

Contamination and Cleanliness Challenges

IPC Conference on Solder and Reliability
Materials, Processes and Tests

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Why Worry about Contamination and Cleanliness?

- Believed to be one of the primary drivers of field issues in electronics today
 - Induces corrosion and metal migration (electrochemical migration – ECM)
- Intermittent behavior lends itself to no-fault-found (NFF) returns
 - Driven by self-healing behavior
 - Difficult to diagnosis
- Pervasive
 - Failure modes observed on batteries, LCDs, PCBAs, wiring, switches, etc.
- Will continue to get worse



Future of Contamination & Cleanliness

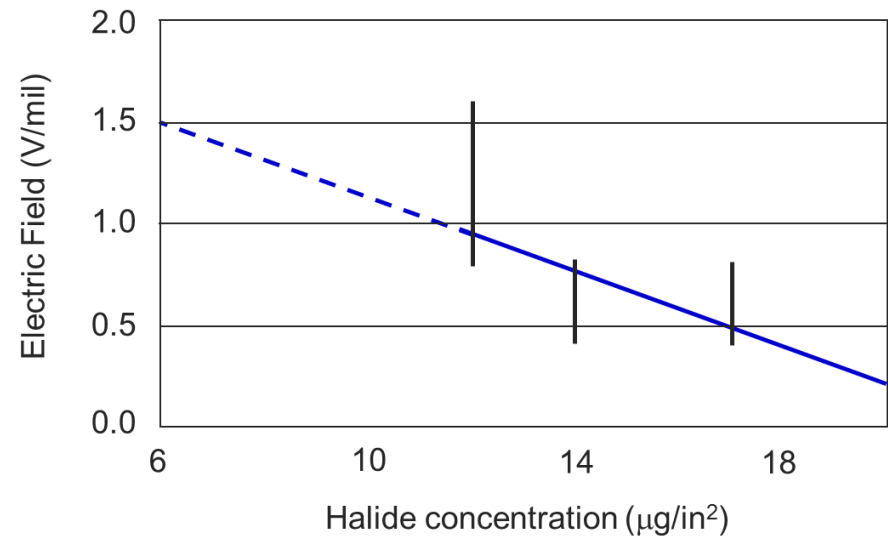
- Continued reductions in pitch between conductors will make future packaging more susceptible
- Increased use of leadless packages (QFN, land grid array, etc.) results in reduction in standoff
 - Will reduce efficiency of cleaning, which may lead to increased concentration of contaminants
- Increased product sales into countries with polluted and tropical environments (East Asia, South Asia, etc.)
 - ECM occurrence very sensitive to ambient humidity conditions
- Pb-Free and smaller bond pads
 - Require more aggressive flux formulations

Example: QFN and Dendritic Growth

- Large area, multi-I/O and low standoff can trap flux under the QFN
- Processes using no-clean flux should be requalified
 - Particular configuration could result in elevated weak organic acid concentrations
- Those processes not using no-clean flux will likely experience dendritic growth without modification of cleaning process
 - Changes in water temperature
 - Changes in saponifier
 - Changes to impingement jets

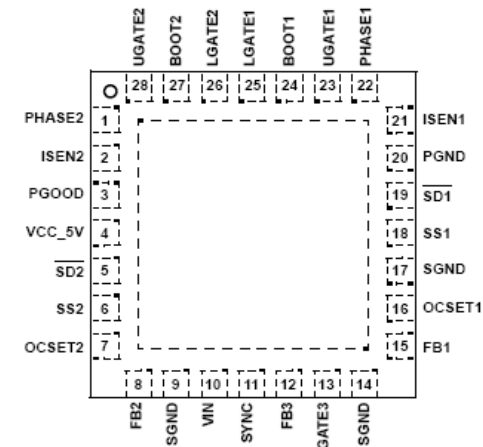
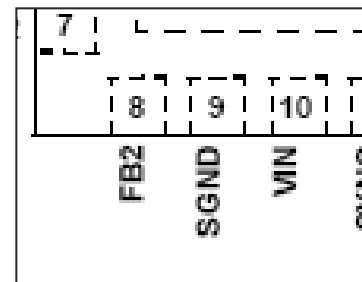
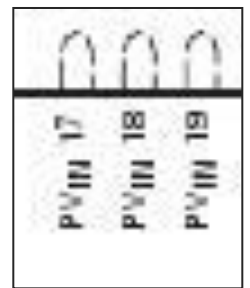
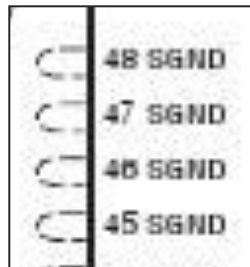
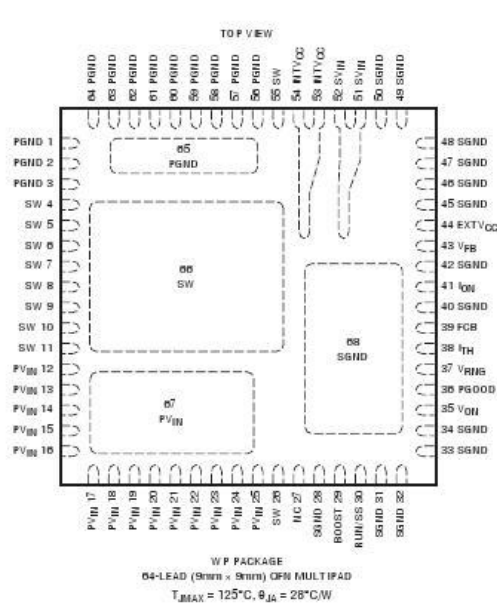
QFN and Dendritic Growth (cont.)

