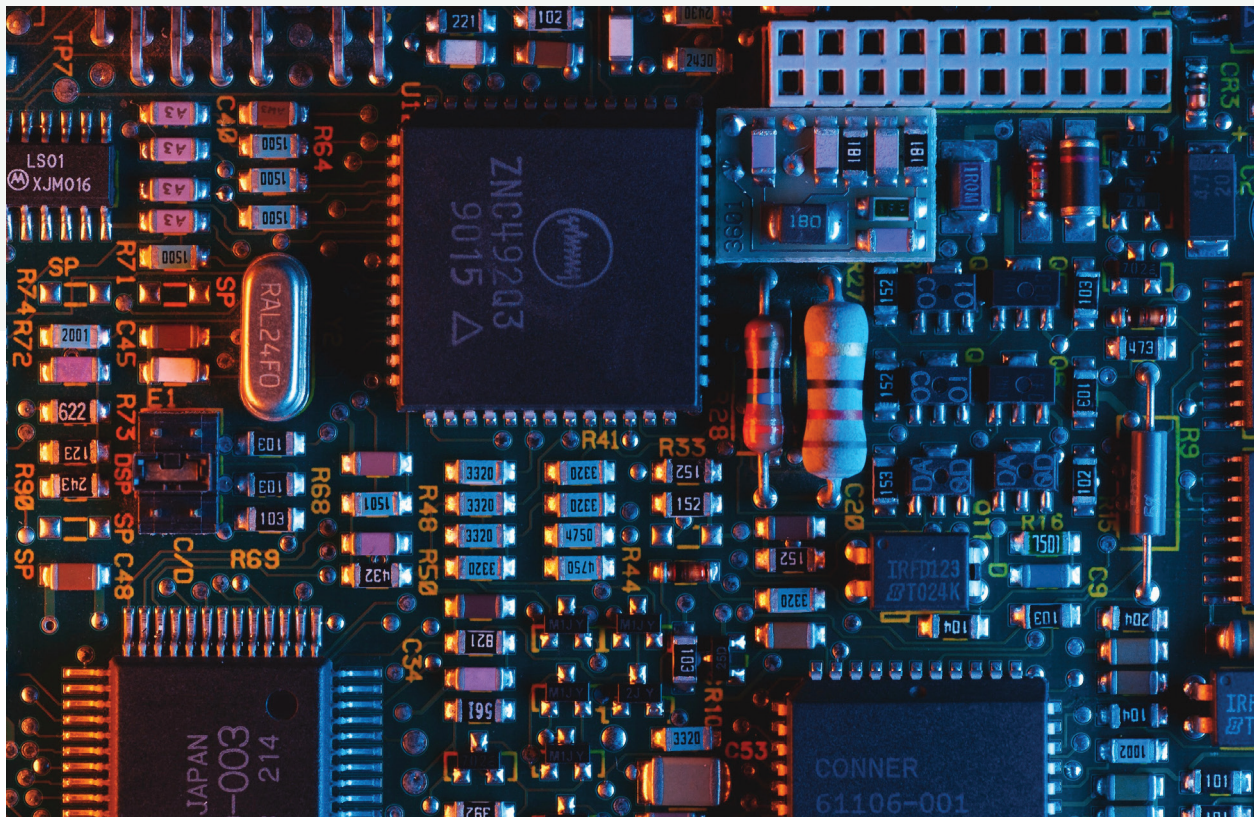




Cleanliness Assessment Correlation to Electronic Hardware Reliability

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Abstract

During the development of a specialized electronics assembly application process, the need for assessment of localized areas of residue entrapment (low standoff components), which are very susceptible to holding small but corrosive levels of processing materials, even after repeated cleaning steps, became evident. Ion chromatography bag extractions were found to be diminishing the sensitivity required to see the small pocket of residue below and on the component surface. These residues were easily solubilized but could not be detected if large areas were extracted, so the use of a localized extraction tool to isolate the 0.1in² area was utilized on these samples and the residues were assessed to optimize the cleaning protocol.

Through validation testing of functional hardware and an optimized cleaning protocol using localized cleanliness assessment techniques, the hardware successfully met product reliability substantiation requirements.

Additional data analysis of localized extraction impact on residues from test hardware also correlated to the environmental assessment for clean and dirty hardware. It is not the cleanliness of the entire assembly that causes the failure but the pocket of contamination between two critical leads on the assembly that causes the failure.

