SIR for reflowed SnPb with WS flux.

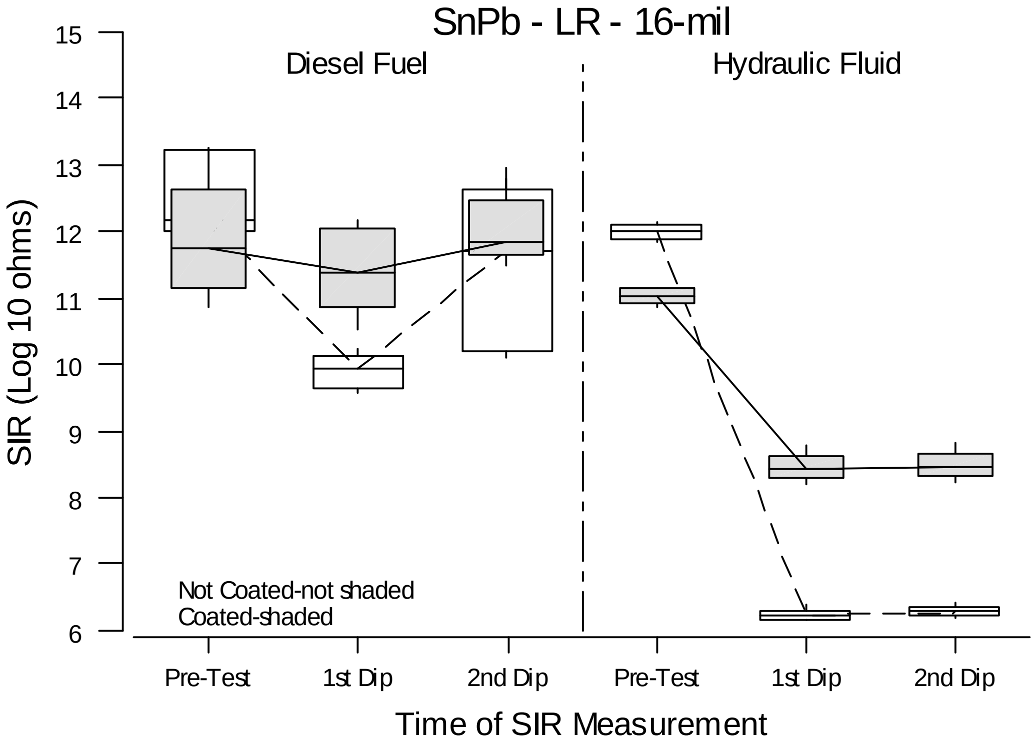

Figure 2.39 SIR Fluids Test Boxplots: SnPb, LR, 16-Mil versus Time of Test

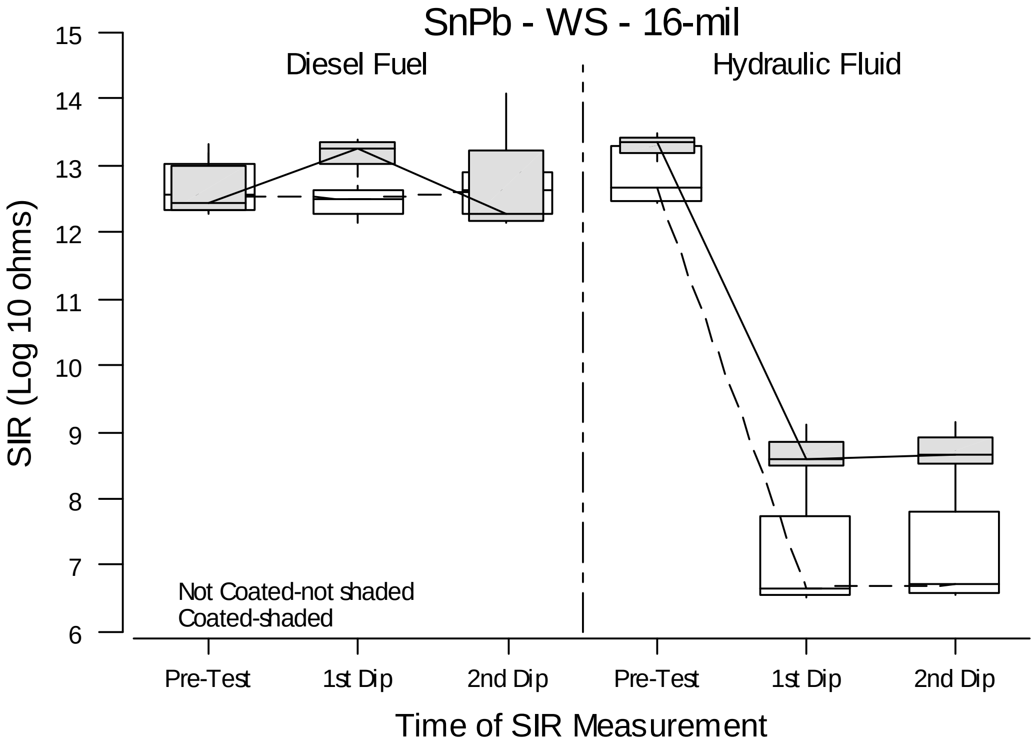

Figure 2.40 SIR Fluids Test Boxplots: SnPb, WS, 16-Mil versus Time of Test

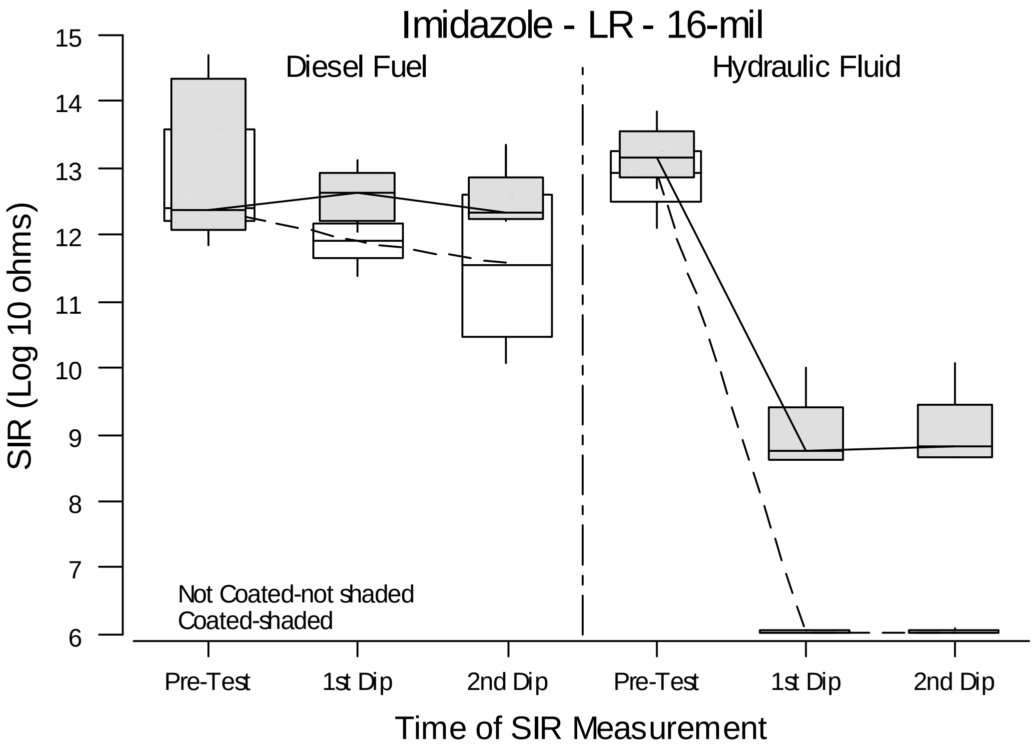

Figure 2.41 SIR Fluids Test Boxplots: Imidazole, LR, 16-Mil versus Time of Test

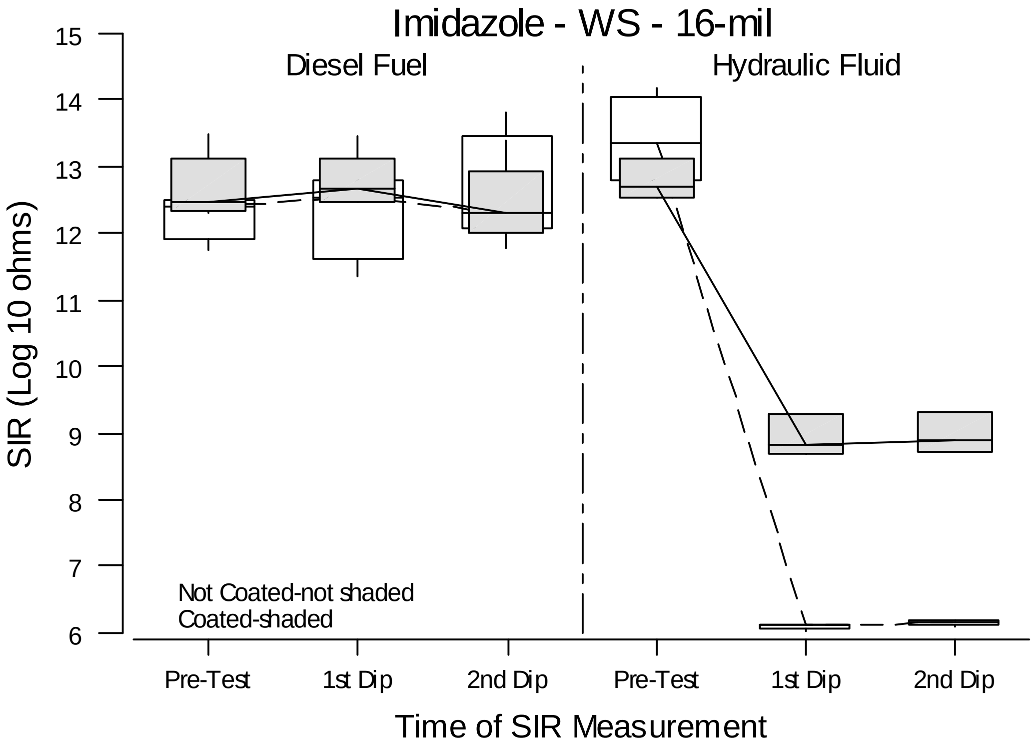

Figure 2.42 SIR Fluids Test Boxplots: Imidazole, WS, 16-Mil versus Time of Test

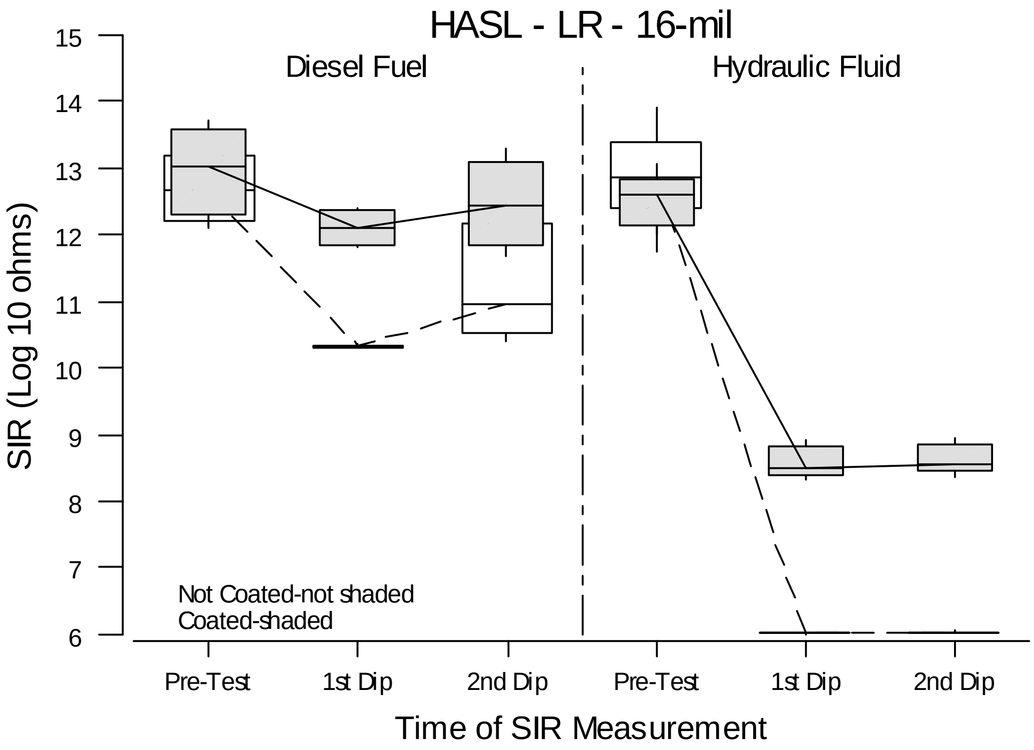

Figure 2.43 SIR Fluids Test Boxplots: HASL, LR, 16-Mil versus Time of Test

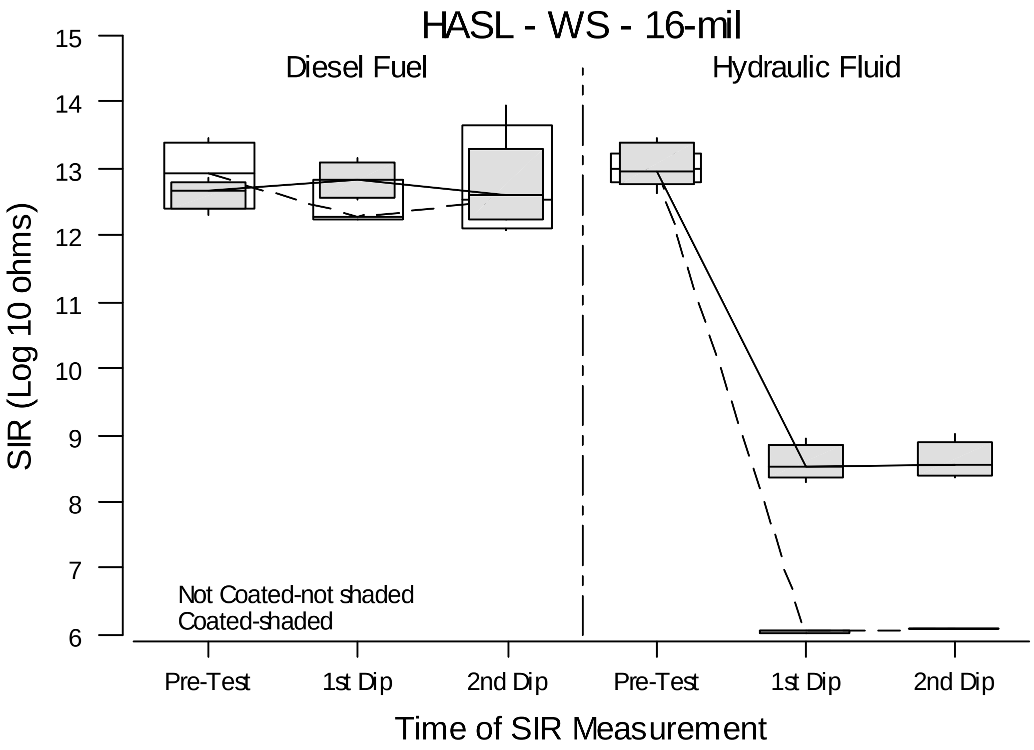

Figure 2.44 SIR Fluids Test Boxplots: HASL, WS, 16-Mil versus Time of Test

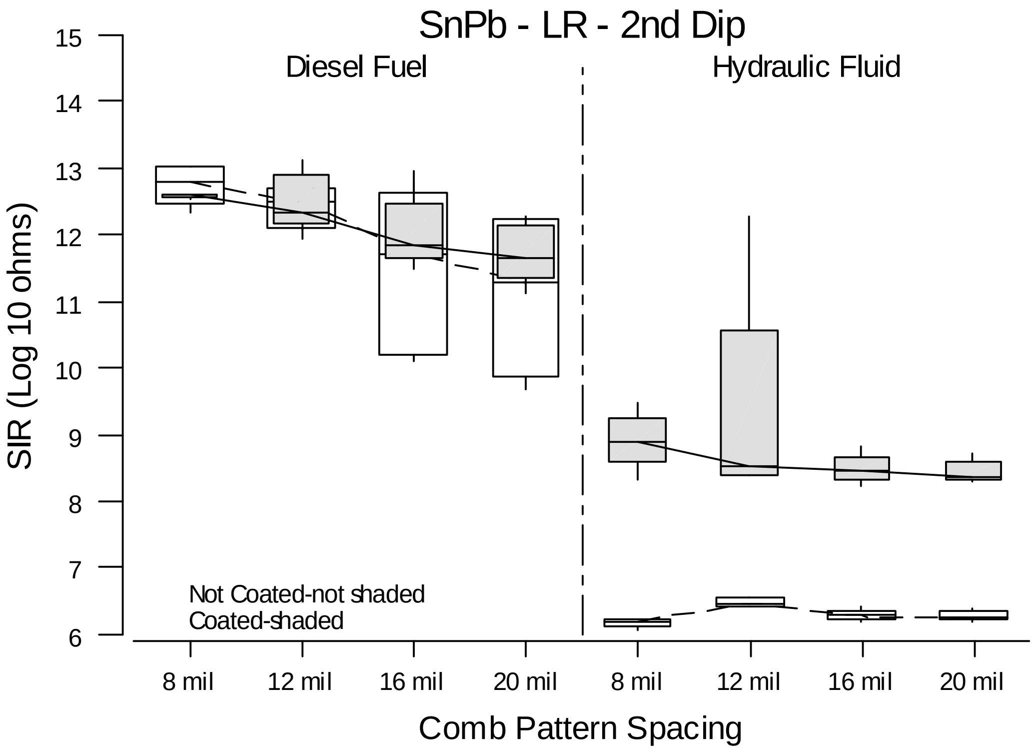

Figure 2.45 SIR Fluids Test Boxplots: SnPb, LR, Post-Test Measurement versus Comb Pattern Spacing

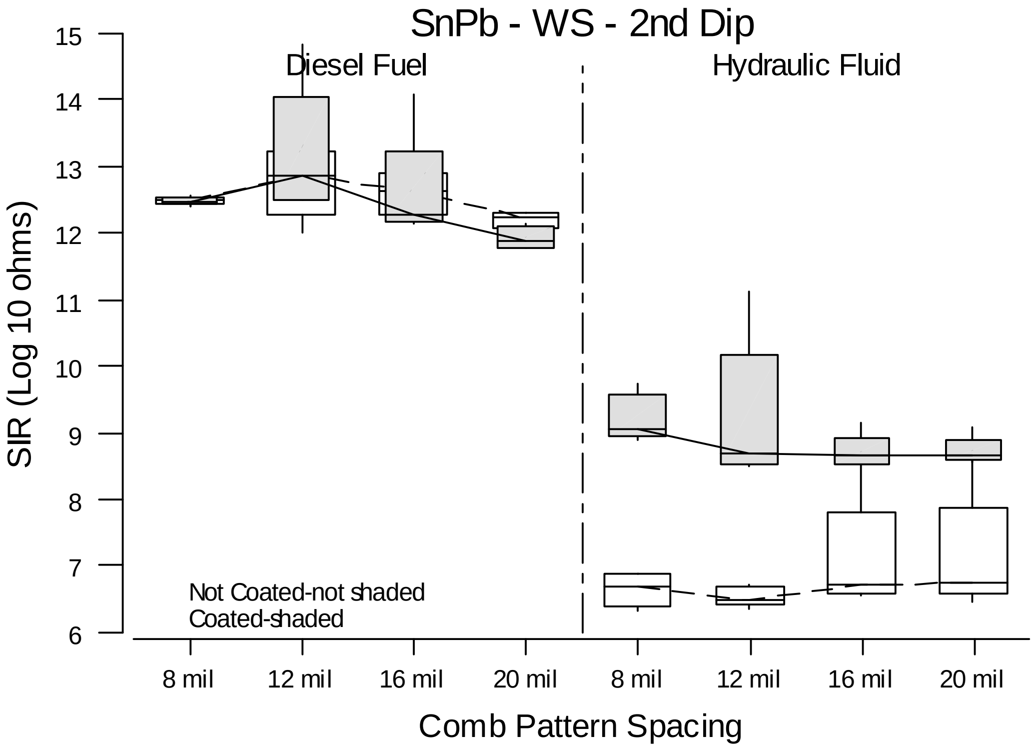

Figure 2.46 SIR Fluids Test Boxplots: SnPb, WS, Post-Test Measurement versus Comb Pattern Spacing

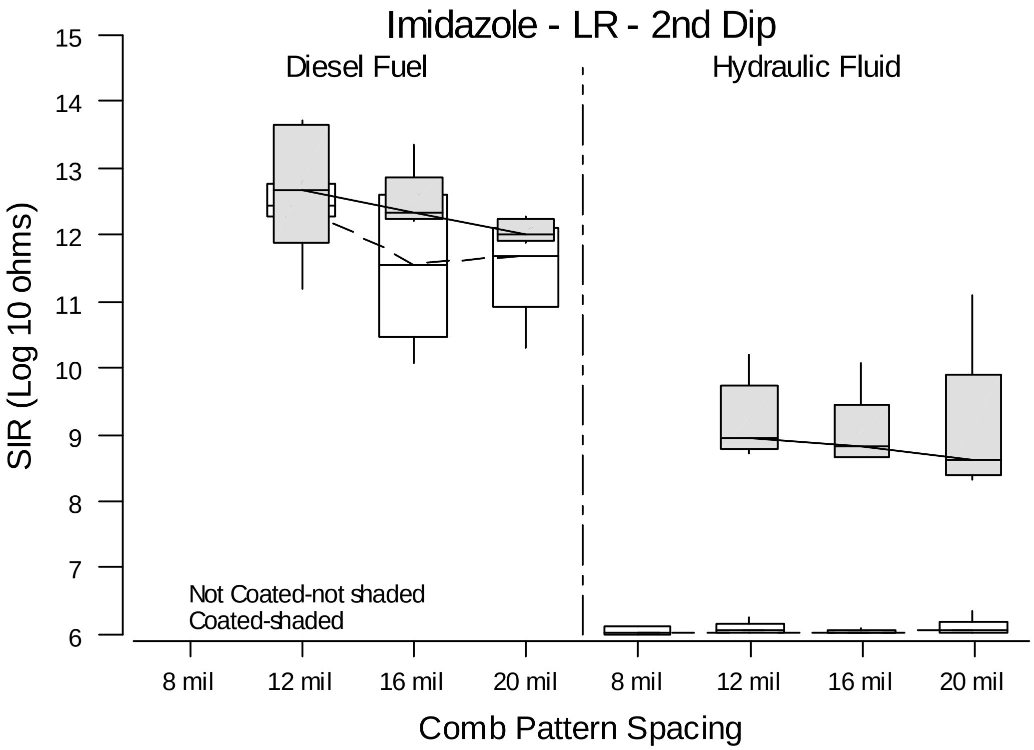

Figure 2.47 SIR Fluids Test Boxplots: Imidazole, LR, Post-Test Measurement versus Comb Pattern Spacing

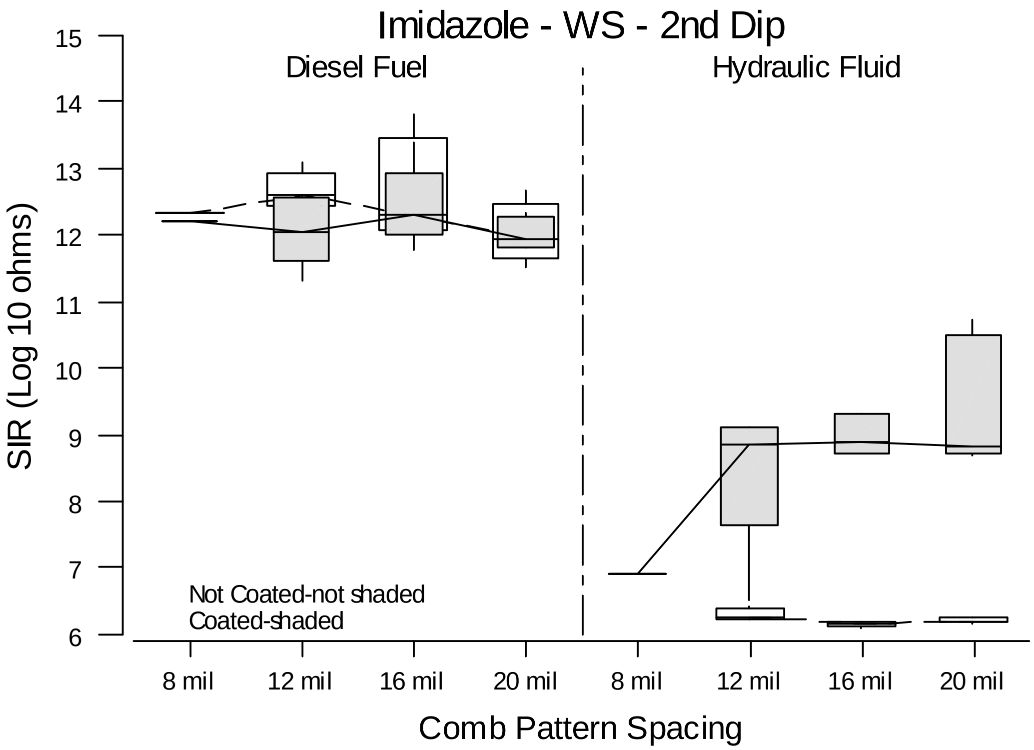

Figure 2.48 SIR Fluids Test Boxplots: Imidazole, LR, Post-Test Measurement versus Comb Pattern Spacing

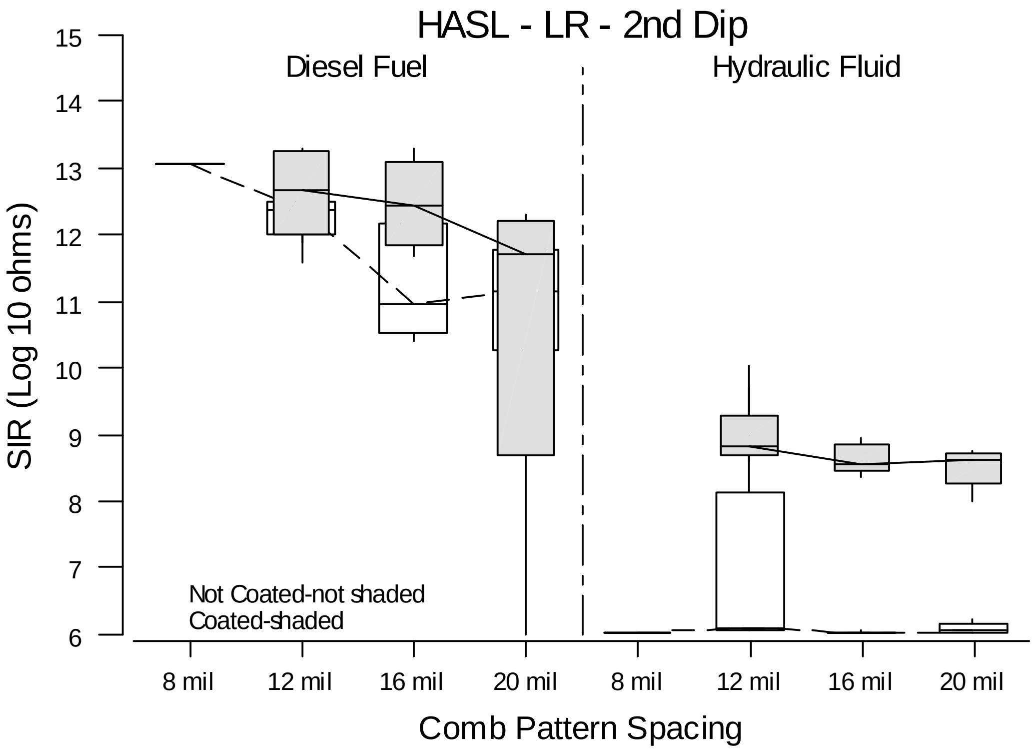

Figure 2.49 SIR Fluids Test Boxplots: HASL, LR, Post-Test Measurement versus Comb Pattern Spacing