- The electric field strength between adjacent conductors is a strong driver for dendritic growth
 - Voltage / distance
- Digital technology typically has a maximum field strength of 0.5 V/mil
 - TSSOP80 with 3.3VDC power and 16 mil pitch
- Previous generation analog / power technology had a maximum field strength of 1.6 V/mil
 - SOT23 with 50VDC power and 50 mil pitch
- Introduction of QFN has resulted in electric fields as high as 3.5 V/mil
 - 24VDC and 16 mil pitch

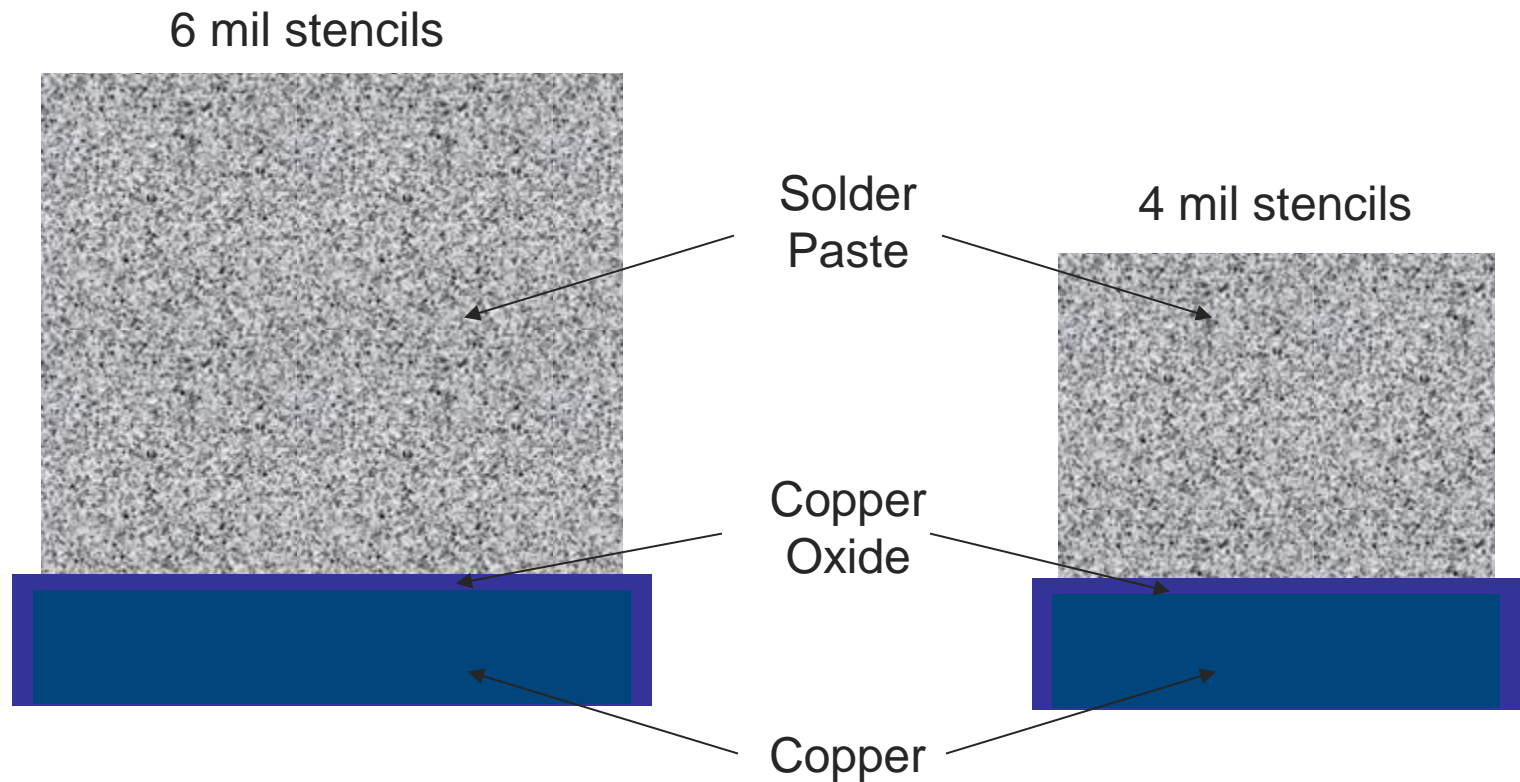


QFN and Dendritic Growth (cont.)

- Some component manufacturers are aware of this issue and separate power and ground
 - Linear Technologies (left) has strong separation power and ground
 - Intersil (right) has power and ground on adjacent pins



Higher Activity Flux



- Reduced bond pads = smaller volumes of solder paste (less flux)
 - Oxide thickness remains the same
- Requires higher activity fluxes

Failure Mode

- Why do you care about excessive contamination or insufficient cleanliness? They lead to:

Electrochemical Migration

(note: not Electromigration; completely different mechanism)

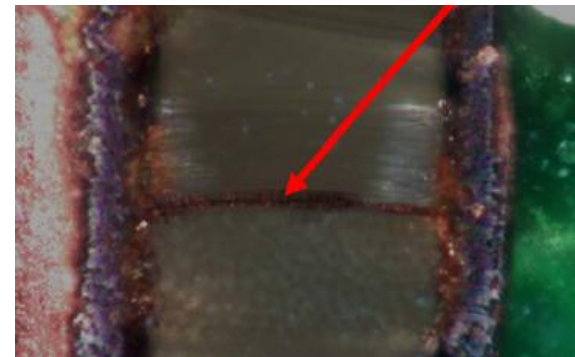
- Understanding the mechanism provides insight into the drivers and appropriate mitigations

What is ECM?

- Movement of metal through an electrolytic solution under an applied electric field between insulated conductors
- Electrochemical migration can occur on or in almost all electronic packaging
 - Die surface
 - Epoxy encapsulant
 - Printed board
 - Passive components
 - Etc.

