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Implementation of Immersion Silver PCB Surface Finish In Compliance With Underwriters Laboratories

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Abstract

At times, the electronics industry changes faster than the testing and regulatory groups serving the industry. In this case, the electronics supply chain thoroughly evaluated the new printed circuit board (PCB) surface finish Immersion Silver. The silver finish was subjected to comprehensive testing and received product specifications throughout all industry sectors between 1995-2003. Specifications within Underwriters Laboratories (UL), however, were not current with the industry testing. UL maintained concerns over the use of silver metal in electronic packages, and implemented special testing for PCB devices using silver in their construction if the device was intended to operate at higher voltage/energy levels. UL's concern with the use of silver revolved around historical accounts of dendrite formation, a type of defect caused by electrochemical migration. The UL restriction began to hinder widespread use of immersion silver by OEM's who had conducted extensive reliability studies. Upon review, it was determined that the UL electrochemical migration test method needed to be updated to reflect changes in PCB technology. Further investigation proved that all surface finishes could fail the UL test method, even if there was no evidence of dendrite formation.

A group of companies from the electronics supply chain formed a Task Group to work with UL in updating their specifications. Later, this group became the IPC 3-11g Metal Finishes Data Acquisition Group. This article describes the testing, demonstrations, revisions, and ongoing work of IPC 3-11g in coordination with Underwriters Laboratories. More specifically, this article will present data from a team project to identify the important parameters affecting electrochemical migration from the viewpoint of UL.

Introduction

The transition in the use of Circuit Board surface finishes has been one of the most dramatic in the history of PCB manufacturing. The use of Hot Air Solder Level (HASL) to replace reflowed tin-lead was a major transition in the 1980's. During the 1990's, the use of OSP grew to more than 25% of the market. Electroless Nickel Immersion Gold (ENIG) was chosen increasingly in the late 1990's, reaching more than 20% of board finishing. Another transition is now underway. During the past two years, the use of Immersion Silver has grown dramatically to the current level of about 8%.[1]

More than 40 years ago, there were failures in the electronics industry attributed to the use of Silver as a conductor material. Failure was due to a phenomenon known as 'electrochemical migration' or 'dendrite formation.' As a result of that experience, some safety and specification groups wrote specifications restricting the use of silver in circuitry. Underwriters Laboratories, concerned with the prevention of fire and shock hazards, included text in UL's documents concerned with the manufacture of printed circuit boards. The principal document affected was UL 796, *UL Standard for Printed Wiring Boards*.[2] This document refers to the use of Silver in sections 7.2 and 9.1.6c, and provides a migration test method for the use of silver in section 23.

Silver is the only PCB surface finish with specific testing requirements. The unique specification for recognition of silver by UL is being addressed by the IPC 3-11g program. IPC 3-11g is a group of circuit board manufacturers, OEM's, chemical suppliers, and testing labs that convened in order to assist UL in updating their standards. The goal of this team is to determine if silver still poses a unique dendrite risk, update the test methods employed by UL, and determine if UL restrictions on the use of silver at UL are still appropriate.

The industry group working on this issue began as an Ad Hoc committee under a broader UL/IPC umbrella. In late November 2002, IPC proposed to recognize the group officially as IPC's 3-11g Metal Finishes Data Acquisition Task Group within the IPC 3-10 Printed Board Base Materials Committee. This team has met at a frequency of about twice a month since October 2001.

IPC 3-11g Purpose
The following text is taken from the working charter of the IPC 3-11g technical committee.

> *To clarify, and if needed, modify UL specification 796 pertaining to the use of Immersion Silver PCB surface finish on non-LVLE categorized electronic equipment.*
>
> *The UL Ag Ad Hoc Task Group was initiated at the IPC Orlando 2001 meeting. At the UL session, and in other gatherings, it was proposed that the application of UL specifications to existing PCB product is not used uniformly. The increasing use of Silver to finish PCB's, and the increasing use of Silver in Pb-free solders will cause violation and misuse of the existing UL specifications. The Group performed some background experiments, devised proposed revisions to UL-796, and presented the proposals for testing at a more realistic voltage. UL was uneasy about removing this specification all at once. At UL's STP group meeting during EXPO 2002, the group decided on a plan for changing the test methods. A new method employing a 40V/mil withstand test (1000V max) was sent for vote and adopted. At EXPO 2003, the STP adopted a recommendation for standardization of more realistic temperature and humidity levels for testing. Future revisions should include use of an insulation resistance test and eventual elimination of testing for Immersion Silver altogether.*

Brief History of IPC-3-11g
The goal of the team is to remove the restriction on immersion silver from UL documentation. The members of the team feel that immersion silver is safe based on at least eight years of experience as a PCB board finish. There are now hundreds of millions of electronic devices in use made using immersion silver. No case of immersion silver-induced electrochemical migration failure has been documented. Since 2001, the team has worked with specialists at UL to explain the testing and performance of board finishes. The 3-11g team has updated their test methods, and are now working to show that immersion silver performs exactly the same as all other board finishes from the perspective of electrochemical migration. Once the restrictions on silver are resolved, the team will continue to review concerns with tin, silver paste, and other materials within international specification organizations.