Introduction

Since the advent of printed circuit manufacturing, preventing flux and other reactive residues from developing into field reliability issues have challenged producers. A number of process factors must be effectively controlled in order to assure satisfactory cleaning. Determining the level of cleaning adequate for the product design has resulted in the development of standard tests to both evaluate design performance (e.g. SIR testing) and production stability (e.g. ROSE testing). The limitations of the current IPC standard test methods are predominantly understood. A new test method is available and substantiation work has been accomplished which demonstrates an instrumentation test technique as suitable for evaluating both design performance and production stability.

Cleanliness Test Evaluation

The primary reliability impact as a result of a circuit board process contamination is the potential for reactive residues to manifest into dendritic growth. Dendrite growth is a phenomenon where molecules or atoms in liquid attach themselves to a solid surface. More molecules and atoms join the solid and make the crystal larger while the tip of the dendrite grows, extending its overall length. The dendrite is metallic and, therefore, an electrical conductor. The dendritic growth may eventually result in an electrical leakage path across isolated electrical circuits, generating a circuit malfunction.

There are multiple factors associated with dendritic growth in electronic equipment. The primary factors, which must exceed a threshold level and occur simultaneously, are moisture, electrical bias, ionic contamination, temperature and time. Other factors, such as electrical spacing, and metallic composition are also significant factors, but are intrinsic to the electrical equipment design.

The C3 (Critical Cleanliness Control) Test Instrument

A cleanliness evaluation instrument for evaluating residues has been developed and is named the C3 (Critical Cleanliness Control).



Figure 1 - The new instrument is a new design cleanliness test instrument incorporating a number of design innovations.

The test instrument, by design, has established controlled conditions for the electrical spacing, electrical bias, moisture content, and temperature so that the ionic contamination level can be effectively related to the elapsed time if and when a fixed leakage current threshold level is developed across the electrodes in the test cell.

Principles of Operation of the Test System

Any production floor or analytical test for cleanliness is only as good as the technique to remove the residue from the surface of the assembly. Process cleanliness relates to the type and level of residues that are able to be brought into solution in critical areas, such as pad to pad or hole to hole on a functioning assembly. These residues are such that the system has been designed to assess. The extraction solution has been designed to achieve effective ionic residue removal using a heated delivery system consisting of 3 stages:

1. solution heating/delivery to the extraction site (micro bursts of steam);
2. soak and ionization time;
3. aspiration of the solution to the collection cell.

This cycle is repeated 9 times to effectively remove the surface residues from a 0.1in² area, generating a sample of approximately 2.5mls of extraction solution to be used during the testing, and afterwards for any additional testing.

System Electrical Testing of the 2.5mls of Solution

Using a sacrificial Y-pattern electrode immersed in the extraction solution sample, a 10 volt bias (+/-0.1VDC) is then applied to the electrode and an internal timer is started to measure the time it takes to achieve a leakage event. The system is measuring the leakage across the electrode generated by the solution, including the residues, extracted from the board surface. A threshold of 500µA has been set to identify when a current leakage event has occurred. This threshold has been set using a combination of SIR and ion chromatography data. The electrical measurement is determined by assessing the time it takes for the extraction solution and the 10 volt-biased electrode to reach a 500µA event. The system works under the theory that the more corrosive/conductive the residue, the faster this event is achieved. The less corrosive or conductive the residue, the longer it will take to achieve. We have found that system timing results to achieve the 500µA event in less than 60 seconds correlates to corrosive residues in excess of our limits and are identified as **Dirty**. Timing events that take longer than 60 seconds have correlated to cleaner, less corrosive residues, and are identified as **Clean**.