ECM Mechanisms

- Some ECM Mechanisms have more definitive descriptions
- Dendritic growth
 - Descriptor for ECM along a surface that produces a dendrite morphology
 - “Tree-like”, “Feather-like”
- Conductive anodic filaments (CAF)
 - Descriptor for migration within a printed circuit board (PCB)



Contamination

- **Two concerns**
 - Hygroscopic contaminants
 - Ionisable contaminants that are soluble in water (e.g., acids, salts)
- **Ionic contaminants of greatest concern**
 - Primarily anions; especially halides (chlorides and bromides)
 - Chemically aggressive due to chemical structure
 - Very common in electronics manufacturing process
 - Decreases pH; few metal ions found in dendrites are soluble at mid to high pH. Cu dendrites require pH less than 5 to form.
 - Silver(I) ions are soluble at higher pH; reason it is one of easiest to form dendrites.
 - Cations primarily assist in the identifying the source of anions
 - Example: Cl with K suggests KCl (salt from human sweat)

Hygroscopic Residues

- Certain contaminants create conditions that increase moisture film thickness
 - Increase risk of condensation
 - Ionic and non-ionic contaminants
- **Examples: Polyglycols**
 - When present, turns surface from hydrophobic (water repelling) to hydrophilic (water attracting)
 - Non-ionic: Not detectable using ion chromatography or Omegameter
- **Not much focus on these in industry**

Sources of Contaminants

- Printed board fabrication process
 - Insufficiently cured polymers
- Rinse water
- Fluxes
- Handling
- Storage & use environment

Ion	Possible Sources
Cl	Board Fab, Solder Flux, Rinse Water, Handling
Br	Printed Board (flame retardants), HASL Flux
Fl	Teflon, Kapton
PO ₄	Cleaners, Red Phosphorus
SO ₄	Rinse Water, Air Pollution, Papers/ Plastics
NO ₄	Rinse Water
Weak Organic Acids	Solder Flux

Printed Board Fabrication Process

- One of the most common source of contaminants
 - Greatest use of active/aggressive chemicals
 - Low margin business (reverse auctions)
 - Increasing use of no-clean assembly process (last chance to clean)

PCB Contaminants (examples)

- **Etching**
 - Chloride-based: Alkaline ammonia (ammonium chloride), cupric chloride, ferric chloride, persulfates (sometimes formulated with mercuric chloride)
 - Other: Peroxide-sulfuric acid
- **Neutralizer**
 - Hydrochloric acid
- **Cleaning and degreasing**
 - Hydrochloric acid, chlorinated solvents (rare)
- **Photoresist stripping**
 - methylene chloride as a solvent
- **Oxide**
 - Sodium chlorite
- **Electroless plating**
 - Sodium hypochlorite (in potassium permanganate)
 - Palladium chlorides (catalyst)
- **Bromide sources**
 - Surface processes
 - Solder masks, marking inks, and fluxes
 - Flame retardant

Fluxes

- **5% of the market uses rosin**
 - Preferred in the early days of electronics manufacturing
 - Insoluble residues encapsulated contaminants
 - Hydrophobic surface
 - Quasi-conformal coating
 - This is decreasing (concerns regarding environmental-friendliness of solvents required to clean)
- **25% uses water soluble fluxes**
- **70% of the market uses no-clean**
 - 80-90% in consumer, computer, telecom markets
 - This is increasing
 - Fine pitch, low clearance, high density greatly decreases cleaning effectiveness
 - Electronics industry very cost sensitive (eliminate one process, increase throughput)

Flux Residues

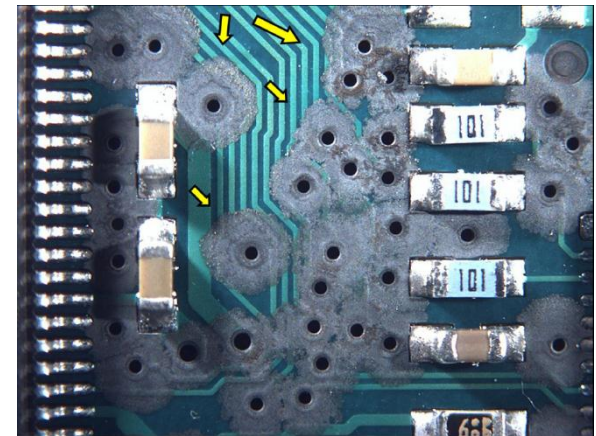
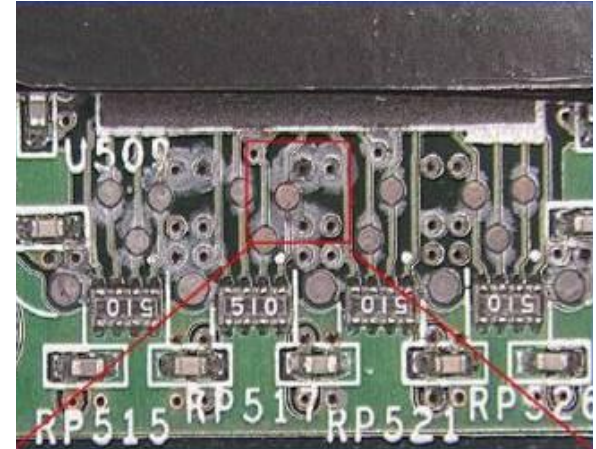
- Residues of no-clean soldering?
 - Water-soluble dicarboxylic acids
 - Hygroscopic polyethylene glycol ethers
- List of potential weak organic acids (WOAs)
 - Benzoic, Butyric, Formic, Lactic, Malonic, Oxalic, Propionic, Succinic, Citric, Glutaric, Adipic, Malic
- Optimum flux
 - Acids are neutralized after soldering process
 - Residual wetting agents are minimized

Handling / Storage / Environment

- **Handling**
 - Salts from human contact (KCl and NaCl)
- **Storage**
 - Cleaning chemicals
 - Outgassing
 - Polymeric materials
- **Use Environment**
 - Dust
 - Evaporated sea water
 - Industrial pollutants

Influence of Pollutants: Creepage Corrosion

- Recent field issues with printed circuit boards (PCBs) plated with immersion silver
 - Sulfur-based creepage corrosion
- Failures in customer locations with elevated levels of sulfur-based gases
 - Rubber manufacturing
 - Sewage/waste-water treatment plants
 - Vehicle exhaust fumes (exit / entrance_ramps)
 - Petroleum refineries
 - Coal-generation power plants
 - Paper mills
 - Landfills
 - Large-scale farms
 - Automotive modeling studios
 - Swamps

