

Process Control of Ionic Contamination Achieving 6-Sigma Criteria in The Assembly of Electronic Circuits

P. Eckold^[1], M. Routley^[2], L. Henneken^[1], G. Naisbitt^[2], R. Fritsch^[1], U. Welzel^[1]

^[1] Robert Bosch GmbH, Automotive Electronics, Stuttgart, Germany

^[2] Gen3 Systems Limited, Farnborough, UK

Abstract

Ionic contamination testing as a process control tool a newly developed testing protocol based on IPC-TM 650 2.3.25, was established to enable monitoring of ionic contamination within series production.

The testing procedure was successfully implemented within the production of high reliability, safety critical electronic circuits, involving multiple production sites around the world. It will be shown in this paper that the test protocol is capable for meeting Six-Sigma-Criteria.

For a Gauge R&R study, a calibration solution of 0.1 wt.-% NaCl was used in order to investigate the repeatability and reproducibility of the test protocol employing newly developed contamination testing systems, which were placed at five locations worldwide. A total failure range of below $0.1 \mu\text{g}/\text{cm}^2 \equiv \text{NaCl}$ at a target value of $1.0 \mu\text{g}/\text{cm}^2 \equiv \text{NaCl}$ ($\pm 8.8\%$) was achieved, combined with manual laboratory handling of fluids (pipette, temperature).

For process control this value is acceptable and demonstrates that ionic contamination testing based on IPC-TM 650 2.3.25 is able to be used as a process control tool in manufacturing of electronic control units.

Introduction

The increasing use of electronic control units in harsh environments, in, especially, high reliability, safety-critical applications, demands full understanding and rigorous control of electrochemical reliability. ^[1-3]

The production of electronic circuits involves more than 20 individual chemical process steps, most of which contain high levels of ionic matter. Electric potentials when combined with a damp or moist operating environment, coupled with the presence of ionic matter, can often increase the probability for dendritic, electrochemical reactions and premature, unpredictable circuit failures. ^[4-6]

For these reasons the analysis of the surface insulation resistance (SIR) can be employed to assess electrochemical reliability of assemblies and thereby establish a qualified manufacturing process. ^[7]

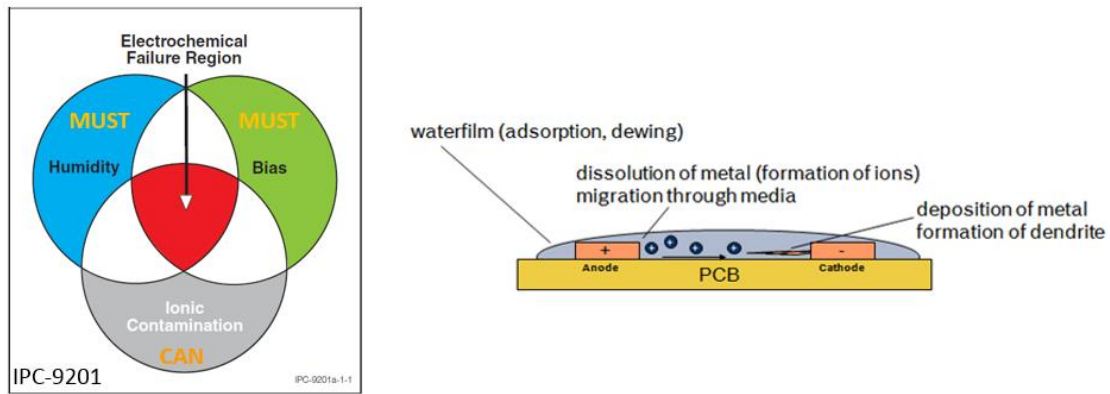


Fig. 1: Influence factors for electrochemical migration (left) and schematic sketch of dendrite formation between conductive paths (right).^[8]

Electrochemical migration (ECM) is known as the migration of electrochemically mobile species between conductive paths caused by an applied voltage. Consequently, metal can dissolve at the anode and deposit at the cathode which leads to the growth of a metallic dendrite.^[2] Figure 1 (left) illustrates the influence factors for ECM. The combination of a closed water film and an applied voltage between two conductive paths is the necessity prerequisite for this failure mode.

Ionic contamination on the surface of printed circuit boards (PCBs) is an acceleration factor which can ...

- ... reduce the dissolution enthalpy of metals.
- ... reduce the dew point.
- ... shift the pH value towards higher / lower regions.
- ... increase the conductivity of the water film.

Thus, ionic contamination is not essential but a supporting factor for ECM. Therefore, the level of ionic contamination has to be controlled during the manufacturing of electronic assemblies using an appropriate process control tool in order to ensure that the individual production process steps (e.g. surface-mount or through-hole technology) are in control in view of the overall level of ionic contamination.

Validation of Humidity Robust Design Elements

The electrochemical reliability of design elements used in printed circuit board assemblies can be evaluated based on IPC-9202^[9] under defined climatic conditions. For this purpose the surface insulation resistance (SIR) has to be assessed at design elements which pertain to actual series production conditions as closely as possible (e.g. series PCB materials, solder paste, ...) applying the B52-test board. Applying specific climatic conditions the humidity robustness of design elements produced using specific material combinations can be evaluated using SIR measurement technology.

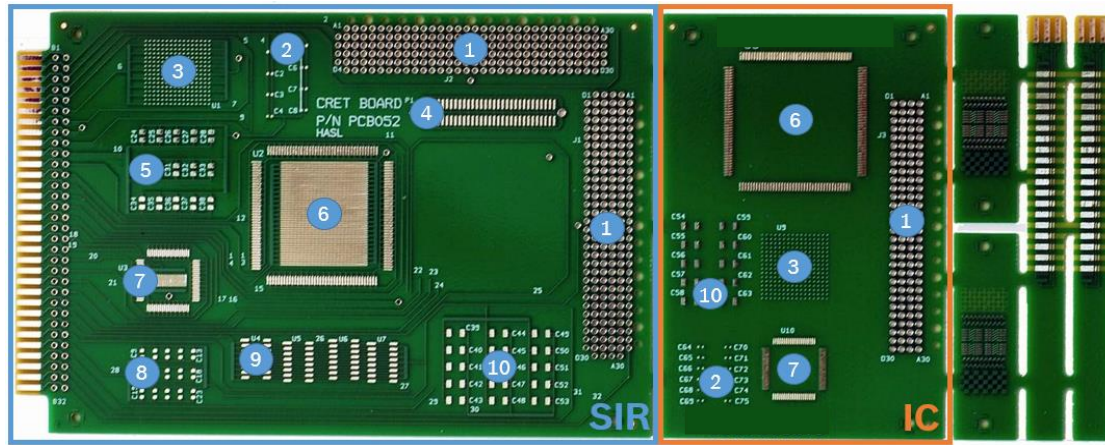


Fig. 2: IPC B52 board consisting of product specific design elements with SIR test structures for validation of electrochemical reliability.

Figure 2 illustrates the principle layout of the B52 board proposed by IPC-9202. The corresponding design elements can be adapted according to the advanced product requirements regarding miniaturization and component portfolio. Consequently, a design element specific test has to be performed in order to ensure the electrochemical reliability of PCBAs under high temperature and high humidity conditions.

Ionic Contamination Testing as a Process Control Tool

Currently used methods for detection of ionic contamination are described within IPC-TM 650 2.3.25.^[10] The original resistivity of solvent extract (ROSE) test was intentionally designed for process control of the cleaning process within manufacturing of electronic control units. Currently applied measurement protocols can be divided into two principal modes of operation: static and dynamic extraction. The different analyser designs combined with the variety of slightly varying measurements procedures makes it almost impossible to compare data from different equipment types. In addition, measurement data are often used focussing on an absolute cleanliness level of no-clean assemblies. It has to be pointed out that these measurement technologies were not designed for creating cleanliness data of electronic control units manufactured with no-clean processes.

However, ionic contamination testing is able to be used as a process control tool in order to monitor the level of ionic residues on electronic assemblies caused by several production processes (e.g. reflow, selective soldering ...) over production time. For this purpose an optimized testing system and protocol based on IPC-TM 650 2.3.25 was implemented in collaboration with system suppliers in order to meet a Six-Sigma criteria, and also between several production sites.

PICT – Process Ionic Contamination Testing

Process ionic contamination testing (PICT) is an optimized testing process compared to conventional ROSE test procedures. PICT is applying a closed loop / static system according to the classification of IPC-TM 650 2.3.25. The working principle is illustrated in Figure 3. Test and regeneration cycles are independent from one another and dissolved ionic residues from the specimens are trapped into an ion exchange column during regeneration until the conductivity of the extraction solution is reduced to a specified level.