Underwriters Laboratories
Underwriters Laboratories is interested in testing materials and systems for safety according to standardized methodologies. In the area of electrical systems, UL is primarily concerned with the prevention of two hazards, fire and shock. UL maintains a core document, *UL-796 Standard for Printed Wiring Boards*, to describe the testing and safety requirements regarding the manufacture and use of rigid circuit boards. The UL 796 document contains the testing methodology specific to silver.

At first, UL only required the “Silver Migration” test for PCB’s to be used in non-LVLE applications. Low Voltage Limited Energy (LVLE) devices were not subject to specific migration testing. However, the various UL groups associated with different end-use segments differed in setting the limits defining LVLE. For example, the telecomm segment decided that many parts used at over 42 volts would be classified as non-LVLE. Other segments had various other voltage and current guidelines, if any could be determined at all. The PCB manufacturing industry found difficulty determining which PCB designs might be classified as non-LVLE. At a higher level, recordkeeping at each OEM became burdensome in determining which of their PCB vendors had achieved recognition for each part number using various voltages.

UL itself began to find difficulty administering the LVLE classification. During 2002, UL decided to eliminate the LVLE designation. It was recognized that many PCB designs would be easily served by the simpler recognition category termed “flammability only.” With the transition of LVLE to the flammability-only rating system, UL effectively required silver migration testing only on designs requiring recognition higher than flammability-only. This transition did seem to ease the interpretation among end-use groups as to which products classified as LVLE. However, there was still ambiguity within the OEM decision-makers as to whether specific part numbers should require flammability-only recognition, or a more rigorous full-recognition designation.

Electrochemical Migration
Metals subjected to humidity and electrical bias will form dendritic growth in the presence of corrosive electrolyte. Conducting ions within the electrolyte may derive from corrosion of the metal conductors, or from improperly cleaned circuit board substrates. Contamination may derive from the manufacturing of the bare PCB, subsequent handling, or from the application of corrosive fluxes without adequate cleaning. Studies have determined that failure due to electrochemical migration is based primarily on the cleanliness of the parts. In fact, during the transition to so-called ‘no-clean’ assembly for environmental reasons during the 1980’s and 1990’s, the topic of electrochemical migration was thoroughly investigated. The IPC Electrochemical Migration team IPC 5-32 recommends testing according to IPC-TM-650 2.6.14.1. Much more summary information is contained within IPC TR-476A (May 1997.)

In the 1950's and 1960's, there were selected instances of failure on primitive circuit boards due, in part, to the use of conductors made of silver. These conductors were made by electroplating several mils of pure silver onto substrates. The silver was to be used in many cases as a surface for mechanical switching; exploiting silver's property as the most contact-friendly metal. The thick silver was placed in uncontrolled environments with significant extraneous ionic contaminants and used for high force mechanical switching. In some cases, the deformed metal and ionics interacted under bias in condensing environments to form metallic dendrites.[3] As conductor metals corroded, the soluble ions migrated towards the opposite polarity of adjacent circuitry. A supply of electrons traveling through the condensed water sufficed to reduce the ions into metal dendrites. (Figure 1) Eventually, the dendrites could support enough current to form a short circuit and produce a fire hazard. In certain conductive aqueous environments, pure silver formed dendrites more quickly than other elements.

Much has changed in the manufacture of circuit boards since those original failures. Modern circuitry is highly functional, well tested, and well specified with many international standards such as IPC. In fact, these organizations continuously update tests for such functions as resistance to electrochemical migration, and surface insulation resistance. New coatings for protecting the solderability of the boards (PCB surface finishes) have been tested according to the migration and SIR test methodologies to ensure compliance. In addition, new immersion silver processes are designed to overcome the threats to repeating the dendrite formation.