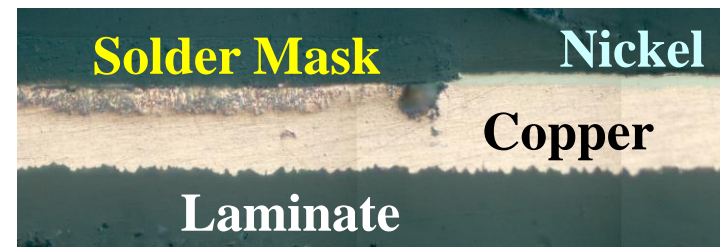
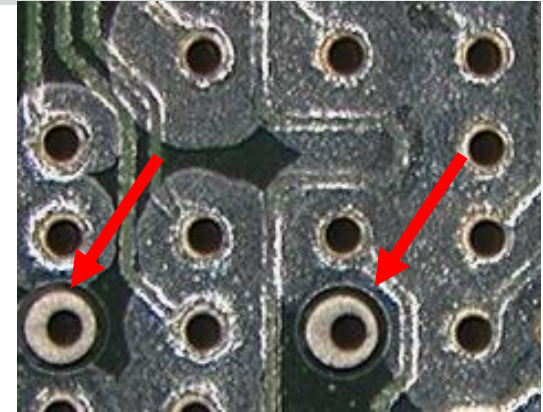


P. Mazurkiewicz , ISTFA 2006

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Creepage Corrosion: Observations

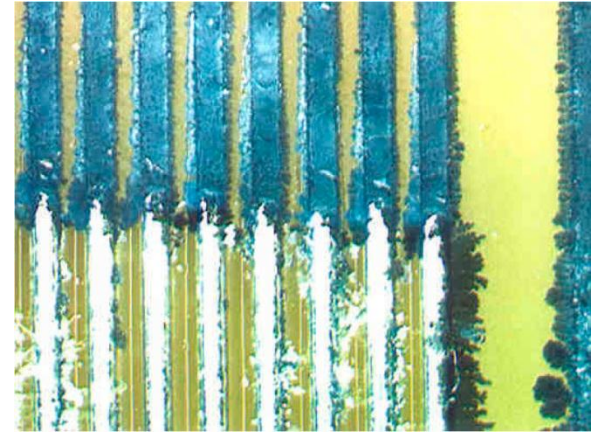
- Galvanic corrosion
 - Failures at locations with thin or absent immersion silver
 - Edge of solder mask, deep in plated through hole barrel
 - Copper and silver in contact
- Similar mechanism observed with electroless nickel / immersion gold (ENIG) plating
 - Corrosion of copper trace at solder mask edge



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Creepage Corrosion: Observations

- Failure behavior not observed during qualification testing [Mixed Flowing Gas (MFG) Testing Class III]
 - Reason 1: Lack of appropriate structures in test vehicle
 - Reason 2: Test conditions may not be appropriate
- Strong indication that creepage mechanism requires that one or more MFG test parameters are exceeded
 - Especially %RH
 - Hillman: >75%RH
 - Cullen: 93%RH



Class	RH (%)	Temp (°C)	H ₂ S (ppb)	Cl ₂ (ppb)	NO ₂ (ppb)	SO ₂ (ppb)
I	----	----	----	----	----	----
II	70±2	30±2	10±5	10±3	200±50	----
IIA	70±2	30±1	10±5	10±3	200±50	100±20
III	75±2	30±2	100±20	20±5	200±50	----
IIIA	70±2	30±1	100±20	20±5	200±50	200±50
IV	75±2	40±2	200±20	30±5	200±50	----

Pollutants: Not Always in Industrial Settings

Drywall Sulfur Fumes Blamed for A.C. & Electrical Equipment failures

Chinese Drywall Cited in Building Woes

- The drywall is emitting sulfur-based gases that are corroding air-conditioner coils, computer wiring and metal picture frames.

Drywall blamed for A.C. failures

- Air-conditioning coils have turned black, along with wiring, piping and even silver jewelry.
- "We have definitely identified that a combination of sulfide gases are the cause of the corrosion," said Robert P. DeMott, managing principal of Environ.
- "Foul odors reported by people living in the homes may also be caused by the combination of sulfur gases being released from the drywall,

Chinese drywall class action lawsuit

- LEE COUNTY, Fla. - The Lawsuit was filed against Knauf Plasterboard Tianjin Co., LTD, The Knauf Group, Rothchilt International Limited and the Banner Supply Company.
- Known as "Chinese Drywall", it was manufactured overseas and was made from waste materials. As a result, it emits sulfur compounds that corrode copper wiring and other metals found in homes.

Monday, January 12, 2009 As of 12:00 PM

THE WALL STREET JOURNAL.

news-press.com
Fort Myers, Florida • Southwest Florida



Copper Corroded by Sulfur flumes

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Contamination / Cleanliness

Detection, Measurement, and Requirements

How to Measure Cleanliness?

- **Standard ion chromatography (IC) testing**
 - IPC-TM-650, Method 2.3.28A
 - Submerge whole board; 75 IPA / 25 DI
- **Updated IC**
 - IPC-TM-650, Method 2.3.28.2
 - Submerge whole board; 10 IPA / 90 DI (Delphi requirements)
- **Modified IC**
 - Use of saponifiers or alternative solvent
 - Submerge whole board
- **Localized Testing**
 - C3 from Foresite

PCB Cleanliness Control: Industry Specs

- IPC-6012B, Qualification and Performance Specification for Rigid Printed Boards, Section 3.9
 - Requires confirmation of board cleanliness before solder resist application
 - When specified, requires confirmation of board cleanliness after solder resist or solderability plating
- Board cleanliness before solder resist shall not be greater than 10 ug/in² of NaCl equivalent (total ionics)
 - Based on military specifications from >30 years ago
- Board cleanliness after solder resist shall meet the requirements specified by the customer

Cleanliness Control: Test Procedures

- IPC-6012B specifies a Resistance of Solvent Extract (ROSE) method
 - Defined by IPC-TM-650 2.3.25
- IPC-6012B specifies this measurement should be performed on production boards every lot
 - Class 1 boards: Sampling Plan 6.5
 - Class 2 and 3 boards: Sample Plan 4.0
- Sampling plan (example)
 - If a lot contains 500 panels of a Class 2 product, 11 panels should be subjected to ROSE measurements for cleanliness testing