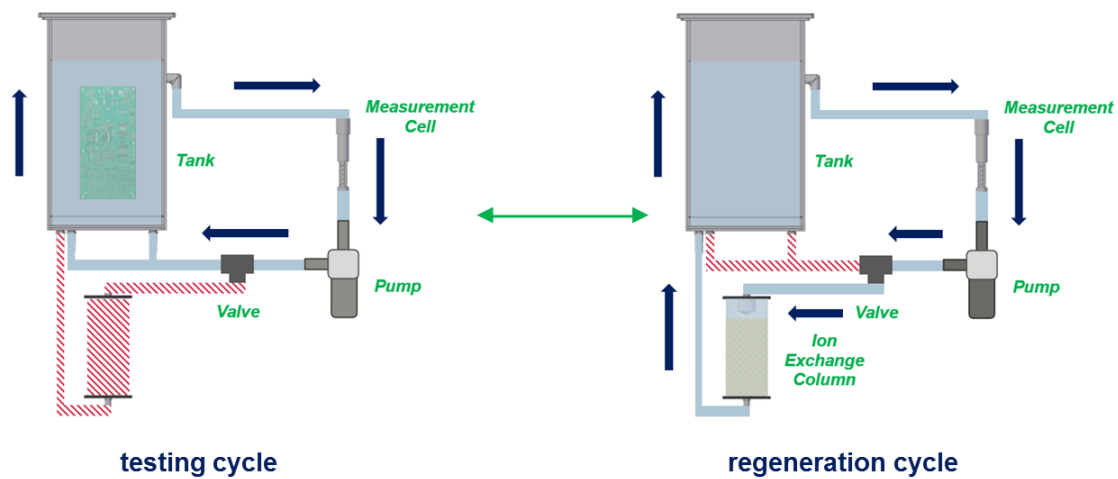


Fig. 3: Measurement Principle of PICT in testing (left) and regeneration (right) mode as a closed loop / static testing system in accordance with IPC-TM 650 2.3.25.

The flow rate of the solution was optimized to avoid undue turbulence during the test cycle. Thus, a fast removal of ionic contaminants from the printed circuit assembly is possible and the testing time can be reduced. Furthermore, the influence of the atmospheric reaction of carbon dioxide to carbonic acid was decreased. Nevertheless, the carbon dioxide compensation is a key factor in achieving reproducible measurement results for ionic contamination analyses. Dependent on the environmental conditions (e.g. atmospheric composition, temperature, relative humidity ...) the solvent conductivity is increased due to the formation of carbonic acid and its subsequent decomposition to hydronium and carbonate ions. Test measurements with the testing solution under the corresponding environmental conditions and the application of a mathematical algorithm lead to a site-specific carbon dioxide tolerance factor for compensation. The analysis of solutions with low concentrations of ionic matter requires a high accuracy of the conductivity measurement cell. For this purpose a solid-state measuring cell is applied, which is connected to a ballistic amplifier. Thus, a measurement accuracy of $\pm 0.005 \mu\text{S}/\text{cm}$ can be achieved.

In order to use ionic contamination as a process control tool in electronic manufacturing a gauge study was performed for analysing the repeatability and the reproducibility over different production sites. The test equipment was installed in five different production sites worldwide and set up according to the technical requirements of the supplier. In general, 2 ml of a test solution of 0.1 wt.-% sodium chloride was injected and circulated through the conductivity probe in the analyser. The constantly measured solution conductivity was recalculated to sodium chloride equivalent ($\text{NaCl}_{\text{eq.}} / \mu\text{g}/\text{cm}^2$) based on a given surface area.

The results of the analysis on repeatability is shown in Figure 4. For this purpose, 40 measurements of a 0.1 wt.-% sodium chloride solution was carried out over three days at one manufacturing site. No outlier in the data was detected. Based on the existing data an internal failure of the analyser would have been detected with a probability of 96.8 %. Furthermore, a slight increase of the instruments reading was observed during each of the three days, with the level dropping overnight. This effect can be attributed to the temperature of the measurement solution during subsequently performed measurements during one day. An increased temperature of the solution leads to an increased mobility of ionic species and consequently to an increased conductivity level. The process was evaluated to be capable for allowing demand of tolerances ($\pm 10 \%$) achieving a C_{gk} value of 2.23. In total the repeatability of the analyser meets Six-Sigma-requirements.

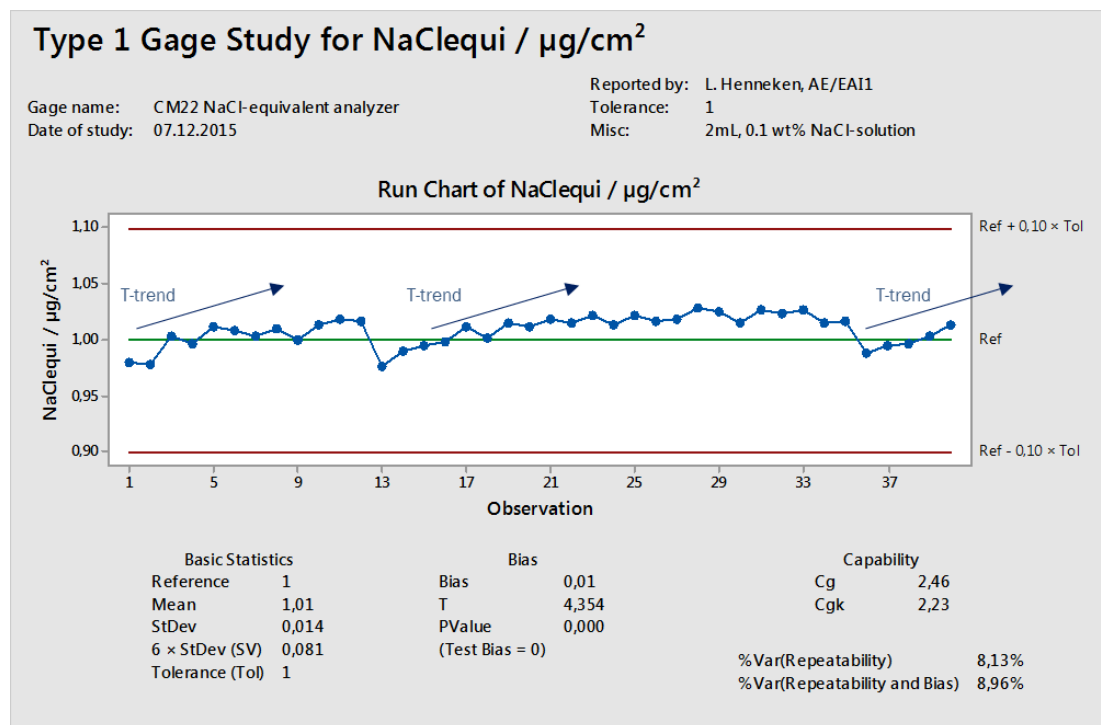


Fig. 4: Analysis of repeatability of $\text{NaCl}_{\text{eq.}} / \mu\text{g}/\text{cm}^2$ based on 40 measurements of 0.1 wt.-% sodium chloride solution at one site.

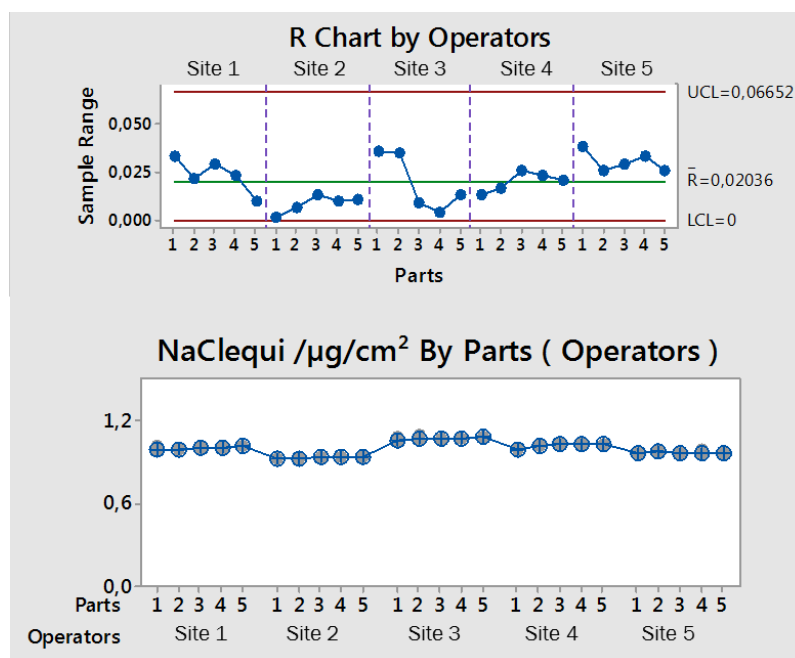


Fig. 5: Results from round robin test of ionic contamination measurement at five different production site worldwide.