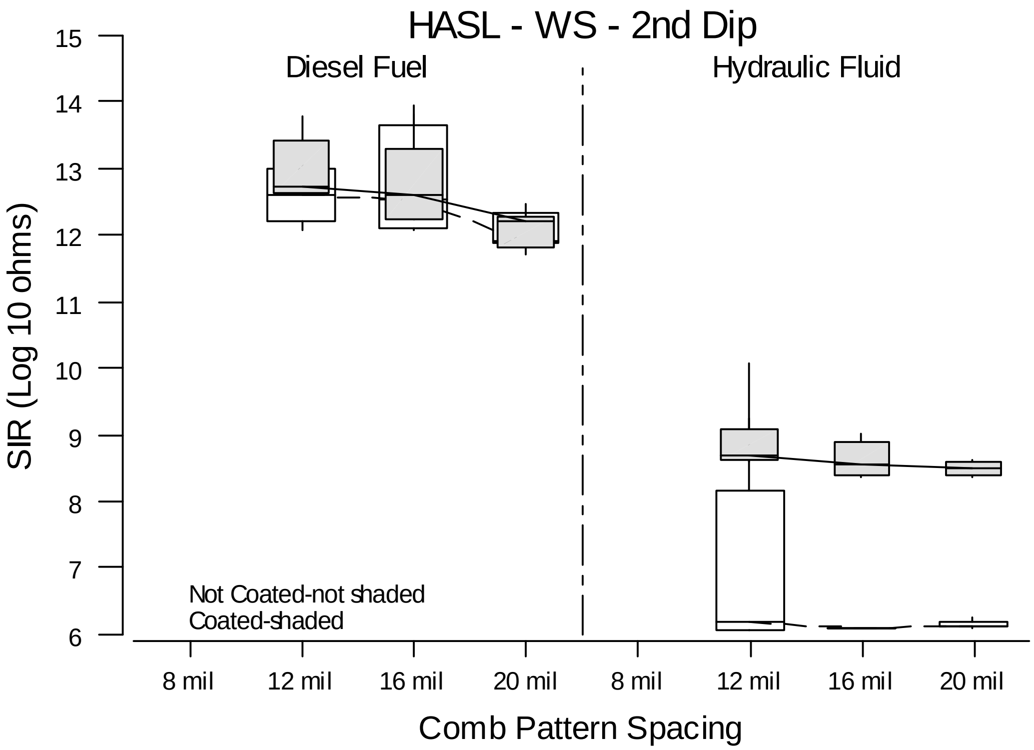

Figure 2.50 SIR Fluids Test Boxplots: HASL, WS, Post-Test Measurement versus Comb Pattern Spacing

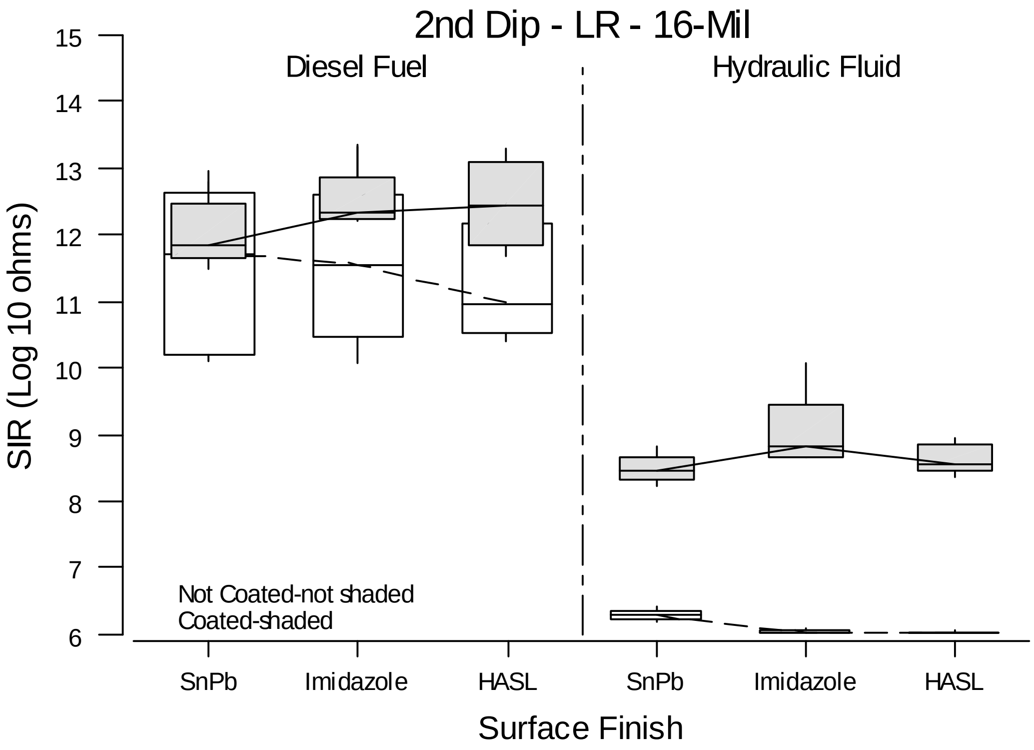

Figure 2.51 SIR Fluids Test Boxplots: HASL, LR, Post-Test Measurement versus Comb Pattern Spacing

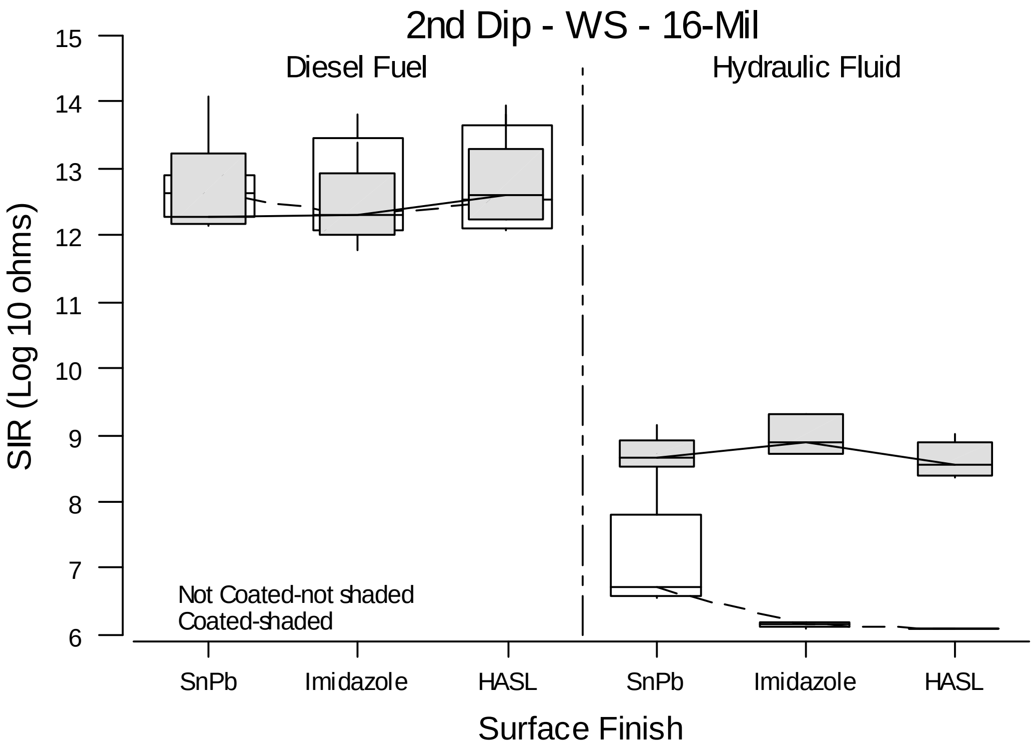

Figure 2.52 SIR Fluids Test Boxplots: HASL, LR, Post-Test Measurement versus Comb Pattern Spacing

Conformal Coating Versus No Conformal Coating. Predicted means for the models after the 2nd dip in fluids are given in Table 2.27. These predictions show conformal coating does not have much effect on SIR for boards subjected to diesel fuel, as very acceptable levels of SIR are projected for every experimental combination. On the other hand, exposure to hydraulic fluid has a serious affect on SIR for coated and uncoated boards. The average predicted mean at 16 mils in Table 2.27 for coated boards is 8.75 log 10 ohms, and for uncoated boards, is 6.28. As noted earlier, the minimum acceptable level for SIR is 8 log 10 ohms.

2.20 Summary of Conformal Coating Screening Experiments

Screening experiments were conducted to evaluate the need for conformal coating in three different environments: (1) 1 week exposure to 85°*C* / 85% RH, (2) 10 cycles of 6.5 *hr* each in a condensing atmosphere, and (3) exposure to diesel fuel and hydraulic fluid. SIR was measured on a modified IPC-B-24 board. Boxplots were used to display the SIR measurements and GLM analyses were performed on each data set to identify the statistically significant experimental factors.

Composite Graphs. Figures 2.53 to 2.56 show composite graphs comparing SIR performance of coated and uncoated boards in all three test environments used in the screening tests. SIR for the 16-mil spacing is plotted against surface finish in these composite graphs for each flux. Figures 2.53 and 2.54 present results during test exposure at: 168 *hr* for the 85°*C* / 85% RH test, Cycle 10 for the condensing atmosphere test, and after the first dip for the fluids exposure test. Figures 2.55 and 2.56 present post-test SIR measurements.

Coating Versus No Coating. The boxplots in Figures 2.53 to 2.56 are supplemented with statistical analyses comparing the mean SIR for conformally coated boards with mean SIR for uncoated boards for each combination of experimental factors. Two-sample t-tests were used to determine if the respective population means were significantly different at a 5% level of significance. Table 2.28 contains t-test results for each pair of boxplots in Figures 2.53 to 2.56 (16-mil spacing only) and also for 8-, 12-, and 20-mil spacings. As with Tables 2.10 and 2.20, the symbols in the body of Table 2.28 have the following interpretations: positive entries denote a significant increase in mean SIR when conformal coating is used; “0” denotes no significant difference in mean SIR for coated and uncoated boards, and negative entries denote a significant decrease in mean SIR when coating is used.

A brief summary of the test results is now given for each of the environmental conditions.

85/85 Test. A comparison of the 85/85 results in Figures 2.53 and 2.54 with their respective counterparts in Figures 2.55 and 2.56 shows lower SIR during test exposure, which is to be expected. Reflowed SnPb with either LR or WS flux has significantly lower mean SIR with conformal coating during test exposure and at post 24 *hr*. The t-test results in Table 2.28 show significant decreases in mean SIR from using coating with reflowed SnPb both during test exposure and at post 24 *hr*.

Coated and uncoated imidazole boards with LR flux give almost identical results during test exposure and at post 24 *hr* test. The same is true of imidazole with WS flux during test exposure, but coating and WS flux give significantly lower SIR at post 24 *hr*. The t-test results in Table 2.28 show no benefits from using coating with imidazole either during test exposure or at post 24 *hr* and a significant decrease in mean SIR at post 24 *hr* test with WS flux when coating is used.

HASL boards have increased mean SIR when coating is used with LR flux either during test exposure or at post test. However, as shown in Table 2.28, coating with WS flux does not change mean SIR during exposure and post-test mean SIR is significantly lower with WS flux and coating. Thus, all three surface finishes had significantly lower mean SIR at post 24 *hr* when soldered with WS flux.

Three different test voltages were used in the 85/85 experiment. Overall, voltage had no noticeable affect on SIR and comb pattern spacing did not appear to be an issue other than some bridging problems on 8-mil imidazole and HASL processed boards due to the application of too much solder paste combined with solder mask. In addition, exposed copper on the vertical edge of pads or circuit lines did not have a negative effect on SIR.

Condensing Atmosphere Test. The third column in Table 2.28 shows that reflowed SnPb benefits greatly from coating during test exposure with either flux. This is a noticeable change for reflowed SnPb from the 85/85 test where coating significantly lowered mean SIR. However, reflowed SnPb boards do not benefit from coating at post-test. Imidazole boards benefit from

Table 2.23 GLM Results for Fluids Tests with 8-Mil Spacing

	Diesel Fuel			Hydraulic Fluid		
Experimental Variables	**Pre-Test**	**1st Dip**	**2nd Dip**	**Pre-Test**	**1st Dip**	**2nd Dip**
Constant		10.07	12.71	11.18	6.14	6.17
SnPb						
Imidazole						
Conformal. Coating		1.02				
Flux		2.45	-0.26	1.70	0.45	0.46
SnPb*Coating					2.26	2.67
Imid*Coating						
SnPb*Flux						
Imidazole*Flux						
Coating*Flux		-1.01				
SnPb*Coat*Flux						
Imidazole*Coat*Flux						
Model R^2		93.7%	37.5%	29.9%	96.9%	96.5%
St. Dev.		0.30	0.18	1.34	0.27	0.28
Missing Observations Out of 60	37	37	37	36	36	36

Table 2.24 GLM Results for Fluids Tests with 12-Mil Spacing

	Diesel Fuel			Hydraulic Fluid		
Experimental Variables	**Pre-Test**	**1st Dip**	**2nd Dip**	**Pre-Test**	**1st Dip**	**2nd Dip**
Constant	12.36	10.90	12.36	12.34	6.50	6.55
SnPb		-0.57		0.32		
Imidazole		1.90				
Conformal. Coating		1.55	0.30		2.45	2.45
Flux	0.74	1.48	0.36			
SnPb*Coating				-1.08		
Imid*Coating		-1.67				
SnPb*Flux		1.30				
Imidazole*Flux	-0.75	-1.88				
Coating*Flux		-1.65				
SnPb*Coat*Flux				1.31		
Imidazole*Coat*Flux		1.79	-0.94			
Model R^2	17.1%	81.1%	20.7%	37.5%	62.8%	62.9%
St. Dev.	0.79	0.42	0.54	0.40	0.96	0.96
Missing Observations Out of 60	0	0	0	0	0	0

Table 2.25 GLM Results for Fluids Tests with 16-Mil Spacing

	Diesel Fuel			Hydraulic Fluid		
Experimental Variables	**Pre-Test**	**1st Dip**	**2nd Dip**	**Pre-Test**	**1st Dip**	**2nd Dip**
Constant	12.72	10.45	11.44	12.95	6.09	6.12
SnPb		-0.54		-1.13		
Imidazole		1.32				
Conformal. Coating		1.51	0.89	-0.61	2.45	2.46
Flux		1.82	1.22			
SnPb*Coating	-0.47					
Imid*Coating		-0.57		0.87	0.41	0.41
SnPb*Flux		0.75		1.14	0.96	0.98
Imidazole*Flux		-1.11		0.46		
Coating*Flux		-0.80	-0.94	0.85		
SnPb*Coat*Flux					-0.83	-0.85
Imidazole*Coat*Flux				-1.73		
Model R^2	7.4%	88.4%	31.9%	72.8%	93.2%	93.3%
St. Dev.	0.65	0.39	0.75	0.42	0.35	0.35
Missing Observations Out of 60	3	3	3	3	3	3

Table 2.26 GLM Results for Fluids Tests with 20-Mil Spacing

	Diesel Fuel			Hydraulic Fluid		
Experimental Variables	**Pre-Test**	**1st Dip**	**2nd Dip**	**Pre-Test**	**1st Dip**	**2nd Dip**
Constant	12.10	10.58	11.37	12.30	6.19	6.17
SnPb		-0.42				
Imidazole		0.89		0.57		
Conformal. Coating	-0.65	1.45			2.17	2.32
Flux		2.18	0.69	0.70		
SnPb*Coating				-1.07		
Imid*Coating		-0.35			0.85	0.76
SnPb*Flux					0.61	0.96
Imidazole*Flux		-1.11		-0.46		
Coating*Flux	0.79	-0.97				
SnPb*Coat*Flux				0.92		-0.73
Imidazole*Coat*Flux						
Model R^2	12.1%	90.4%	12.9%	70.0%	86.3%	87.1%
St. Dev.	0.85	0.32	0.91	0.36	0.52	0.51
Missing Observations Out of 60	0	0	0	0	0	0

Table 2.27 Predicted Means from the GLM Analyses for SIR after 2nd Dip in Fluid

				Diesel Fuel				Hydraulic Fluid			
Surface	**Coating**	**Flux**	**n**	**8**	**12**	**16**	**20**	**8**	**12**	**16**	**20**
SnPb	**No**	**LR**	5	12.71	12.36	11.44	11.37	6.17	6.55	6.12	6.17
		WS	5	12.45	12.72	12.65	12.06	6.63	6.55	7.10	7.13
	Yes	**LR**	5	12.71	12.66	12.32	11.37	8.84	9.00	8.59	8.49
		WS	5	12.45	13.02	12.60	12.06	9.30	9.00	8.71	8.73
Imid	**No**	**LR**	5	12.71	12.36	11.44	11.37	6.17	6.55	6.12	6.17
		WS	5	12.45	12.72	12.65	12.06	6.63	6.55	6.12	6.17
	Yes	**LR**	5	12.71	12.66	12.32	11.37	6.17	9.00	9.00	9.25
		WS	5	12.45	12.08	12.60	12.06	6.63	9.00	9.00	9.25
HASL	**No**	**LR**	5	12.71	12.36	11.44	11.37	6.17	6.55	6.12	6.17
		WS	5	12.45	12.72	12.65	12.06	6.63	6.55	6.12	6.17
	Yes	**LR**	5	12.71	12.66	12.32	11.37	6.17	9.00	8.59	8.49
		WS	5	12.45	13.02	12.60	12.06	6.63	9.00	8.59	8.49

coating with either flux during test exposure but not at post-test. Mean SIR for coated HASL boards does not differ from mean SIR for uncoated boards either during test exposure or at post-test.

Fluids Test. The boxplots for diesel fuel and hydraulic fluid in Figures 2.53 and 2.54 represent SIR after the 1st dip. These graphs are similar to their respective counterparts in Figures 2.55 and 2.56 for SIR after the 2nd dip. As shown in Table 2.28, several combinations of experimental factors have a significant increase in mean SIR after the 1st dip in diesel when coating is used. However, there is not a single increase in mean SIR noted after the 2nd (post-test) in diesel fuel.

The preponderance of positive numbers in the last two columns of Table 2.28 underscores the value of coating in providing a significant increase in mean SIR for all boards dipped in hydraulic fluid. However, as mentioned previously, mean SIR in the hydraulic fluid test for coated boards was just above the minimum acceptable level of 8 log 10 ohms.

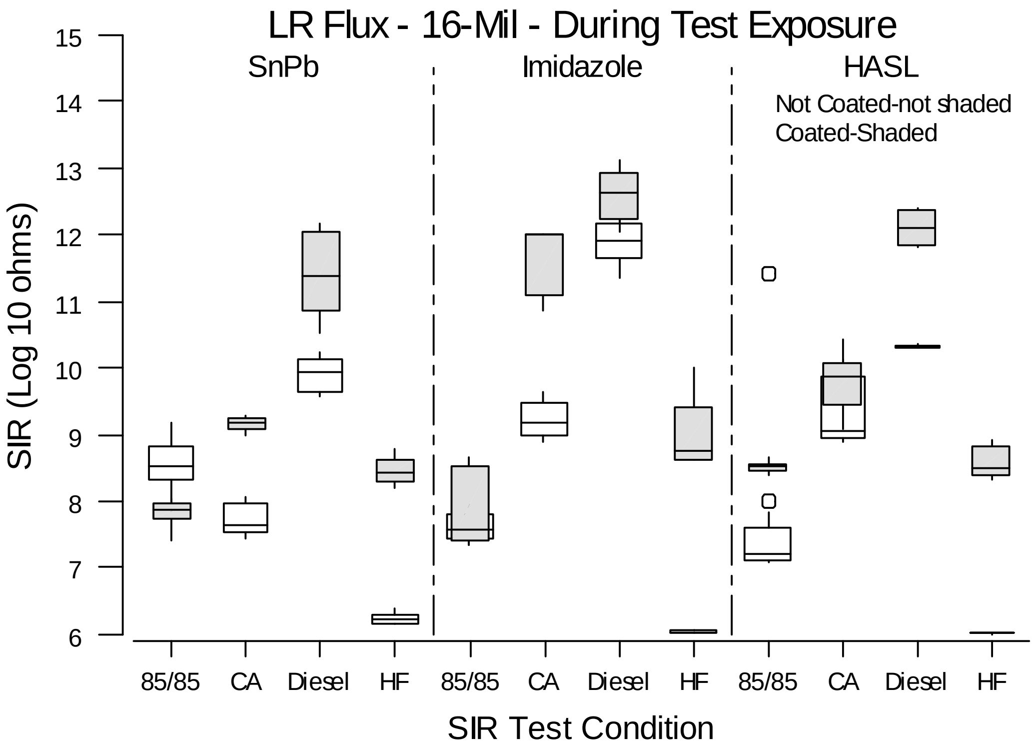

Figure 2.53 A Comparison of SIR Measurements During Test Exposure for Three Conformal Coating Screening Experiments by Surface Finish for 16-Mil Spacing and LR Flux

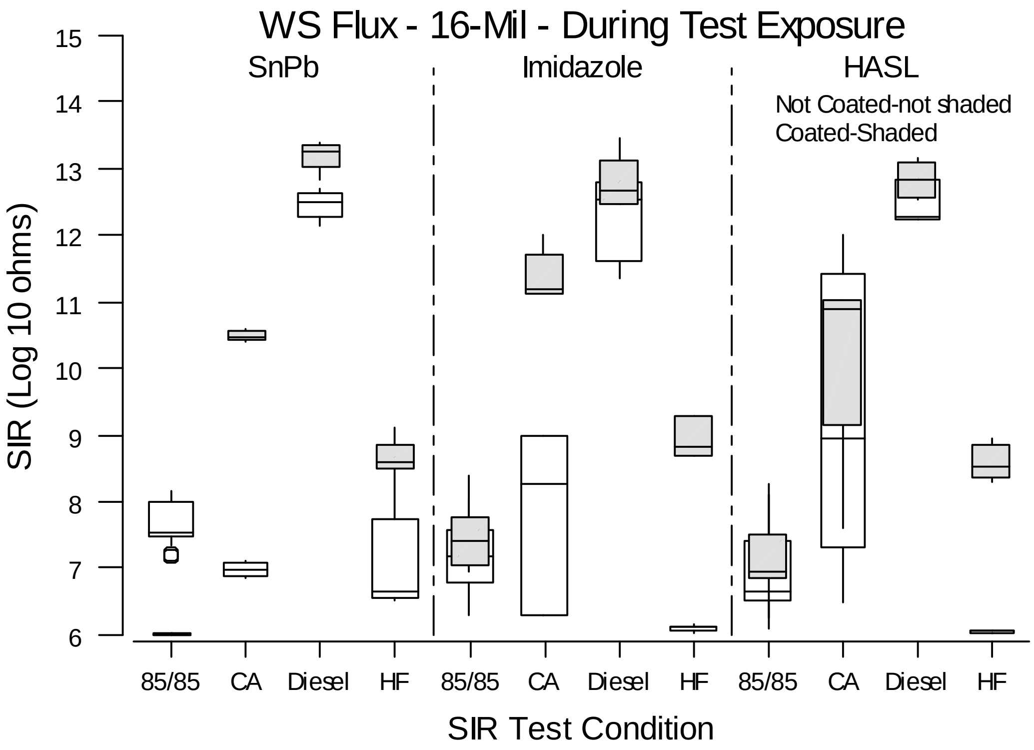

Figure 2.54 A Comparison of SIR Measurements During Test Exposure for Three Conformal Coating Screening Experiments by Surface Finish for 16-Mil Spacing and WS Flux

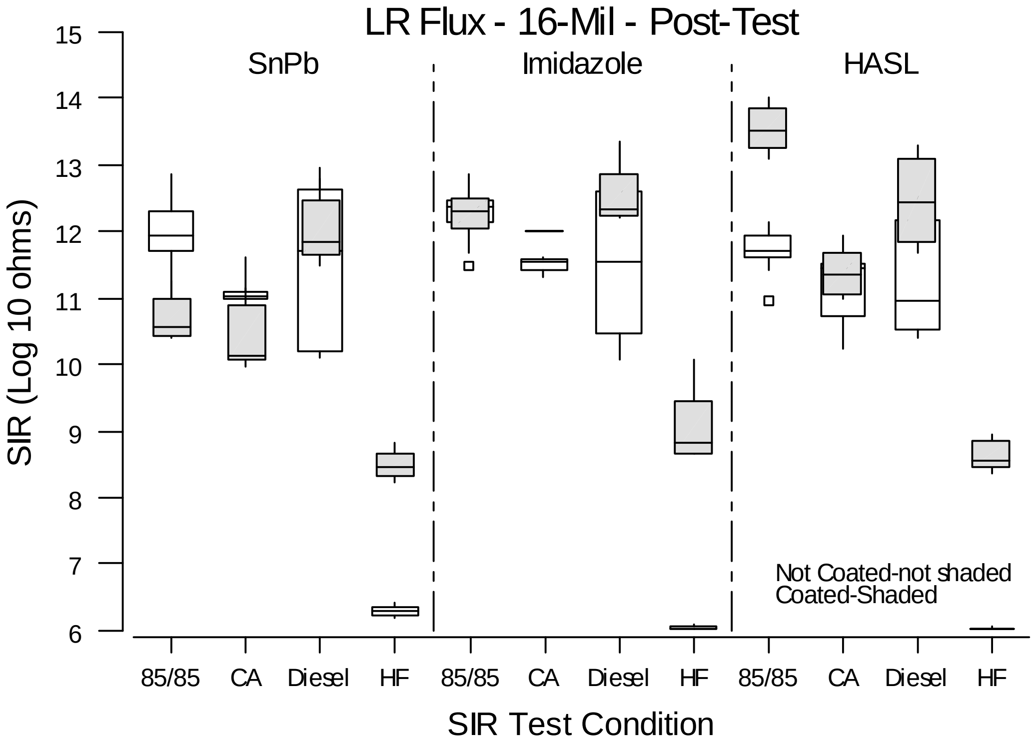

Figure 2.55 A Comparison of Post-Test SIR Measurements for Three Conformal Coating Screening Experiments by Surface Finish for 16-Mil Comb Pattern Spacing and LR Flux

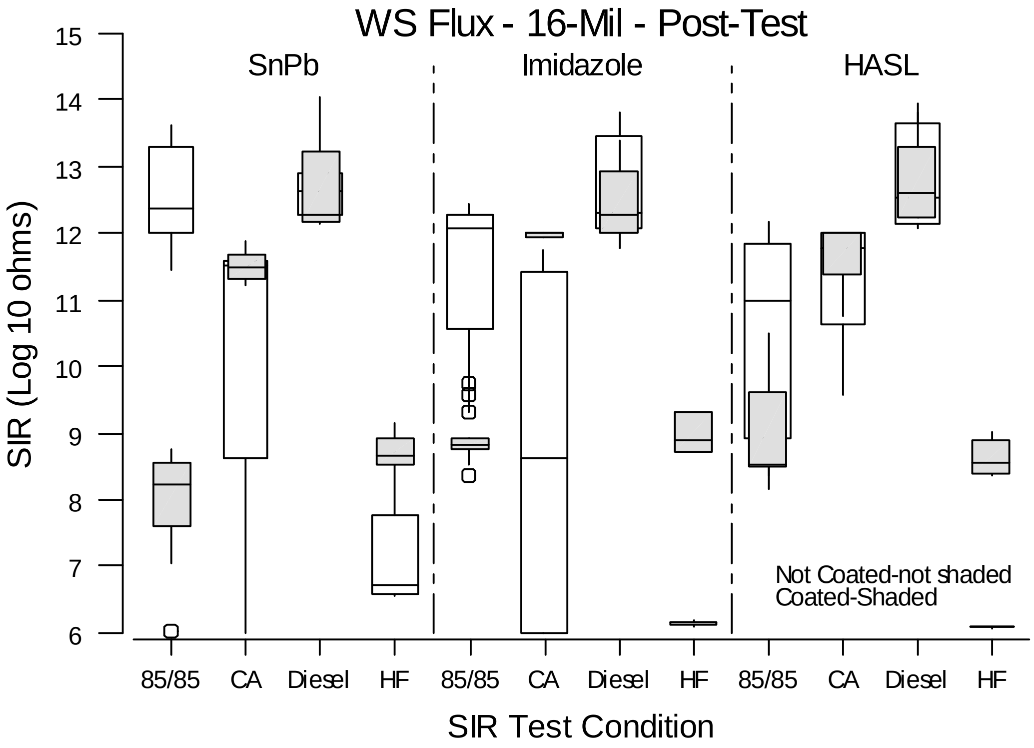

Figure 2.56 A Comparison of Post-Test SIR Measurements for Three Conformal Coating Screening Experiments by Surface Finish for 16-Mil Comb Pattern Spacing and WS Flux

Table 2.28 Differences in Mean SIR for Coated and Uncoated Boards for each Combination of Experimental Factors (positive values denote the magnitude of significant increases in mean SIR (log 10 ohms) with coating; “0” denotes no difference in mean SIR; negative values denote the magnitude of significant decreases in mean SIR (log 10 ohms) SIR with coating)

			85° C / 85% RH		Condensing Atmosphere		Diesel Fuel		Hydraulic Fluid	
			168 hr	Post 24 hr	Cy. 10	Post Test	1st Dip	Post Test	1st Dip	Post Test
SnPb	**LR**	**8**	-0.2	-0.6	1.5	-1.0	1.1	0	2.7	2.7
		12	-0.7	-0.9	1.5	0	1.6	0	2.8	2.8
		16	-0.7	-1.2	1.4	0	1.5	0	2.2	2.2
		20	-0.6	-1.2	1.3	-1.0	1.3	0	2.2	2.2
	WS	**8**	-1.3	-4.7	0	0	0	0	2.6	2.6
		12	-1.6	-4.6	2.8	0	0	0	2.7	2.7
		16	-1.2	-4.6	3.5	0	0.8	0	1.6	1.6
		20	-1.2	-3.8	2.3	0	0.3	-0.3	1.6	1.6
Imidazole	**LR**	**8**								
		12	0	-0.3	2.5	0.8	0	0	3.1	3.1
		16	0	0	2.4	0	0.7	0	2.9	3.0
		20	0	0	0	0	1.0	0	2.9	2.9
	WS	**8**								
		12	0	-2.8		0	0	0	2.2	2.2
		16	0	-2.5	3.5	0	0	0	2.8	2.8
		20	0	-2.1	3.4		0	0	3.2	3.2
HASL	**LR**	**8**			0					
		12	0.9	2.0	0	0	1.5	0	2.0	2.0
		16	1.3	1.8	0	0	1.8	0	2.6	2.6
		20	1.1	1.8		0	1.7	0	2.4	2.4
	WS	**8**								
		12	0	-1.9	0	0	0	0	1.9	1.9
		16	0	-1.6	0	0	0	0	2.5	2.5
		20	0	-1.8	0	0	0.6	0	2.3	2.3

3. Evaluation of Alternative Surface Finishes

3.1 Background on Alternative Surface Finishes

Fused SnPb Surface Finishes. Surface finishes are applied to printed wiring boards (PWBs) to prevent oxidation of exposed copper conductors on the board, thus ensuring a solderable surface when components are later added. The most widely used processes are HASL with solder mask, which is used mainly for commercial applications, and plated and reflowed SnPb, which is used mainly for military applications. In both processes, SnPb is fused onto exposed copper surfaces. In the HASL process, the PWB is fluxed and then dipped in liquid solder. After dipping, the excess solder is removed with hot air knives (hot air solder leveling). In the plated and reflowed SnPb process, SnPb is plated on the cooper conductors and then reflowed by dipping in a hot oil bath.