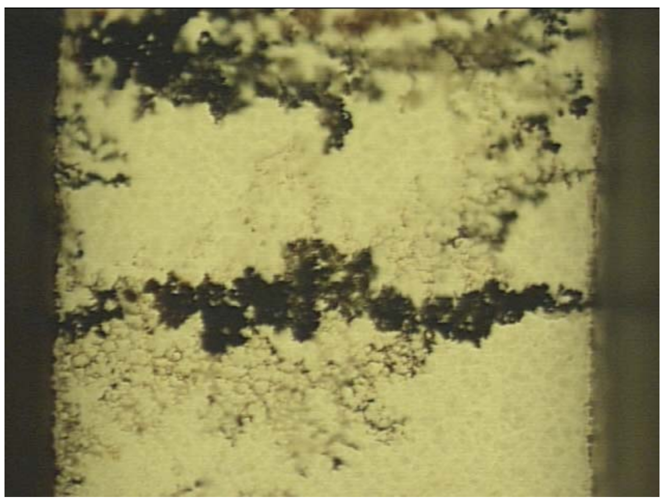


Figure 1 - Back-Lit Image Demonstrating Metal Dendrite Growth of HASL

For clarification purposes, the phenomenon of dendrite formation is different from whisker formation and conductive anodic filament (CAF) formation, although the three defects are frequently confused. The occurrence known as whiskering is linked to intermetallic formation and the deposit's crystal stress. Stress results in movement, and as the metal grain boundaries slide, they force single-crystal whiskers up to 200 microns from the surface. The concern is that whiskers can act to short-circuit closely spaced conductors, change impedance values, or act as RF antennas.[4] Whiskers seem to appear only in tin and zinc, whereas dendrite formation can occur with any metal. In the future, as a separate project, the 3-11g committee plans to review restrictions applied to tin by Telcordia and other organizations. Conductive anodic filament formation involves a growth of conductive metal salts, usually along capillary-like fractures within PCB substrate materials. CAF formation is largely dependent on substrate material and drilling parameters. Interestingly, some of the early literature reporting electrochemical migration was actually what would now be termed CAF. The inferior substrate materials of the time, such as paper phenolic boards, were vulnerable to CAF formation.

Circuit Board Surface Finishes

PCB surface finishes are typically the final chemical process applied to a bare circuit board construction. The selection of a board finish should be the result of carefully balancing several demands[5]. It is important to consider functional, process, and logistical metrics of a finishing process. The chemical process needs to be widely available in order to satisfy the worldwide procurement demands of large OEM's. Approved PCB vendors must have competence in each chosen chemical plating process. Solderability, contact functionality and shelf-life of the board are among other functional considerations of a surface finish. With new circuitry designs, the electrical and surface contact properties of the coating may become the highest priority when selecting a board finish.

Immersion Silver consists of a very thin (0.15-0.55 micron) coating of nearly pure silver. In this aspect, immersion silver is 100x thinner than traditional electroplated silver deposits. A slight amount of organic material is typically deposited within the immersion silver intended to prevent tarnish and electromigration. The metal coating is deposited via a relatively simple conveyorized or vertical chemical process. Benefits of immersion silver include flatness, Pb-free, inspectability at assembly, lack of soldermask attack, and surface contact functionality. Relative to other PCB coatings, immersion silver does not suffer from the black-pad interfacial fracture phenomenon, tin-copper intermetallic shelf-life reduction, whisker formation, or sensitivity to weak fluxes. Immersion silver plated on today's clean, well formed; well tested PCB's is proven to be very functional in billions of solder joints in existing electronics devices. For these reasons, OEM's fabricators and assemblers have increasingly used and specified immersion silver during the past 10 years.

Electrochemical Migration Testing of Immersion Silver

Various sets of data exist relating to the electrochemical migration performance of immersion silver. Nearly all electronics manufacturers who use immersion silver as a PCB surface finish have conducted testing for electrochemical migration. Environmental stress testing of silver coatings has included exposure to corrosive fluids, severe shock, and rigorous aging. Many tests were conducted under applied bias. These studies were very useful in answering the questions about dendrite formation. When the USA Environmental Protection Agency worked with Raytheon to study new Pb-free finishes, silver was compared to HASL, ENIG, OSP, reflowed tin/lead, and immersion tin. In this study, all finishes were corroded with dilute acid and allowed to form dendrites during this testing; "While some dendrites were found, there was no correlation to surface finish."[6,7] Dendrites will form on any surface as long as there are residual ions, electrical bias, and condensing environments. As a consequence of this extensive testing, immersion silver is now chosen by military board suppliers in the avionics, navigation, and space equipment fields. Many other OEM's have had similar results in testing migration of various board finishes.[8,9,10,11,12,13]

Several methods exist for conducting the chemical, environmental, and electrical tests required. IPC's document IPC-TR-476A provides an excellent review of the test methods known as of May 1997.[14] The document was produced by the IPC 5-32e Electrical Migration Task Group in conjunction with the IPC 5-30 Cleaning and Coating Committee and reviews the primary factors influencing migration such as electrical bias, moisture absorption, cleanliness, conductor materials, substrate materials, conductor spacing, and temperature. The document used the accumulated knowledge of testing conducted at such organizations as AT&T, Siemens, the US Military, Bellcore, UNISYS, and DuPont to recommend a test method for use in the IPC system. The method now recommended by the IPC 5-32 committee is IPC-TM-650 2.6.14.1. One initial proposal of the 3-11g group was to use this method in place of the UL 796 silver migration test method. Once that method could demonstrate that immersion silver was equally able to prevent electrochemical migration, the group could propose to eliminate migration testing of immersion silver from UL documentation altogether.