Test Procedures: Common Problems

- ROSE is the least sensitive of ionic measurement techniques
 - 5 ug/in² detected by ROSE is equivalent to ~20 ug/in² detected by ion chromatography
- Equipment is not calibrated
- Insufficient volume of solution is used
- Insufficient surface area
 - Panels are preferred over single boards
- Cut-outs are not considered when calculating surface area
- Insufficient measurement time
 - 7 to 10 minutes is preferred

Technique	Technology	Equivalency Factor
ROSE	Static / Unheated	1
Omega-Meter	Static / Heated	~1.5
Ionograph	Dynamic / Heated	~2.0
Modified-ROSE, Zero-Ion, etc.	Varied	~4.0 (?)
Ion Chromatography	80C for 1 hr	~4.0

Test Procedures: Best Practice

- Ion Chromatography (IC) is the ‘gold standard’
 - Some, but very few, PCB manufacturers qualify lots based on IC results
- Larger group uses IC to baseline ROSE / Omegameter / Ionograph (R/O/I) results
 - Perform lot qualification with R/O/I
 - Periodically recalibrate with IC (every week, month, or quarter)

PCB Cleanliness: Moving Forward

- Extensive effort to update PCB Cleanliness Standards
- IPC-5701: Users Guide for Cleanliness of Unpopulated Printed Boards (2003)
- IPC-5702: Guidelines for OEMs in Determining Acceptable Levels of Cleanliness of Unpopulated Printed Boards (2007)
- IPC-5703: Guidelines for Printed Board Fabricators in Determining Acceptable Levels of Cleanliness of Unpopulated Printed Boards (Draft)
- **IPC-5704: Cleanliness Requirements for Unpopulated Printed Boards (2010)**

Cleanliness Controls: Ion Chromatography

- Contamination tends to be controlled through industrial specifications (IPC-6012, J-STD-001)
 - Primarily based on original military specification
 - 10 $\mu\text{g}/\text{in}^2$ of NaCl 'equivalent'
 - Calculated to result in 2 megaohm surface insulation resistance (SIR)
 - Not necessarily best practice
- Best practice is contamination controlled through ion chromatography (IC) testing
 - IPC-TM-650, Method 2.3.28A

	Pauls	General Electric	NDCEE	DoD*	IPC*	ACI
Chloride ($\mu\text{g}/\text{in}^2$)	2	3.5	4.5	6.1	6.1	10
Bromide ($\mu\text{g}/\text{in}^2$)	20	10	15	7.8	7.8	15

*Based on R/O/I testing

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Major Appliance Manufacturer (IC)

Contaminant	Incoming PCB	Processed PCB	
	Maximum Level (ug/in ²)	Maximum Level (ug/in ²)	Upper Control Limit (ug/in ²)
Ammonium	<0.5		<2
Bromide	3	10	8
Calcium	<0.5		<1
Chloride	2.5	3.5	3
Fluoride	<0.5		<1
Magnesium	<0.5		<1
Nitrate	<0.5		<2
Nitrite	<0.5		<1
Phosphate	<0.5		<1
Potassium	<3		<3
Sodium	<3		<3
Sulfate	3	3	2
Total	5	18	14
Weak Organic Compounds	200	200	50

Mitigation -- Cleaning

PCB Cleaning: Process Flow

- **At a minimum, PCB manufacturers should clean the PCB:**
 - Immediately before the application of solder resist
 - Immediately after the application of any solderability plating
 - HASL
 - Electroless Nickel and Immersion Gold
 - Immersion Tin
 - Immersion Silver
- **Some PCB manufacturers also perform a final clean**
 - Should not substitute cleaning after solderability plating
 - Residues from plating operations can become more difficult to remove with any time delay

PCB Cleaning Process: Requirements

- **Final rinse with deionized (DI) water**
 - 2-8 MΩ is preferred; >10 MΩ may be too aggressive
 - Distilled water is insufficient
 - 'City' water is unacceptable
- **Potential options**
 - Use of saponifier during the cleaning process
 - Heated DI water is nice, but not absolutely necessary
- **Common problems**
 - DI water is only used if specified by the customer
 - DI water is turned off to reduce water and energy usage
 - Failure to monitor DI water at the source
 - Failure to alarm the DI water on the manufacturing floor

Mitigation PCBA Cleaning

When to Clean?

- **Very high reliability applications**
 - Medical, Military, Avionics, Industrial, Telecom
- **Sensitive circuitry**
 - High-impedance circuits
 - High-frequency circuits
- **Operation in uncontrolled environments**
- **Use of conformal coating**
 - Concern over compatibility
- **Note: Some high-reliability markets have moved away from cleaning**
 - Automotive, Enterprise, etc.

Industry Standards on PCBA Cleaning

- Requirements driven by J-STD-001
 - Mandates 10ug/in² (1.56 ug/cm²) for ROL0 or ROL1 (others based on limit established by user)
- Section 6.1
 - Assemblies should be cleaned after each soldering operation so that subsequent placement and soldering operations are not impaired by contamination
- Section 8.2.2
 - Cleanliness testing is not required (unless specified by the customer)
 - SPC not required (testing should be random, but sample plan not provided)
 - Minimum once every production shift
 - If any assembly fails, the entire lot shall be evaluated and re-cleaned and a random sample of this lot and each lot cleaned since performing the last acceptable cleanliness test shall be tested
- Some guidance provided by two handbooks
 - Guidelines for Cleaning of Printed Boards and Assemblies, IPC-AC-62B (2012)
 - Aqueous Post Solder Cleaning Handbook, IPC-CH-65B (2012),

Critical Aspects of PCBA Cleaning

- Solder Paste / Flux Chemistry
- Component Selection and Board Design
- Equipment
 - Batch vs. Inline
 - Critical equipment parameters
- Cleaning Solution
 - Includes solvent, chemistry, and temperature
- Process Location
 - When to clean?
- Cleanliness Requirements and Assessment

What's Missing?