Fused SnPb processes have advantages and disadvantages:

Advantages

- Solid deposit of metal and maintains solderability
- Oxygen diffuses slowly through the solder and typically only a thin coating of tin oxide will form on the surface
- During soldering, the solder will melt and aid the flux in dispersing the oxides
- Low cost
- Common, well understood processes

Disadvantages

- High processing temperatures — PWBs are typically exposed to temperatures of about 500°*F*, which can cause delamination and warpage
- Lead — added cost of handling a hazardous material and the threat of future restrictions or limitations of lead use.
- Planarity — surface tension of the solder causes the solder to be thicker in the center of a pad than at the edges. This can cause problems with fine pitch components, particularly if the planarity of the component leads is less than perfect.
- Fused SnPb coatings that are too thin are susceptible to incomplete coverage or to being consumed by intermetallic growth. Tin in fused SnPb coatings reacts with the copper to form intermetallics. These intermetallics grow slowly with time, but, if the coating is too thin, the solder will be consumed, leaving only unsolderable intermetallics behind.
- Fused SnPb can mask other problems. It is possible, through the use of aggressive fluxes, to put a fused SnPb coating on a normally unsolderable board. This type of problem is not usually discovered until dewetting occurs in the soldering process, either reflow or wave.

Alternative Surface Finishes. As shown in Figure 1.1, a three-part evaluation was planned for alternative surface finishes for PWBs. The screening phase of this plan was used to study alternatives to the fused SnPb surface finish process. ASFs are now used in industry in some commercial applications. The CCAMTF evaluation made use of available industry information about ASFs to avoid duplication of efforts and to ensure effectiveness and wide-spread use.

Two screening experiments based on solderability tests were conducted to compare the performance of HASL and six ASFs: two organic solderability preservatives — benzimidazole and imidazole; immersion Au over electroless Ni plating; immersion Ag plating; electroplated Pd over Cu, and immersion Au over electroplated Pd on Cu.

This evaluation built on the results of the NCMS 5-year evaluation of PWB surface finishes and extended those results by:

- Evaluating benzimidazole
- Including immersion Ag
- Expanding the data base on immersion Au
- Evaluating the effect of processing in both open air and nitrogen

Results of the screening experiment expand existing data bases on the performance of imidazole and immersion Au, and provide data for benzimidazole, immersion Ag, and electroplated Pd.

3.2 Test Vehicle Fabrication and Surface Finish Application

The first surface finish solderability experiment used copper coupons and the second experiment used an IPC-B-24 with slight modifications. These test vehicles were furnished by Texas Instruments Printed

Table 3.1 Processing Details for the Application of Alternative Surface Finishes

Surface Finish	Processing Details
Benzimidazole	Entech 106A© processed at TI Austin, TX Process: 1. Cleaner — Removes greases and residues from resist striping 2. Microetch — Sodium persulfate based copper etchant, to remove oxides and prepare the Cu surface for coating 3. Acid rinse — Sulfuric acid, final etch rinse and deoxidize the copper prior to coating 4. Benzimidazole — Organic, corrosion resistant coating for Cu 5. Dry — Forced air oven All processing was done on vertical basket racks. The coating is an entirely electroless process for finishing Cu circuitry for “surface mount” and “pin in hole” technology. Final Finish —.All exposed Cu surfaces are coated with a 0.2 to 0.5 micron thick organic coating. The appearance is a satin, reddish copper color.
Imidazole	Processed by Lucent Technologies, Richmond, VA Process: 1. Cleaner — removes greases and residues from resist striping 2. Microetch — Sodium persulfate based Cu etchant, to remove oxides and prepare the Cu surface for coating 3. Acid conditioner — Phosphoric acid, final etch rinse and deoxidize the Cu prior to coating 4. Imidazole coating — Organic, corrosion resistant coating for Cu 5. Dry — Forced air oven All processing done in horizontal equipment. The coating is an entirely electroless process for finishing Cu circuitry for “surface mount” and “pin in hole” technology. Final Finish —.All exposed Cu surfaces will be coated with a 30 to 100 *A* thick organic coating. The appearance is a satin, reddish copper color.
Immersion Au over Electroless Ni	Processed by IBM Process: 1. Acid cleaner — Removes light soils and resist stripper residues 2. Cu etch — Removes Cu oxides and prepares the surface for plating 3. Activator — Seeds the Cu surface for electroless Ni plating 4. Electroless Ni — Deposits Ni on exposed Cu traces. Rate 7.6 µ *in*/*hr*. 5. Immersion Au — Deposits Au on exposed Ni traces 6. Hot air dry — Removes water Final finish — matte gold color. Au thickness is 0.1 micron, Ni is 150 to 160 µ *in* thick

Circuit Resources fabrication site in Austin. TI applied the benzimidazole surface finish; Lucent Technologies applied the imidazole, palladium, and HASL surface finishes; IBM applied immersion Au; and Alpha Metals applied immersion Ag. Table 3.1 gives details of the application processes for each surface finish.

Table 3.1 Continued

Surface Finish	Processing Details
Immersion Ag	AlphaLevel 3000© processed by Alpha Metals Process 1. Pre-cleaner — Acid based, removes surface oils and residual organic residues from soldermask developing 2. Micro etch — Peroxide/sulfuric based Cu etchant, provides optimum topography for Ag deposit. 3. Pre-condition — Drag-in bath and antioxidant for the immersion Ag bath 4. AlphaLevel 3000© protective coating — 3-4 μ*in* Ag covered with an organic monomolecular layer for improved oxidation resistance All processing done on horizontal, conveyorized equipment. AlphaLevel is an entirely electroless process for finishing Cu circuitry for surface mount and pin in hole technology. Final finish — All exposed Cu surfaces are a matte silver colored finish
Electroplated Pd	PallaTech© PDLF Palladium Plating processed by Lucent Technologies, Murray Hill, NJ Process: After copper plating palladium is applied as a replacement for tin- lead etch resist. The process steps after copper plate are as follows: 1. Rinse 2. Acid Soak Clean 3. Rinse 4. 20% sulfuric acid 5. Rinse 6. PallaTech® PdLF Palladium plate (approximately 1 *min*) 7. Rinse 8. Resist strip 9. Rinse 10. Copper etch Processing was done via vertical electrolytic rack plating. Pd thickness and appearance — Pd thickness is 1250-1750 *A*, the metal is a semi-bright silver color.

3.3 Screening Experiment 4: Process Exposure for Wetting Balance and SERA Tests

Figure 3.1 gives a two-dimensional representation of the solderability test matrix for the first ASF screening experiment. The second solderability test matrix is discussed in Section 3.8. Six solderability tests were used in this experiment: three based on wetting balance and three on sequential electrochemical reduction analysis (SERA).

Thirty-five of the copper test coupons (five coupons from each surface finish) were subjected to solderability tests (wetting balance and SERA) at the TI facility in Austin after fabrication. The remaining 140 coupons were shipped to the EMPF in Indianapolis for exposure to process conditions. These coupons were organized into four groups of size 35, with each group containing an equal number of coupons from each surface finish category. These groups were exposed to the following process conditions (preliminary tests were used to determine the length of the bake times):

Table 3.1 Continued

Surface Finish	Processing Details
Immersion Au over Electroplated Pd	AuRoTech® DG Immersion Gold/PallaTech® PdLF Palladium Plating processed by Lucent Technologies, Murray Hill, NJ Process: After copper plating, PallaTech® PdLF palladium is applied as a replacement for tin- lead etch resist. The process steps after copper plate are as follows: 1. Rinse 2. Acid Soak Clean 3. Rinse 4. 20% sulfuric acid 5. Rinse 6. PallaTech® PdLF Palladium plate (approximately 1 *min*) 7. Rinse 8. Resist strip 9. Rinse 10. Copper etch 11. Rinse 12. 10% Sulfuric Acid 13. Rinse 14. AuRoTech® DG Immersion Gold Pd thickness: 1250 to 1750 *A* Immersion Au: 200 to 300 *A* Processing was done via vertical electrolytic rack plating. Final appearance — Pale yellow
HASL	Processed by Lucent Technologies, Richmond, VA Imidazole process — cleans and protects the copper surface. Super HASL — Applies molten solder to the imidazole coated Cu surface. The HASL process is done in a horizontal machine. The coating is an entirely electroless process for finishing Cu circuitry for “surface mount” and “pin in hole” technology. Final Finish — All exposed Cu surfaces are coated with a 100 to 1000 µ *in* of Sn60 Solder. The appearance is a bright silver solder finish.

1. Run through the reflow oven in air — simulates a double-sided surface mount or mixed technology process
2. Run through the reflow oven in nitrogen — same as (1)
3. Bake in air for 8 *hr* at 105° *C* and then run through the reflow oven in air — simulates a typical bake to remove moisture
4. Bake in nitrogen for 8 *hr* at 105° *C* and then run through the reflow oven in nitrogen — same as (3)

Simulated reflow soldering (no solder paste applied) was in an Electrovert Omniflow seven-zone reflow oven. This oven is heated by forced air convection. For reflow processing in nitrogen, oxygen content was kept under 20 *ppm.*

Bakes were done in a vacuum oven with no convection. For the bake in nitrogen, the boards were placed in the oven, the air was evacuated, and the chamber was back-filled with nitrogen. At one atmosphere the chamber was not air-tight, so for the

Solderability Test Condition

Surface Finish	Solderability after fabrication	Run through reflow oven in air	Run through reflow oven in nitrogen	Bake for 8 hrs in air and run through reflow oven in air	Bake for 8 hrs in N and run through reflow in nitrogen
Benzimidazole					
Imidazole					
Immersion Au over Ni plating					
Immersion Ag					
Electroplated Pd over Cu					
Immersion Au over Pd / Cu					
HASL					

Figure 3.1 Two-Dimensional Representation of the Test Matrix for the First Alternative Surface Finish Screening Experiment (5 test coupons per cell, 175 total test coupons)

nitrogen bake, the oven was kept at just under one atmosphere.

These process conditions allow a comparison between open air and nitrogen processing. The last two conditions were selected to stress the OSP finishes. The six solderability tests were done on each test coupon after process exposure.

3.4 Wetting Balance and SERA Testing

After process exposure, the test coupons were returned to the TI facility in Austin for wetting balance and SERA tests. Three separate responses were recorded for each of these solderability tests.

Wetting Balance Test. The wetting balance apparatus is used to determine the ability of a specimen to wet with molten solder. Solderability is measured by the change in weight of a specimen immersed in molten solder. The test is conducted under isothermal conditions (usually 245°*C*) and weight changes are recorded over the entire test period.

The test specimen is suspended from a precision weighing balance. The solder pot is usually raised (some units move the specimen instead) until the specimens reaches the solder surface. This contact starts the test time. The specimen is immersed into the solder to a specified depth (3-5 *mm*) and held at that position throughout the remaining test time. When the test is complete the specimen is automatically removed the solder.

Figure 3.2 presents a typical graph of weight versus time from the wetting balance test. The boxed letters indicate the following: (A) specimen contacts the solder surface and reaches the full immersion depth; (B) wetting begins and reaches zero force (flat meniscus); (C) wetting continues to increase as the solder meniscus rises above the solder surface; (D) meniscus reaches steady state and maintains this level until the end of the test — maximum force achieved; and (E) end of test and the specimen is withdrawn.

Several measures of wettability can be extracted from the curve in Figure 3.2. Some of the most common wetting balance measurements are:

- Time to zero force (*sec*) —time required for the weight of the specimen to return to zero force plus a correction for the buoyancy of the specimen

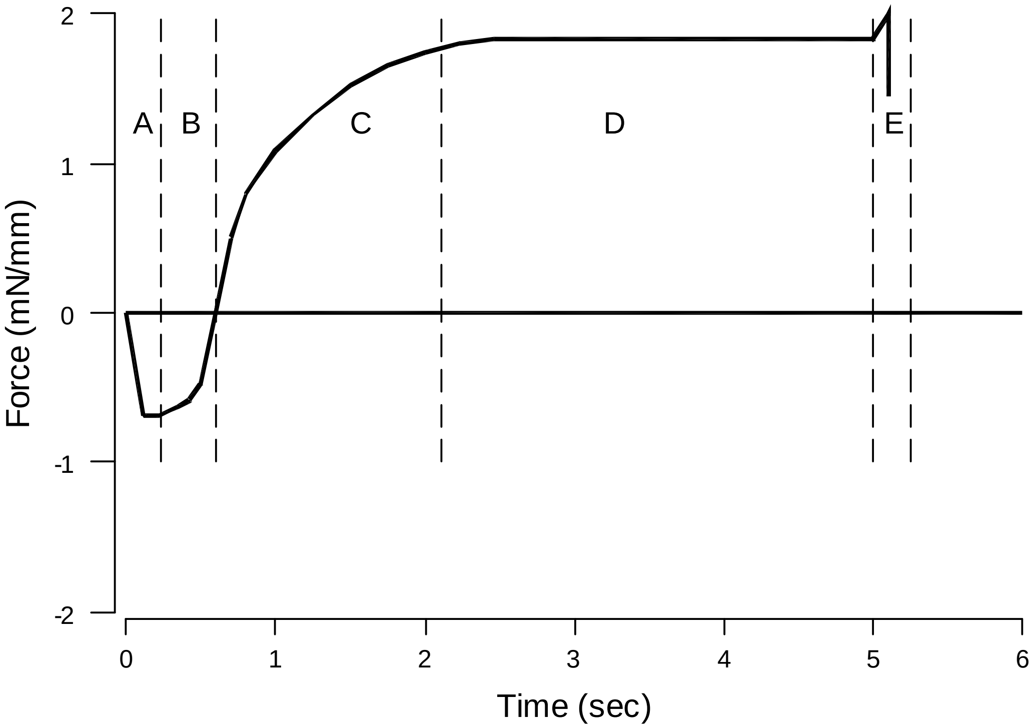

Figure 3.2 Typical Wetting Balance Curve

- Force at 2 *sec* (μ*N*/*mm*) — force measured after 2 *sec* immersion
- Time to 2/3 maximum force (*sec*) — time required to achieve 2/3 of the maximum wetting force

The wetting balance test uses an Actiec 2 flux formulation by Multicore that is 25% Water White rosin + 0.2% by weight Dimethylene Hydrochloride in IPA.

SERA. SERA is a potentiometric method of sequentially reducing metal oxides to their basis metals. The test is used to determine the oxide type and thickness on the surface of a metallic finish. SERA measures the potential required to reduce the metallic surface and the time required to reduce it. Current density is kept constant and voltage is plotted against time. Since each metal oxide has a specific reduction potential, it is possible to determine the specific oxide type present. By measuring the potential versus time, the SERA curve can be produced. A typical SERA curve is shown in Figure 3.3. An estimate of the thickness of the oxide is obtained by integrating the curve in Figure 3.3. Some of the common characteristics used to quantify solderability are:

- V_2 — Reduction potential for SnO or CuO
- V_3 — Reduction potential for Sn_2O or Cu_2O
- V_f — Final voltage (Hydrogen over voltage for specific metal)
- Q_1 — Charge to reduce intermetallic CuSn
- Q_2 — Area under the curve at potential V_2
- Q_3 — Area under the curve at potential V_3

The label VOC in Figure 3.3 is the last open circuit voltage measured for the SERA curve. There is a relationship between SnPb oxidation and solderability. More electropositive values for V_2 indicate better solderability for SnPb or Sn finishes. When V_2 voltages are high, the SnO is at a minimum and low levels of SnO present on the surface of SnPb have been shown to reduce solder joint defects. V_2 voltages above -1.07 VDC are considered acceptable. Good boards generally run between -0.8 and -0.9 VDC. Other SERA characteristics also show trends, but the correlation to soldering defects is best for V_2.

All test specimens were evaluated by first using SERA and then the wetting balance test. This sequence was possible since the SERA test is non-destructive and could be done on the opposite end of the coupon used for the wetting balance test. Three SERA responses were made: final voltage (V_f), second plateau voltage (V_2), and area under the curve (Q_3). Cell means for these tests are given in Table 3.2.

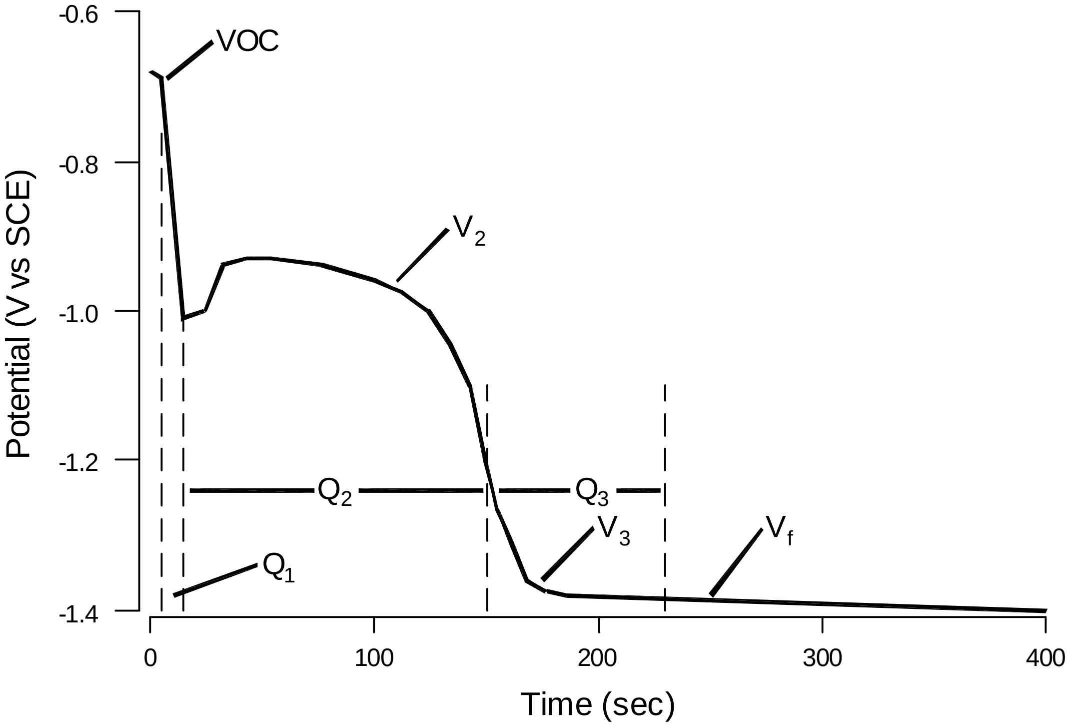

Figure 3.3 Typical SERA Curve

3.5 Comparison of Wetting Balance and SERA

A main goal of the ASF evaluation was to down-select surface finishes for the next phase of the program. Each of the three wetting balance and SERA tests provides three responses that could potentially be used for downselection. However, these six measurements will not necessarily agree on their choice of surface finishes. That is, there could be disagreement between the two families of tests (wetting balance and SERA) or there may be disagreement within a family. The agreement can be quantified by computing all pairwise correlations on the test measurements or can be viewed graphically with matrix plots that show all pairwise scatterplots for the test measurements. Figures 3.4 to 3.10 contain matrix plots for each surface finish. In these graphs, a linear relation indicates correlation or agreement between the measurements recorded for two different tests.

The three graphs in the upper left-hand corner of each of these figures are pairwise scatterplots for the three wetting balance tests. The linearity in these graphs indicates generally strong agreement within this family of tests. There is less agreement within this family for immersion Ag and HASL (see Figures 3.7 and 3.10). The high degree of agreement within this family indicates that only one of the three measurements is needed for downselection.

The family of SERA graphs is shown in the three graphs in the lower right-hand corner of Figures 3.4 to 3.10. These graphs indicate a general lack of agreement within the SERA tests, but there does appear to be good agreement between V_2 and V_f for immersion Au/Pd. The one outlier for Q3 makes it difficult to judge the amount of agreement for the other two SERA tests for immersion Au/Pd.

The nine graphs in the lower left-hand corner of these figures compare each wetting balance test with each SERA test. Few of these graphs indicate any agreement and several appear to show a random pattern. This implies the two sets of tests do not agree on the performance of the surface finishes. This lack of agreement is not necessarily unexpected, as the SERA tests were performed using a borate buffer solution designed for the evaluation of copper or tin lead surface finishes. The SERA results were based on copper factors for all finishes, therefore, it is not surprising that the other surface finishes (Ag, Au, and Pd) did not correlate. However, this does illustrate just how sensitive SERA is to the surface finish being evaluated.

On the basis of this comparison, the CCAMTF made a decision to use wetting force at 2 *sec* for downselection.

Table 3.2 Cell Means for the Wetting Balance and SERA Tests

Environment	Surface Finish	Wetting Force	Time to Zero	Time to 2/3 Max	V_2	V_f	Q_3
After Fab	**Benzimidazole**	0.198	0.946	2.062	0.858	1.199	1.224
	Imidazole	0.214	0.996	2.018	0.543	1.141	1.050
	Immersion Au	0.002	1.722	2.928	0.898	0.960	0.222
	Immersion Ag	0.208	0.940	1.904	0.556	1.200	2.148
	Electroplated Pd	-0.046	1.768	2.968	0.524	0.708	0.834
	Immersion Au/Pd	0.044	1.508	2.752	0.660	0.867	0.228
	HASL	0.046	1.628	2.960	0.909	1.406	0.876
Reflow Air	**Benzimidazole**	0.100	1.492	2.420	0.897	1.089	0.642
	Imidazole	0.126	1.250	2.350	0.640	1.048	0.948
	Immersion Au	-0.238	2.460	3.754	0.885	0.949	0.180
	Immersion Ag	0.186	1.146	1.954	0.782	1.127	1.638
	Electroplated Pd	0.080	1.610	2.544	0.546	0.703	0.666
	Immersion Au/Pd	0.086	1.300	2.584	0.617	0.716	0.414
	HASL	0.070	1.598	2.456	0.926	1.386	0.978
Reflow N_2	**Benzimidazole**	0.106	1.452	2.312	0.906	1.120	0.810
	Imidazole	0.150	1.178	2.278	0.609	1.105	0.876
	Immersion Au	-0.162	2.196	3.534	0.900	0.951	0.180
	Immersion Ag	0.206	1.014	1.888	0.487	1.145	2.118
	Electroplated Pd	-0.008	1.748	3.028	0.545	0.671	0.612
	Immersion Au/Pd	0.100	1.360	2.556	0.651	0.746	0.354
	HASL	-0.020	1.780	3.098	0.908	1.405	1.428
Air Bake	**Benzimidazole**	-0.350	4.800	*	0.900	1.055	0.000
	Imidazole	-0.370	3.845	4.810	0.528	0.689	0.606
	Immersion Au	-0.260	2.668	3.948	0.904	0.982	0.306
	Immersion Ag	0.172	1.294	2.084	0.681	1.102	4.092
	Electroplated Pd	-0.218	2.098	3.094	0.538	0.687	0.690
	Immersion Au/Pd	-0.184	2.328	3.870	0.783	0.813	0.180
	HASL	0.024	1.652	2.918	0.958	1.383	0.594
N_2 Bake	**Benzimidazole**	-0.180	2.118	3.752	0.961	1.132	1.200
	Imidazole	-0.380	*	*	0.638	0.731	0.054
	Immersion Au	-0.138	2.272	3.696	0.898	0.973	0.444
	Immersion Ag	0.150	1.436	2.068	0.610	1.138	2.298
	Electroplated Pd	-0.336	2.882	4.214	0.598	0.714	0.786
	Immersion Au/Pd	0.030	1.616	3.038	0.907	0.963	0.924
	HASL	0.032	1.644	2.822	0.938	1.365	1.164

3.6 Boxplot Displays for Wetting Force Measurements

The boxplots presented in Figures 3.11 to 3.15 show wetting force for each process condition versus surface finish. To be acceptable, wetting force should be positive. In this respect, the OSPs and immersion Ag are clearly superior to the other finishes after fabrication as shown in Figure 3.11.

Reflow in Air. From Figure 3.12, immersion Au gives unsatisfactory levels of wetting force after reflow in air. The performance of the OSPs decreases from their performance in Figure 3.11, but they still have adequate wetting force. Immersion Ag is invariant to this process condition. Electroplated Pd improves and immersion Au/Pd and HASL are basically unchanged from Figure 3.11.

Reflow in Nitrogen. As shown in Figure 3.13, the OSPs benefit slightly from the nitrogen atmosphere while immersion Au gives poor wetting. Immersion Ag is again invariant to this process condition. Electroplated

Pd does not benefit from nitrogen. Immersion Au/Pd does not change in this environment and the wetting force for HASL decreases.

Bake and Reflow in Air. From Figure 3.14, baking the boards in air for 8 *hr* at 105° *C* and then running them through the reflow oven in air had the expected effect on the OSPs, as both decreased to unacceptable wetting levels. This is also true of immersion Au, electroplated Pd, and immersion Au/Pd. Immersion Ag was again invariant to this process condition and was the only surface finish to give acceptable wetting. The performance of HASL was marginal.

Bake and Reflow in Nitrogen. Benzimidazole can be seen to improve in Figure 3.15 for baking the boards in nitrogen for 8 *hr* at 105° *C* and then running through the reflow oven in nitrogen, but did not demonstrate adequate wetting. Imidazole (the thinner coating of the two OSPs: 30 to 100*A* vs. 2000 to 6000*A*) did not improve with nitrogen. Immersion Au improved, but still did not have adequate wetting. Once again, immersion Ag was invariant to this process condition and had the best wetting of all the surface finishes. The performance of electroplated Pd was degraded in nitrogen and was just above that of imidazole. Immersion Au/Pd was just above zero wetting force and HASL gave marginal performance.