A reproducibility study was carried out using five different analysers, located at different production sites worldwide. Using a set of unified work place instructions and directions regarding the local calibration procedure, an aligned test procedure was ensured. Especially consistency in the laboratory handling of fluids (e.g. pipette, temperature ...) has to be taken into consideration when analysing the results. The total failure range was calculated to be $\pm 8.8\%$ which is an acceptable value for chemical analysis. For the charts in Figure 5 just slight deviation of the measurement values achieved in one site can

be observed. Summarized, ionic contamination testing with optimized parameters is able to be used as a process control tool detecting ionic contamination on printed circuit board assemblies.

Influence of Process Parameters and Process Optimization

The previously described testing protocol can be used to study the influence of certain process parameters on the level of ionic contamination. Figure 6 illustrates a selection of influence factors on the final NaCl_{eq} value on product level.

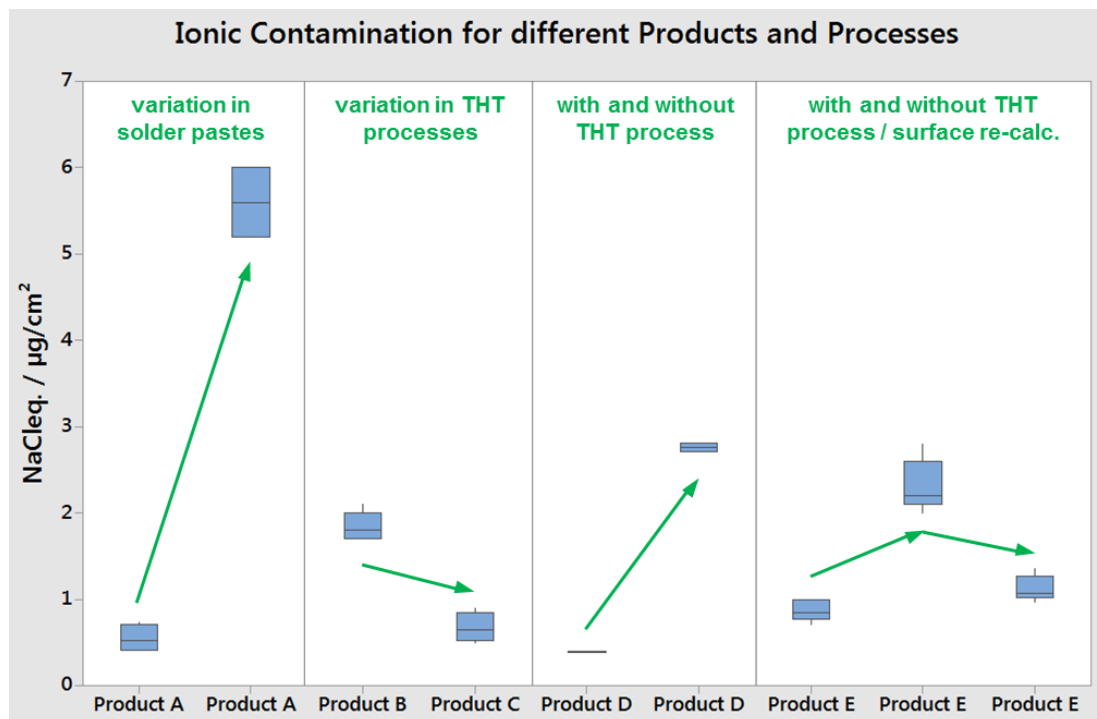


Fig. 6: Ionic Contamination measurements of different products applying different materials and processes.

Variations in materials (e.g. solder paste, flux for selective soldering ...) are strongly affecting the absolute value for ionic matter. Depending on the chemical activity and the encapsulation of flux residues after soldering, the NaCl_{eq} value is varying. It has to be pointed out, that the scattering of the absolute value is increased on product level caused by numerous process steps during the assembly. However, it is possible to detect process deviations and corresponding root cause analysis focussing on process stability can be started and monitored.

Consequently, an overall limit of ionic contamination does not fit to the pool of materials and processes used in electronic manufacturing. Furthermore, ionic contamination testing has to be performed product specific as a process control tool.

Conclusions

As previously emphasised, electrochemical migration is caused by an electric field and a closed water film between neighbouring conductive paths. Ionic contamination is given by materials and processes and can accelerate the electrochemical processes under high temperature and high humidity conditions. Consequently, the measurement of ionic contamination does not predict the humidity reliability of printed board assemblies. The humidity robustness of design elements can be ensured by SIR measurement technology according to the principle of IPC 9202.

The implementation of ionic contamination testing as process control tool (PICT) exhibits advantages to current ROSE test protocols. Due to system optimization and the implementation of unified work place instructions, it was possible to achieve 6 σ criteria for the repeatability and a sufficient reproducibility of recorded ionic contamination data at five different production sites worldwide. Using this approach, process control and methods of process optimizations are possible.

Acknowledgements

The authors would like to acknowledge their respective companies for providing financial support for this research.

References

- [1] D. Minzari, M.S. Jellesen, P. Moller, R. Ambat, *Corros. Sci.* **2011**, 53, 3366-3379.
- [2] P.-E. Tegehall, *Impact of Humidity and Contamination on Surface Insulation Resistance and Electrochemical Migration*, Springer Verlag London, New York **2011**, 227-253.
- [3] B.-I. Noh, S.-B. Jung, *Circuit World* **2008**, 34, 8-13.
- [4] V. Verdingovas, M.S. Jellesen, R. Ambat, *Corros. Eng. Sci. Tech.* **2013**, 48, 426-435.
- [5] D. Mizari, M.S. Jellesen, P. Moller, P. Wahlberg, R. Ambat, *IEEE Trans. Dev. Mater. Reliab.* **2009**, 9, 392-402.
- [6] B.-I. Noh, S.-B. Jung, *J. Mater. Sci.: Mater. Electron.* **2008**, 19, 952-956.
- [7] D.Q. Yu, W. Jillek, E. Schmitt, *J. Mater. Sci.: Mater. Electron.* **2006**, 17, 229-241.
- [8] IPC-9201A – Surface Insulation Resistance Handbook, **2007**.
- [9] IPC-9202 – Material and Process Characterization/Qualification Test Protocol for Assessing Electrochemical Performance, **2011**.
- [10] IPC-TM-650 2.3.25. – Detection and Measurement of Ionizable Surface Contaminants by Resistivity of Solvent Extract (ROSE), **2012**.

Process Control of Ionic Contamination achieving 6-Sigma Criteria in the Assembly of Electronic Circuits

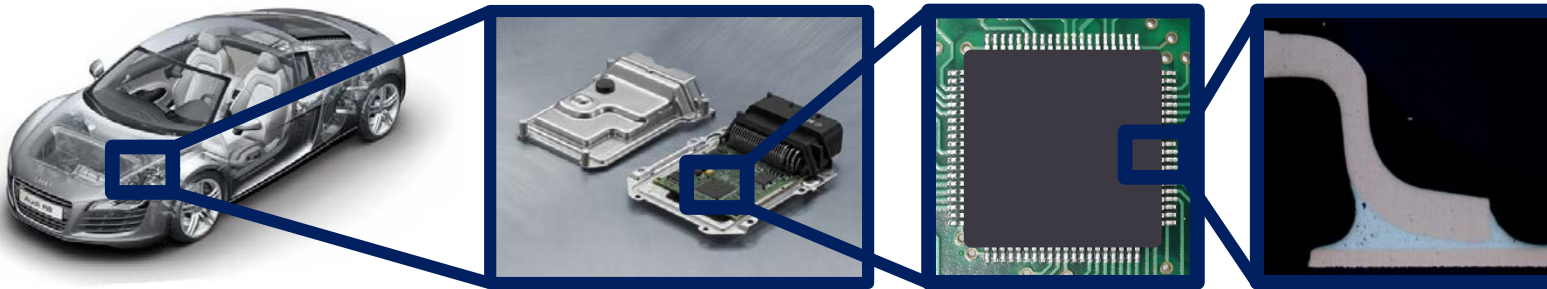
Dr Pierre Eckold of Robert Bosch GmbH & Mark Routley of Gen3 Systems Ltd