UL's Withstand Voltage Test Method

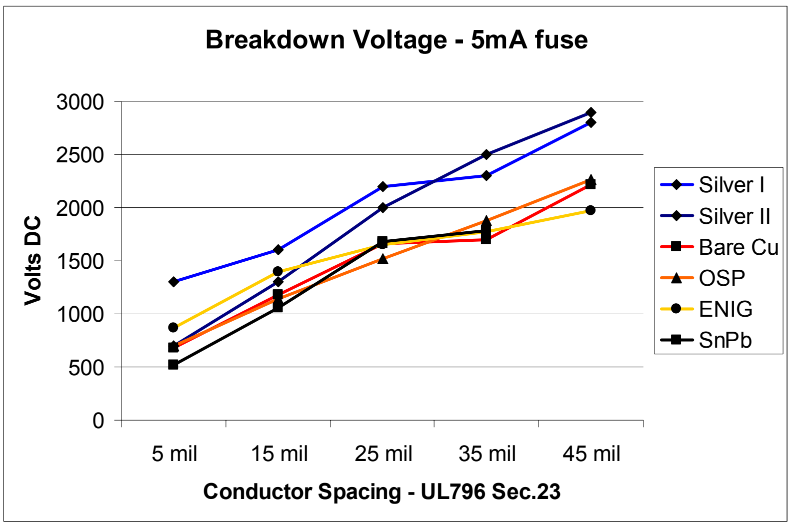
UL's 796 Section 23 details a procedure to be used for testing migration of silver used in PCB's. Basically, the procedure as presented in the 8th edition involved 1) withstand voltage test, 2) environmental conditioning at 23ºC/ 95-100% RH energized at the maximum voltage, 3) follow-up withstand voltage test, and 4) visual inspection for dendrites. The method as given in this document was difficult to pass when applied to modern PCB line spacings. In brief, the withstand voltage test specified application of 1000 volts plus twice the voltage rating requested by the fabricators. For example, a common PCB operating at 120V would endure the application of 1240V across whatever fine lines/spaces were employed on the design. There was no allowance for the fact that most circuitry of a PCB may operate at 5V, while larger spacing will be used in a higher voltage power supply area.

In December of 2001, the 3-11g committee demonstrated the withstand voltage test to a video conference of UL engineers. In all cases, the applied voltage formed an electrical arc through the air between the conductors. The method did not test for electrochemical migration or result in any dendritic growth. Figure 2 depicts the test equipment used and a magnified view of the test coupon after an electrical arc bridged the air gap. Figure 3 clearly demonstrates that the withstand voltage of a pair of parallel conductors is purely a function of conductor spacing, not surface finish.

Following the demonstration of withstanding voltage, UL acted quickly to modify the withstanding voltage to a more realistic 40 volts/mil (1000V max). UL later modified the specification for environmental conditioning from 95-100% RH to 87.5% +/- 2.5% relative humidity. In this way, condensation of water on the test sample, and therefore certain failure, was avoided in the test protocol. UL acted on the humidity requirements following the testimony of industry experts, in addition to demonstration tests conducted at Microtek Labs.

(a) (b)

Figures 2ab - High-Voltage Source Used in Withstand Voltage Test; Test Pattern after Electric Arc



Figures 3 - Dielectric Withstand Test Results

Current Method for UL Recognition

Before discussing the latest progress within 3-11g, it is probably wise to review the UL silver recognition method as of January 2004. Many fabricators and OEM's are unsure as how best to achieve UL compliance. The following steps may provide helpful direction. Be aware that as the 3-11g committee interacts with UL, the procedures are generally becoming less complicated. In fact, by the time of this article's publication, the silver migration test may not be required at all for immersion silver PCB finishes.[15]

- A PCB fabrication company that uses immersion silver as a board finish should contact its regional UL representative. Be sure that the regional representative is current on updated procedures.
- The first step is to inform UL of the fabricator's use of immersion silver. The UL representative will describe procedures needed for a "file update." This shows the industry and the UL end-product engineers that the fabricator is recognized by UL to use immersion silver.
- At this step, the UL engineer will ask the fabricator whether the application is for flammability-only or full-recognition parts.
- The fabricator should then determine from its OEM customers whether or not any boards require recognition higher than "flammability only." The OEM customer may not know if their PCB designs require full recognition. This recognition is relatively uncommon and is used mainly for parts carrying high current at higher voltages. This decision will be dependent upon the device's end-use segment.
- For "full recognition" boards, the fabricator will need to certify with UL for producing such product. The fabricator will need to provide silver migration test samples to UL (or a UL certified laboratory) for physical and electrical evaluation. Testing will certify the manufacture of boards at a certain minimum circuitry spacing and maximum voltage. This testing is only conducted once, as long as boards are produced within the tested spacing and voltage limits.

- Test vehicles may be built similar to the type of design shown in this document. Different samples will need to be submitted for each category of laminate substrate that is planned for manufacturing of “full recognition” PCB’s.
- Finish the samples per UL-supplied sample requirements and submit for UL testing. The fabricator has the option of also submitting a control finish such as OSP or bare copper.
- The test at the time of this writing requires a dielectric withstand “proof” test, 56 days in a humidity chamber energized at the maximum desired voltage, a follow-up dielectric “proof” test, and visual inspection. The PCB shop will be certified according to the minimum spacing and maximum voltage that passed test requirements. These notes will be added to the company’s UL file.