Other Displays. Appendix D contains 30 graphs similar to those in Figures 3.11to 3.15 that show the results for each of the six solderability tests. Figures 3.16 to 3.22 display the wetting force measurements for each surface finish versus process condition. Appendix D also contains 42 graphs similar to those in Figures 3.16 to 3.22 for all solderability tests. The reader is encouraged to study these displays.

3.7 General Linear Modeling for Solderability Tests

Table 3.3 contains the results of the GLM analyses for each of the six solderability tests. The GLM used for that modeling is:

$$\begin{aligned} Y = {} & \beta_0 + \beta_1 D_1 + \beta_2 D_2 + \beta_3 D_3 + \beta_4 D_4 + \beta_5 D_5 \\ & + \beta_6 D_6 + \beta_7 D_7 + \beta_8 D_8 + \beta_9 D_9 + \beta_{10} D_{10} \\ & + \text{24 interaction terms} \end{aligned} \tag{3.1}$$

The base case for this model is HASL after fabrication, and the dummy variables are defined as follows:

D_1 = 0 if surface finish is not benzimidazole
= 1 if surface finish is benzimidazole
D_2 = 0 if surface finish is not imidazole
= 1 if surface finish is imidazole
D_3 = 0 if surface finish is not immersion Au
= 1 if surface finish is immersion Au
D_4 = 0 if surface finish is not immersion Ag
= 1 if surface finish is immersion Ag
D_5 = 0 if surface finish is not electroplated Pd
= 1 if surface finish is electroplated Pd
D_6 = 0 if surface finish is not immersion Au/Pd
= 1 if surface finish is immersion Au/Pd
D_7 = 0 if process is not reflow in air
= 1 if process is reflow in air
D_8 = 0 if process is not reflow in nitrogen
= 1 if process is reflow in nitrogen
D_9 = 0 if process is not bake and reflow in air
= 1 if process is bake and reflow in air
D_{10} = 0 if process is not bake & reflow in N_2
= 1 if process is bake and reflow in N_2

The 24 interaction terms in the model result from combining the first six dummy variables with the last four dummy variables.

The constant term in the GLM analysis for Wetting Force in Table 3.3 indicates that the base case (HASL after fabrication) has a wetting force of 0.03 µ*N/mm*. Other coefficients indicate benzimidazole (0.11), imidazole (0.13), and immersion Ag (0.16) all get significant increases over the base case HASL, while electroplated Pd (-0.06) gets a decrease.

No coefficients are listed for the process conditions for the Wetting Force model, indicating that no process condition is significant by itself. However, as was shown by the boxplots in Figures 3.16 to 3.22, process conditions interact with surface finishes. For example, benzimidazole and imidazole do not differ from their initial increase over the base case when reflowed in air or nitrogen, but both fall off when exposed to baking conditions. Immersion Au falls off in all conditions after fabrication, while immersion Ag is invariant to process condition. electroplated Pd improves after reflow in air, which helps to offset its initial decrease after fabrication, but it also decreases in the baking environment. Immersion Au/Pd improves a slight amount for reflow in either air or nitrogen, while it falls off when baked in air, but not so when baked in nitrogen.

Mean Prediction. The predicted means for the GLM for Wetting Force at 2 *sec* are given in Table 3.4. The predictions show excellent agreement with the observed means in Table 3.2.

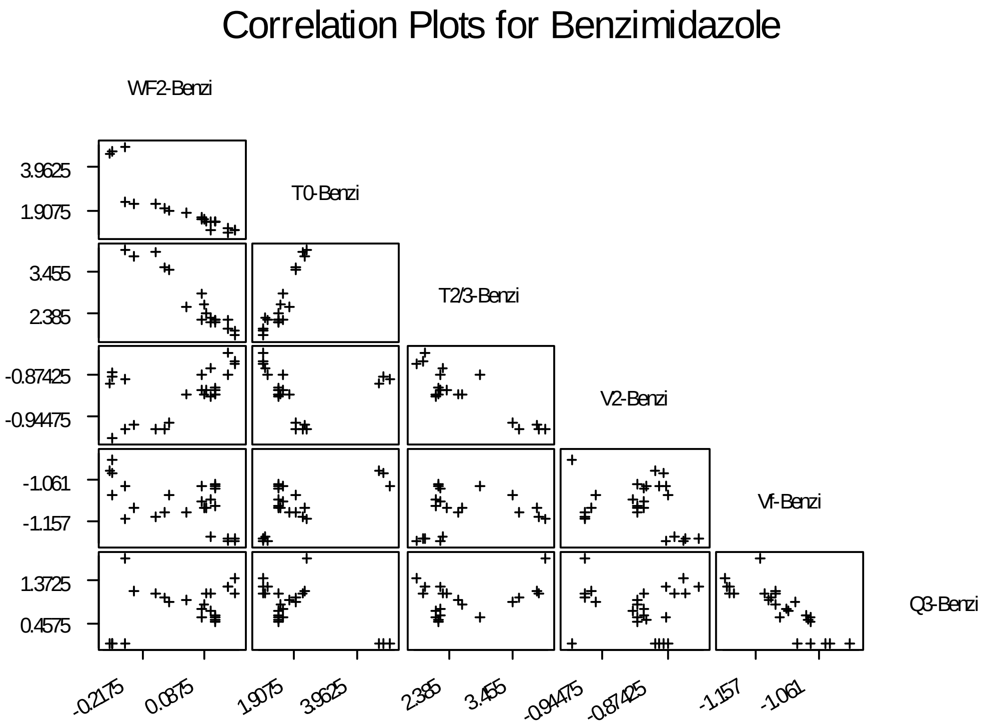

Figure 3.4 Matrix Plot of Wetting Balance and SERA Test Results for Benzimidazole

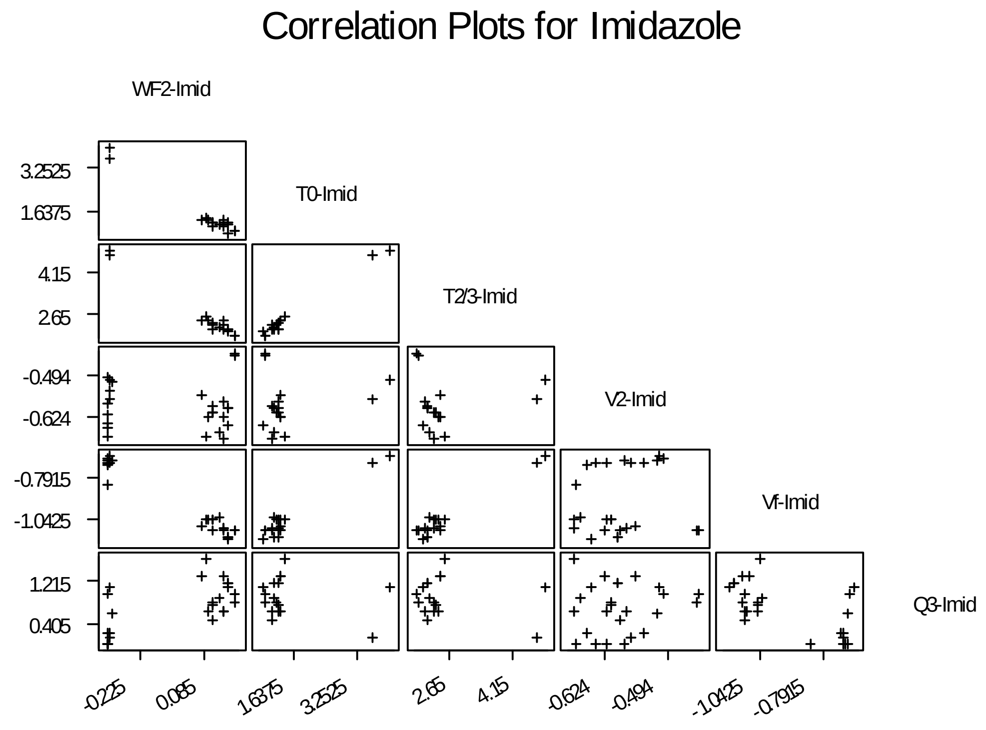

Figure 3.5 Matrix Plot of Wetting Balance and SERA Test Results for Imidazole

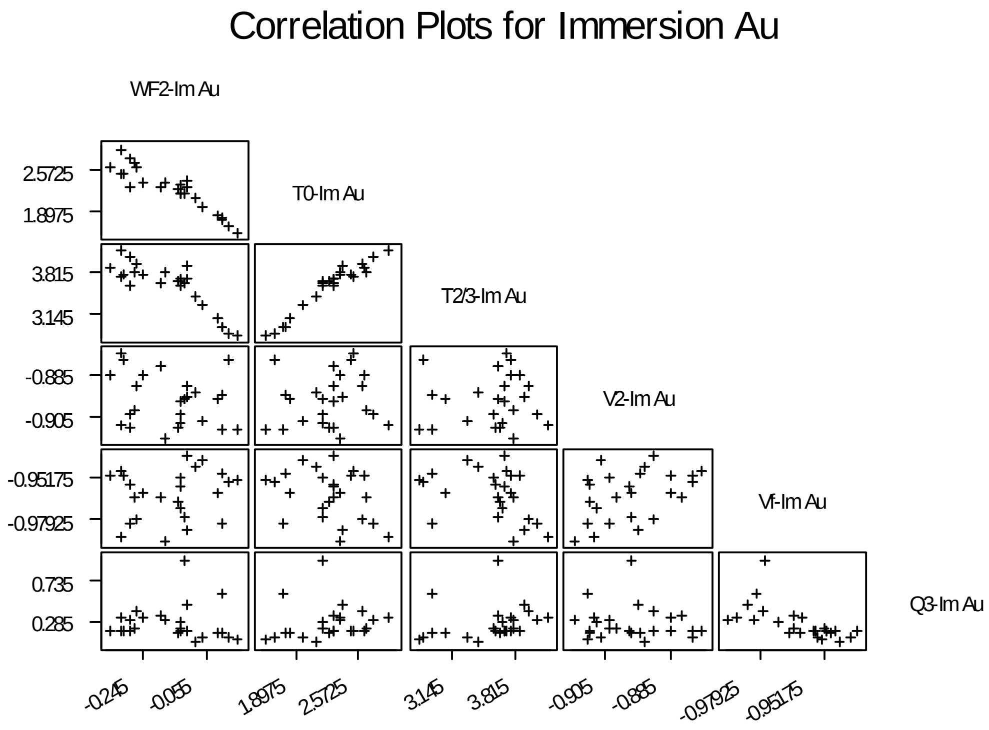

Figure 3.6 Matrix Plot of Wetting Balance and SERA Test Results for Immersion Au

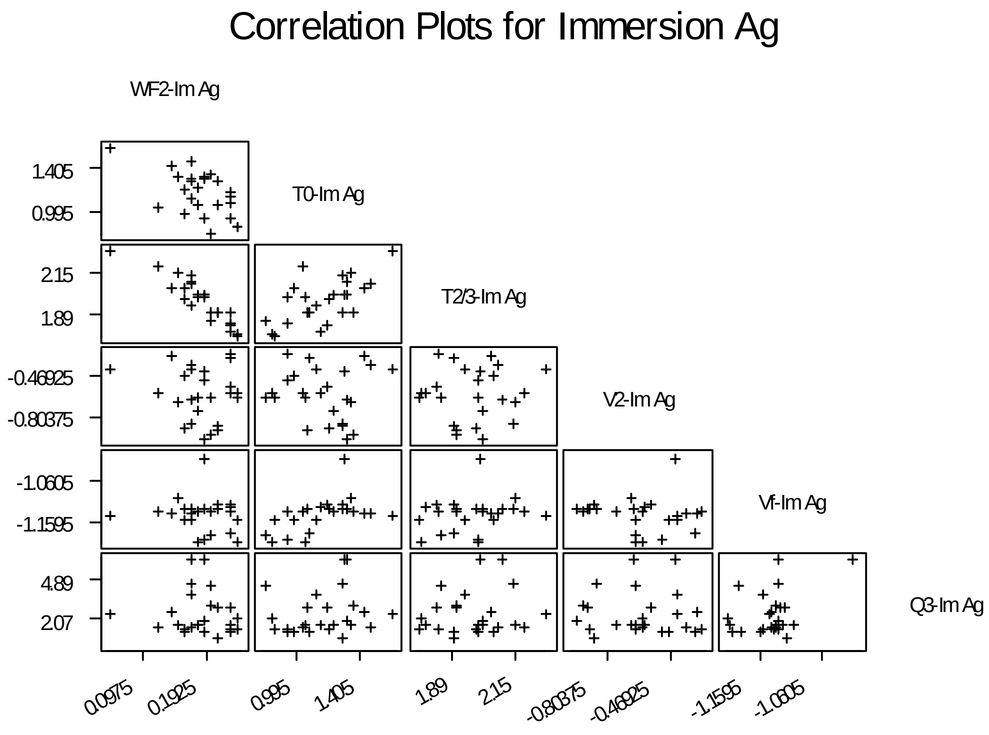

Figure 3.7 Matrix Plot of Wetting Balance and SERA Test Results for Immersion Ag

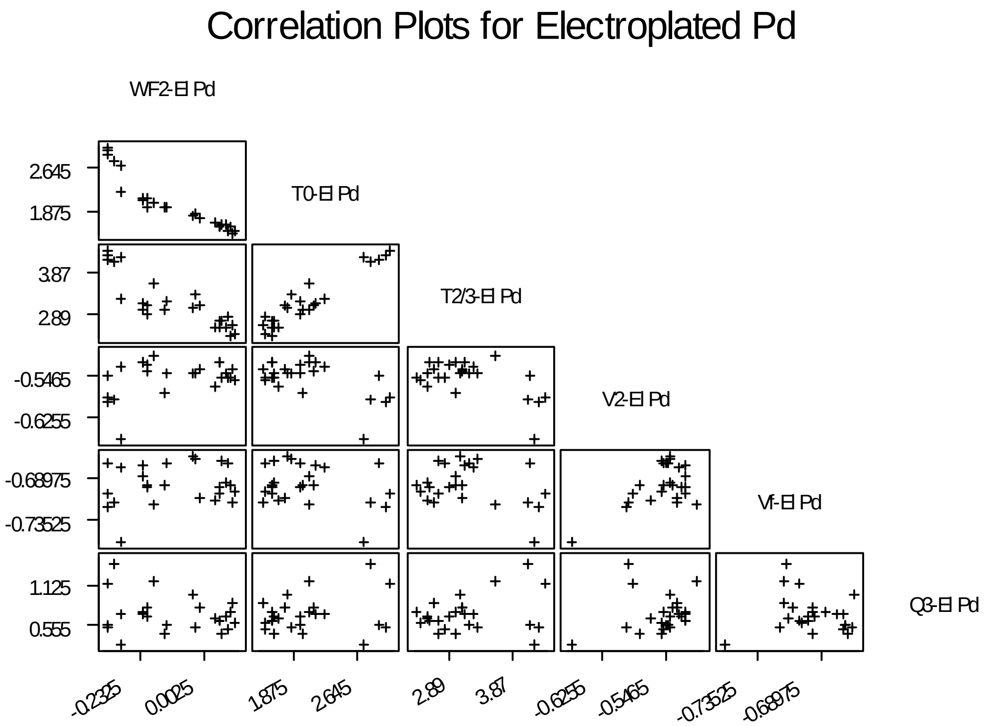

Figure 3.8 Matrix Plot of Wetting Balance and SERA Test Results for Electroplated Pd

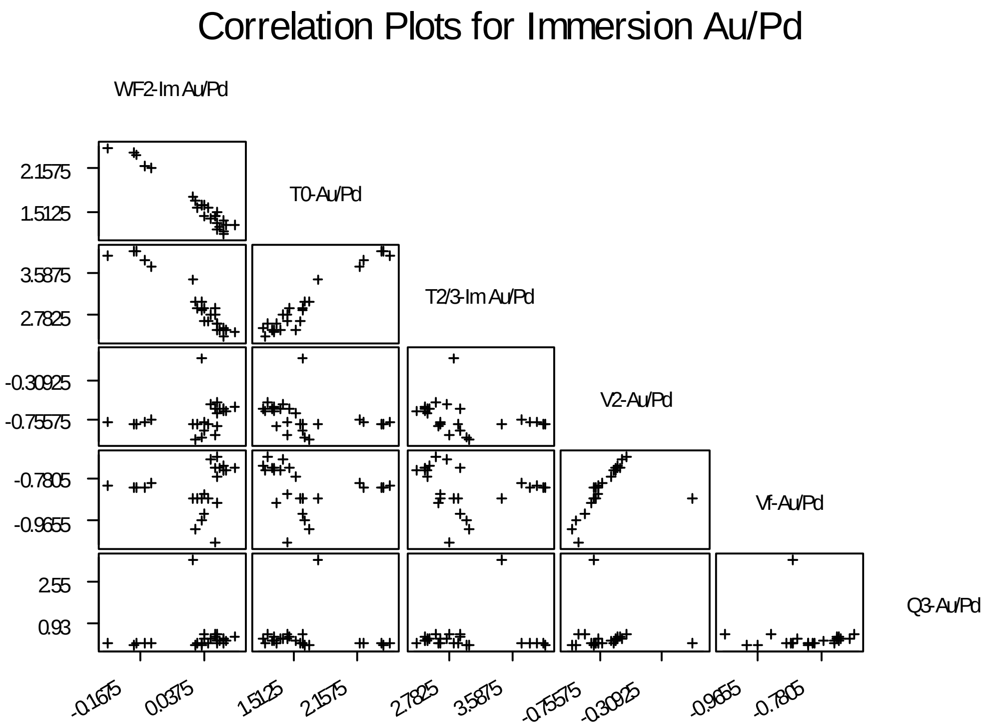

Figure 3.9 Matrix Plot of Wetting Balance and SERA Test Results for Immersion Au/Pd

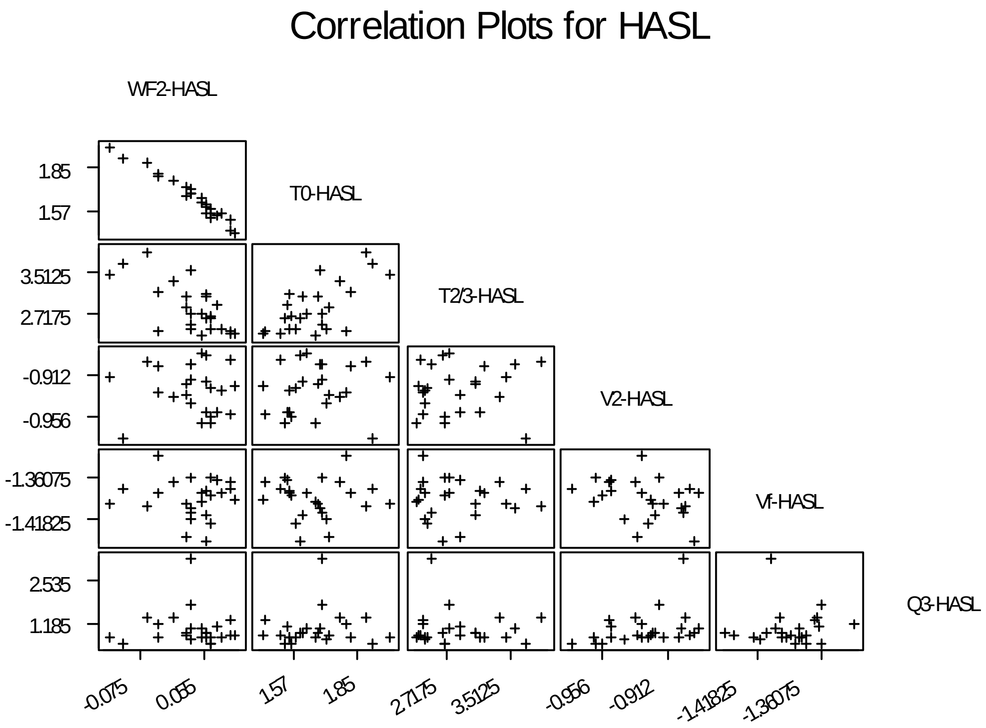

Figure 3.10 Matrix Plot of Wetting Balance and SERA Test Results for HASL

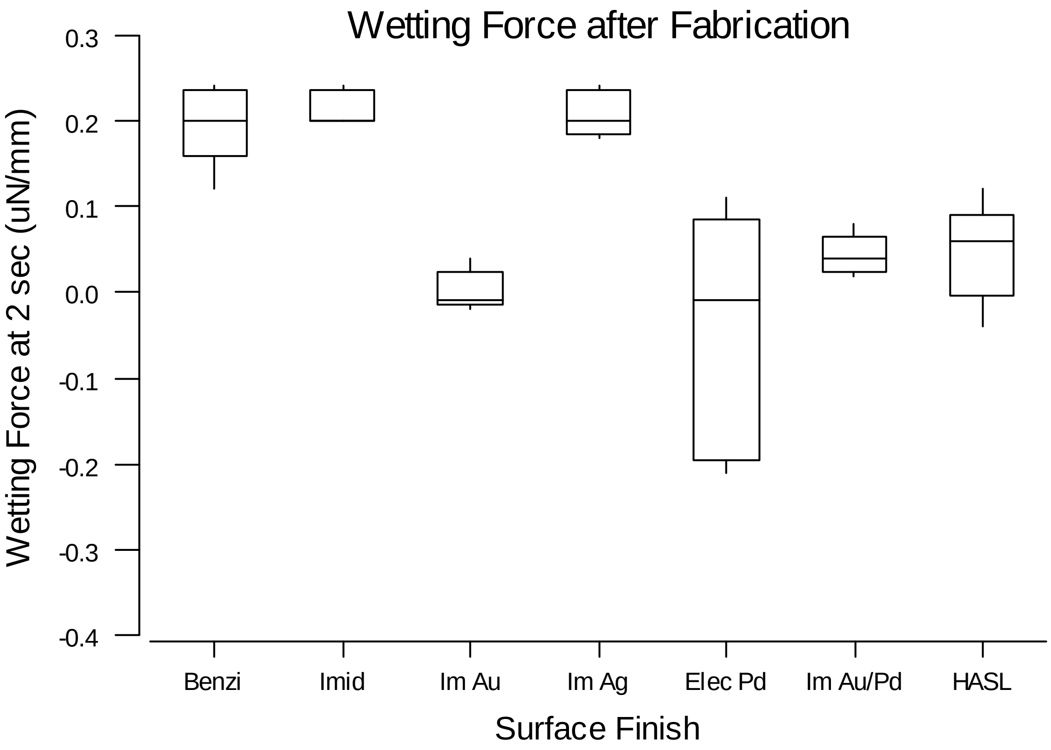

Figure 3.11 Boxplots of Wetting Force for After Fabrication versus Surface Finish

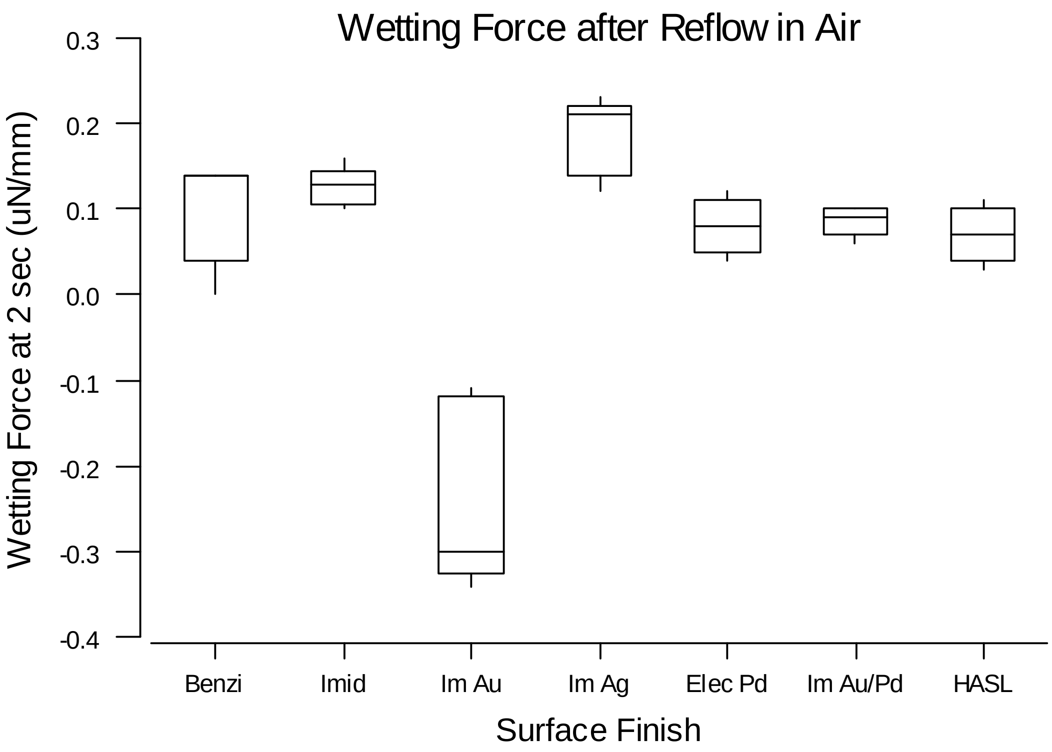

Figure 3.12 Boxplots of Wetting Force for After Reflow in Air versus Surface Finish

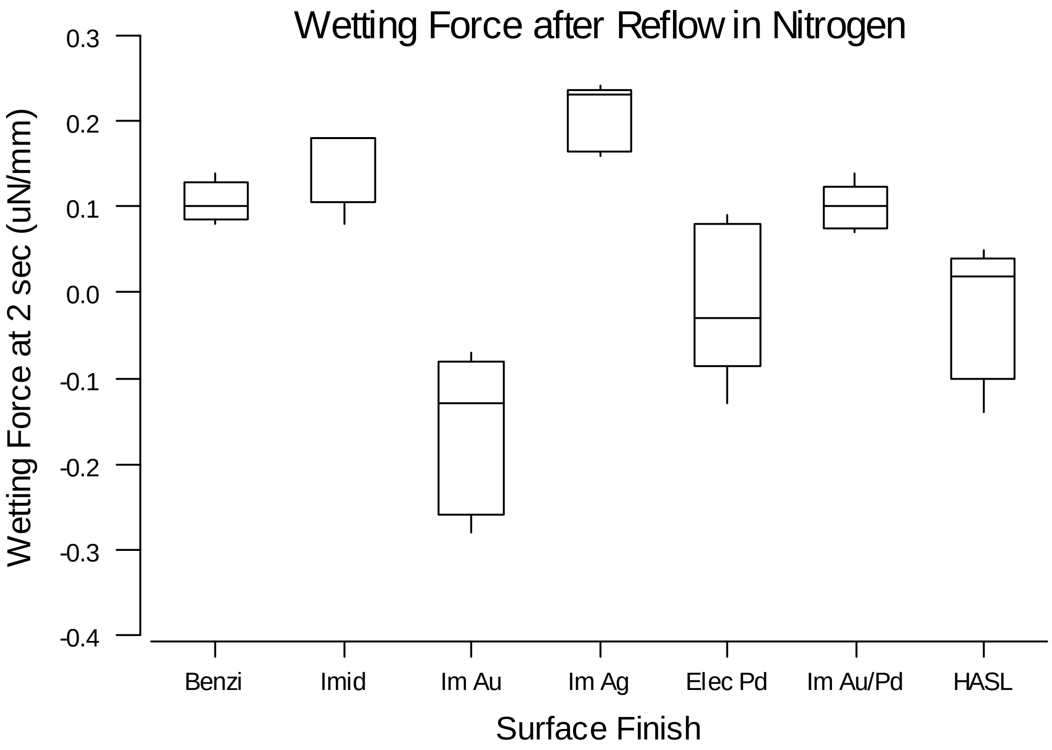

Figure 3.13 Boxplots of Wetting Force for After Reflow in Nitrogen versus Surface Finish