Content

1. Modern Day Electronics
2. Interaction of Humidity with Interconnect Technology
3. Validation of Humidity Robust Design Elements
4. Measurement Technologies for Ionic Contamination
5. Ionic Contamination Testing as Process Control Tool
6. PICT – Process Ionic Contamination Testing
7. Conclusions

Modern Electronic Control Units

- ... are the products behind the products



- highly reliable electronic control units under high temperature / humidity conditions

Increasing Requirements

- miniaturization
- high voltage / current applications
- increased lifetime



motor management



ABS/ESP



e-bike



wiper systems



transmission control



camera systems



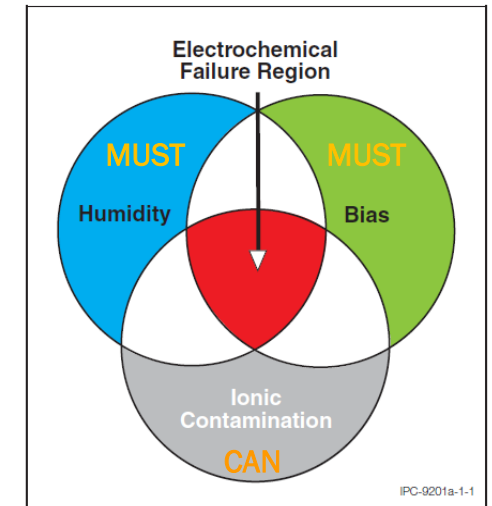
steering

Product Design

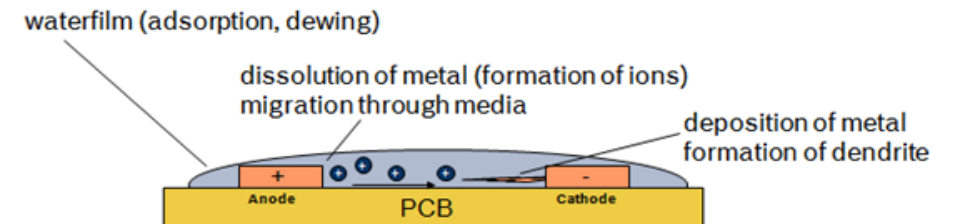
- material / housing concept
- chemical interactions
- knowledge of detailed cause-effect-relations

Interaction of Humidity with Interconnect Technology

- combination of closed water film and electric field between neighbouring conductive paths causes electrochemical migration
- electrochemical migration (ECM):
 - migration of electrochemically mobile species from anode towards cathode through electrolyte
→ metal deposition at cathode
→ dendrite growth
 - deep understanding of used materials regarding their properties under high temperature / humidity conditions during release process
 - validation of design elements applying B52 approach under high temperature / humidity
- influence of ionic contamination:
 - ionic matter is given by materials / processes with technical grade
 - can
 - ... reduce dissolution enthalpy of metals
 - ... reduce local dew point
 - ... shift pH value
 - ... increase conductivity of water film
 - no essential factor for electrochemical migration
→ to be controlled during manufacturing of electronic assemblies

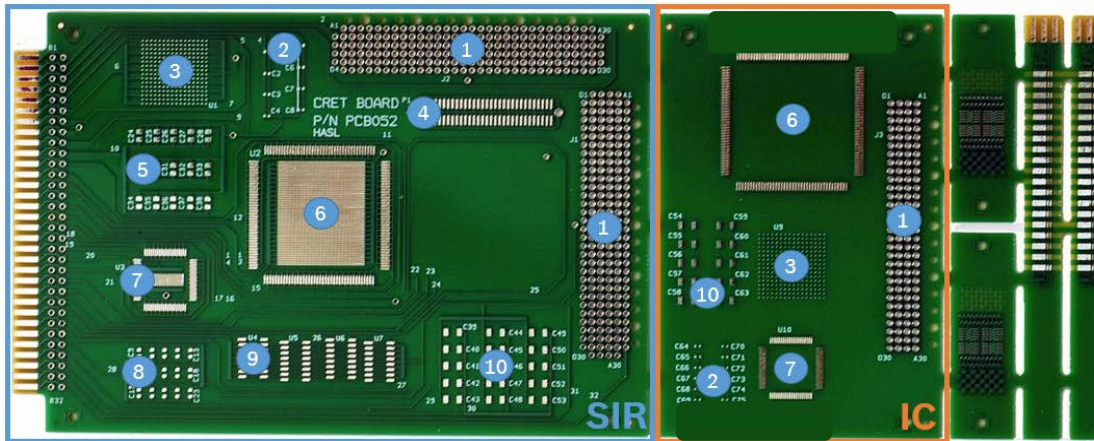


VENN Diagram illustrating influence factors on ECM [1]

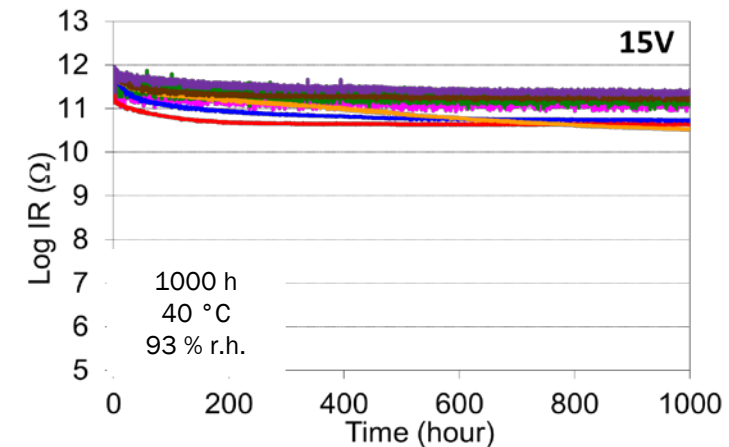


Validation of Humidity Robust Design Elements

- absolute contamination level is design-dependent and does not predict humidity robustness of specific assembly / product
- electrochemical reliability evaluated on PCB assembly level acc. to IPC-9202
 - as close to actual series production conditions as possible (e.g. series PCB material, solder paste, ...)
 - measurement of surface insulation resistance (SIR) using model components under defined climatic conditions
 - measurement of ionic contamination can be referenced to SIR results
→ BUT: no direct correlation between level of ionic contamination and its robustness against ECM



IPC B52 Board



Examples of SIR measurement data

Measurement Technologies for Ionic Contamination

- **Ion Chromatography**

- *separation and analysis of ionic species dissolved from PCBA after extraction*
- *fingerprint of ionic species in $\mu\text{g}/\text{cm}^2$ (integral value)*

- **Resistivity of Solvent Extraction**

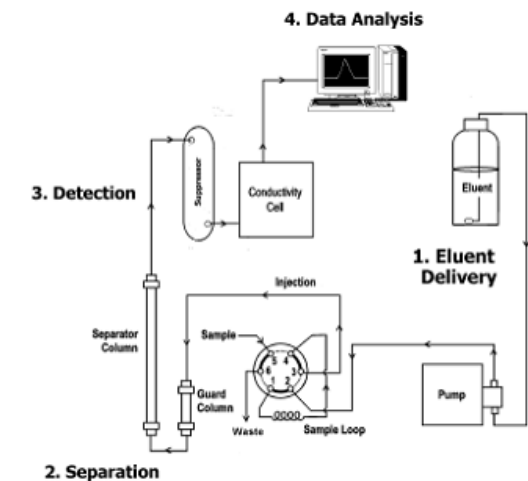
- *measurement of solution conductivity after PCBA extraction*
- *sum of ionic species in $\mu\text{g}/\text{cm}^2$ (integral value)*

- **Local Extraction**

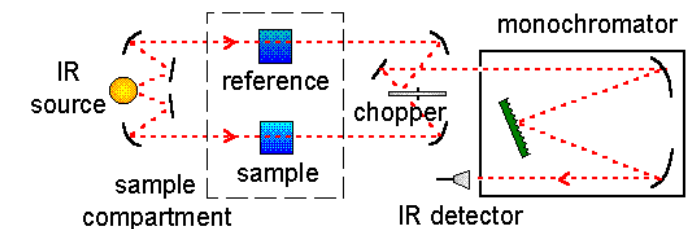
- *potentiostatic measurement of electrical current through an extraction solution locally extracted from PCBA*
- *sum of ionic species soluble in extract in μA (local value)*

- **Fourier Transform Infrared Spectroscopy**

- *detection of characteristic molecular vibrations caused by excitation via monochromatic light*
- *fingerprint of organic ionic species (local value)*