- Minimal information on cleaning
 - Other than 'no-clean'
- Information needed
 - How to clean (cleaning solution, cleaning process)
 - What to clean (amount and type of residues)
- Why no cleaning information?
 - Partially driven by process temperature, board design, and board materials

Missing Information (example)

- **‘Water Soluble’ is not equivalent to ‘Water Washable’**
 - Rosin-based flux residues can be removed by water in combination with a saponifier
 - Non-water soluble flux residues can be removed through impingement (residue is softened by heated water and “knocked” off by force of sprayed water striking the residue)
- **‘No-Clean’ can sometimes be cleaned**
 - Sometimes, it can not

Component Selection / Board Design

- **Challenges**
 - High density
 - Low standoff
- **High density**
 - Number of components per area
 - Number of tall / wide components
- **Low standoff components**
 - Chip components (0402, 0603, etc.)
 - Area array components (BGA, CSP, etc.)
 - Bottom-terminated components (LGA, QFN, etc.)

Chip Components

- **Some debate about worst-case**
 - Larger components (e.g., 2512) have more surface area
 - Smaller components (0402, 0603) tend to have lower standoffs (1-2 mil vs. 3-4 mil)
- **Potential design improvements for cleaning**
 - No traces under components (most common)
 - Smaller bond pads (lifts up the component)
 - Thinner solder mask (increases standoff)
 - Components in parallel (prevents blocking of cleaning solution)
 - Board cutouts (primarily for larger chip components)

Best Practices: PCBA Cleanliness

- Confirm incoming PCB cleanliness
- Clean after soldering operations
- Control and measure
 - Water quality going into process
 - Assembly cleanliness

Process Location: Where to Clean?

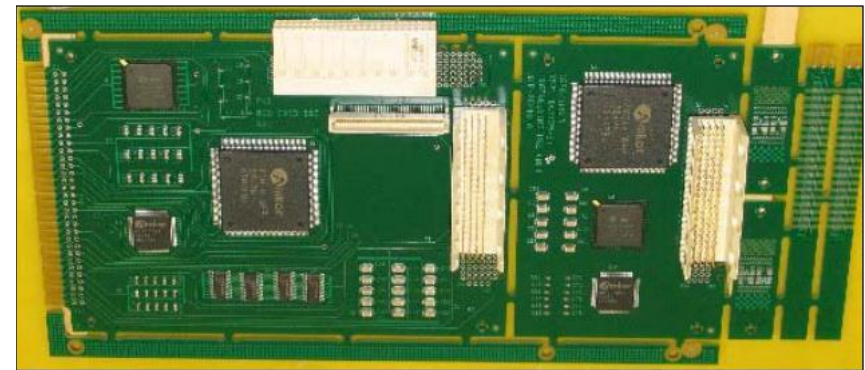
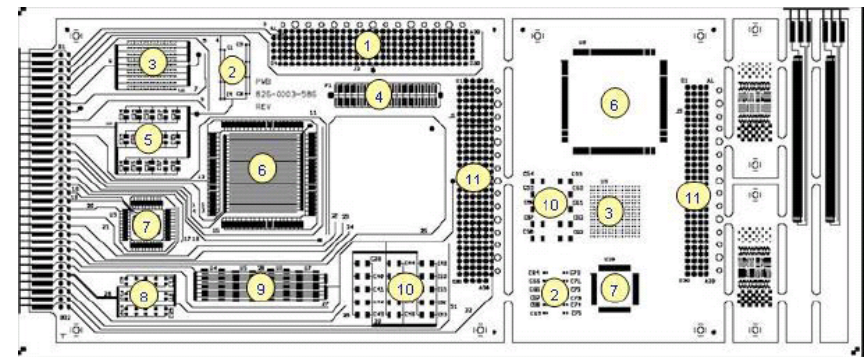
- One of the biggest variables in cleaning operations
- Clean at the end
 - After all repair and rework
- Clean twice
 - Once after standard assembly processes, once after manual processes (e.g., repair and rework)
 - Can be driven by cleaning-sensitive components
- Clean after every assembly process
 - Addresses concerns with density, flux compatibility (heterogeneous contamination), and time sensitivity

Test Vehicle Qualification

- Fabricate from same material as production unit (board, solder mask, solder, flux)
 - Use of dummy parts and comb patterns
- Consider IPC B-52
 - Can be modified to mimic existing designs and process
 - Ensure minimum of two structures
 - Smallest spacing at relevant voltage
 - Highest electric field at relevant spacing
- Can clean test vehicle before use if relevant
 - Assesses materials and cleaning interaction (not board contamination)

IPC-B-52 (IEC TB-57)

- The latest generation of test coupons
- Similar to designs from NPL, Rockwell Collins, & IBM
 - Main SIR Test Board
 - IC Test Coupon
 - Solder Mask Adhesion
 - SIR mini-coupons
- Packages
 - 0402 – 1206
 - QFP (no 0.4mm pitch)
 - SOICs and BGAs
 - Through-Hole Header
 - Comb patterns (5 mil)