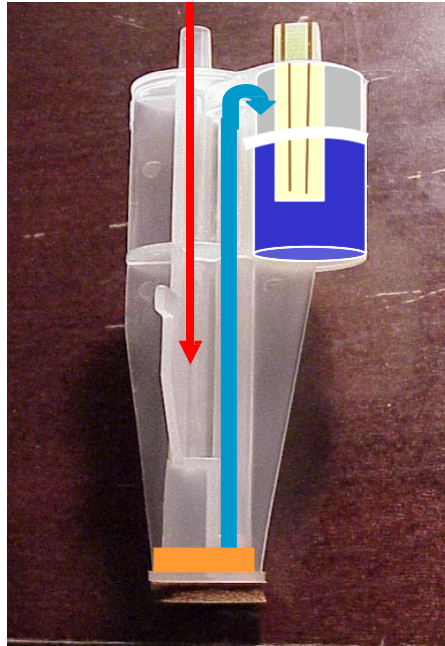
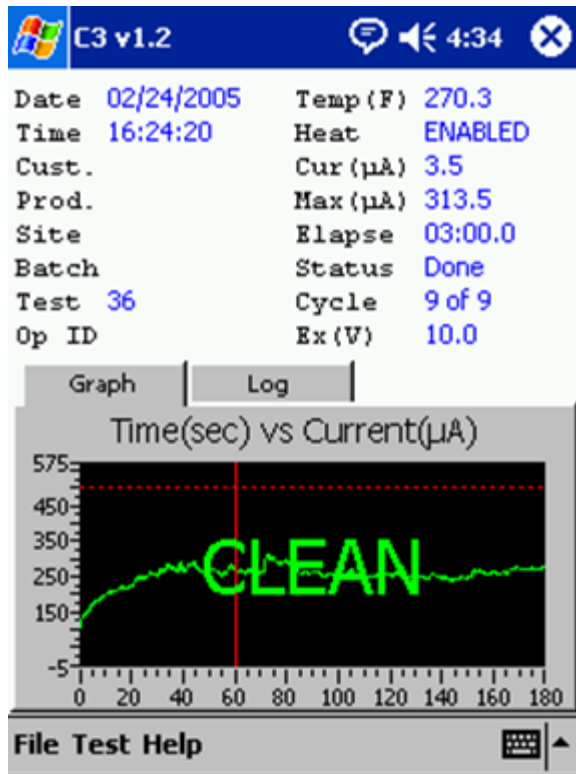


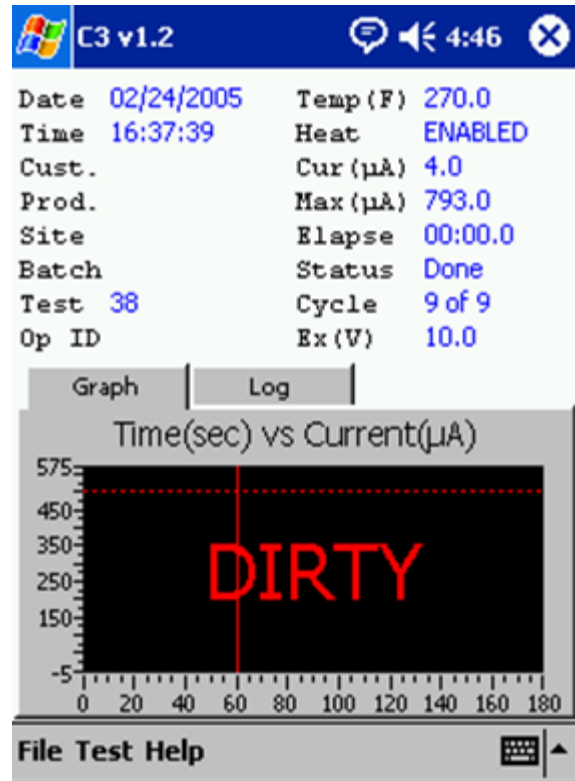
Figure 2 – Test Cell
Heated Extraction Solution Inlet
Extraction Chamber
Aspiration Pathway of Solution
Solution in Collection Cell

This limit of Clean and Dirty at 60 or 120 seconds is based on the achievable cleanliness limits that we have developed in this cleanliness specification.

The extraction solution sample can subsequently be analyzed by ion chromatography to quantify the ionic residue types and levels found on the PCBA and an understanding of the residue level with a direct electrical effect can be created.



Results on a Board with Low Ionic Residues
Class 1-2 setting of 60 or Class 3 of 120 seconds



Results on a Board with High Chloride
(A short occurred in < 1 second)

The test time of the system is approx. 7 minutes (4 minutes to extract the residue and up to 3 minutes to run the electrical assessment of the residue on the electrode).

Current Industry Assessment Methods

Current industry standard nondestructive cleanliness test methods (reference IPC-TR-583) are based upon methods involving product immersion in a solvent solution. The intent is for the solvent solution to mobilize any ionic contaminants into the solution. The solution is then brought in contact with a resistivity probe for measurement. Results are compared to contaminant levels with predicted adverse impact on product reliability. The effectiveness of a cleanliness test method is determined through comparison to the Surface Insulation Resistance (SIR) destructive test method and actual product field reliability performance. The SIR test involves sample coupon preparation followed by an electrical burn-in, typically at 85°C/85%RH with resistance measurement readings collected initially, and at 24, 96, 168 hours, and final ambient conditions.