As of January 2004, details of the modifications UL has made to the updated test method are not included in older versions of UL 796. Updated conditions are given in Table 1. Test vehicle specifics are shown in Figures 4 and 5.

Table 1 - Conditions for Silver Migration Test in UL 796, Section 23

Test vehicle standard spacing:	12 mils (0.3 mm)
Other test vehicle spacings:	fabricator’s choice
Withstand voltage (proof test):	40 volts/mil (1.6 kV/mm); 1000V max
Conditioning chamber temperature:	35ºC +/- 2ºC
Conditioning chamber relative humidity	87.5 +/- 2.5% RH
Time in chamber:	56 days (1344 hours)
Electrical bias in chamber:	requested voltage rating

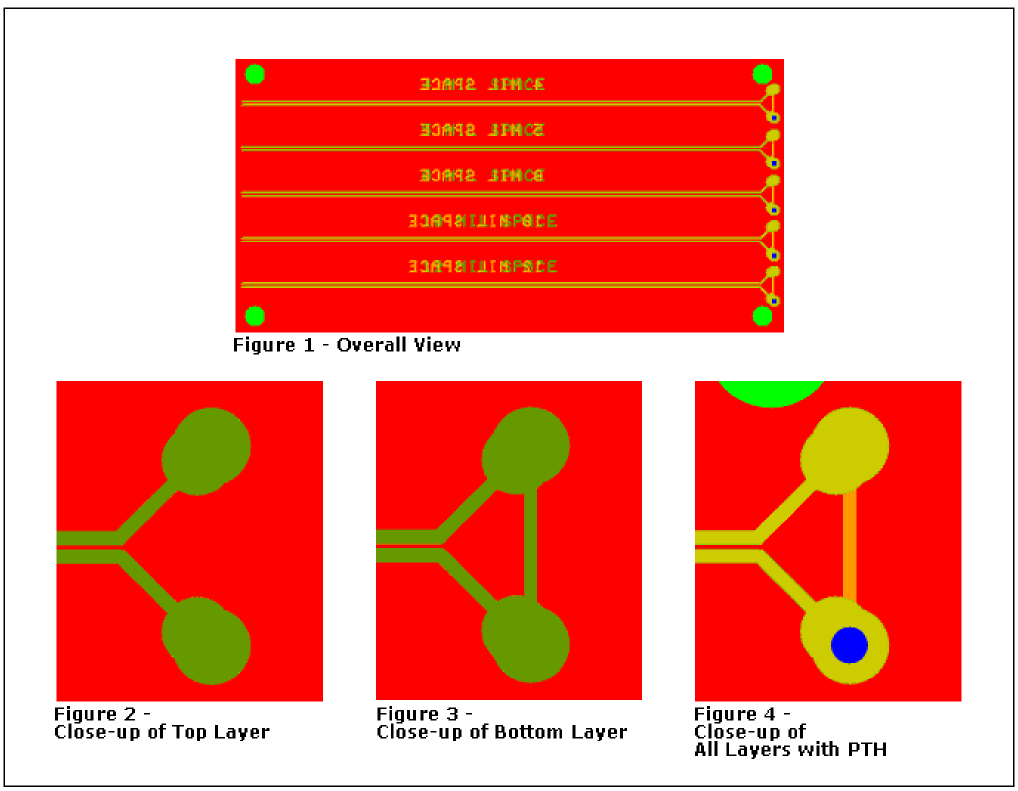


Figure 4 - Test Board Design Recommendations for Use in Submissions to a UL-Certified Lab