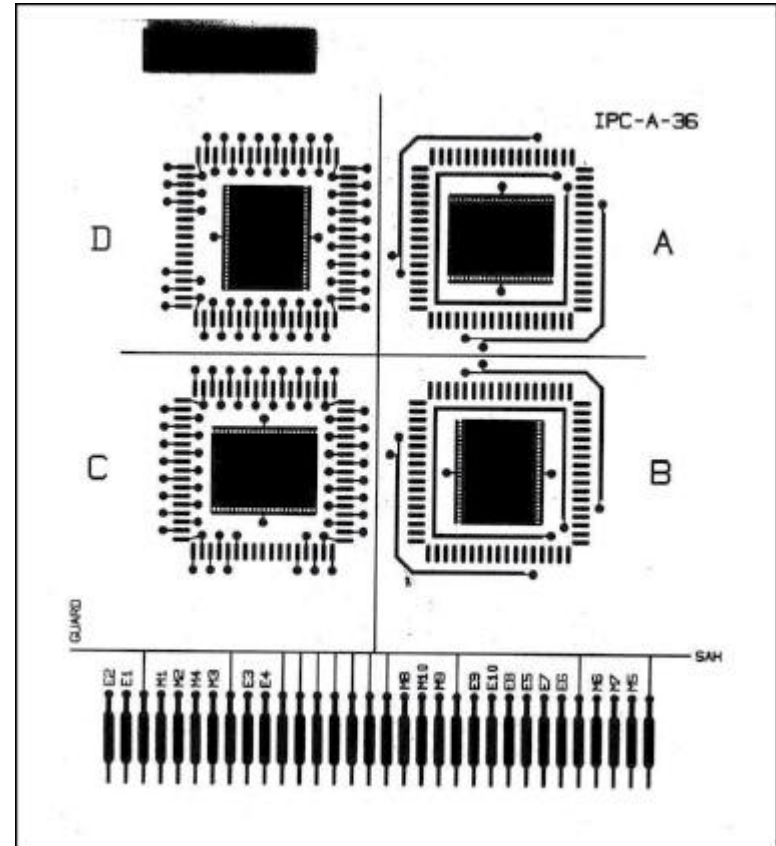


Not specifically called out in any TM-650 test method

Solutions

IPC A-36D, IPC B-36

- IPC A-36D: Cleaning Alternatives Artwork - IPC-D-350 Format
- Used in cleaning studies
- 4 quadrants utilizing both surface mount patterns and vias
- Each with 68 I/O chip carrier sites and 10 SIR test points



Recommended Test Method

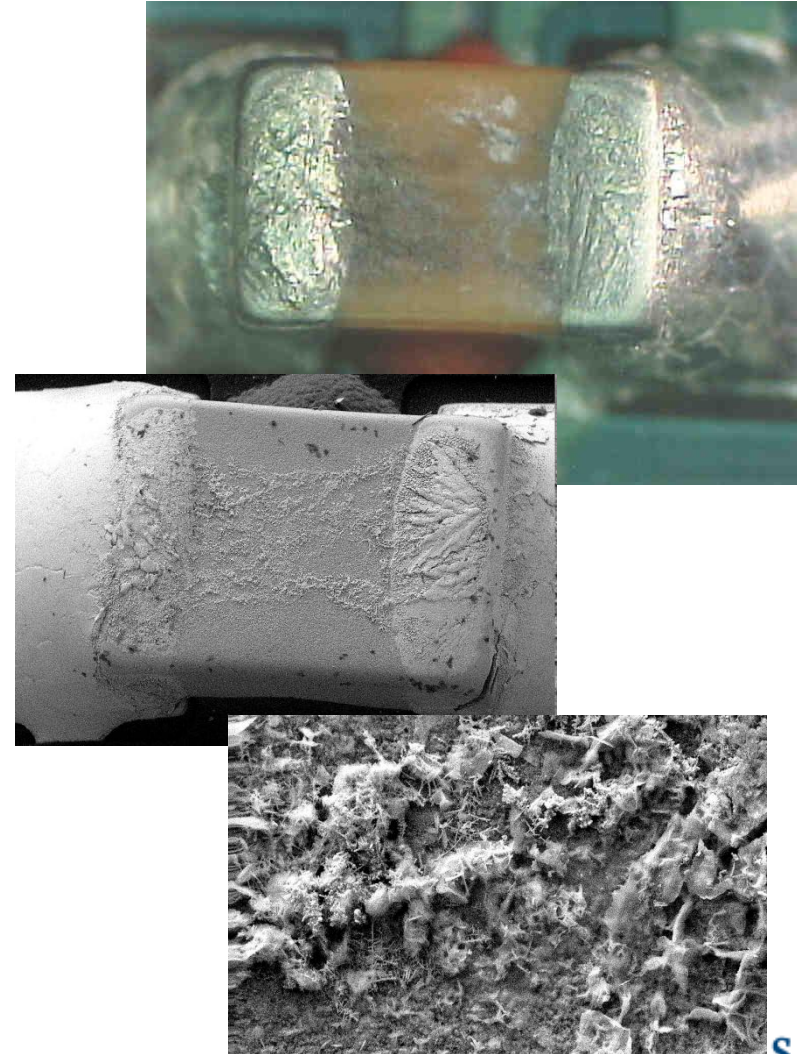
- Flux application and preconditioning
 - Solder paste / Wave solder / Rework
 - Clean
- Exposure to mild temperature and maximum humidity without condensation
 - 35 to 40°C / 93%RH
 - 72 to 120 hours of exposure
 - Continuous monitoring (1 second per reading)

Product Qualification

- Consider testing entire product, if resource- or time-limited
 - 40°C/93%RH for 72 to 120 hours
 - Extend time period if using conformal coating or potting material
- Do not test at 85°C/85%RH for dendritic growth (surface ECM)
 - Some issues with CAF as well
- Study by Sohm and Ray (Bell Labs) demonstrated degradation of weak organic acid residues above ~55°C
 - Reduces their effect on surface insulation resistance
- Turbini (Georgia Tech) demonstrated breakdown of polyglycols at elevated temperature as well
 - Absorption into board can increase risk of CAF