The approach of immersion, solvent extraction, and resistivity detection are replaced with direct site examination, steam extraction, and electrical measurement of dendrite formation on electrodes with the test. How the different approaches effect cleanliness test performance requires explanation.

Module Immersion in Solvent vs. Direct Site Examination

A disadvantage of the current standard test methods is that contaminant levels can be high in a particular pwb site location, and the test methods failure level threshold is not exceeded. This can occur because the localized high concentration is diluted when the entire module is immersed. The test addresses this condition by allowing direct site examination (within physical limitations between the substrate and the test probe). Direct site examination does not eliminate the possibility of high contaminant levels in a particular location going undetected. However, each product can be evaluated for locations most likely to collect residues to mitigate this risk. These locations are identified and specified in final inspection instructions as controlled test locations. Additionally, the immersion method, by design, provides a “normalized” cleanliness value for the product. In order to acquire a similar result, multiple test sites are identified and tested so that cleanliness level variation within the product can be appraised.

Solvent Extraction vs. Steam Extraction

There are significant differences between these two techniques. One is the temperature and the other is mechanical surface action. Solvent extraction is generally at room ambient conditions (25°C) whereas the steam extraction will result in warming at the extraction location. Along with the warming, the steam impinges (as opposed to static solvent contact) the surface. When results of both extraction methods are compared, sufficient agreement in detectability is demonstrated (our 150 board test/IPC Method Comparison Battery Report).

Conductivity Detection vs. Dendritic Growth Detection

Utilizing conductivity detection relies on the principle that the ionic strength of the solution correlates to the occurrence of corrosion (dendrite formation) onset by contamination. Utilizing instrumentation for direct detection of dendrite formation eliminates uncertainty associated with this correlation. On the instrument, the electrodes are spaced 0.050” apart and are configured as a Y-pattern as specified in MIL-STD-202 (the electrodes are used for the water drop test in pwb manufacturing). There is a 10VDC potential across the electrodes. The presence of a dendrite is indicated when 500µA of current is drawn across the electrodes (or a resistance of 20kohms). The time required for the detector to reach the 500µA threshold is measured. The higher the contaminant level, the sooner the 500µA threshold is reached. The electrode operational life is self-limited, as it will self-destruct by means of corrosion after 5-6 minutes of operation.

The test method employs a combination of the principles from both solvent extraction and SIR cleanliness test methods to arrive at a test method which successfully reduces testing cost, improves testing quality, and shortens testing process time.

Cleanliness Test Performance Evaluations

Since 2002, Foresite has been utilizing the C3 in testing services - typically performing 60-80 analyses each day. Extrapolating this utilization level indicates more than 20,000 analyses have been performed with the instrumentation. Numerous commercial electronic reliability investigations by us have been accomplished utilizing the C3 instrument.

Test / 200 Board Comparison Study

In 2003, we composed a 200-board study consisting of comparisons of our test instrument performance to the established cleanliness evaluation methods. In the 200 board study, there were a number of pwb substrates, flux loads, and cleaning level combinations. Of the 200 boards, fifty (50) were prepared with no clean flux and not cleaned prior to cleanliness testing. The other 150 boards were prepared with varying levels of water-soluble flux and subsequently, fifty (50) were water-only cleaned, fifty (50) were cleaned in a 3% saponifier aqueous solution, and fifty (50) were cleaned in 10% saponifier aqueous solution. The saponifier was Envirogold 816. Each group of fifty (50) was divided into five (5) printed wiring board (pwb) type samples with a ten (10) board sample size. The pwb types were HASL clean, HASL medium, HASL dirty, Immersion Silver, and Copper OSP. For the purposes of this analysis, the results from the Immersion Silver and Copper OSP as well as the no clean flux are not evaluated. These conditions are not of interest because they are not utilized in BAE Systems designs or processes.

The remaining experimental data fit neatly into a 2x3 factorial design with ten (10) replications. The study provides data to evaluate the test performance in comparison with cleanliness tests currently recognized as cleanliness test methods in the IPC J-STD-001 standard. A comparison of multiple regression analysis results for the different methods demonstrate the data presented in Table 1.