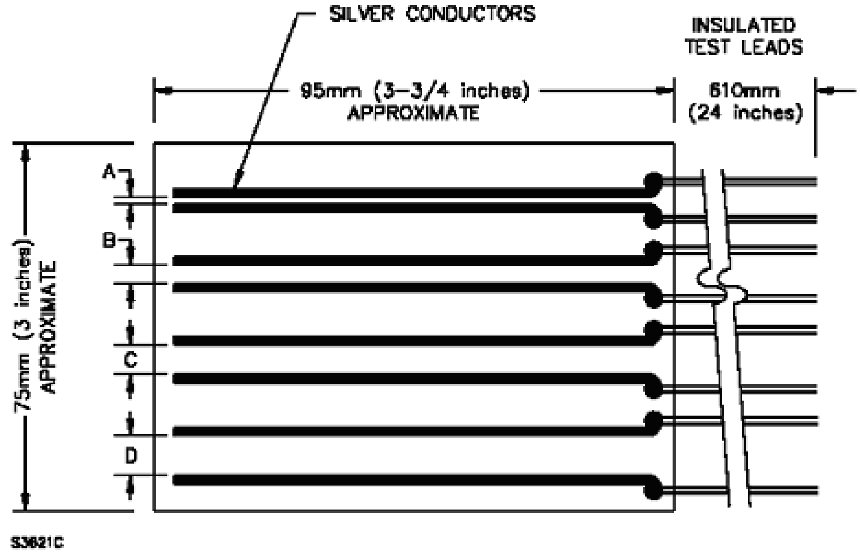


Figure 5 - Schematic Design Guide for Test Boards as Contained in UL 796

Recent 3-11g Electrochemical Migration Testing
As stated previously, a central goal of the industry members of the 3-11g committee was the elimination of testing that specifically applied to immersion silver and did not apply to other PCB surface finishes. It was the team's sentiment that there was no performance difference between commonly used surface finishes with respect to migration and dendrite formation, so special requirements for silver were arbitrary and discriminatory. The industry members presented various sets of data to UL in support this claim. The data sets, however, did not form a seamless, convincing story, due to the numerous authors, test methods, and controls. In addition, there was no data in some cases to support other claims that the group presented. In particular, the group proposed that a single standard voltage of 10V as used in the IPC test method was more effective than the use of an always-changing voltage in UL testing (depending on the type of electronic device to be rated.) Some literature suggested that lower voltages allowed for dendrites to form while higher voltages would vaporize the dendrites before they were detected electrically or visually. The team was unable to gather substantiation for the above claims.

As there was no existing set of data comparing all predominant surface finishes using a common test methodology, and further, comparing a standard methodology to the UL 796 method, the team embarked on an experimental project. In overview, the experiment was designed to test surface finish variations, applied voltage variations, and the method variations between UL 796 Section 23 and IPC's TM-650 2.6.14.1. Table 2 summarizes the voltage and line spacing conditions tested in the 3-11g experiment. The team decided to test the standard UL method, the standard IPC method, and a set of conditions which adopted parameters from both methods. For example, the IPC method calls for 596 hours under temp/humidity; in the 3-11g test, the samples were measured after 596 hours as well as the 1344 hours typical of the UL methodology. The applied voltages were selected to cover all possibilities, but were somewhat restricted by the actual equipment available.

Surface Finishes
- Bare Copper (control)
- Electroless Nickel Immersion Gold (ENIG)
- Electrolytic Silver
- Immersion Silver (four vendors)

Test Methods
1) UL 796 Section 23:
- withstand voltage test at 40V/mil
- environmental conditioning at 35ºC/ 87.5% RH for 1344 hours under applied bias
  applied voltage to be determined by fabricator according to desired rating, 1/8 amp fuse
- repeat withstand voltage test at 40V/mil
- visual inspection at 10x for dendrites
- UL 796 Figure 23.1 test pattern (parallel conductors modified for spacing)

2) IPC TM-650 2.6.14.1:

- 96 hours at 35ºC/ 85% RH, measure SIR
- 500 hours at 35ºC/ 85% RH under 10V applied bias, measure SIR
- visual inspection for dendrites
- IPC-B-25A test coupon (comb pattern modified for spacing), 1MegΩ current limiting resistor

Table 2 - Conditions for 3-11g Silver Migration Test Comparisons

Proposed

	Parallel		Comb			
	12/4	12/12	4/4	6/6	12/12	25/50
1V/mil	4V	12V	4V	0.7V	12V	50V
20V/mil	80V	240V	80V	80V	240V	96V
10V fixed	10V	10V	10V	10V	10V	10V

Actual

	Parallel		Comb			
	12/4	12/12	4/4	6/6	12/12	25/50
1V/mil	4V	12V	4V	6V	12V	50V
20V/mil	80V	240V	80V	120V	240V	1000V
10V fixed	10V	10V	10V	10V	10V	10V

The experimentation was conducted according to the following project goals.

1) Determine is immersion silver is any more vulnerable to electrochemical migration relative to other finishes.
2) Determine if the IPC (Telcordia) method is more/less rigorous than the UL method for electrochemical migration testing.
3) Identify the utility of all new finishes for use on modern substrate materials to resist electrochemical migration.
4) Institute an exception for immersion silver within UL-796 so that no special testing is required by fabricators using the finish.

Figure 6 shows the measured insulation resistance of all finishes after three-day stabilization in the temperature and humidity environment without applied electrical bias. There was no substantial difference among the bare copper, electroless nickel immersion gold, and immersion silver finishes. There was an overall lowered resistance value for electrolytic silver, labeled E-Ag in the following figures.

Figure 7 shows the same data for the samples following environmental conditioning under electrical bias for 500 additional hours. These data represent thousands of test measurements. In addition to the typical 10V applied bias, these summary charts include all voltage settings tested: 1V/mil and 20 V/mil.