Schematic of Ion Chromatography measurement system

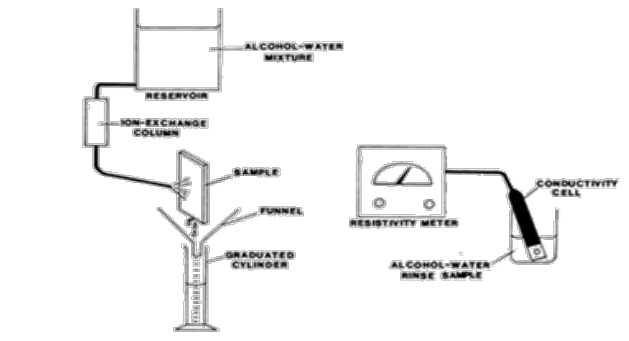


Schematic of FTIR measurement system

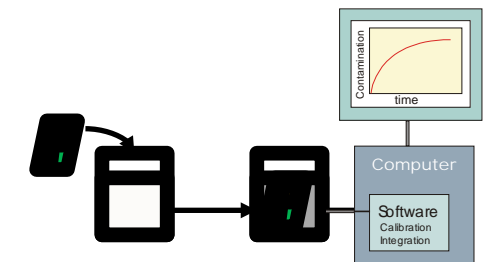
Ionic Contamination Testing as Process Control Tool

- original Resistivity Of Solvent Extract test
 - PCB rinsed with deionized water / isopropanol mixture
 - measurement of solvent conductivity and recalculation to $\text{NaCl}_{\text{eq.}} / \mu\text{g}/\text{cm}^2$
 - current applied methods
 - static extraction: keep same extraction solution, just circulated
 - dynamic extraction: solution passed through ion exchange filter

→ results from different equipment types cannot be compared
- current use of applied methods focus on absolute cleanliness level
- Ionic Contamination Testing as Process Control Tool
 - measurement principle according to IPC-TM 650 2.3.25
 - used only as process control tool → SPC chart (no cleanliness testing)
 - requirement: repeatability (6σ) + sufficient reproducibility between production sites
 - optimized testing system and protocol in cooperation with system suppliers



Original ROSE measurement

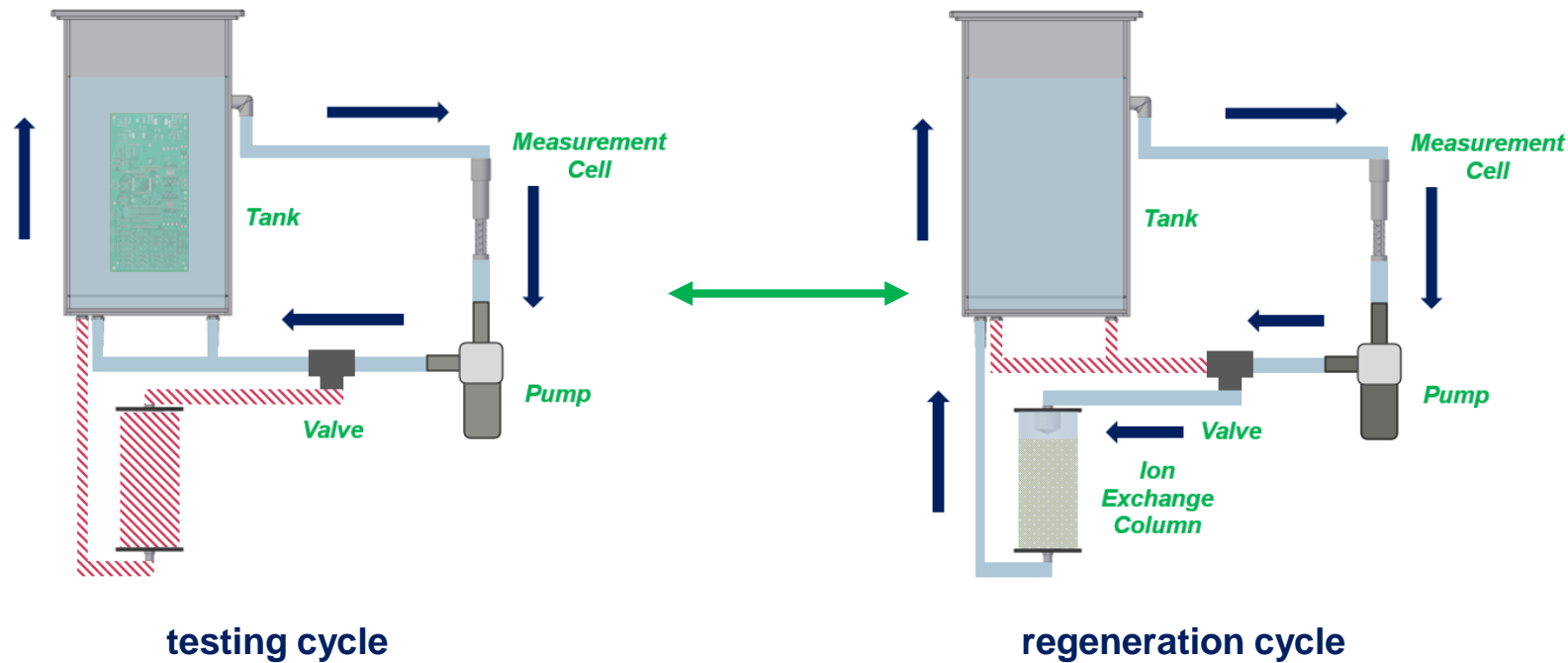


Schematic of automated ROSE measurement

→ process control focussed on relative comparison over production time

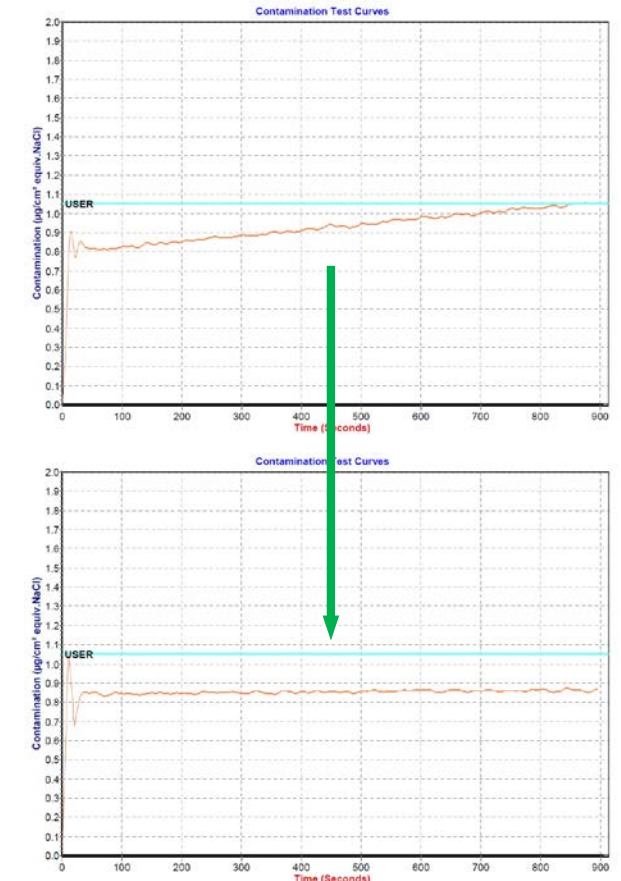
PICT – Process Ionic Contamination Testing

- optimization of testing process compared to conventional ROSE test procedure
 - closed loop / static testing system
 - testing and regeneration cycle are independent from one another
 - calibration of system using test solutions
 - regeneration towards a known “base line” for testing to commence