Table 1 - Adjusted R-Square Values for Various Cleanliness Tests

TEST	Adj. R-square
Our test	0.99
SIR	0.84
IC	0.74
ROSE	0.59

The adjusted R-square values for our test y-hat model exhibits the best data fit, demonstrating that the test is at least comparable (and likely performs better) than existing standard test methods.

Chart 1 “Our test vs. other test measures” demonstrates the sensitivity of the test instrument to detect contaminant levels. The chart indicates when chloride levels are below about a 5.0µg/in² threshold, dendrite formation does not occur in the test cell. The other measurement methods have less sensitivity in making distinctions between the contaminant levels as well as having the measurement system disadvantages described above.

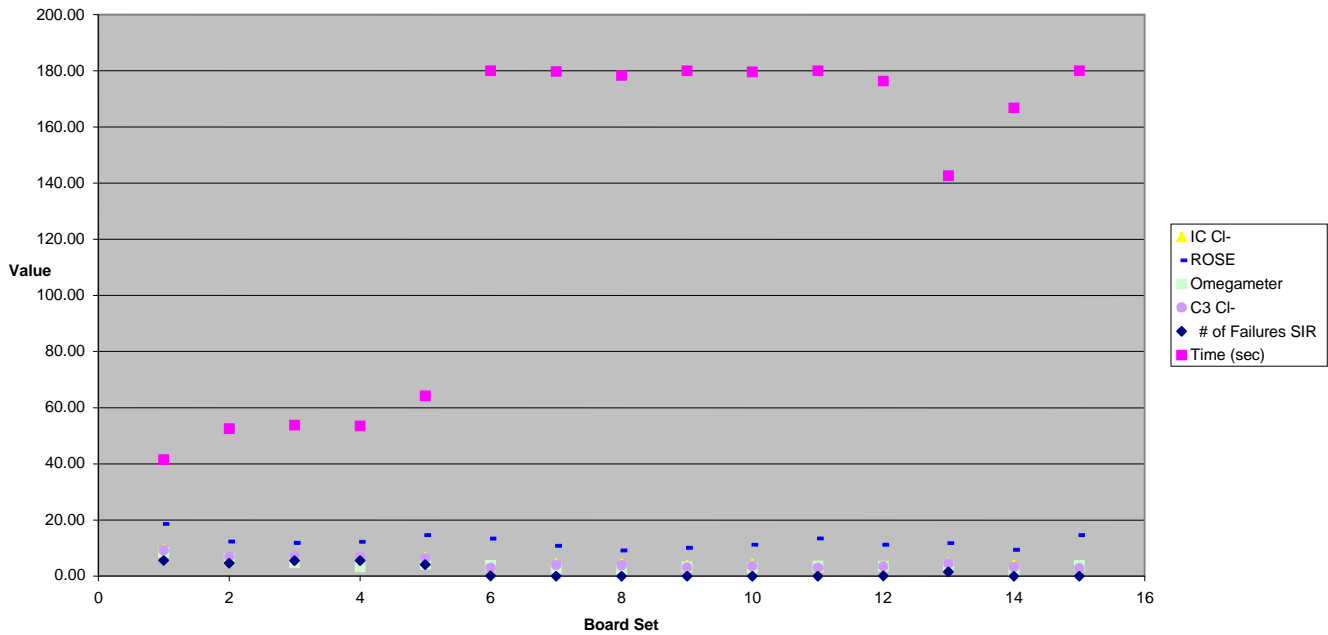


Chart 1 "Our test vs. other test measures"