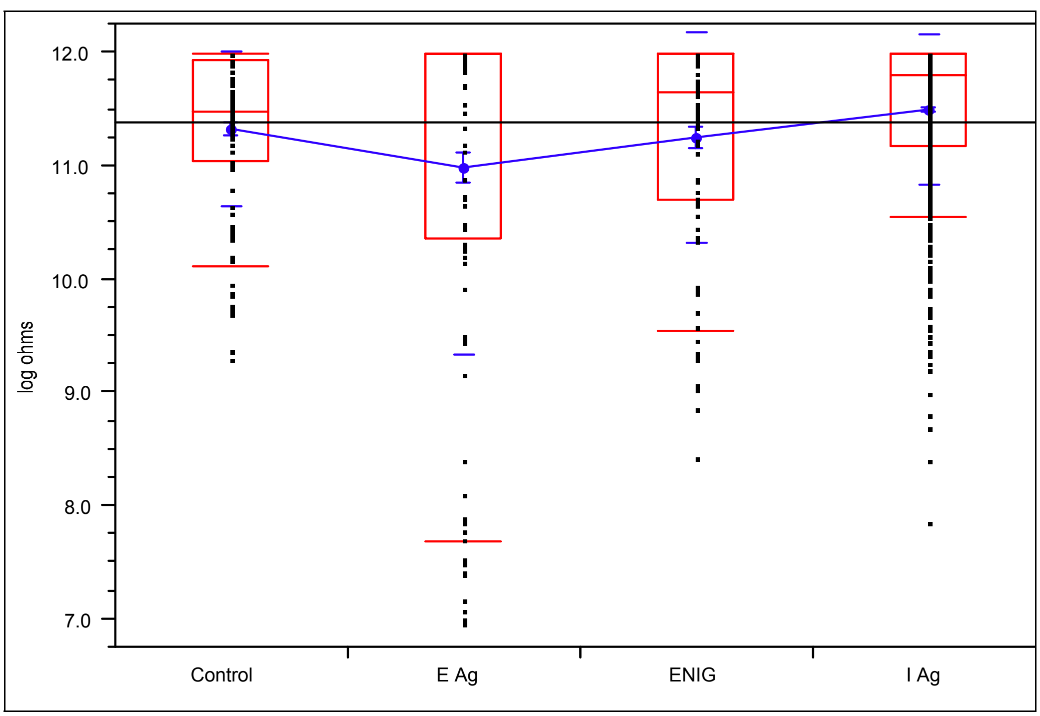


Figure 6 - SIR Test Results at 96 Hours

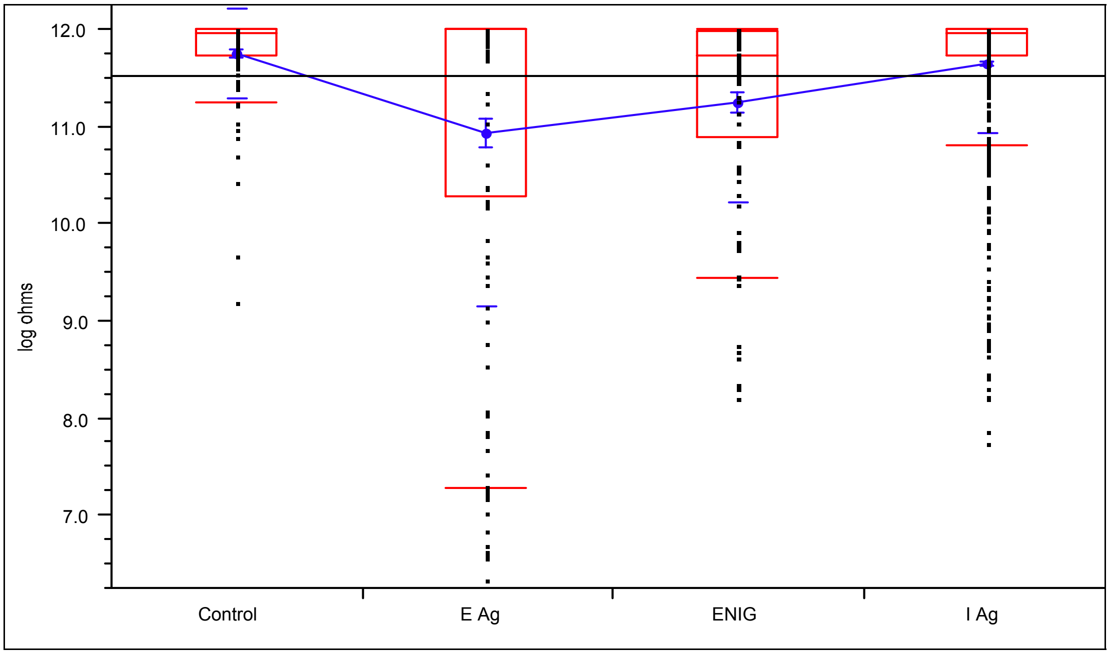


Figure 7 - Electrochemical Migration Test Results at 596 Hours

Figure 8 shows a comparison of results obtained using different applied voltages, 1V/mil and 20 V/mil. The results support the hypothesis that higher voltages do not lead to a higher failure rate. Higher voltages may lead to the faster formation of dendrites in theory, but higher voltages may also lead to the destruction of those dendrites once formed.

All data presented so far represents measurements taken using the IPC test method. The UL test method did not provide any failures or information for graphical representation. Each of the sets of parallel patterns on the test vehicle (see Figure 9) passed the initial dielectric withstand test and passed the final dielectric withstand test. None of the 1/8 amp fuses was tripped during the 1344 hours under temp/humidity/bias. Visual examination of all test boards was not complete at the time of this article's writing.