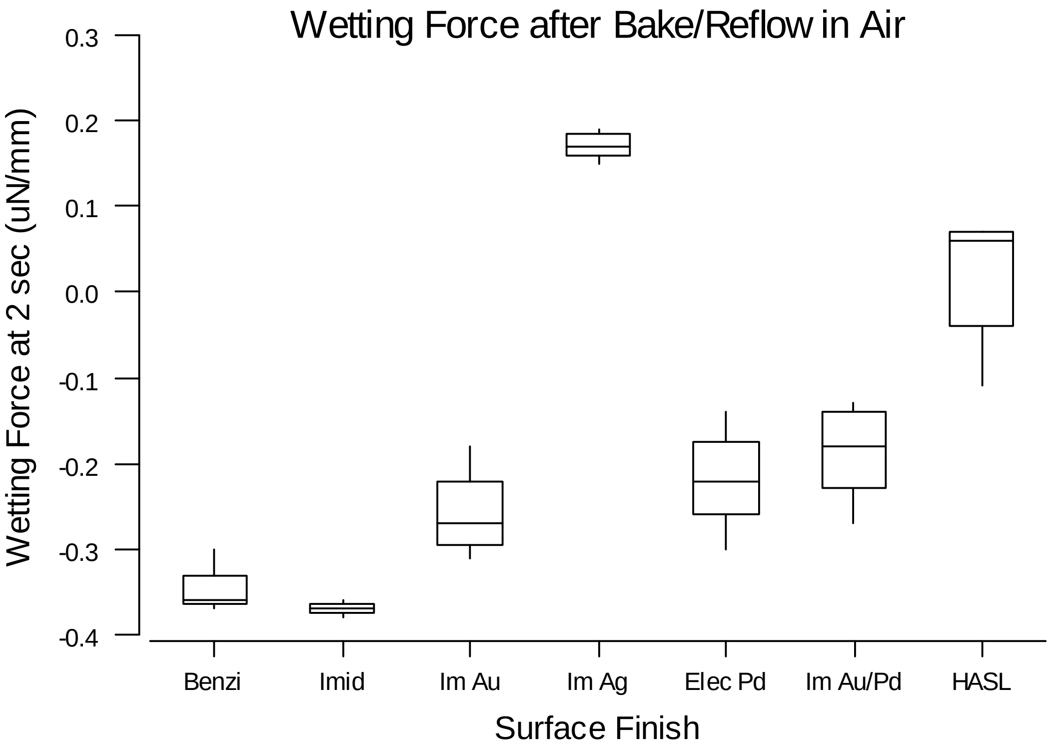

Figure 3.14 Boxplots of Wetting Force for After Bake and Reflow in Air versus Surface Finish

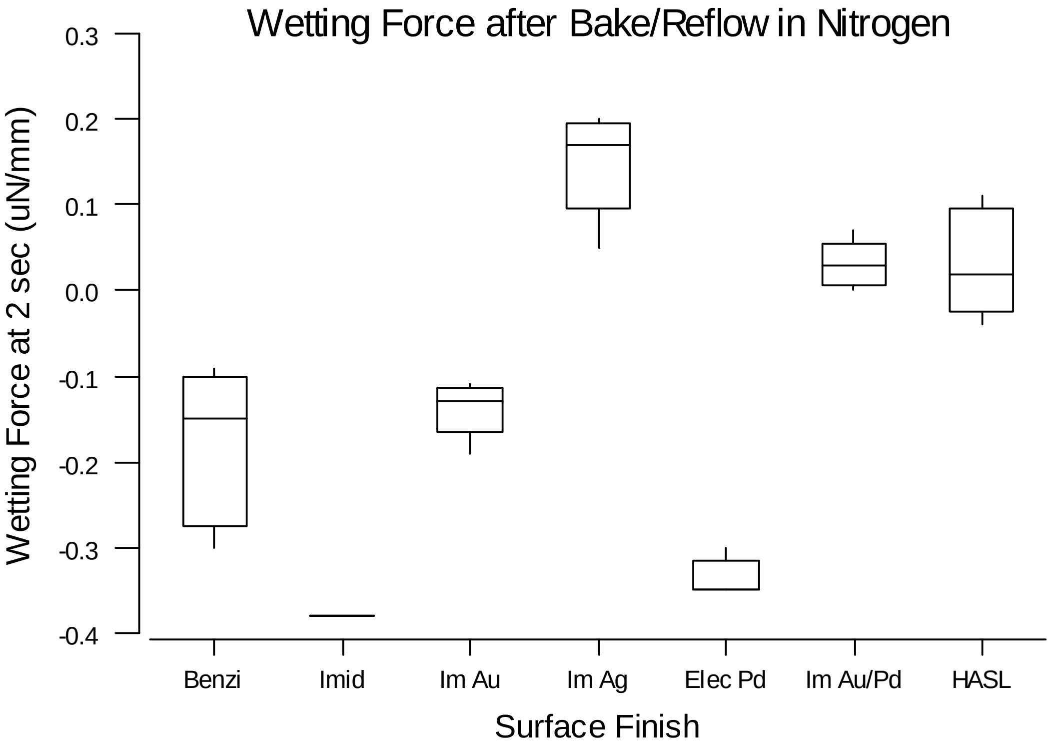

Figure 3.15 Boxplots of Wetting Force for After Bake and Reflow in Nitrogen versus Surface Finish

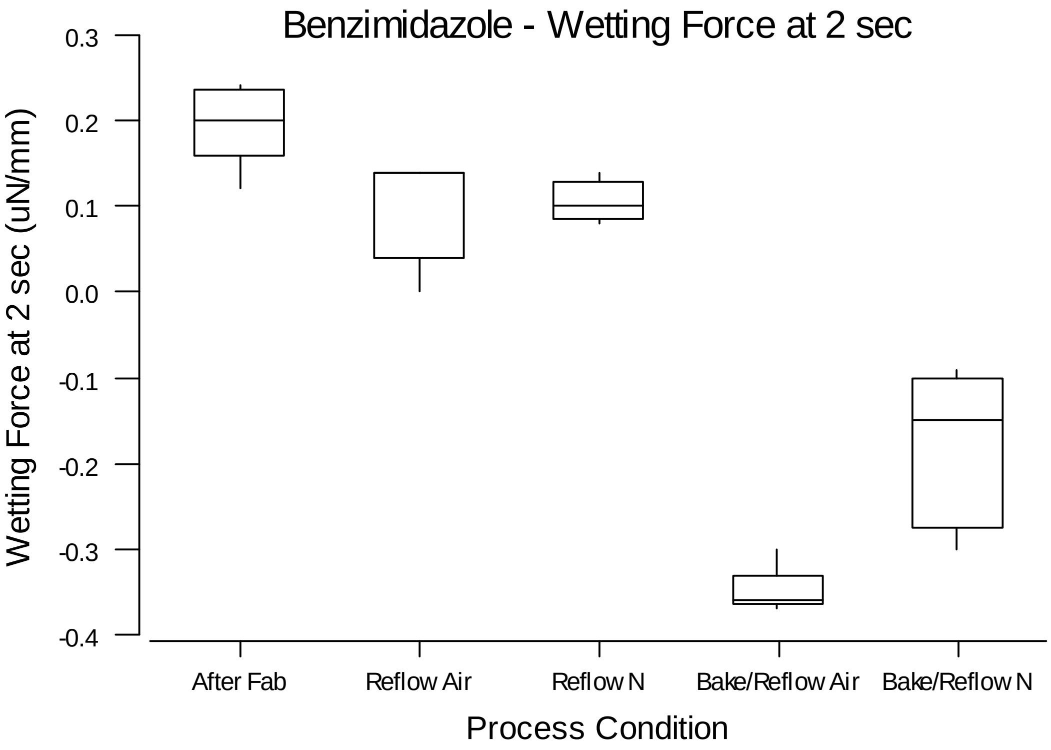

Figure 3.16 Boxplots of Wetting Force for Benzimidazole versus Process Condition

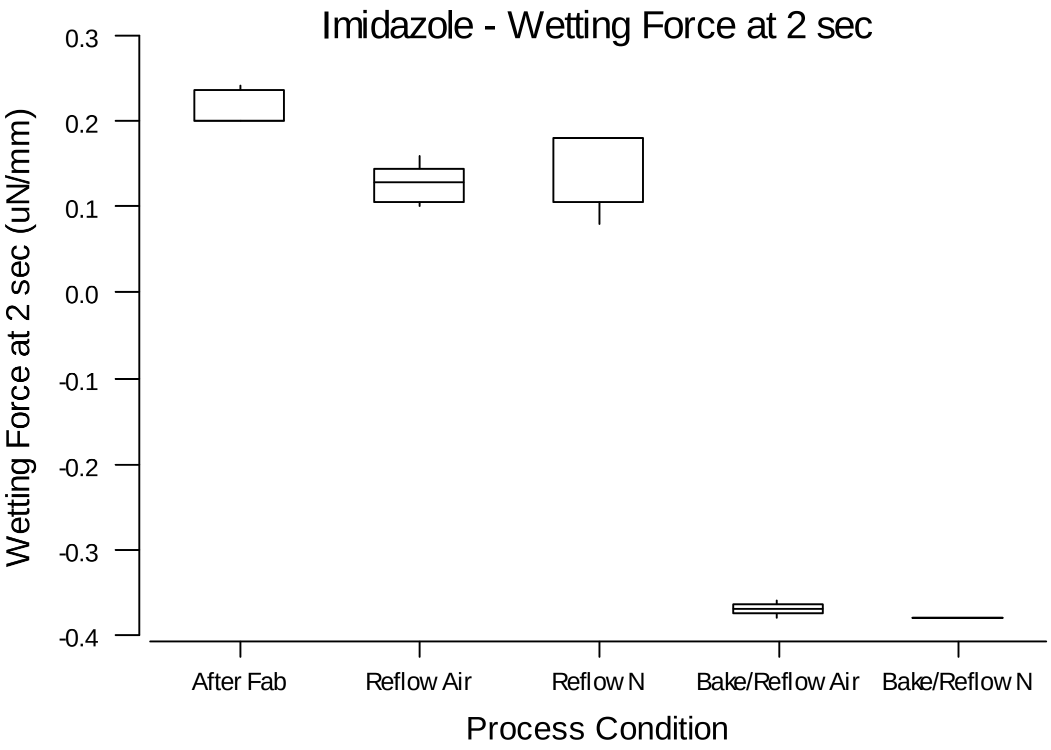

Figure 3.17 Boxplots of Wetting Force for Imidazole versus Process Condition

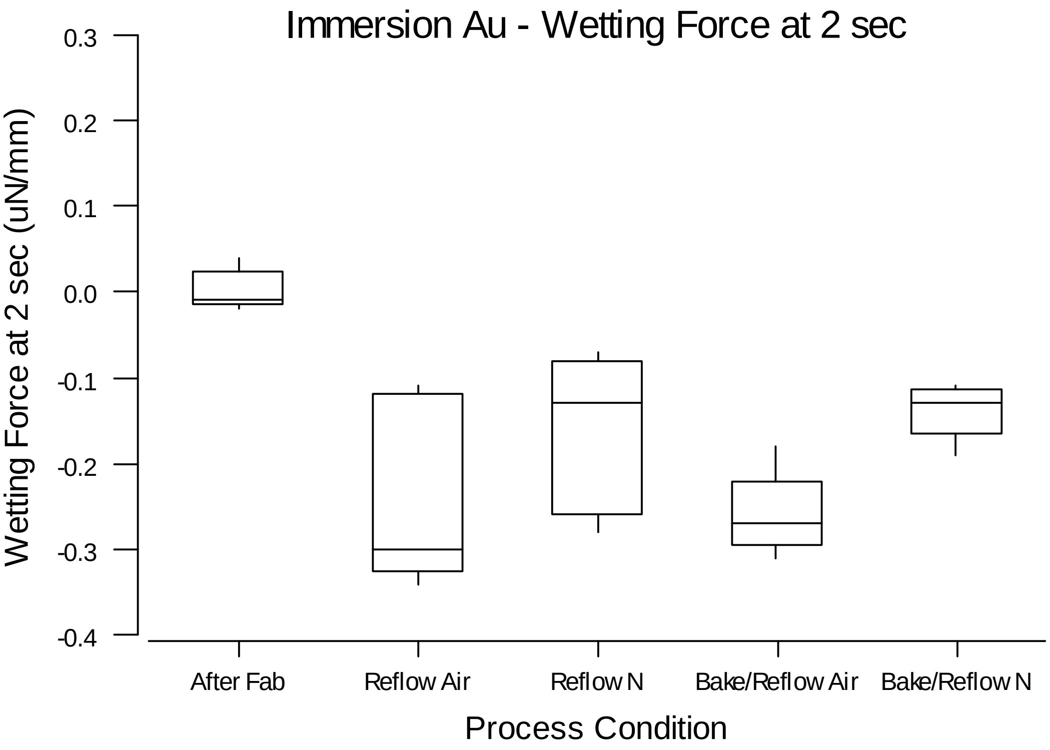

Figure 3.18 Boxplots of Wetting Force for Immersion Au versus Process Condition

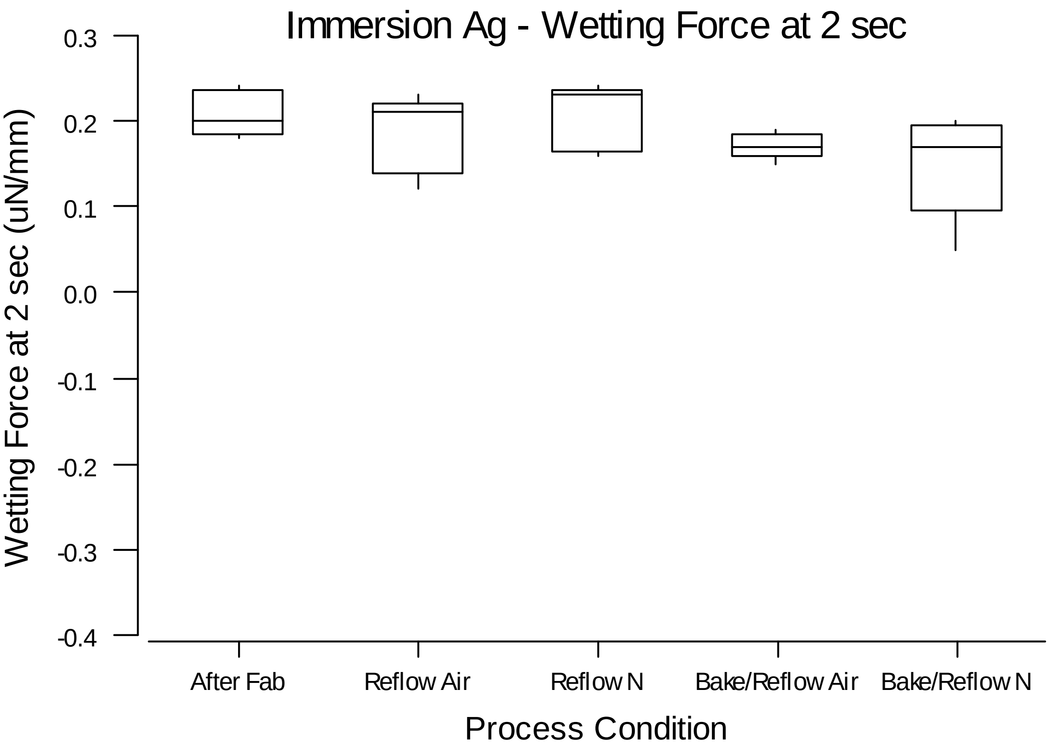

Figure 3.19 Boxplots of Wetting Force for Immersion Ag versus Process Condition

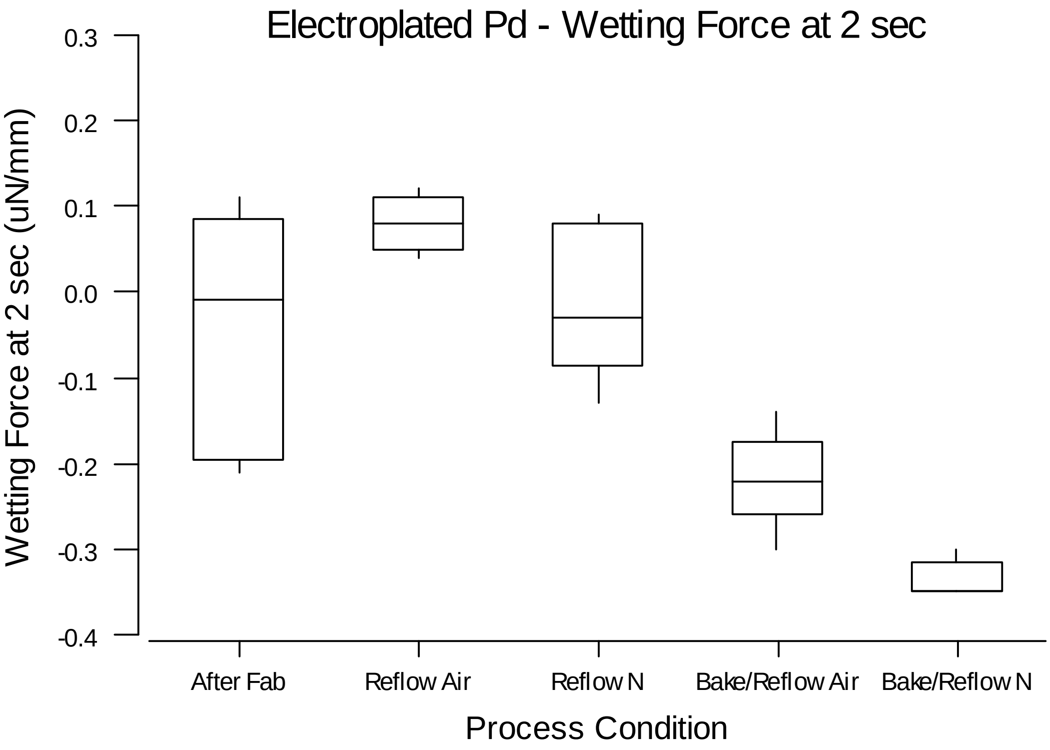

Figure 3.20 Boxplots of Wetting Force for Electroplated Pd versus Process Condition

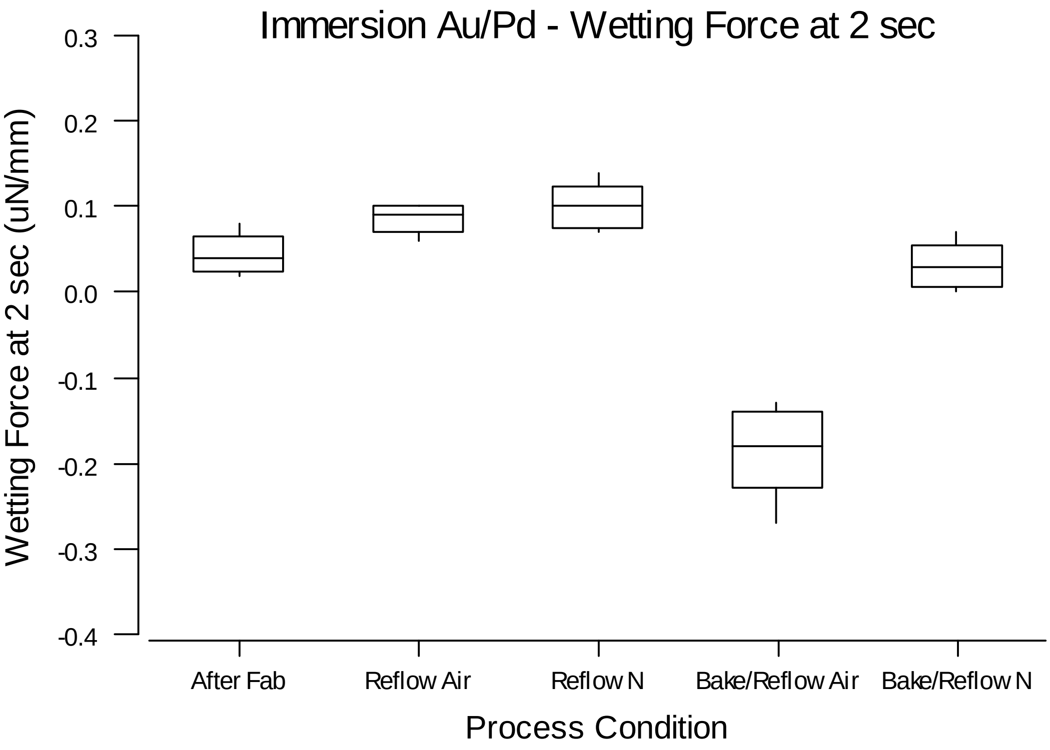

Figure 3.21 Boxplots of Wetting Force for Immersion Au/Pd versus Process Condition

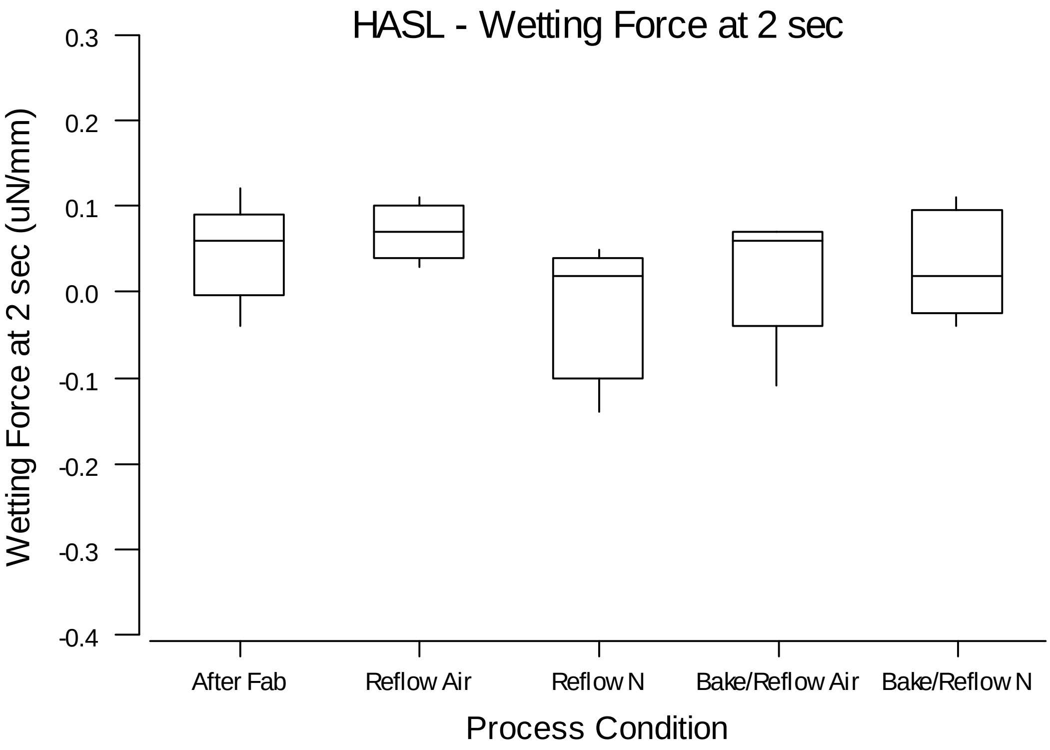

Figure 3.22 Boxplots of Wetting Force for HASL versus Process Condition

Conclusions on ASFs. On the basis of the GLM results for wetting force, immersion Ag is the best ASF and both OSPs give excellent results in the non-baking environments. The performance of immersion Au/Pd is enhanced by processing in nitrogen. On the other hand, neither immersion Au or electroplated Pd appear to be candidates for further investigation.

3.8 Screening Experiment 5: Test Vehicle and Process Exposure for the Spread Test

The second ASF screening experiment utilized a spread test performed on a slightly modified IPC-B-24 test board (see Figure 2.2). Modifications of this board included a 0.400 *in* sampling point that allows evaluation of the surface finish, larger tooling holes (0.125 *in*) to accommodate a larger variety of printers, and fiducials (0.050 *in*) to allow vision alignment during printing.

The modified B-24 boards were produced by Texas Instruments Printed Circuits Resources board fabrication shop in Austin. TI applied the benzimidazole surface finish. Lucent Technologies applied imidazole, palladium, and HASL surface finishes. IBM applied immersion Au, and Alpha Metals applied immersion Ag. (See Table 3.1 for details on surface finish application.) After fabrication, the test boards were shipped to the EMPF for processing.

Figure 3.23 gives a 3-D representation of the test matrix for the second ASF screening evaluation. Half the screening boards were processed with a low-residue, halide-free flux. The remainder were processed with a halide containing water soluble flux. The low-residue paste was Multicore NC40 (ANSI/J-STD-004 flux designation ROL0). The water soluble paste was Multicore WS12 (ANSI/J-STD-004 flux designation ORM1). Five boards were processed for each experimental cell shown in Figure 3.23 (560 total test boards).

The test boards were subjected to one of the following manufacturing processing conditions:

1. As received: printed with paste and reflowed in air — the most solderable condition of each finish
2. As received: printed with paste and reflowed in nitrogen — same as (1)

Table 3.3 GLM Results for all Solderability Tests

Experimental Variables	**Wetting Force**	**Time to Zero Force**	**Time to 2/3 Max**	**V_2**	**V_f**	**Q_3**
Constant	0.03	1.71	2.93	-0.90	-1.39	0.84
Benzimidazole	0.11	-0.76	-0.83		0.19	
Imidazole	0.13	-0.71	-0.87	0.32	0.26	
Immersion Au					0.42	-0.63
Immersion Ag	0.16	-0.73	-0.91	0.37	0.19	1.13
Electroplated Pd	-0.06			0.36	0.69	
Immersion Au/Pd		-0.28		0.26	0.52	-0.48
Reflow Air		-0.11	-0.40			
Reflow Nitrogen			0.18		0.01	
Bake/Reflow Air						
Bake/Reflow Nitrogen				-0.05		0.29
Benzi*Reflow Air		0.66	0.72		0.11	
Benzi*Reflow N		0.51			0.07	
Benzi*Bake/Reflow Air	-0.48	3.85			0.14	-0.84
Benzi*Bake/Reflow N	-0.31	1.17	1.65		0.07	
Imid*Reflow Air		0.37	0.69		0.08	
Imid*Reflow N		0.18				
Imid*Bake/Reflow Air	-0.53	2.85	2.75		0.44	
Imid*Bake/Reflow N	-0.54				0.40	-1.08
Im Au*Reflow Air	-0.27	0.86	1.23			
Im Au*Reflow N	-0.19	0.49	0.43			
Im Au*Bake/Reflow Air	-0.29	0.96	1.02			
Im Au*Bake/Reflow N	-0.17	0.56	0.77			
Im Ag*Reflow Air		0.28	0.33	-0.24	0.07	
Im Ag*Reflow N			-0.31		0.04	
Im Ag*Bake/Reflow Air		0.32		-0.15	0.10	2.11
Im Ag*Bake/Reflow N		0.46			0.06	
Elec Pd*Reflow Air	0.11					
Elec Pd*Reflow N						
Elec Pd*Bake/Reflow Air	-0.19	0.39				
Elec Pd*Bake/Reflow N	-0.31	1.17	1.29			
Im Au/Pd*Reflow Air	0.06				0.15	
Im Au/Pd*Reflow N	0.07		-0.55		0.11	
Im Au/Pd*Bake/Reflow Air	-0.21	0.90	0.94	-0.14	0.05	
Im Au/Pd*Bake/Reflow N		0.19		-0.22	-0.10	
Model R^2	96.8%	91.4%	90.3%	76.6%	98.9%	61.9%
Standard Deviation	0.13	0.06	0.24	0.09	0.03	0.62

Table 3.4 Predicted Means for Wetting Force at 2 *sec* from the GLM Analysis

Surface Finish	Process Condition				
	After Fabrication	Reflow in Air	Reflow in Nitrogen	Bake and Reflow Air	Bake and Reflow N_2
Benzimidazole	0.135	0.135	0.135	-0.350	-0.180
Imidazole	0.163	0.163	0.163	-0.370	-0.380
Immersion Au	0.029	-0.238	-0.162	-0.260	-0.138
Immersion Ag	0.184	0.184	0.184	0.184	0.184
Electroplated Pd	-0.027	0.080	-0.027	-0.218	-0.336
Immersion Au/Pd	0.029	0.086	0.100	-0.184	0.029
HASL	0.029	0.029	0.029	0.029	0.029

3. Pass through the reflow oven in air without paste; then print paste and reflow in air — simulates a double-sided surface mount or mixed technology process
4. Pass through the reflow oven in nitrogen without paste; then print paste and reflow in nitrogen — same as (3)
5. Bake in air for 8 *hr* at 105° *C* (to simulate a moisture bake); then print paste and reflow in air — simulates a typical bake to remove moisture
6. Bake in nitrogen for 8 *hr* at 105° *C* and then print paste and reflow in nitrogen — same as (5)
7. Storage at 50° *C*, 90% RH for 168 *hr*; then print paste and reflow in air — simulates warehouse storage conditions in places like Mexico and Asia
8. Storage at 35° *C*, 90% RH for 168 *hr*; then print paste and reflow in air — same as (7)

The stencil was a laser cut 5-mil thick stainless steel stencil made by Alpha Metals. The stencil apertures were cut in a trapezoidal shape to aid in paste release. Each paste deposit was 0.050 *in* by 0.016 *in*.