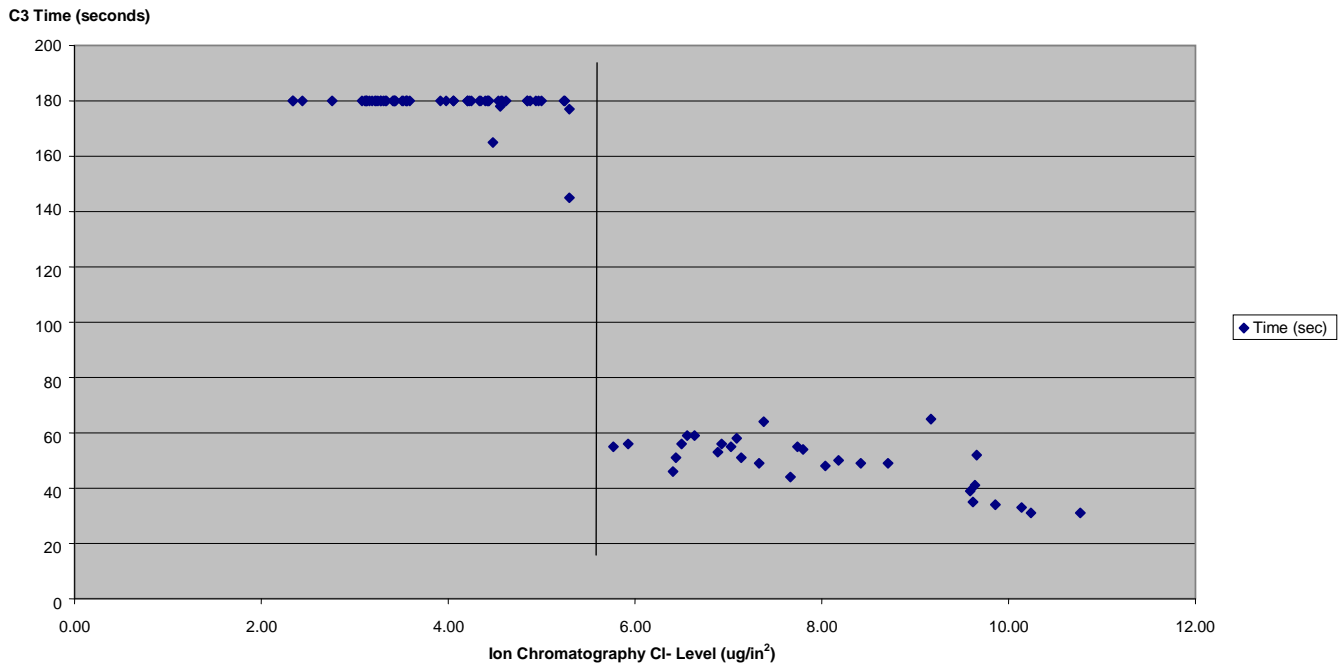


Chart 2

Chart 2 is a scatter plot depicting the elapsed time (seconds) before dendrite growth is detected by the instrument compared to the chloride ion concentration (as measured using the ion chromatography test method). The data indicate that chloride levels below $5.3\mu\text{g}/\text{in}^2$ do not result in the test cell developing any dendritic growth. When chloride levels exceed $5.7\mu\text{g}/\text{in}^2$, the instrument repeatedly develops dendritic growth in the test cell.

IPC-Handbook-001 paragraph 8.41, ion chromatography testing (March 1998) states the following in regards to chloride ion levels. “Results from a number of industry studies involving IC analysis have shown the following guidelines to be reasonable breakpoints for chloride content. Chloride content increases risks of electrolytic failure when exceeding the following levels” (in $\mu\text{g}/\text{in}^2$): 2.5 for low solid fluxes; 4.5 for high-solid rosin fluxes; 5.0 for water soluble flux; 2.0 for bare boards with tin-lead metallization.

Chloride Ion System Test Response Study

In order to better understand the test response to the chloride ion, we prepared solutions on known chloride concentrations and delivered precise volumes of the solutions on glass slides in order to simulate residue deposits in the known risk level range. Chart 3 graphically displays the results of the experiment, as well as the least squares linear regression estimate. The correlation coefficient for the least squares fit is 0.97.