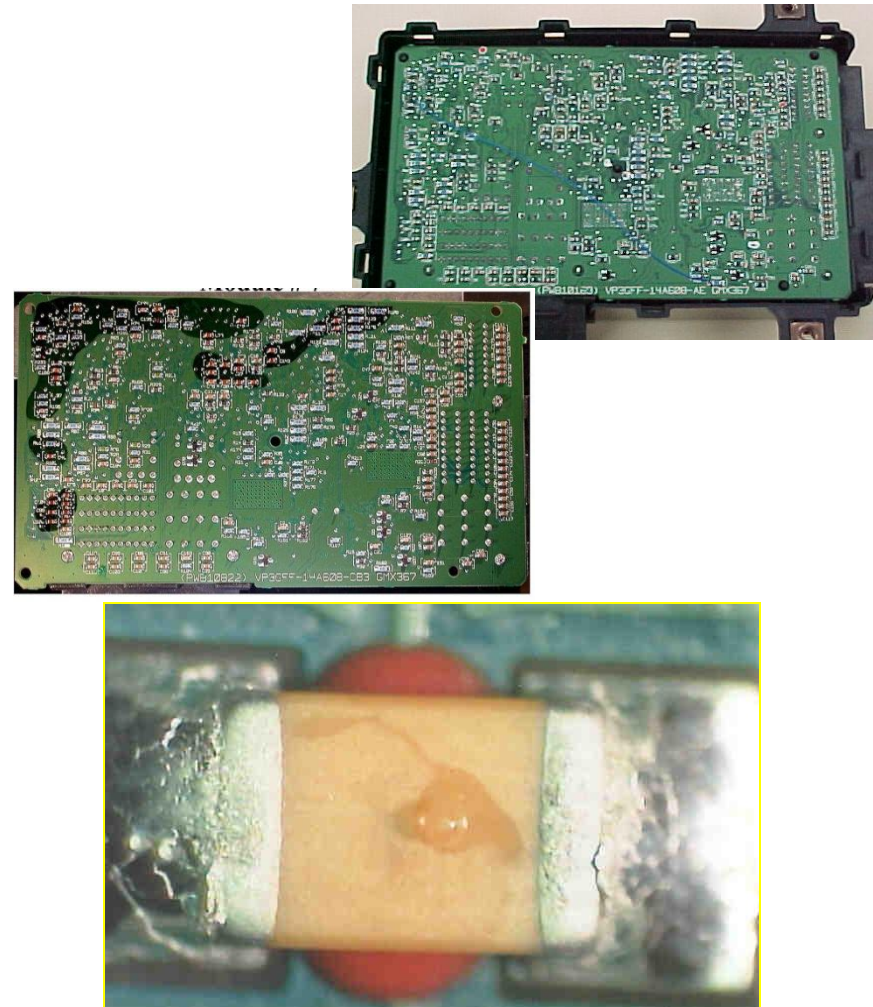
Case Study

- Automotive module subjected to frost test (moisture susceptibility)
 - Soaked at -20C for 2 hours.
 - Transferred to 45C/95-100%RH in less than 1 min.
 - Functional/parametric tests performed at 5, 30 and 120 minutes
- Dendritic growth observed on several ceramic chip capacitors



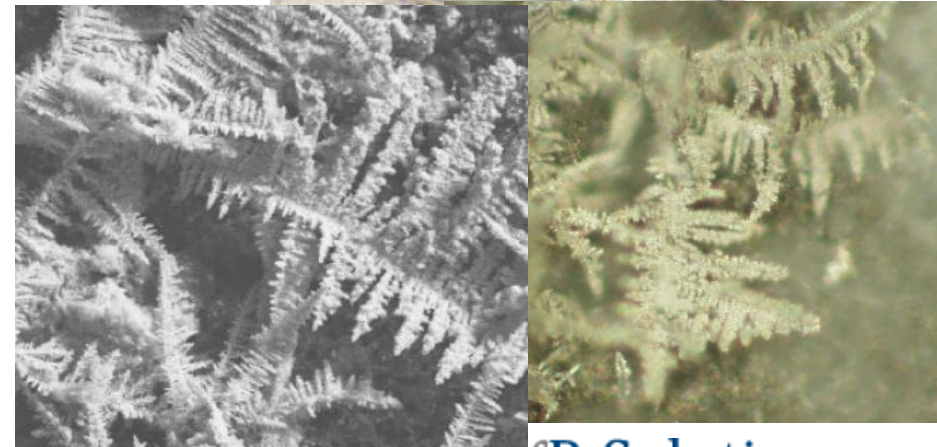
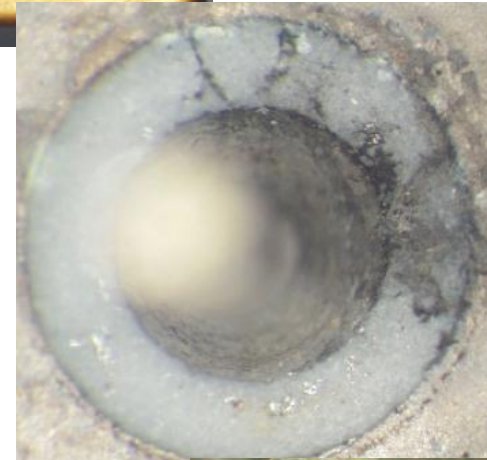
Case Study

- Multiple root causes
- Capacitors located adjacent to holes and cut outs in housing
 - Created ducting condition for condensation on cold board
- Excessive flux residue from wave soldering process
- Previous designs
 - Conformally coated
 - No wave soldering (paste in hole)
 - Cleaned
- Failure mode was intermittent
 - Design verification vehicle passed
 - Product verification vehicle failed
 - Both had dendrites!



Case Study

- Avionics system
 - Failure during test
- Conformal coating on the top extended down the sides of the package
 - Did not cover the leads, seals, or the package bottom
- Residual RMA solder flux identified
 - Vapor degreasing process did not reach under component
- Pin to case resistance of 140 k Ω



Conclusion

- Contamination and Cleanliness requirements should be clearly detailed to the supply chain
 - PCB
 - PCBA
 - LCD
 - Etc.
- Cleanliness should be validated
 - Materials compatibility (test coupon)
 - Product qualification
 - Ongoing cleanliness assessment (IC)

Thank You!

- Questions?
 - Contact Cheryl Tulkoff, ctulkoff@dfrsolutions.com, 512-913-8624
 - www.dfrsolutions.com
- Connect with me in LinkedIn as well!

Speaker Biography

- Cheryl Tulkoff has over 22 years of experience in electronics manufacturing with an emphasis on failure analysis and reliability. She has worked throughout the electronics manufacturing life cycle beginning with semiconductor fabrication processes, into printed circuit board fabrication and assembly, through functional and reliability testing, and culminating in the analysis and evaluation of field returns. She has also managed no clean and RoHS-compliant conversion programs and has developed and managed comprehensive reliability programs.
- Cheryl earned her Bachelor of Mechanical Engineering degree from Georgia Tech. She is a published author, experienced public speaker and trainer and a Senior member of both ASQ and IEEE. She has held leadership positions in the IEEE Central Texas Chapter, IEEE WIE (Women In Engineering), and IEEE ASTR (Accelerated Stress Testing and Reliability) sections. She chaired the annual IEEE ASTR workshop for four years, is an ASQ Certified Reliability Engineer and a member of SMTA and iMAPS.
- She has a strong passion for pre-college STEM (Science, Technology, Engineering, and Math) outreach and volunteers with several organizations that specialize in encouraging pre-college students to pursue careers in these fields.