The pastes were stored in a refrigerator until about 24 *hr* before use. The pastes were printed on an MPM Ultraprint stencil printer. The squeegees were stainless steel and a double print was used to eliminate variations caused by printing direction. The print speed varied from 0.9 to 1.2 *in*/*sec*, and the total force on the squeegee was 12 *lb*. The typical print speed for the low-residue paste was 1.1 *in*/*sec*. The print speed for the WS paste varied as its viscosity changed. The print speed started at 0.9 *in*/*sec* and was increased to 1.2 as the paste became thinner.

Reflow soldering was done in an Electrovert Omniflow seven-zone reflow oven. This oven is heated by forced air convection. For reflow soldering in nitrogen, oxygen content was kept under 20 *ppm*.

Bakes were done in a vacuum oven with no convection. For the bake in nitrogen, the boards were placed in the oven, the air was evacuated, and the chamber was back-filled with nitrogen. At one atmosphere the chamber was not air-tight, so for the nitrogen bake the oven was kept at just under one atmosphere.

To minimize the effects of finish degradation during conditioning, all boards were stored in a low-humidity nitrogen environment when not subjected to the various treatments.

The boards soldered with LR flux were not cleaned after soldering. The boards soldered with WS flux were cleaned after soldering using an aqueous process.

3.9 The Spread Test

Each comb pattern shown on the B-24 in Figure 2.2 has 35 lines. These lines are 0.016 *in* wide and are separated by 0.020 *in* spaces. On three of the patterns the lines were printed with paste deposits 0.100 *in* long by 0.016 *in* wide (the width of the line) separated by gaps of 0.003 *in* on the first line and increased by 0.003 *in* increments on the remaining lines until the gap was 0.105 *in* on the last line. On the remaining pattern the gap started at 0.105 *in* on the first line and incrementally increased by 0.005 *in* on the remaining lines. The average gap width spanned was reported for each board. Solder mask

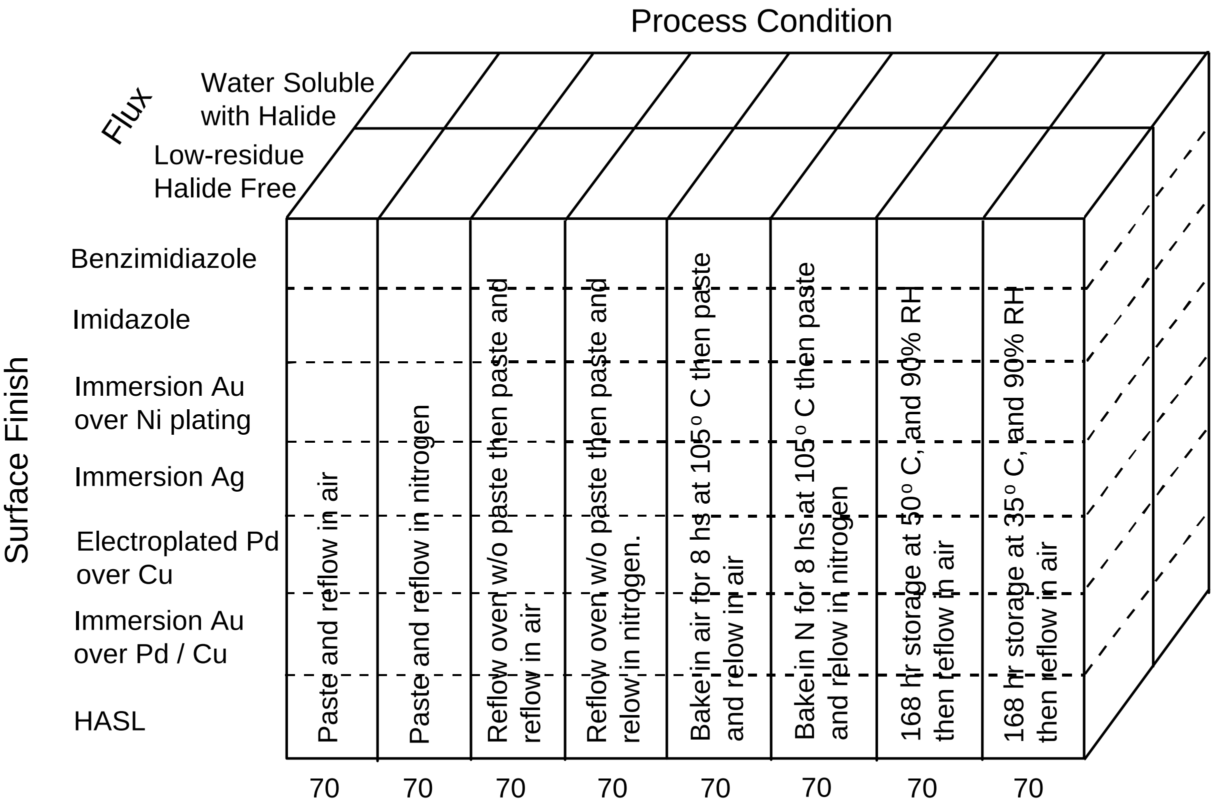

Figure 3.23 Three-Dimensional Representation of the Test Matrix for the Second Alternative Surface Finish Screening Experiment (5 test boards per cell, 560 total test boards)

was applied on the copper pads that connect to the 16-mil lines.

When the test was done, it became apparent that the gap width spanned on the HASL boards could not be determined since solder paste deposited on top of SnPb makes it visually impossible to determine if the gap had been spanned. Thus, the bottom layer of the planned test matrix in Figure 3.23 was not included in the spread test.

A second problem occurred with electroplated Pd and immersion Au/Pd on WS flux boards. These boards soldered poorly, and the paste changed character quickly; hence these boards were dropped from the test matrix, resulting in no data being recorded for these two rows (16 cells) in the test matrix. The means for the remaining experimental cells are shown in Table 3.5.

3.10 Boxplot Displays for Spread Test Measurements

Boxplots are presented in Figures 3.24 to 3.29 showing spread test results for each surface finish versus process condition, while Figures 3.30 to 3.37 display each process condition versus surface finish. Results for both fluxes appear in each figure except where either electroplated Pd or immersion Au/Pd is involved. Since there are no results for HASL, there is no known standard against which to compare the spread test results. Good spread is required for wetting to the corners of the pads for surface mount or for good top-side wetting with through hole, but the exact magnitude of the spread is somewhat application dependent. None of the boards processed in the spread test experiment experienced dewetting or non-wetting, so all results are probably acceptable. However, the magnitude of the spread is process dependent as will be shown in the discussion that follows.

OSPs. Figure 3.24 shows that benzimidazole performs best in a nitrogen atmosphere with LR flux (these results were truncated at 90 mils). The same is true of imidazole in Figure 3.25, but the magnitude of the spread is less than that achieved with benzimidazole. The 168 *hr* storage gave approximately the same level of spread as did the other non-nitrogen processes.

Noble Metals. Based on the poor performance of immersion Au in the wetting force tests presented earlier in this section, the results in Figure 3.26 may come as a surprise. Immersion Au had the best spreading ability over all process conditions with either flux, with the sole exception of benzimidazole after processing in N_2. These results can be seen by comparing the means in Table 3.5 As shown in Figure 3.27, immersion Ag with LR flux is a strong second to immersion Au, with the exception of three of the eight processing conditions where benzimidazole has better spread. Immersion Ag is invariant to the process condition, as was the case in the wetting force experiments. The immersion Ag results could possibly have been affected by a change in process sequence. Immersion Ag surfaces are readily tarnished, so an organic inhibitor is included in the plating bath to protect the surface. However, this inhibitor was removed by the application of a liquid photo-imageable solder mask. This could lower the solderability of the immersion Ag boards in the spread test.

Figure 3.28 underscores the poor spreading ability of electroplated Pd. This surface finish also performed poorly in the wetting force experiment. As was true in the previous experiments, immersion Au/Pd benefits from processing in nitrogen, as shown in Figure 3.29.

The benefits of using nitrogen with benzimidazole, imidazole, immersion Au, immersion Au/Pd, and, to a lesser degree, electroplated Pd, can be seen by comparing Figures 3.30, 3.32, and 3.34 with their respective counterparts in Figures 3.31, 3.33, and 3.35. As mentioned above, immersion Ag is invariant to process condition.

Figures 3.36 and 3.37 show that the spreading ability of immersion Au and immersion Ag was not impacted by the 168 *hr* storage. The reader should keep in mind that, as was stated previously, none of the boards processed in the experiment experienced dewetting or non-wetting. Also, note there does not appear to be much difference between the two storage temperatures used in the experiment.

3.11 General Linear Modeling for Spread Tests

The GLM used for the analysis of the spread test results is as follows:

$$\begin{aligned} Y = {} & \beta_0 + \beta_1 D_1 + \beta_2 D_2 + \beta_3 D_3 + \beta_4 D_4 + \beta_5 D_5 \\ & + \beta_6 D_6 + \beta_7 D_7 + \beta_8 D_8 + \beta_9 D_9 + \beta_{10} D_{10} + \beta_{11} D_{11} \\ & + \beta_{12} D_{12} + \beta_{13} D_{13} + \text{ 66 interaction terms} \qquad (3.2) \end{aligned}$$

For ease of comparison, the base case is usually a well studied process — the other experiments in this report used HASL. However, HASL is not part of the spread test data base; so, a different base case had to be defined. Benzimidazole with LR flux and processing in air without paste after fabrication was chosen as the base case for this model. The dummy variables in the GLM are defined as follows:

D_1 = 0 if surface finish is not imidazole
= 1 if surface finish is imidazole
D_2 = 0 if surface finish is not immersion Au
= 1 if surface finish is immersion Au
D_3 = 0 if surface finish is not immersion Ag
= 1 if surface finish is immersion Ag
D_4 = 0 if surface finish is not electroplated Pd
= 1 if surface finish is electroplated Pd
D_5 = 0 if surface finish is not immersion Au/Pd
= 1 if surface finish is immersion Au/Pd
D_6 = 0 if flux is not water soluble with halide
= 1 if flux is water soluble with halide
D_7 = 0 if not reflowed in nitrogen
= 1 if reflowed in nitrogen
D_8 = 0 if not pasted and reflowed in air
= 1 if pasted and reflowed in air
D_9 = 0 if not pasted and reflowed in N_2
= 1 if pasted and reflowed in N_2
D_{10} = 0 if not baked for 8 *hr* and reflowed in air
= 1 if baked for 8 *hr* and reflowed in air
D_{11} = 0 if not baked for 8 *hr* and reflowed in N_2
= 1 if baked for 8 *hr* and reflowed in N_2
D_{12} = 0 if not stored at 50°*C* and reflowed in air
= 1 if stored at 50°*C* and reflowed in air
D_{13} = 0 if not stored at 35°*C* and reflowed in air
= 1 if stored at 35°*C* and reflowed in air

The interaction terms include all combinations of the experimental factors except those involving flux with either electroplated Pd or immersion Au/Pd. These terms were not included because no data were obtained for these finishes with WS flux.

Table 3.6 contains the results of the GLM analyses for the spread test data. The coefficients shown in that table are expressed in mils. The constant term indicates that the base case (benzimidazole with LR flux and processing in air after fabrication) has a spread of 5.5 mils (the actual observed mean in Table 3.5 is 6.6 mils).

Table 3.5 Cell Means for the Spread Test

		Process Condition							
Surface Finish	**Flux**	**Reflow Air**	**Reflow N_2**	**No Paste Reflow Air**	**No Paste Reflow N_2**	**Bake & Reflow Air**	**Bake & Reflow N_2**	**Store 50°C & Reflow**	**Store 35°C & Reflow**
Benzimid	**LR**	6.6	90.0	7.8	23.8	6.8	44.0	6.0	6.8
	WS	7.4	20.2	6.4	17.0	5.0	17.6	5.8	6.2
Imidazole	**LR**	10.8	40.6	6.6	29.8	5.2	4.6	7.2	9.4
	WS	5.6	21.0	4.5	21.0	4.6	8.0	4.8	4.0
Im Au	**LR**	63.2	74.4	55.4	66.4	60.0	67.6	54.4	56.2
	WS	70.6	80.8	66.8	77.6	58.2	76.6	59.8	37.8
Im Ag	**LR**	28.2	38.0	32.4	32.6	27.2	30.8	28.2	27.0
	WS	14.8	32.6	13.4	31.4	10.0	29.2	20.6	19.0
Elec Pd	**LR**	3.4	6.2	3.0	7.0	2.4	4.0	4.0	3.2
	WS								
Im Au/Pd	**LR**	5.2	40.2	3.8	80.8	4.3	40.2	3.4	4.6
	WS								

The positive coefficients for immersion Au (53.4) and immersion Ag (23.1) indicate significant increases over the base case. The same is true for processing in nitrogen: reflow after fabrication in N_2 (84.5), paste and reflow in N_2 (17.4), and bake and reflow in N_2 (36.6). However, all coefficients relative to a given combination of surface finish, flux, and process condition, must be summed to correctly judge the change from the base case. Of course, these values can be found as the predicted means.

Mean Prediction. The predicted means from the GLM for the spread test are given in Table 3.7. The predictions show excellent agreement with the observed means in Table 3.5.

Conclusions on ASFs. On the basis of the GLM results, immersion Au gives the best spread results with immersion Ag and benzimidazole in competition for second place. The performance of immersion Au/Pd is enhanced by processing in nitrogen, while electroplated Pd gives the poorest results.

The most intriguing result relative to the two solderability tests is that immersion Au gave the poorest results for the wetting force test, but it gave the best results in the spread test. Good wetting is an important and well accepted metric for good solderability. As the following discussion shows, hasher environments affected wetting for most of the surfaces, but wetting for immersion Au was also adversely affected by non-harsh environments.

HASL was included in the wetting force experiments since it is a well known process and can, therefore, serve as a basis for evaluating the performance of the other surface finishes. Figure 3.11 shows that all surface finishes are competitive with HASL after fabrication, with the possible exception of electroplated Pd, and that benzimidazole, imidazole, and immersion Ag are clearly superior to HASL. After reflow in air, as shown in Figure 3.12, immersion Au clearly has the poorest wetting and immersion Ag has the best, with the remaining surface finishes equivalent to HASL. It can be seen in Figure 3.13 that immersion Au, electroplated Pd, and even HASL and negatively impacted by reflow in nitrogen, while benzimidazole, imidazole, immersion Ag, and immersion Au/Pd all are superior to HASL. The harsher environment represented by the 8 hr bake in air Figure 3.14 shows all surface finishes significantly lower than HASL, with the exception of immersion Ag which has significantly better wetting than HASL. When the 8 *hr* bake is done in nitrogen, as shown in Figure 3.15, benzimidazole, immersion Au, and immersion Au/Pd all improve, with the latter being equivalent to HASL.

Since HASL was not evaluated in the spread test, there is no well known process to compare against. However, it has been stated previously that while spread is clearly process dependent, none of the boards processed in the spread test experiment experienced dewetting or non-wetting in any of the environments. Thus, while all surface finishes did not have the same spread, the observed spreads are probably acceptable for all finishes and, therefore, the spread test results may not be a good discriminator for downselection.

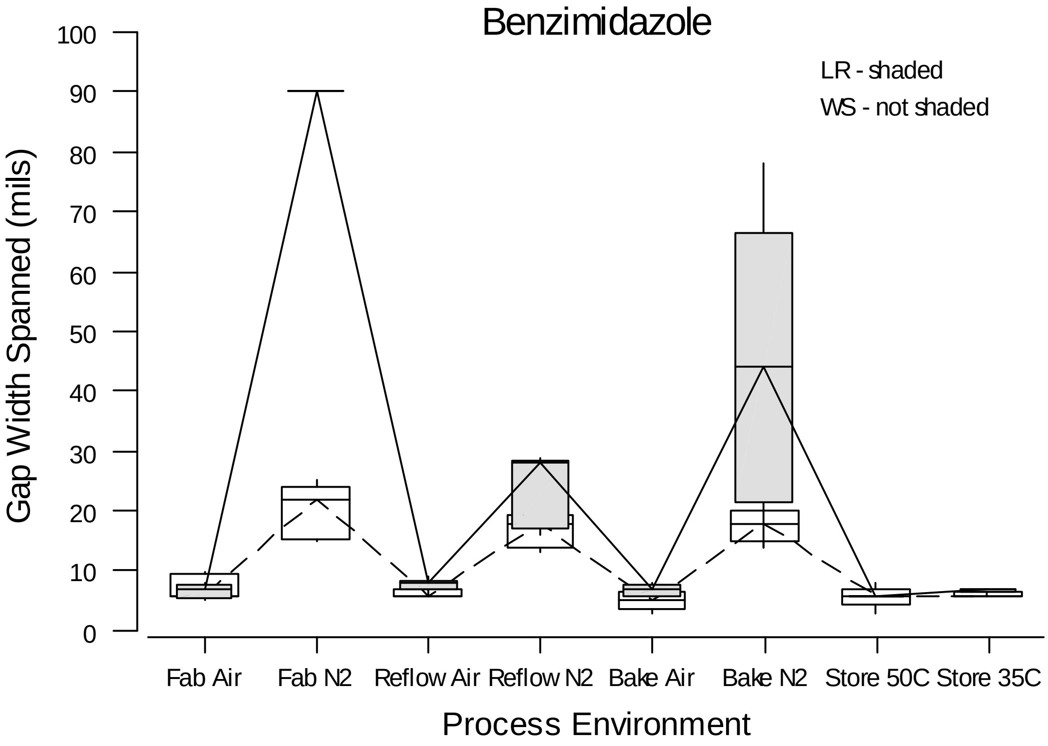

Figure 3.24 Boxplots of Spread Test Results for Benzimidazole by Process Condition

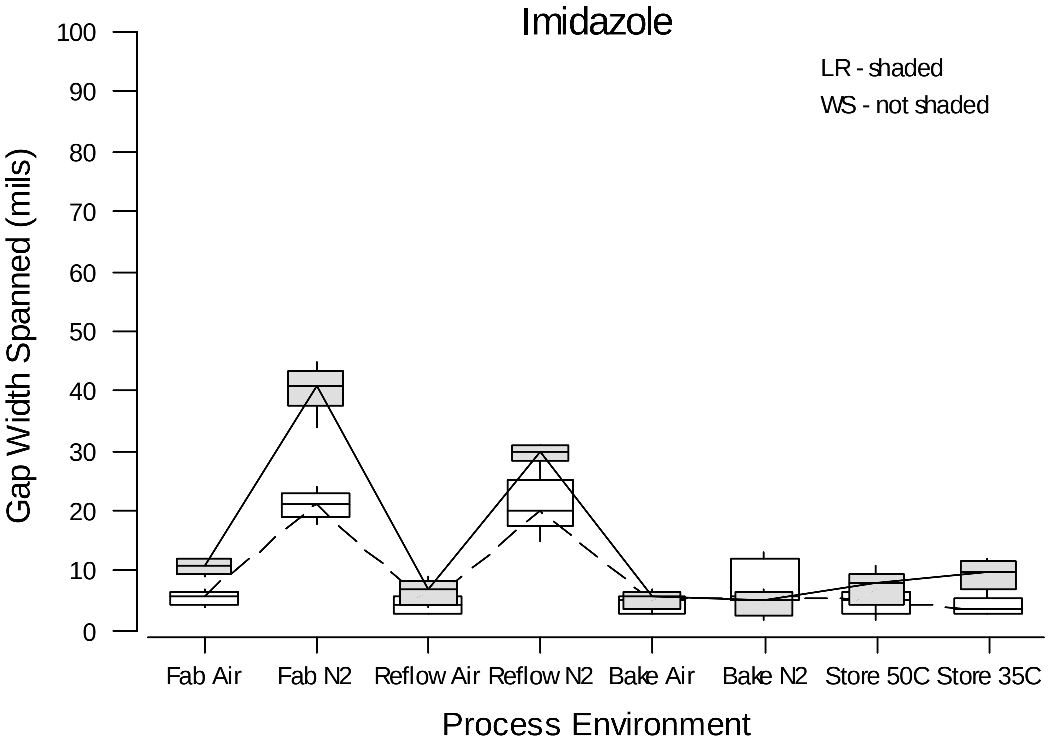

Figure 3.25 Boxplots of Spread Test Results for Imidazole by Process Condition

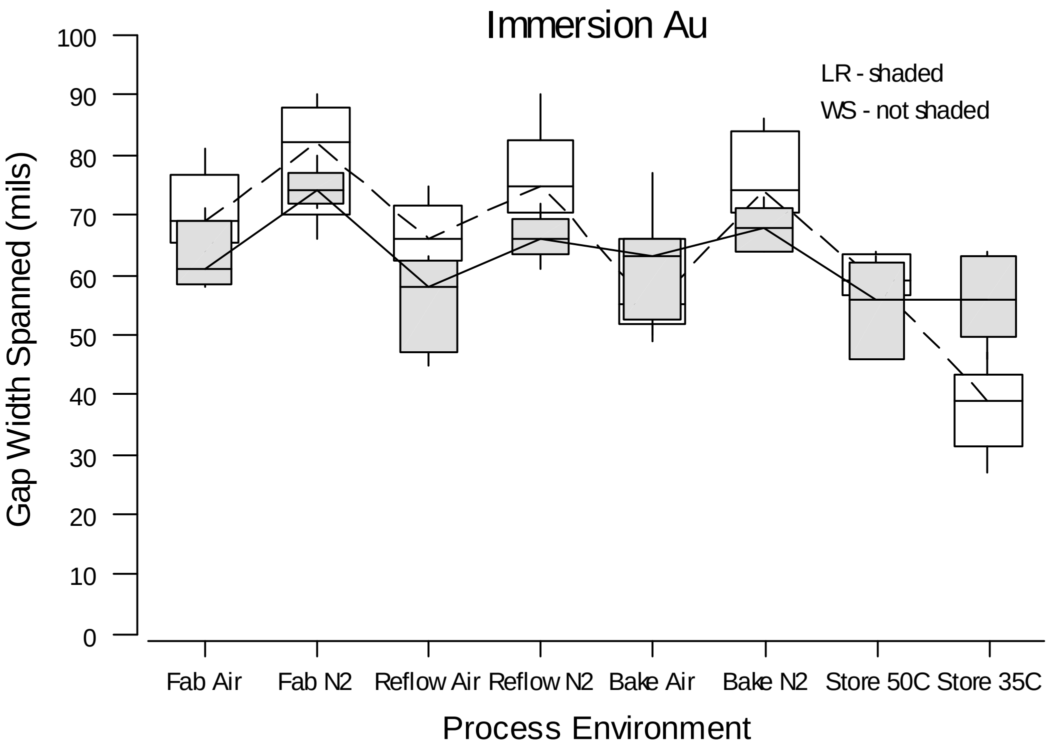

Figure 3.26 Boxplots of Spread Test Results for Immersion Au by Process Condition

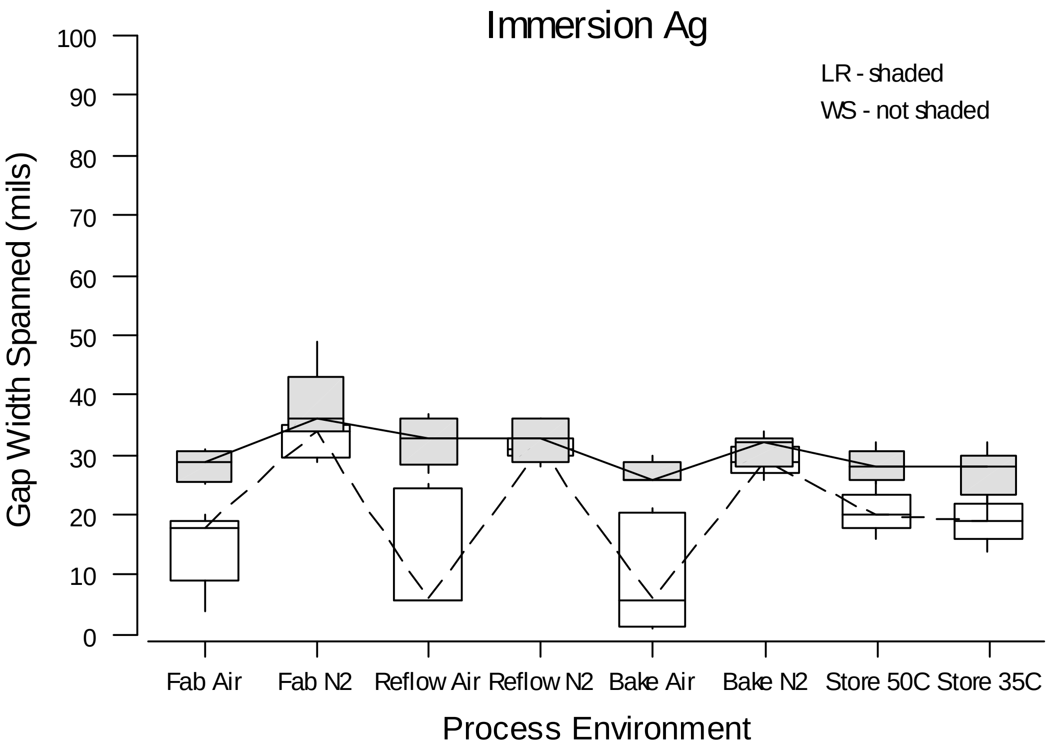

Figure 3.27 Boxplots of Spread Test Results for Immersion Ag by Process Condition

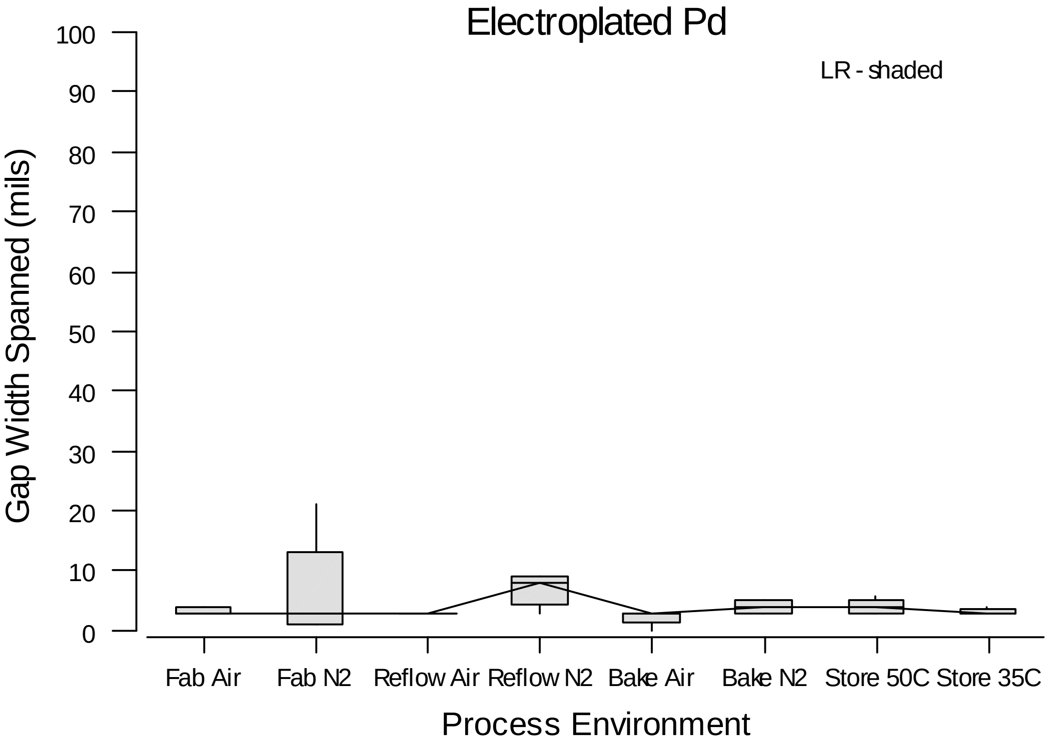

Figure 3.28 Boxplots of Spread Test Results for Electroplated Pd by Process Condition