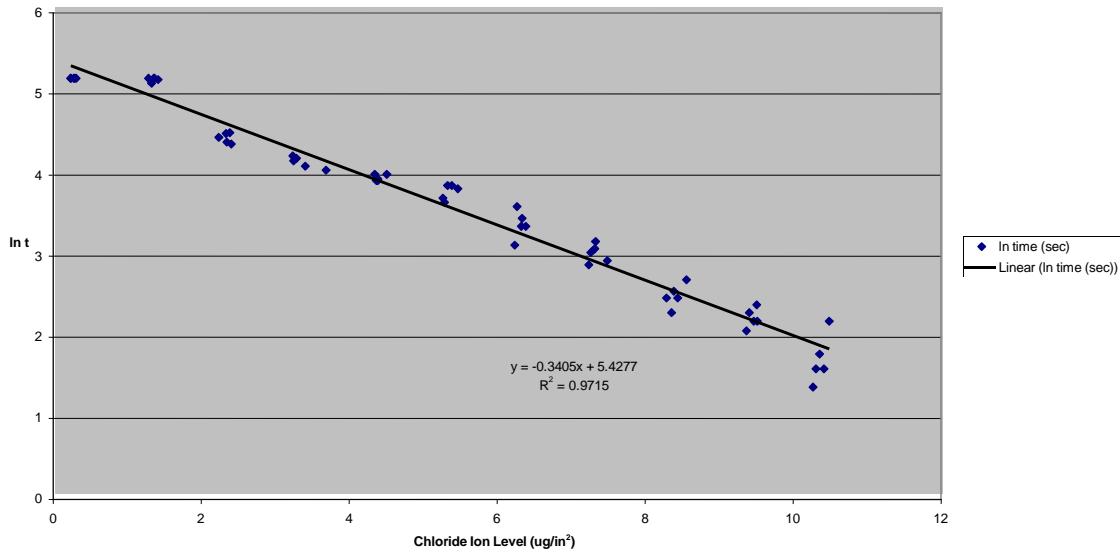


Figure 3 - Chloride Ion Response Study

Table 2 exhibits the statistical characteristics of the least squares regression. The F test demonstrates high confidence in the model parameters. There is some variation not accounted for in the model.

Table 2 - ANOVA Table

Source	SS	df	MS	F-zero	F-crit
Regression	64.8706	1	64.8706	1801.96	12.15
Error	1.9002	53	0.036		
Total	66.7708	54			

F-zero is much greater than F-critical. Thus, we can conclude R² not equal to zero and b₁ is not equal to zero with at 99.9% confidence

First, as the chloride level increases, the range of the ln t test values increase. This may be simply a result of the measurement values getting smaller, making the variation between the values higher. Also, the spread of the data has a third-order shape to it. The measurements at the 0.0-1.0µg/in² range are essentially flat, and then there is a drop through 2.0 µg/in² to the 3.0-5.0µg/in² moderately down-sloping range, and from 5.0µg/in² the least squares slope closely follows the data scatter.

Based upon this qualitative examination of the data, and the IPC J-HDBK-001 chloride content breakpoints, a threshold for the conformal coat removal process is established at 3.0µg/in². Based upon the variability of the observations, the predicted time is determined by statistical calculation. Table 2 depicts key values in the calculation. From the least squares model derived from the chloride ion test data, when the chloride level is 3.0µg/in², any future time value will be 88 +/- 32 (or 56 to 120) seconds with 95% confidence. Therefore, the test threshold can be set at 120 seconds to ensure a high confidence of detecting even trace levels of chloride ion 1.5µg/in² below the threshold recommended for high-solid rosin fluxes.

Effect of Multiple Residue Components on the Test Measurement

When the chloride ion study and the 200 board study chloride ion levels are compared, it is seen that the time exhibits different behaviors between the two studies. The 200 board study samples were water soluble flux residues on a pwb surface, whereas the chloride ion study was from pure chloride ion standard reagents on a glass slide. The different behavior is attributable to the variation of the residue chemistry. An analytical treatment of interference and interaction effects is beyond the scope of this project. The strength of a group of ions, and thus their potential to produce an electrochemical reaction is dependent upon the collective size, electronegativity, and mobility of the ions.

Since the test design effectively simulates the electrochemical reaction failure mode, it is not necessary to establish the ionic components identities and concentration levels in order to predict the residue's reactive potential. There are numerous reactive residues that are not comprised of the chloride ion. For example, the reactive component in the conformal coat removal process is predominantly the hydroxide ion. For this reason, the drained battery failure report demonstrates the test instrument's capability to detect other than chloride ionic residues which can lead to high leakage current conditions from contaminant residues. Similarly, various concentration levels of 411 and 816 are blended and tested in the test instrument to establish that the instrument has the capability to effectively screen for contaminant residue levels which could lead to degraded circuit performance.