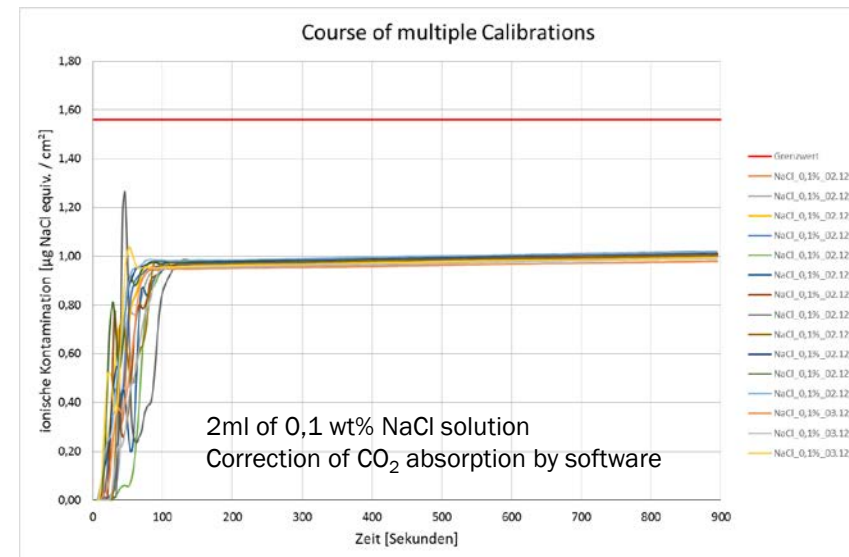
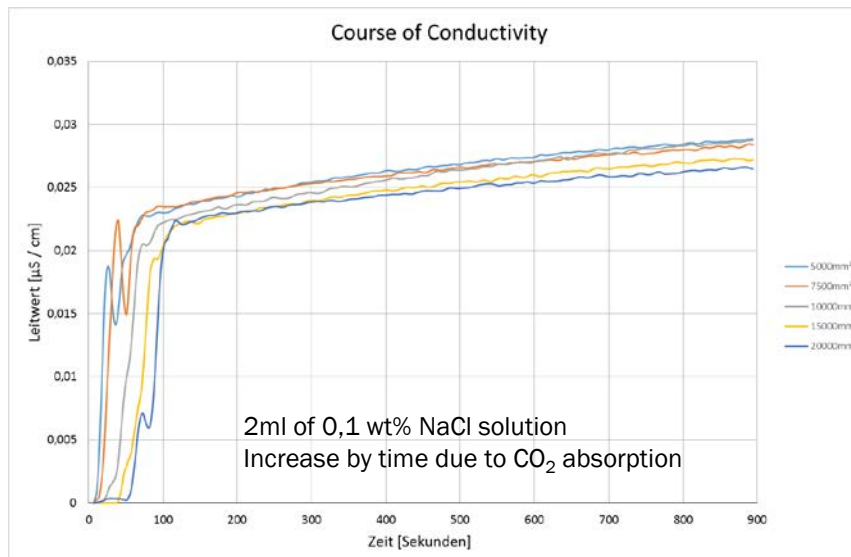
PICT – Process Ionic Contamination Testing

- optimization of testing process compared to conventional ROSE test procedure
 - flow rate
 - high circulation rate without creating undue turbulence during test cycle
 - fast removal of ionic contaminants from PCBA
 - reduction of testing time
 - CO₂ compensation
 - increased solvent conductivity during test cycle due to CO₃²⁻ formation
 - strongly dependent on environment (important for plant implementation)
 - implementation of site specific CO₂ tolerance factor for compensation
 - accuracy of conductivity measurement cell
 - solid state measuring cell connected to ballistic amplifier
 - measurement accuracy of ±0.005 µS/cm



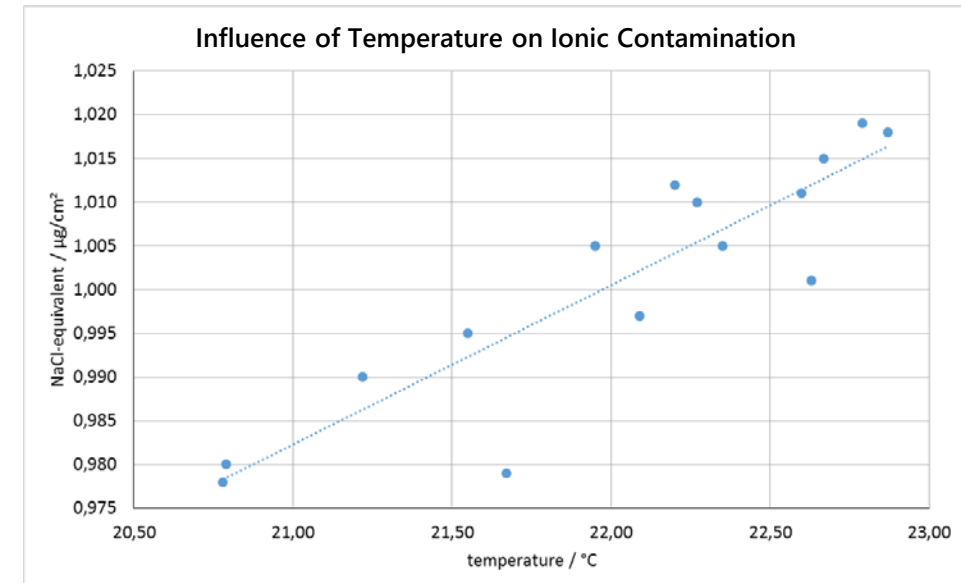
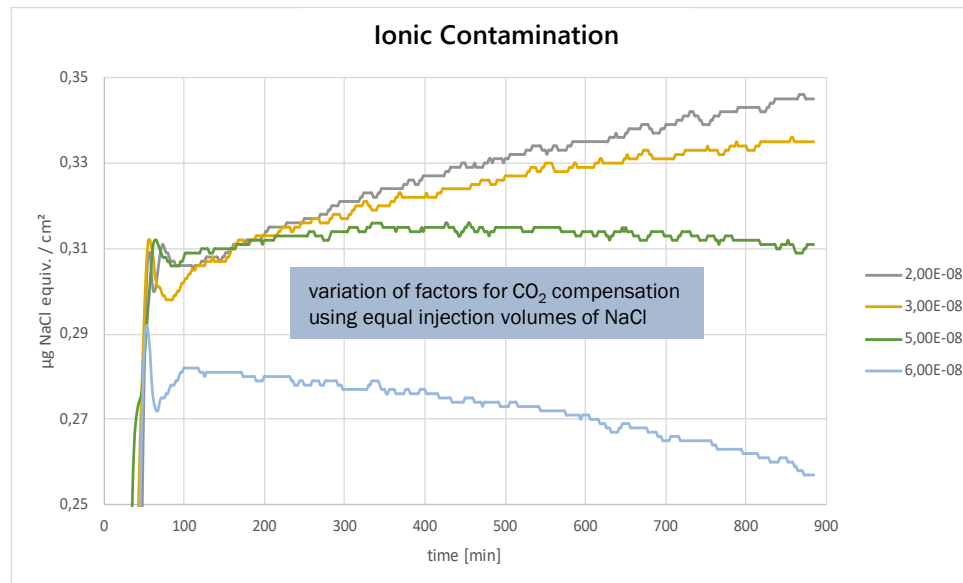
Ionic Contamination Testing as Process Control Tool

- Gauge Study - Measurement of fluids (one site)
- general procedure
 - injection of test solution (0.1 wt. -% NaCl)
 - circulation through the conductivity probe in analyser (record of time course)
 - recalculation of $\text{NaCl}_{\text{eq.}} / \mu\text{g}/\text{cm}^2$ at the end of measurement time based on given surface area