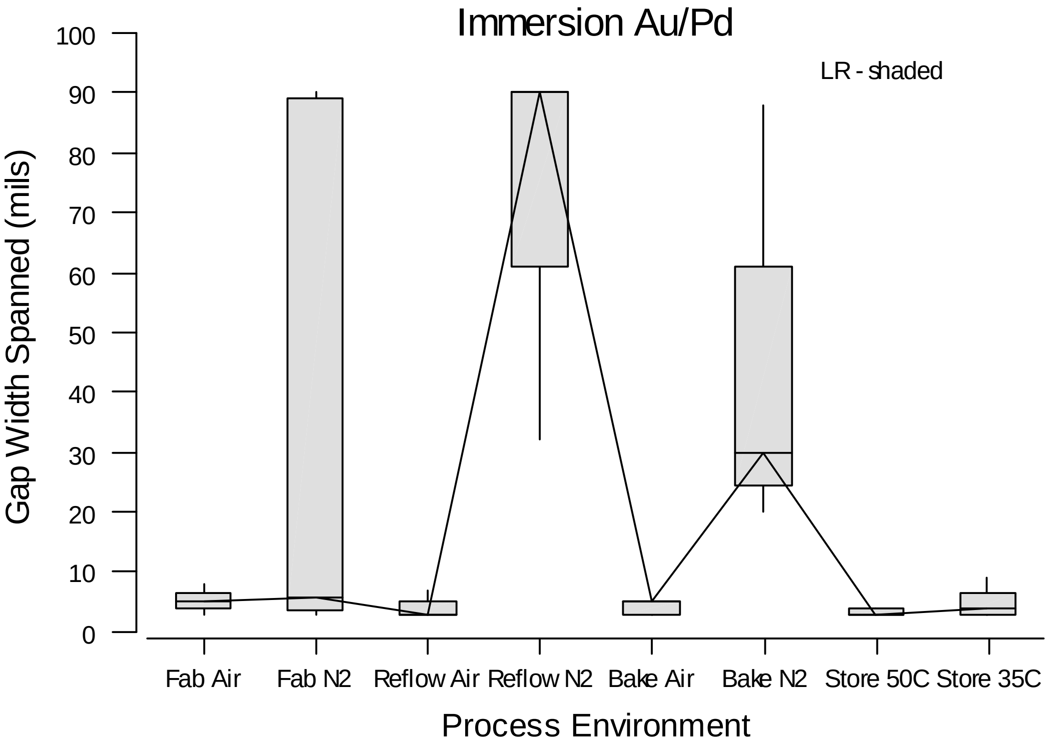

Figure 3.29 Boxplots of Spread Test Results for Immersion Au/Pd by Process Condition

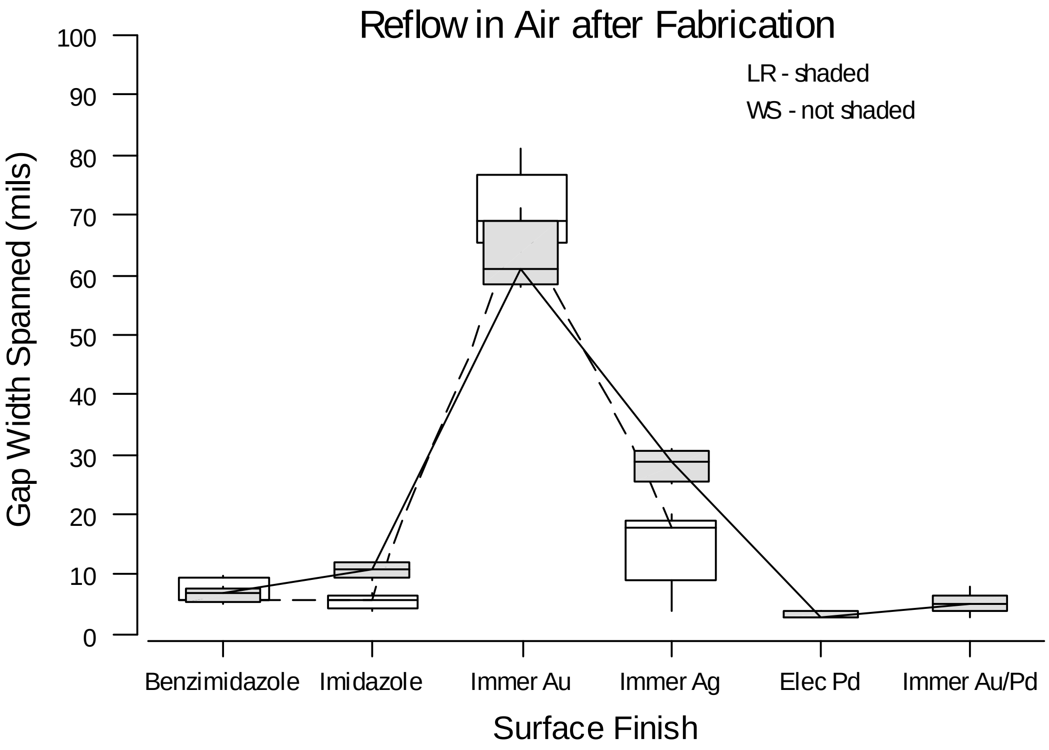

Figure 3.30 Boxplots of Spread Test Results for Reflow in Air by Surface Finish

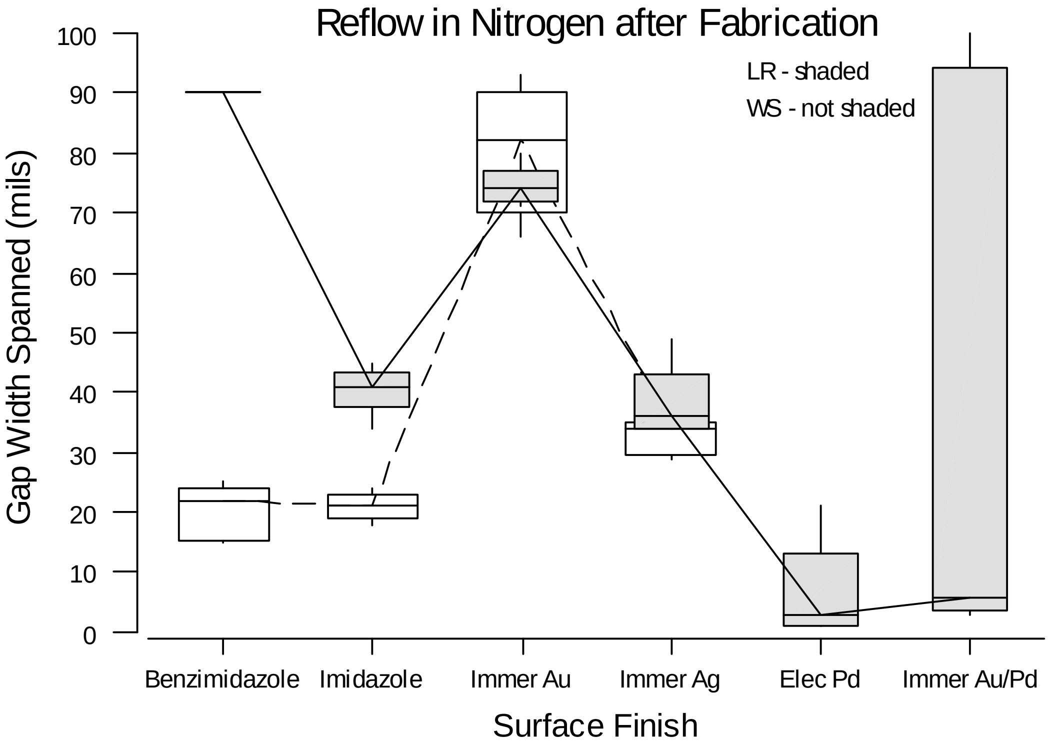

Figure 3.31 Boxplots of Spread Test Results for Reflow in Nitrogen by Surface Finish

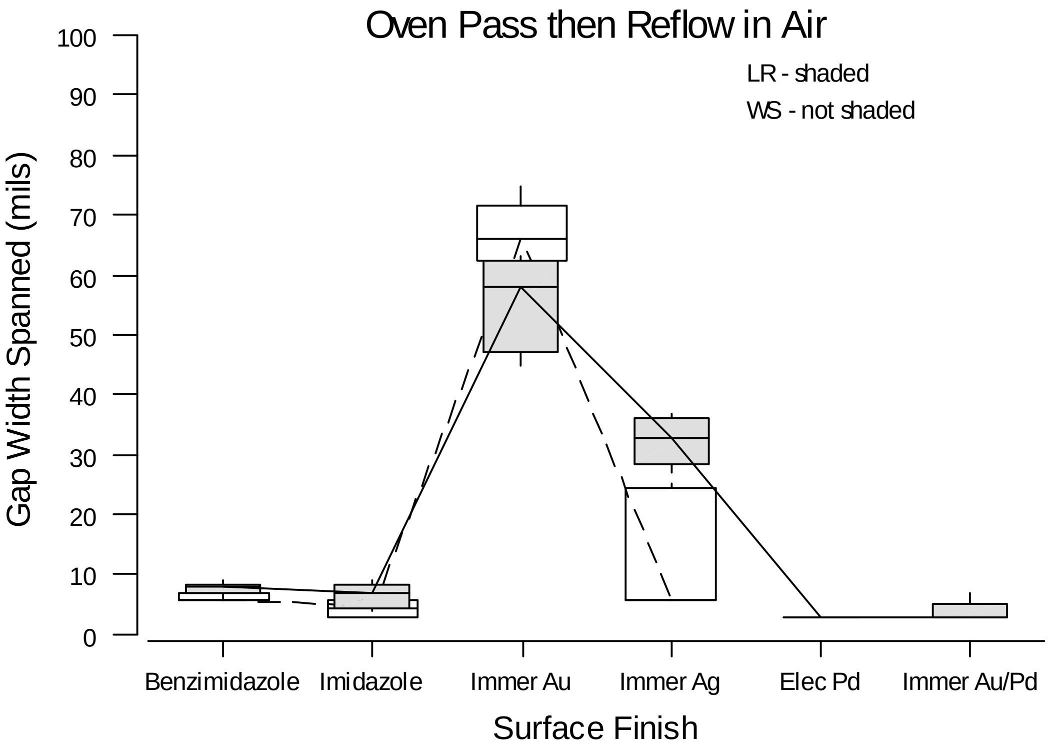

Figure 3.32 Boxplots of Spread Test Results for Oven Pass / Reflow in Air by Surface Finish

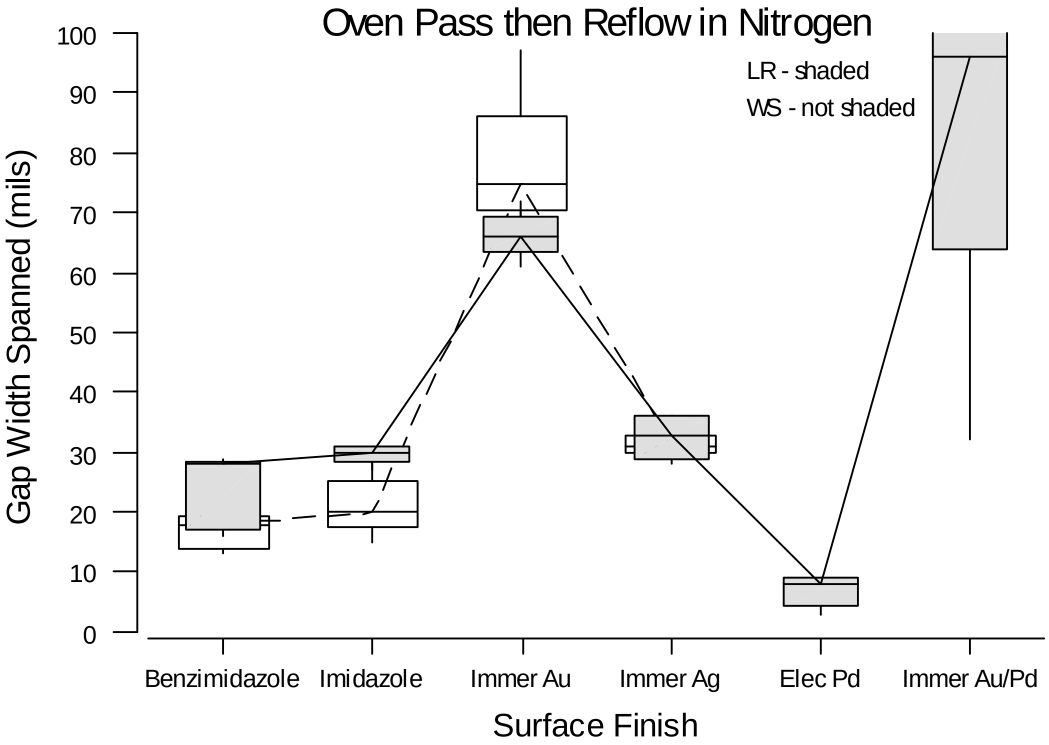

Figure 3.33 Boxplots of Spread Test Results for Oven Pass / Reflow in Nitrogen by Surface Finish

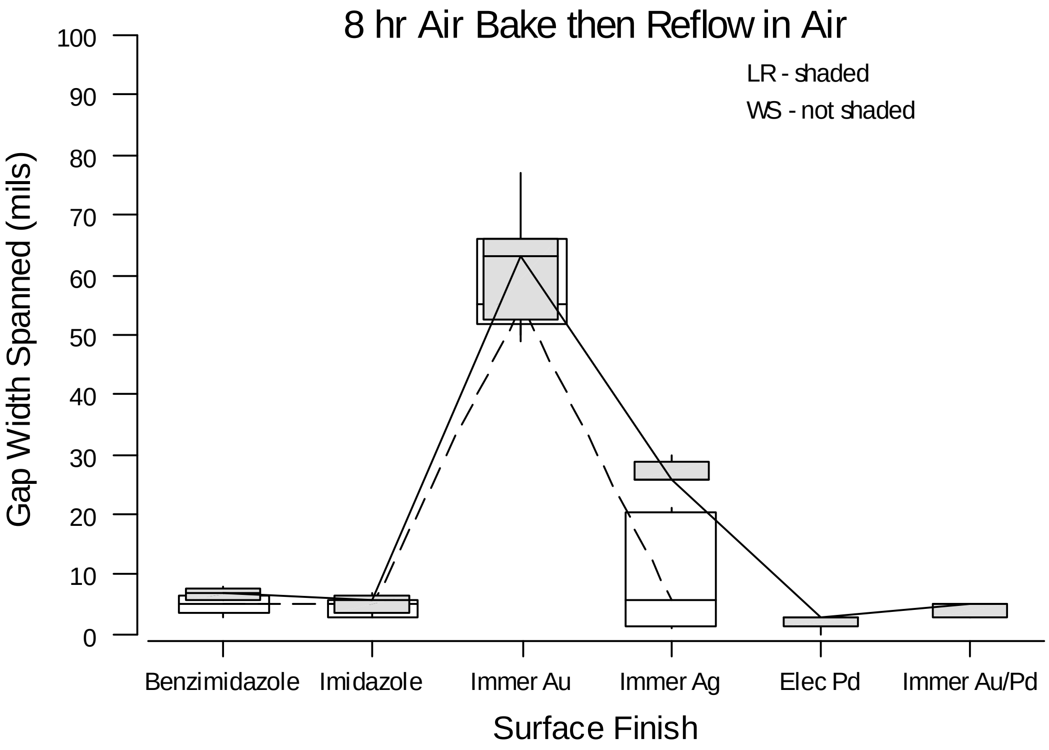

Figure 3.34 Boxplots of Spread Test Results for 8 *hr* Bake and Reflow in Air by Surface Finish

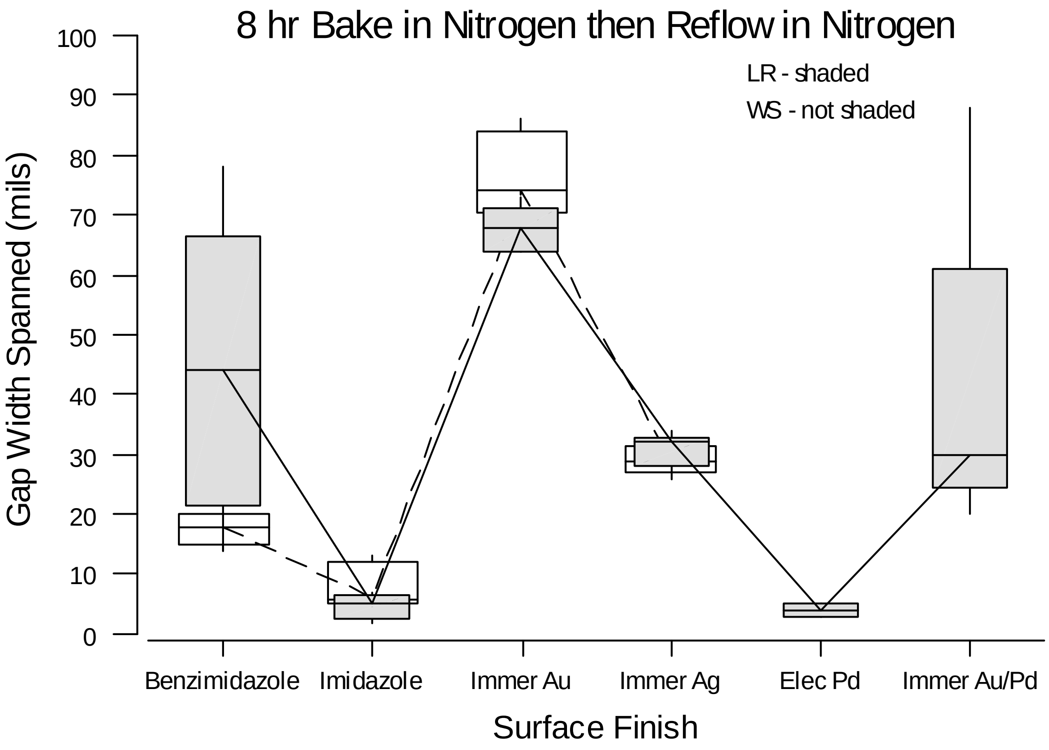

Figure 3.35 Boxplots of Spread Test Results for 8 *hr* Bake and Reflow in Nitrogen by Surface Finish

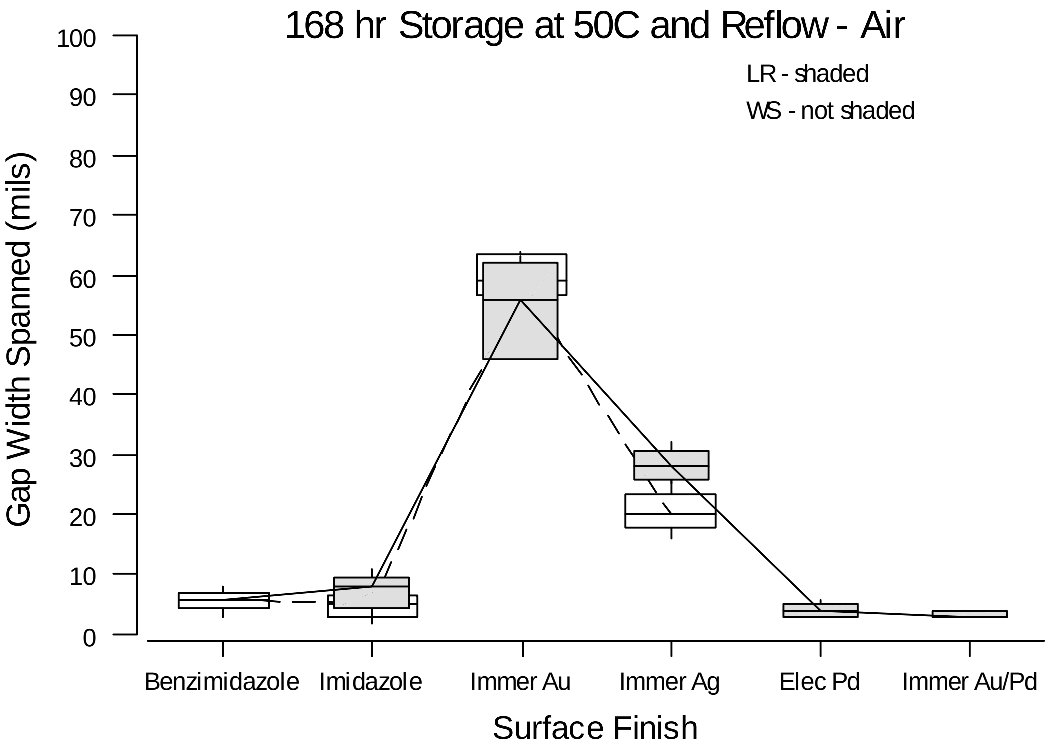

Figure 3.36 Boxplots of Spread Test Results for 168 hr Storage at 50°*C* in Air / Reflow by Surface Finish

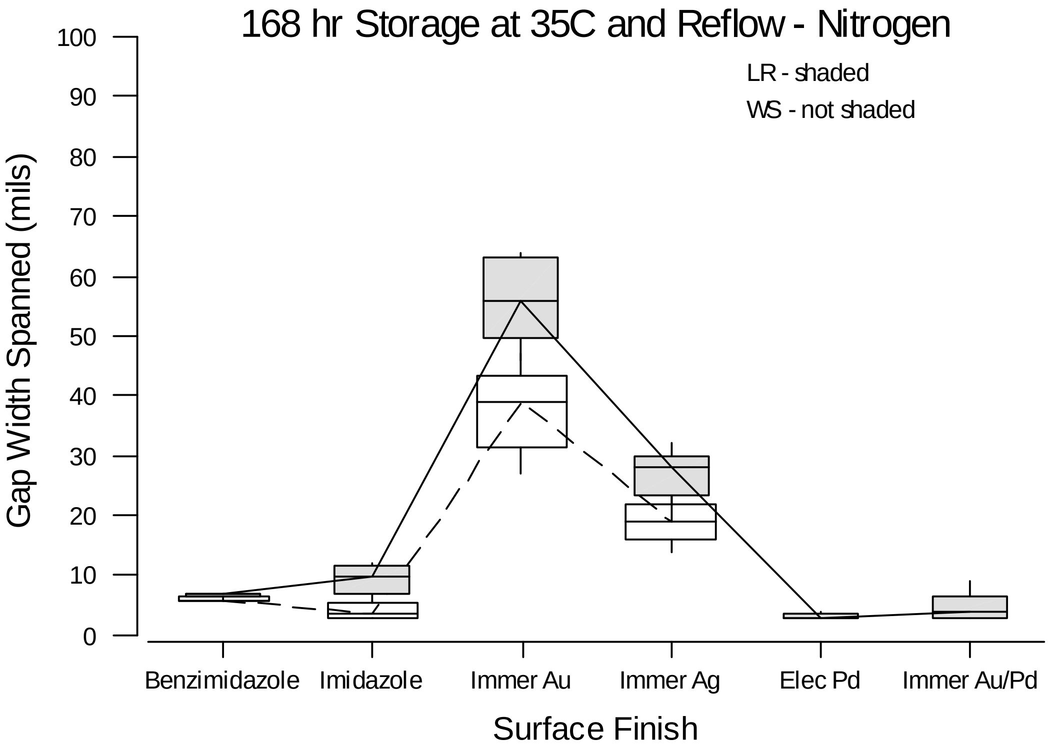

Figure 3.37 Boxplots of Spread Test Results for 168 hr Storage at 35°*C* in Air / Reflow by Surface Finish

3.12 Summary of Solderability Screening Experiments

Two screening experiments were used to evaluate the solderability of ASFs. One experiment involved six separate solderability tests on copper coupons. After comparing these six test measurements, wetting force at 2 *sec* was selected as the best of the six metrics for downselecting surface finishes. The second experiment quantified the average gap spanned after paste was applied with gaps to the lines composing the comb pattern on a modified IPC-B-24 board. Boxplots were used to display these test results, and GLM analyses were performed with each data set to identify the statistically significant experimental factors.

Figures 3.38 to 3.41 contain composite graphs comparing the results of the two experiments for each surface finish. The vertical axis of these graphs represents wetting force observed on the copper coupons, as recorded at TI's board facility in Austin. The horizontal axis represents spread test measurements recorded at the EMPF on the modified IPC-B-24 board. The desired direction for both axes is toward higher values.

Boxes have been created within each graph to represent the range of measurements observed for each surface finish. Thus, each box provides an estimate of the "experimental space" for the outcomes of the two tests. All but one surface finish in Figure 3.38 are in the upper left-hand corner and above zero wetting force. The exception is immersion Au, which is in the lower right-hand corner. The location of the box for immersion Au indicates good spreading and poor wetting force. Comparing Figures 3.38 and 3.39 shows the benefit of nitrogen with reflow as the boxes in the latter figure have all moved upward and to the right (the desired directions for improvement).

Figures 3.40 and 3.41 offer similar comparisons for an 8-*hr* bake prior to reflow. In Figure 3.40, the OSPs, electroplated Pd, and immersion Au/Pd are all in the lower left-hand corner, indicating poor wetting and low spread. Immersion Ag is in the upper left-hand corner, which shows that it is invariant to this environment. Wetting and spread both increased for benzimidazole and immersion Au/Pd when processed in nitrogen, as shown in Figure 3.41. However, nitrogen does not improve either metric for imidazole or electroplated Pd.

Immersion Ag had the best overall performance in the two screening experiments. OSPs were competitive with immersion Ag in the non-baking environments. Neither OSP showed adequate wetting when measured by the wetting balance test in the baking environment. Immersion Au/Pd with nitrogen produced results that make it a possible candidate for further evaluation. On the other hand, there seems to be little support for continued evaluation of either immersion Au (cost is also a factor for this surface finish) or electroplated Pd.

Benzimidazole and imidazole gave similar results, but benzimidazole was selected over imidazole for Phases 1 and 2. Reasons for selecting benzimidazole were based more on practical considerations than on technical reasons. Specifically, only one OSP was selected to reduce the size and cost of Phases 1 and 2. In addition, benzimidazole is currently being used by CCAMTF military participants.

3.13 SIR Testing with ASF Test Vehicles

At the conclusion of the solderability experiments, LR boards used in the spread test with the following finishes: benzimidazole, immersion Au, immersion Ag, electroplated Pd, and immersion Au/Pd, were subjected to SIR testing in the 85/85 environment. The purpose of this additional test was to ensure that these additional surface finishes would give SIR results comparable to those observed on the surface finishes used in the original SIR 85/85 test. Two boards were tested for each of the additional surface finishes. The results of this testing were previously given in the last five rows of Table 2.1. The 16-mil results in that table show that the initial SIR was low for electroplated Pd, but acceptable for all other finishes (approximately10 to 11.5 megohms). During environment, this group of boards faired as well as the other finishes used in the original SIR 85/85 screening experiment, with electroplated Pd giving the lowest SIR. At post 24 *hr*, all boards had acceptable SIR (approximately 10.2 to 12.7 megohms).

These LR boards were also checked for surface contaminants by CSL. Results of these analyses are given in Table 3.8 for chloride, bromide, and weak organic acids in μg/*in*^{2}. The values in Table 3.8 are all well within acceptable limits of 2.5 μg/*in*^{2}.