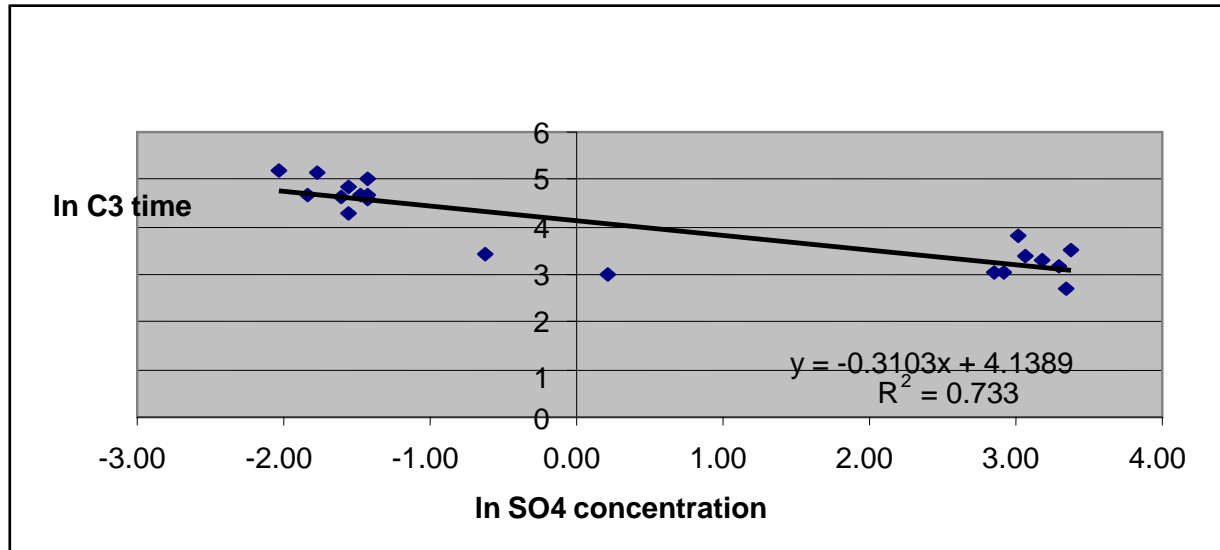
Drained Battery Failure Report

Throughout the discussion of the test instrument, the focus has been on the response of the instrument to chloride ion concentration levels due to its association with solder flux chemistry. We have obtained permission from a client to share results of a reliability investigation involving sixty (60) analytical tests. This investigation was initiated to determine the reason the client's smoke alarm batteries were losing their electrical storage capacity in about two weeks. The circuit was evaluated and our test sites were selected based upon the components circuit function. Our test identified high contamination in a capacitor location. The cell contents were transferred for ion chromatography analysis and high sulfate ion concentration was associated with the test failures. Investigation at the capacitor manufacturer discovered the high levels of sulfate ion

were due to residues of methyl sulfonic acid which were not removed due to a rinse system malfunction in the production of the capacitors. Upon corrective action, the battery life returned to a level exceeding eighteen (18) months.

Chart 3 is a scatter plot of the test time vs. the sulfate ion concentration. There is a predominant distinction between the test time response between the high and low sulfate ion concentrations. The smoke alarm battery case conclusively establishes that the test will capably detect reactive contaminants regardless of the ionic species responsible for the reactive condition.

Chart 3 - ln SO₄ vs. ln time



Conclusions

Our Test Instrument is an effective tool for detecting ionic residues, which can manifest into an electrochemical reaction, resulting in dendritic growth. Dendritic growth can result in increased leakage current in electronic circuits leading to product malfunction. The effectiveness of the test to detect reactive residues is not dependent on the chemistry of the ionic residue but measures the corrosive nature of the residues. The method shows correlation with the SIR and reliability testing. The extraction used is a localized assessment of a selected area (pad to pad) and the electrical measurement as a direct result on the corrosive nature of the residues extracted from the selected area of the board surface. This tool will not give the general ionic cleanliness number of the assembly as historically done, but will allow us to look at selected areas to understand the corrosive nature of the residues. The instrument is just a different assessment technique for determining cleanliness and is not intended to replace the traditional tools that control the process, but to enhance the understanding of the pockets of contamination and their impact on product reliability. If the traditional total board soaking testers that assess general cleanliness to control your process meets your control and quality needs this tool will not meet your needs.

The test time pass/fail acceptance threshold setting is 120 seconds. When the time exceeds 120 seconds, the test yields a pass result. This level of assessment correlated with reliability and functional testing on high reliability hardware when looking at known areas of the assembly.

References

Evaluation of Low-Residue Soldering for Military and Commercial Applications: A Report from the Low-Residue Soldering Task Force. June 1985.

- IPC 9201 Surface Insulation Resistance Handbook
- IPC J-STD-001 Requirements for Soldered Electrical and Electronic Assemblies
- IPC-TR-583 An In-Depth Look At Ionic Cleanliness Testing