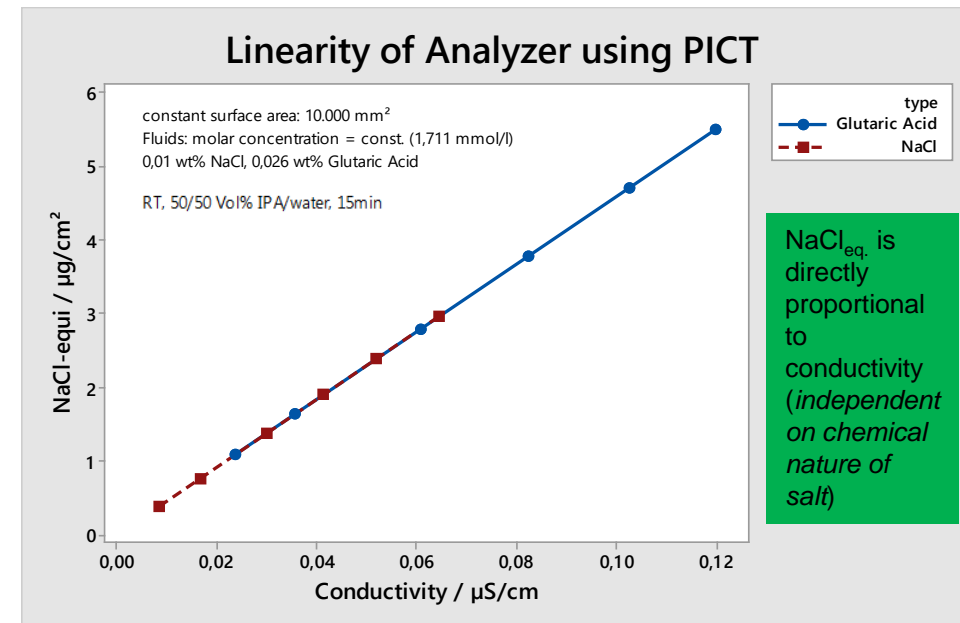
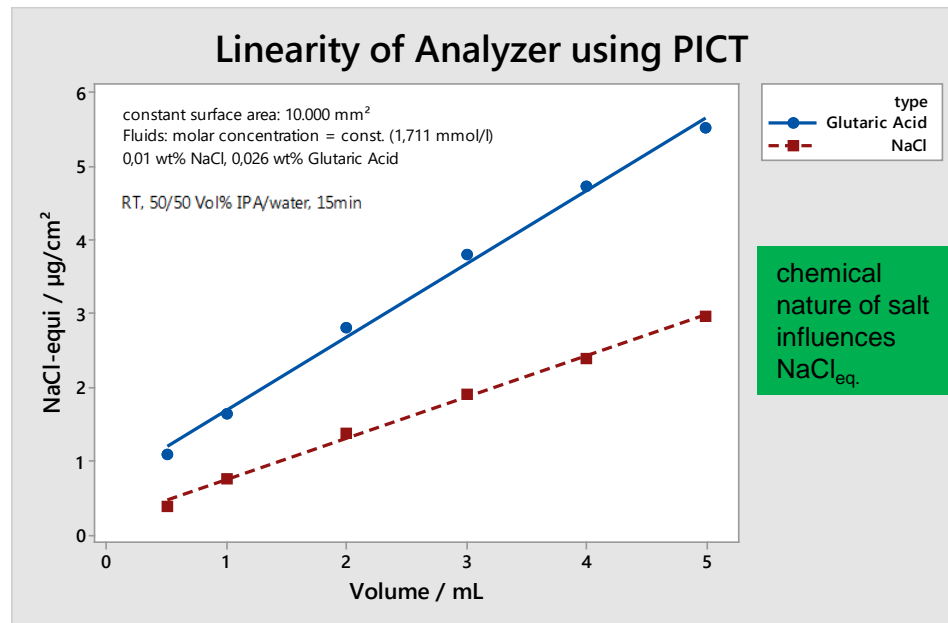
Ionic Contamination Testing as Process Control Tool

- Gauge Study - Measurement of fluids (one site)
- factors of influence
 - CO_2 compensation → important for plant implementation
 - solvent type / temperature



Ionic Contamination Testing as Process Control Tool

- Gauge Study - Measurement of fluids (one site)
 - factors of influence
 - chemical nature of injection solution: sodium chloride vs. glutaric acid
- linearity is given by applying PICT test procedure



Ionic Contamination Testing as Process Control Tool

- Gauge Study - Measurement of fluids (one site)
- 40 measurements with 0.1 wt.-% NaCl solution were carried out

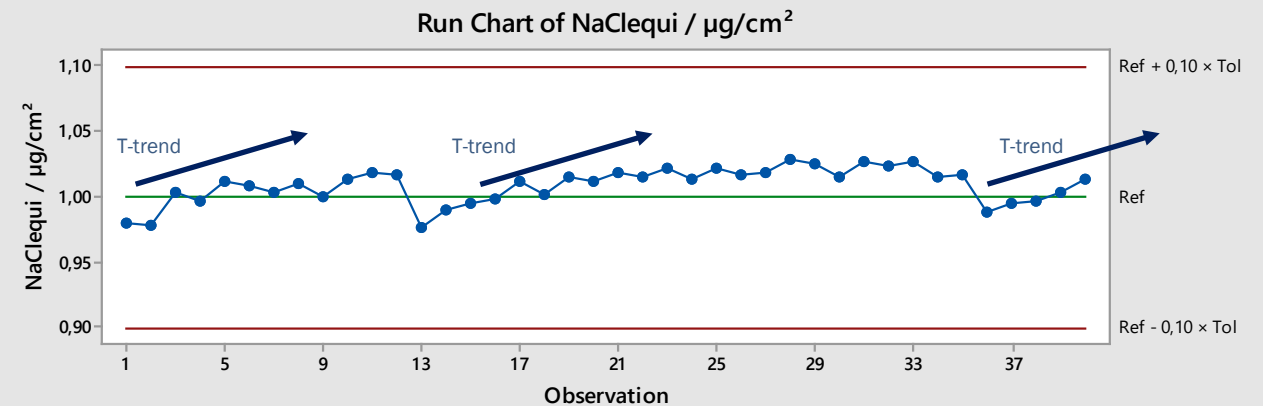
- no outlier in data detected
(based on existing data: 96.8 % probability for occurrence of one failure for internal failure of analyser)
- temperature trend was observed
- capable for allowing demand of tolerance ($\pm 10\%$)
- repeatability of analyser meets 6σ requirements

Type 1 Gage Study for NaClequi / $\mu\text{g}/\text{cm}^2$

Gage name: NaCleq. analyzer
Date of study: 07.12.2015

Reported by: L Henneken, AE/EAI1
Tolerance: 1
Misc: 2mL, 0.1 wt% NaCl-solution

T-trend is seen;
Measurements at three different days



Basic Statistics
Reference 1
Mean 1,01
StDev 0,014
 $6 \times \text{StDev (SV)}$ 0,081
Tolerance (Tol) 1

Bias
Bias 0,01
T 4,354
PValue 0,000
(Test Bias = 0)

Capability
Cg 2,46
Cgk 2,23

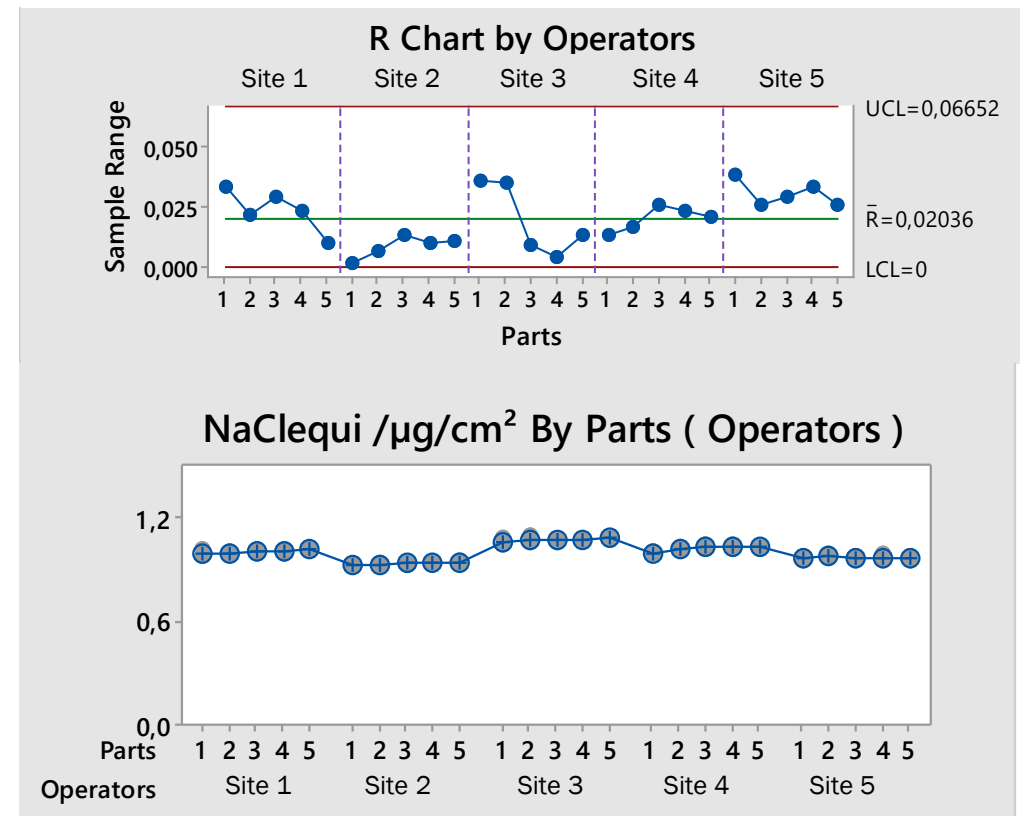
%Var(Repeatability) 8,13%
%Var(Repeatability and Bias) 8,96%

Ionic Contamination Testing as Process Control Tool

- Gauge Study - Measurement of fluids (different sites)

- round robin test at five different production sites
→ unified work place instruction and directive incl. local calibration

- five different analysers combined with laboratory handling of fluids (e.g.: pipette, temperature, ...) for measurements
→ total failure range of $\pm 8.8\%$
- acceptable for chemical analyses
- capable measurement system of detecting improper changes in contamination level