Table 3.6 GLM Results for Spread Tests (coefficients are mils)

Experimental Variables	Spread Test	Experimental Variables	Spread Test
Constant	5.5	Im Ag*Paste and Reflow in N_2	-13.4
Imidazole		Im Ag*Bake and Reflow in Air	
Immersion Au	53.4	Im Ag*Bake and Reflow in N_2	-34.4
Immersion Ag	23.1	Im Ag*168 hr @ 50°C & Reflow	
Electroplated Pd		Im Ag*168 hr @ 35°C & Reflow	
Immersion Au/Pd		Im Pd*Reflow after Fab in N_2	-83.8
Flux		Im Pd*Paste and Reflow in Air	
Reflow after Fab in N_2	84.5	Im Pd*Paste and Reflow in N_2	-15.9
Paste and Reflow in Air		Elec Pd*Bake and Reflow in Air	
Paste and Reflow in N_2	17.4	Elec Pd*Bake and Reflow in N_2	-38.1
Bake and Reflow in Air		Elec Pd*168 hr @ 50°C & Reflow	
Bake and Reflow in N_2	36.6	Elec Pd*168 hr @ 35°C & Reflow	
Store 168 hr 50°C and Reflow		Im Au/Pd*Reflow after Fab in N_2	-49.8
Store 168 hr 35°C and Reflow		Im Au/Pd*Paste and Reflow in Air	
Imidazole*Flux		Im Au/Pd*Paste and Reflow in N_2	57.9
Immersion Au*Flux	9.3	Im Au/Pd*Bake and Reflow in Air	
Immersion Ag*Flux	-13.0	Im Au/Pd*Bake and Reflow in N_2	
Reflow after Fab in N_2*Flux	-69.8	Im Au/Pd*168 hr @ 50°C & Reflow	
Paste and Reflow in Air*Flux		Im Au/Pd*168 hr @ 35°C & Reflow	
Paste and Reflow in N_2*Flux		Imidazole*Reflow after Fab in N_2*Flux	50.2
Bake and Reflow in Air*Flux		Imidazole*Paste and Reflow in Air*Flux	
Bake and Reflow in N_2*Flux	-24.5	Imidazole*Paste and Reflow in N_2*Flux	
Store 168 hr 50°C and Reflow*Flux		Imidazole*Bake and Reflow in Air*Flux	
Store 168 hr 35°C and Reflow*Flux		Imidazole*Bake and Reflow in N_2*Flux	27.9
Imidazole*Reflow after Fab in N_2	-49.4	Imidazole*168 hr @ 50°C & Reflow*Flux	
Imidazole*Paste and Reflow in Air		Imidazole*168 hr @ 35°C & Reflow*Flux	
Imidazole*Paste and Reflow in N_2		Im Au*Reflow after Fab in N_2*Flux	66.9
Imidazole*Bake and Reflow in Air		Im Au*Paste and Reflow in Air*Flux	
Imidazole*Bake and Reflow in N_2	-37.5	Im Au*Paste and Reflow in N_2*Flux	
Imidazole*168 hr @ 50°C & Reflow		Im Au*Bake and Reflow in Air*Flux	-10.0
Imidazole*168 hr @ 35°C & Reflow		Im Au*Bake and Reflow in N_2*Flux	24.2
Im Au*Reflow after Fab in N_2	-69.0	Im Au*168 hr @ 50°C & Reflow*Flux	
Im Au*Paste and Reflow in Air		Im Au*168 hr @ 35°C & Reflow*Flux	-30.4
Im Au*Paste and Reflow in N_2	-9.0	Im Ag*Reflow after Fab in N_2*Flux	77.4
Im Au*Bake and Reflow in Air		Im Ag*Paste and Reflow in Air*Flux	
Im Au*Bake and Reflow in N_2	-27.9	Im Ag*Paste and Reflow in N_2*Flux	11.8
Im Au*168 hr @ 50°C & Reflow	-6.5	Im Ag*Bake and Reflow in Air*Flux	
Im Au*168 hr @ 35°C & Reflow		Im Ag*Bake and Reflow in N_2*Flux	35.9
Im Ag*Reflow after Fab in N_2	-75.1	Im Ag*168 hr @ 50°C & Reflow*Flux	
Im Ag*Paste and Reflow in Air		Im Ag*168 hr @ 35°C & Reflow*Flux	

Model R^2: 90.2%   Standard Deviation: 8.5

Table 3.7 Predicted Means from the GLM for Spread Test

		Process Condition							
Surface Finish	Flux	Reflow Air	Reflow N_2	No Paste Reflow Air	No Paste Reflow N_2	Bake & Reflow Air	Bake & Reflow N_2	Store 50°C & Reflow	Store 35°C & Reflow
Benzimid	**LR**	5.5	90.0	5.5	22.9	5.5	42.1	5.5	5.5
	WS	5.5	20.2	5.5	22.9	5.5	17.6	5.5	5.5
Imidazole	**LR**	5.5	40.6	5.5	22.9	5.5	4.6	5.5	5.5
	WS	5.5	21.0	5.5	22.9	5.5	8.0	5.5	5.5
Im Au	**LR**	58.9	74.4	58.9	67.4	58.9	67.6	52.5	58.9
	WS	68.2	80.7	68.2	76.6	58.2	76.6	61.7	37.8
Im Ag	**LR**	28.6	38.0	28.6	32.6	28.6	30.8	28.6	28.6
	WS	15.6	32.6	15.6	31.4	15.6	29.2	15.6	15.6
Elec Pd	**LR**	5.5	6.2	5.5	7.0	5.5	4.0	5.5	5.5
	WS								
Im Au/Pd	**LR**	5.5	40.2	5.5	80.8	5.5	42.1	5.5	5.5
	WS								

Table 3.8 Contaminant Levels (μ*glin*^{2}) LR Boards Used in SIR Test

Surface Finish	Chloride	Bromide	Weak Organic Acids
Benzimidazole	1.31	1.17	2.11
Immersion Au	0.82	1.11	1.89
Immersion Ag	1.36	1.21	1.64
Electroplated Pd	1.41	1.27	2.08
Immersion Au/Pd	1.38	1.06	1.47

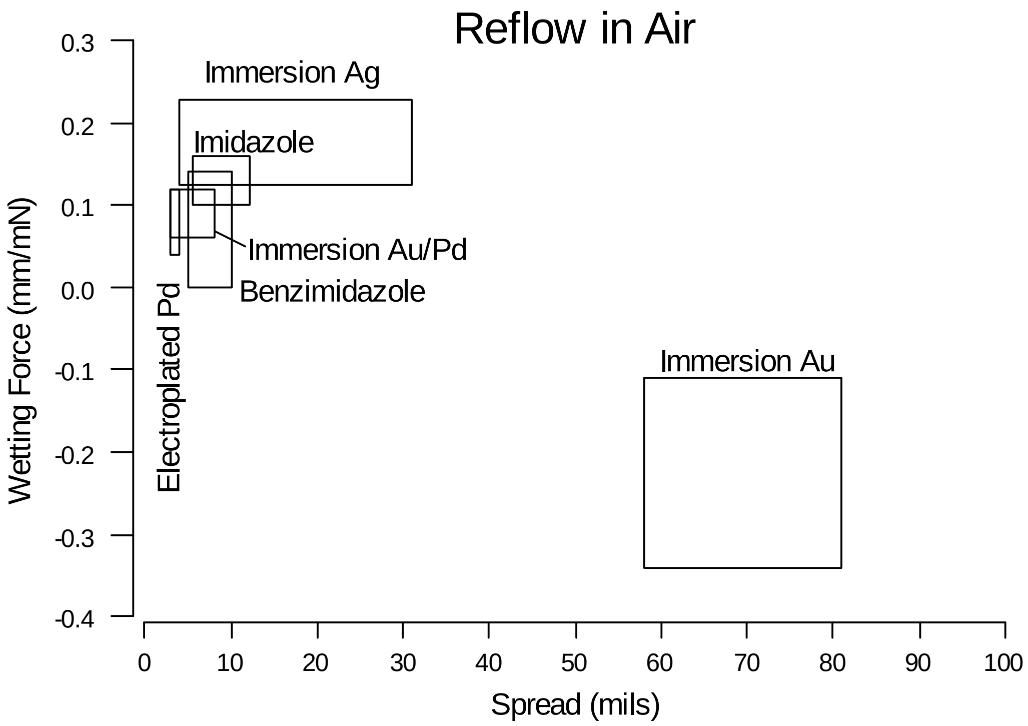

Figure 3.38 Comparison of the Wetting Force and Spread Test Results for Reflow in Air

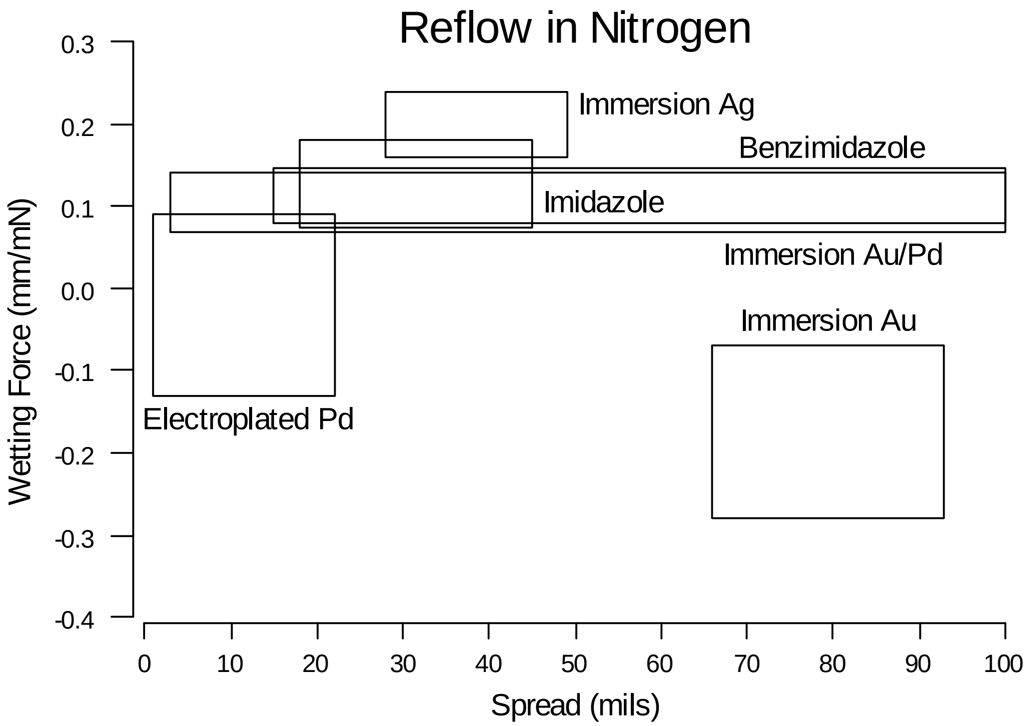

Figure 3.39 Comparison of the Wetting Force and Spread Test Results for Reflow in Nitrogen

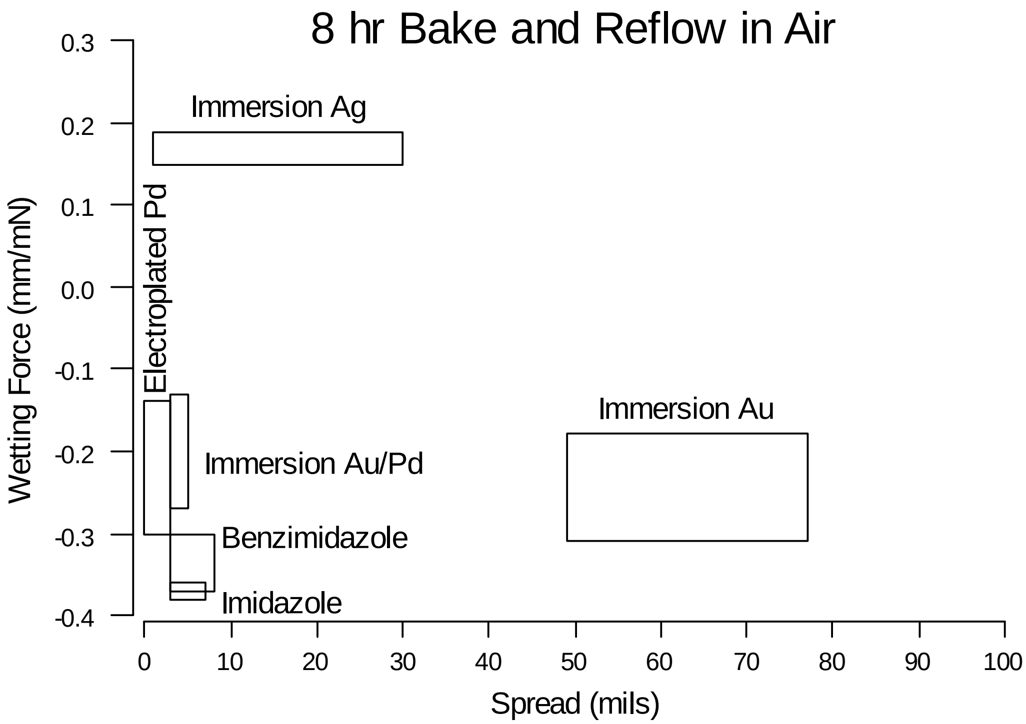

Figure 3.40 Comparison of the Wetting Force and Spread Test Results for Bake and Reflow in Air

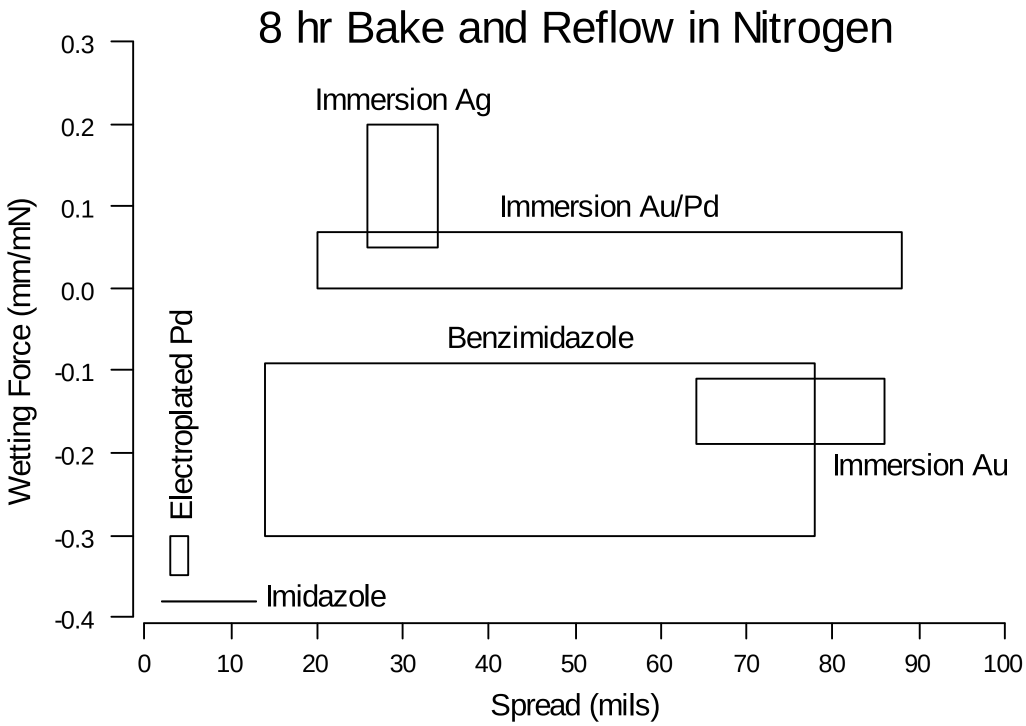

Figure 3.41 Comparison of the Wetting Force and Spread Test Results for Bake and Reflow in Nitrogen

4. Phase 1 Test Program

As shown in Figure 1.1, Phase 1 of the CCAMTF program is based on the results of the five screening experiments presented in Sections 2 and 3. Phase 1 differs from the screening phase in two significant aspects. First, conformal coating and alternative surface finishes will be evaluated on a single test vehicle, rather than on separate vehicles. Second, Phase 1 will utilize a functional PWA. The functional test vehicle selected for this evaluation is the PWA designed by the LRSTF. Details of the LRSTF PWA are discussed in subsection 4.3.

4.1 Purpose of Phase 1

The purpose of Phase 1 is to assess circuit performance of a functional test vehicle under applicable environmental stresses. The electrical performance of functional test vehicles that have no conformal coating will be compared against the performance of coated test vehicles in one segment of the Phase 1 test plan. Circuit performance of selected PWB ASFs will be compared against HASL as the baseline in the second segment of the Phase 1 test plan. Phase 2 will also use the test vehicles manufactured for Phase 1. Phase 2 will focus on reliability testing, including thermal shock, thermal cycle, mechanical shock, and vibration.

4.2 Phase 1 Test Matrix

Figure 4.1 gives a three-dimensional representation of the test matrix for Phase 1. The LRSTF PWB will be processed with four different surface finishes: benzimidazole, immersion Ag, immersion Au/Pd, and HASL with solder mask (control). Each surface finish will be divided into two groups, which will be processed with two different assembly processes. The fluxes and atmosphere (open air or nitrogen) for these processes will be chosen to give the best performance for a given surface finish and will not necessarily be the same for all surface finishes. One-third of the boards for each surface finish/process combination will be coated with acrylic; the second third will be coated with parylene as in the screening experiments; and the final third will not be coated.

The LRSTF PWAs will be subjected to the same test conditions used in the conformal coat screening study: temperature/humidity (3 weeks exposure to 85° *C* / 85% RH compared to 1 week in the screening phase), condensing atmosphere, and exposure to fluids. The 85/85 results can be compared directly with previous performance data from the LRSTF program. Visual inspection of solder connections will be completed and documented prior to environmental exposure.

4.3 LRSTF Functional PWA

The LRSTF used input from many stakeholders to develop a functional test vehicle, with up to 27 separate electrical responses. This PWA is shown in Figure 4.2. The LRSTF PWA was designed to meet the requirements of a wide range of customers and has quadrants containing the following circuitry:

- High voltage, low current
- High current, low voltage
- High frequency
- High speed digital

The LRSTF PWA provides flexibility for test design by allowing for inclusion of only those features of interest in a particular application. For example, the circuitry in each quadrant of the board performs independently of the circuitry in the other quadrants. This allows the LRSTF PWA to be used in a reduced mode.

Each quadrant of the LRSTF PWA contains both through-hole and surface mount components that perform independently of one another. Two stranded wires can be hand soldered to terminals on the board if desired. Thus, the LRSTF board can be subjected to multiple processing steps — wave, reflow, and hand soldering. Also, if only surface mount (or through-hole) technology is of interest, the through-hole (or surface mount) components can be left off the board as can the stranded wires. This simply reduces the number of electrical responses. The CCAMTF made a decision to use only commercial components (where available)on the LRSTF PWA.

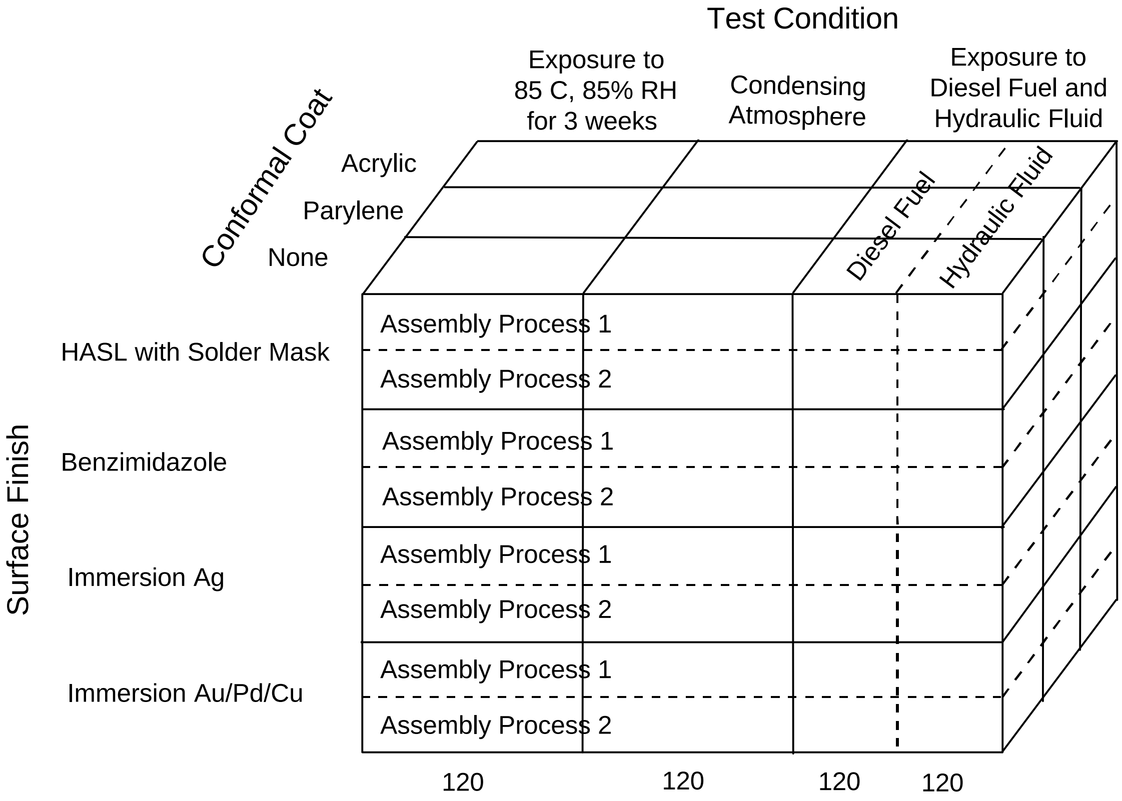

Figure 4.1 Three-Dimensional Representation of the Test Matrix for Phase 1 (5 test boards per cell)

4.4 Fabrication, Processing, and Coating Application for the LRSTF PWA

The LRSTF PWB will be fabricated at the Texas Instruments Printed Circuit Resources board fabrication shop in Austin. TI will also apply the benzimidazole surface finish; Alpha Metals will apply immersion Ag; Lucent Technologies will apply the immersion Au/Pd and HASL finishes. The boards will be shipped to the EMPF for assembly processing. After processing, one-third of the PWAs shown in Figure 4.1 will be shipped to Hughes Electronics for coating with parylene and another one-third will be shipped to Honeywell in Albuquerque for acrylic coating.

4.5 Environmental Exposure

All environmental tests specified in the test matrix will be completed at TI's facility in McKinney, TX. The reasons for using only one test location are that the tests must be done near the test equipment (see next subsection) and they must be tested by the same technicians to eliminate possible sources of extraneous variation.

Environmental Testing at 85°*C* / 85% RH. The PWAs exposed to the 85°*C* / 85% RH environment will be tested prior to exposure and at the end of each week of testing. Good experimental design practices will be followed to control extraneous sources of variation. For example, the PWAs will be placed randomly in the test chamber. Moreover, if all 120 PWAs cannot be accommodated in the test chamber at the same time, they will be randomized to maintain balance among the experimental factors at each test time. A staggered ramp will be used to prevent condensation (during ramp up, the temperature is raised to test conditions before the humidity is raised and the procedure is reversed during ramp down).

Condensing Atmosphere Test. The condensing atmosphere test will follow the 10-cycle procedure outlined in subsection 2.12 and will have the temperature/ humidity profile shown in Figure 2.24. However, as explained in the next subsection, some modifications will be made on the actual time of testing.

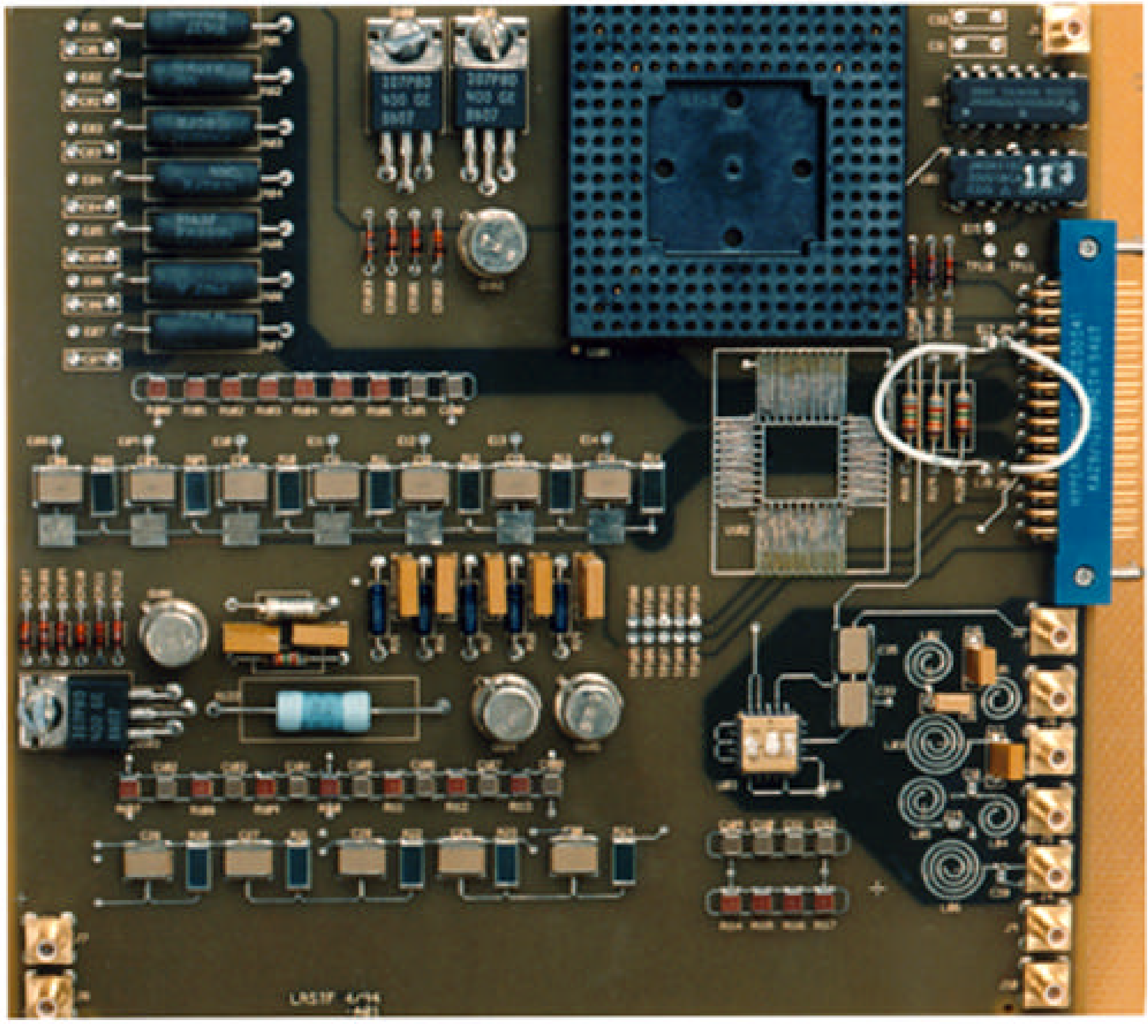

Figure 4.2 The LRSTF PWA

Randomization procedures similar to those discussed in the previous subsection will also be used in this experiment to control possible sources of extraneous variation.

Fluids Tests. The 120 boards specified in the test matrix for exposure to automotive fluids will provide an understanding of how processed, coated and uncoated assemblies perform after exposure to Type 2 diesel fuel and Mil-Spec hydraulic fluid. The question of interest in this test is how the absence of coating affects the electrical performance and electromigration of electronic assemblies when they are exposed to typical automotive and military fluids. All electrical measurements will be made at room temperature conditions, before and after fluid exposure for all processing conditions.

The fluids test will follow the test protocol outlined in subsection 2.16. Since diesel fuel exposure did not affect SIR in the screening experiment, the possibility exists that the LRSTF PWA's will be exposed sequentially to diesel fuel and then to hydraulic fluid. This will reduce the number of PWAs required for Phase 1 and make more available for Phase 2.

4.6 Electrical Testing of the LRSTF PWA

Electrical testing of the LRSTF PWA is not trivial and can be very time consuming. For example, during the LRSTF evaluation, two technicians working in parallel tested one board in 10 *min*. Based on this estimate, a single pass of the 480 LRSTF boards in Figure 4.1 would require 80 *hr* of testing. Texas

Instruments is investigating automating the electrical testing to shorten the required test time. However, there is a major physical limitation to automating electrical testing. In the screening phase, it was possible to do in-situ testing by cabling the B-24 boards directly to the test equipment. The complexity of the required wiring harness for a large number of LRSTF PWAs makes in-situ testing unreasonable. Thus, these assemblies must be removed from the test chamber for testing.

Removal from the chamber is not a concern in the temperature/humidity tests, as the LRSTF PWAs will be tested prior to environmental exposure and at the end of each of week, for a total of four sets of tests. This is the same test protocol followed by the LRSTF. However, the test protocol for the condensing atmosphere test must be modified. In the screening phase, 12 sets of SIR measurements were made during the condensing atmosphere test — pre- and post-test plus tests, and at the end of each of the 10 cycles. The later measurements were made in-situ by using a wiring harness to connect the B-24 board directly to the test equipment. Since this is not possible with the LRSTF PWA, either the test chamber would have to be powered down at the end of each cycle (resulting in 10 sets of one cycle each) or the condensing atmosphere test measurements would have to be restricted to pre- and post-test. The CCAMTF chose the latter option for the condensing atmosphere test.

The fluids tests consist of pre- and post-dip measurements, with another measurement after the first dip. The test procedure outlined in subsection 2.16 will be modified to allow more time for testing between dips.