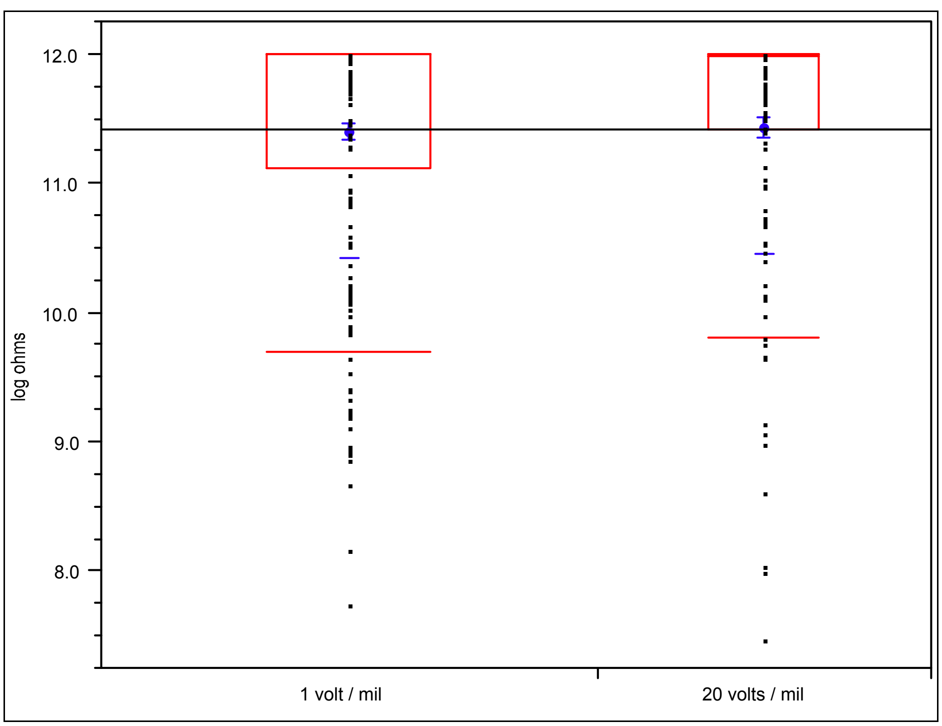


Figure 8 - Electrochemical Migration Test Results at 1344 Hours

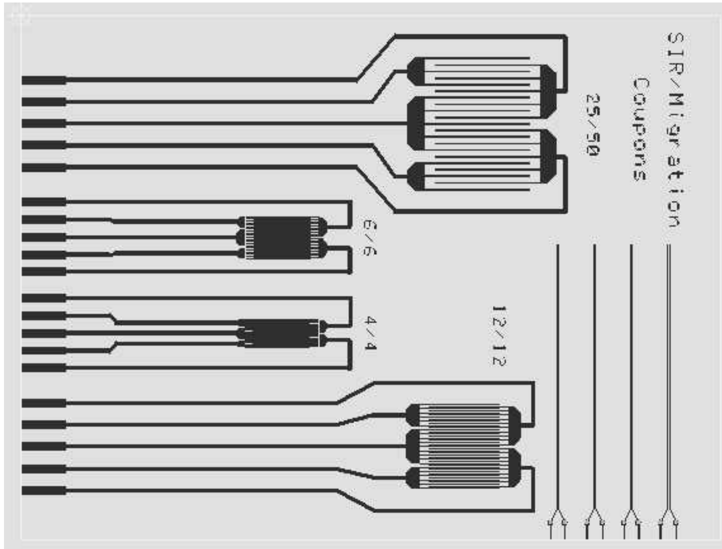


Figure 9 - Test Vehicle used in 3-11g Silver Migration Test Comparisons

Summary

Due to historical concerns over the electrochemical migration failures of thick, pure, electrodeposited silver, Underwriters Laboratories implemented a restriction on the use of silver in high-energy electronics. A group of industry members with a stake in the implication of UL's procedures formed an Ad Hoc committee to investigate the situation. The group later became the IPC-3-11g Metal Finishes Data Acquisition Task Group. IPC 3-11g worked closely with UL starting in late 2001 to review, revise, and recommend the procedures used in UL-796 to test for electrochemical migration. The teamwork of the committee with UL proved to be a very positive experience, resulting in numerous interim adjustments to the test methods. The group eventually conducted extensive testing and produced data supporting the hypothesis that immersion silver has no increased tendency to exhibit dendrite formation. With supporting test results, UL engineers will propose an exemption for immersion silver that would allow full recognition of fabricators using immersion silver without additional costly testing (all non-related recognition procedures, such as substrate and soldermask testing is unaffected by the proposal.) Nearing the conclusion of this successful and intensive project, the 3-11g committee is refocusing its efforts on other projects, such as the use of silver-filled conductive adhesives, Pb-free solders, and tin according to various regulatory groups.

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