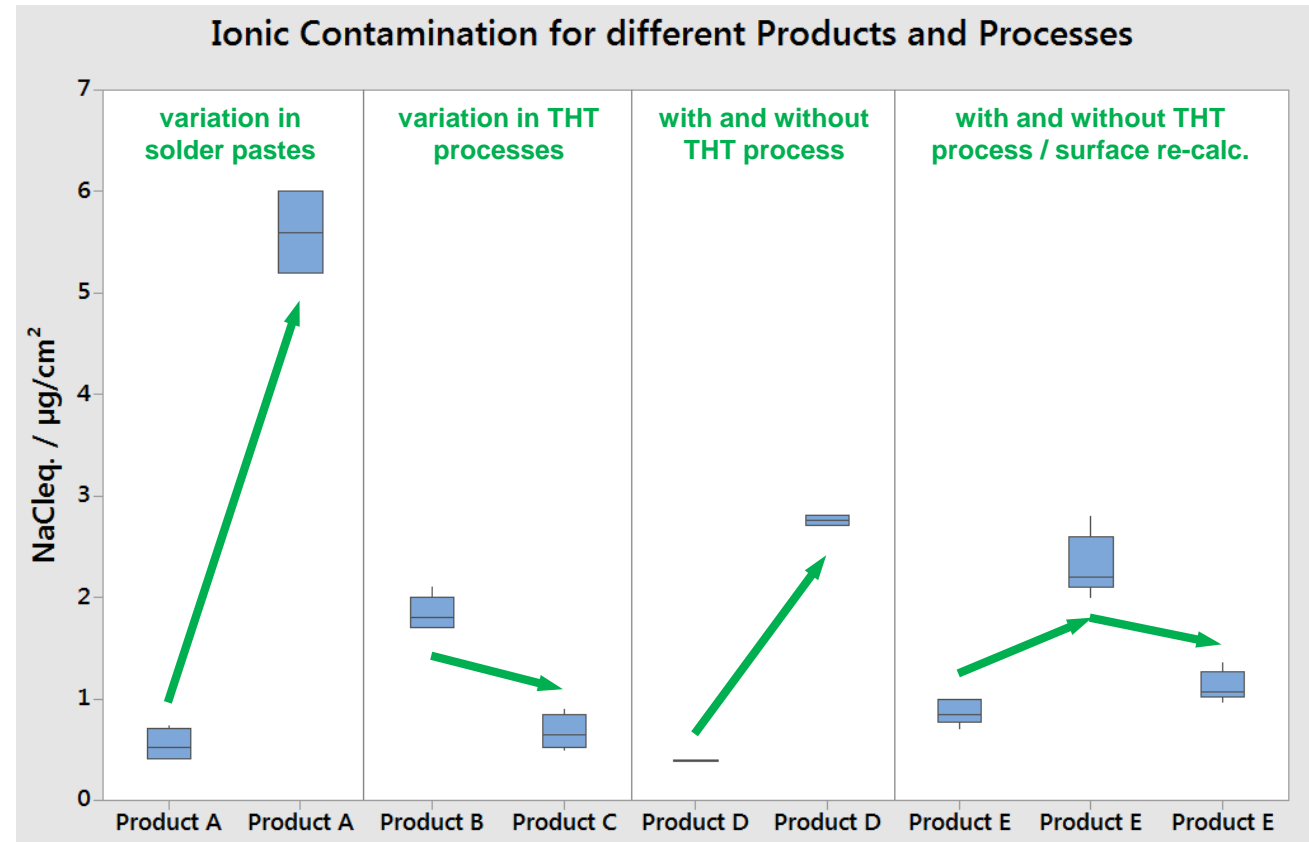


Ionic Contamination Testing as Process Control Tool

- Influence of Manufacturing Processes on Ionic Contamination Level

- larger scattering of data in ionic contamination on product level
→ caused by numerous process steps

- control tool in assembly process due to comparable measurement capability
- ionic contamination strongly influenced by materials, processes and rules for surface calculation
→ process deviations can be detected and root cause analysis started
- comparison of like with like

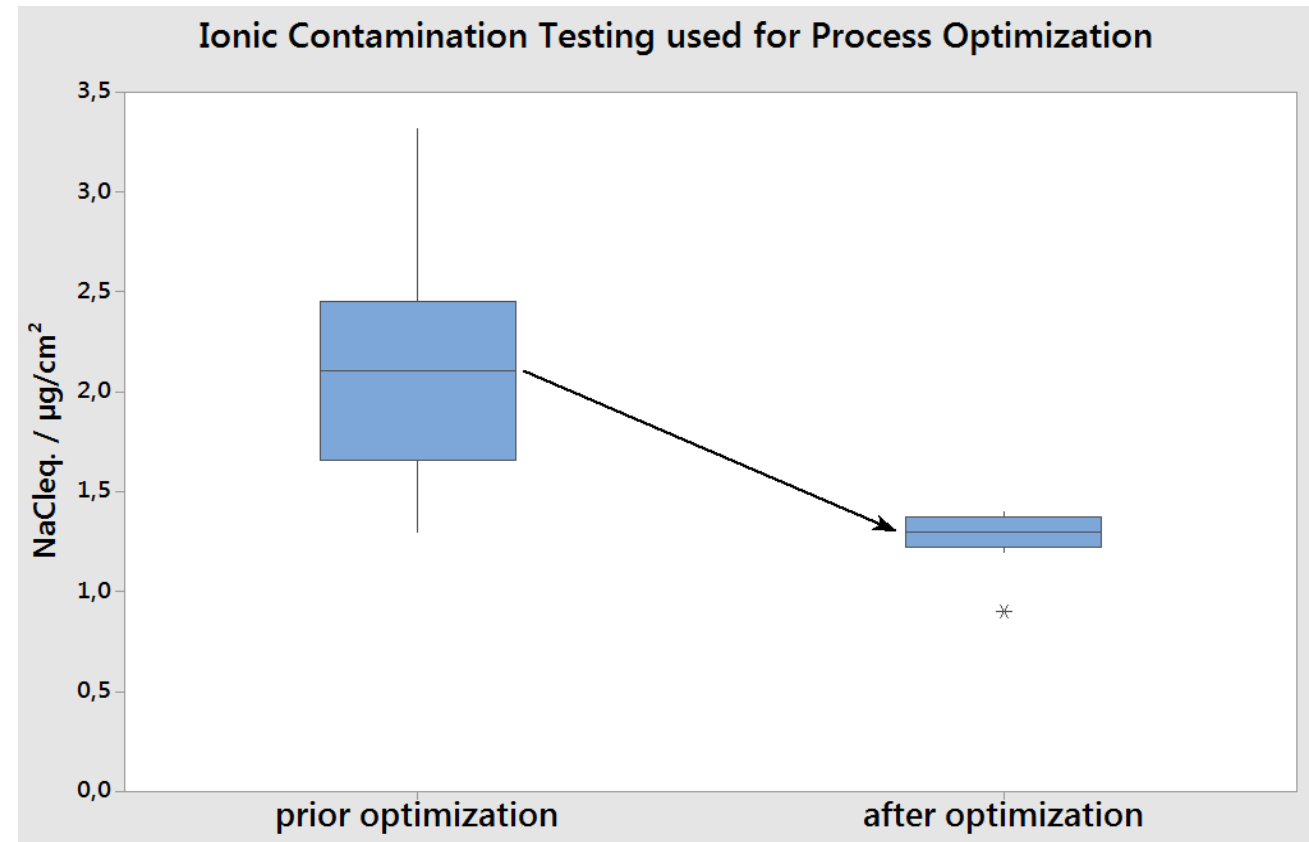


Ionic Contamination Testing as Process Control Tool

- Process Control and Optimization Tool

- value for ionic contamination to be used as characteristic value for process optimization

- optimized fluxing parameters for specific product were evaluated
- reduction of flux application without any influences on production quality was achieved
- PICT is used as process control tool at different manufacturing sites aligning manufacturing processes



Conclusions

- humidity robustness of design elements ensured by SIR measurement technology under high temperature and high humidity conditions
- absolute value of ionic contamination does not predict reliability
- ionic contamination testing as process control exhibits advantages to current ROSE test protocols
 - achieving 6σ criteria for manufacturing of electronic control units
 - complementary to material / design element release based on SIR measurements applying B52 approach
- process control / optimization at different manufacturing site world wide possible

Acknowledgements

- Lothar Henneken, Roman Fritsch and Udo Welzel, *Robert Bosch GmbH*
- Graham Naisbitt and Alasdair Naisbitt, *Gen3 Systems Ltd*
- Brian Ellis, “System” *founder*

Thank you for your attention

Any Questions?