Paper presented by

Kirsten Stentoft and Marie Louise Petersen
In

RAMS conference 2008, Las Vegas, USA

Electronics in Harsh Environments - Product Verification and Validation

Kirsten Stentoft, B.Sc. Electronics, Danfoss Drives A/S
Marie Louise Petersen, M.Sc. Chemistry, Danfoss A/S

Key Words: Quality, harsh environments, testing, verification, industrial applications

SUMMARY & CONCLUSIONS

The demand for robust electronics is continuously increasing, as electronics is used in almost any products and placed everywhere. The customer expects industrial products to operate at least 5 years without failures, no matter the location.

In order to be able to design products which are robust against harsh environments, the specific conditions at the customers must be known and understood. Following, the requirements for the entire product and the single parts must be specified properly. The final product shall be able to pass robustness tests, such as aggressive gases, humidity and contamination. Requirements to the suppliers of single parts and components shall include cleanliness and lifetime data in harsh environments.

Danfoss has developed a simple three step 'aggressive sub 3' test procedure for new products, which involves exposure in salt mist, aggressive gasses and cyclic humidity. These tests show good conformity with real life scenarios, but exact acceleration factors relative to the customer environment can not be established, since too many factors are unknown. However it is possible to make life tests with various stress levels and thereby determine acceleration factors for single or few stressors. Other 'must' tests are dust tests, condensing humidity tests and temperature cycling. It is also very important to analyze market feed-backs and thereby get more knowledge about the customers and the products, to be able to make ongoing improvements.

1 INTRODUCTION

Today electronics is integrated in almost all products compared to the situation 20 years ago. At that time electronic products were placed in clean and dry environments, which is not the case any longer. This combined with the fact that the components and spaces between them are getting smaller and smaller, often result in failures in the field. Many of these failures are caused by humidity, dust and aggressive gasses combined with contamination on/in the components and PCBs [g] from the suppliers. Knowledge about levels of harsh testing is needed together with knowledge about user environments and analysis of failures from the field.

This paper gives examples of field failures as well as contamination on PCBs and components from suppliers. Furthermore, how to perform aggressive gas testing without using expensive equipment and how to measure customer environments are described together with comparison of test methods and advices about 'Do' and 'Do Not', when designing electronics to be used in harsh environments.

In this paper harsh environments are defined as a mix of contamination, aggressive gasses and high humidity. The effect of these impacts will increase by higher temperatures.

The products in question are electronic industrial products and not consumer goods.

2 PRODUCT DEVELOPMENT, PRODUCTION AND USE

Roughly the processes can be divided into 5 main phases: Design, Production, Transport, Storage and Use. An illustration of the progress is shown in Figure 1.

In the Design phase the robustness, mechanical concept and circuit design are fixed and tested. These three properties are basis for the product's ability to operate in harsh environments. If the design is not optimized regarding airflow, risk of local condensing, sufficient distances between conducting parts, tightness, circuit design margins and mechanical robustness, it is very difficult to optimize the robustness later on.

The Production phase includes part manufacturers and own production processes. In this phase there is a large risk of contamination and process residues.

During Transportation there also is a risk of harsh environments such as high and low temperatures and high humidity.

The Storage phase includes all kind of storage in the entire life cycle. As long as the product is packed properly there are no problems, but if an unpacked product is stored in a production facility outside shelters, there is a risk of harsh environment.

The Use phase is normally the longest period in the life cycle, and therefore the environmental impacts are accumulated and may cause problems, even if the environment seems to be mild.

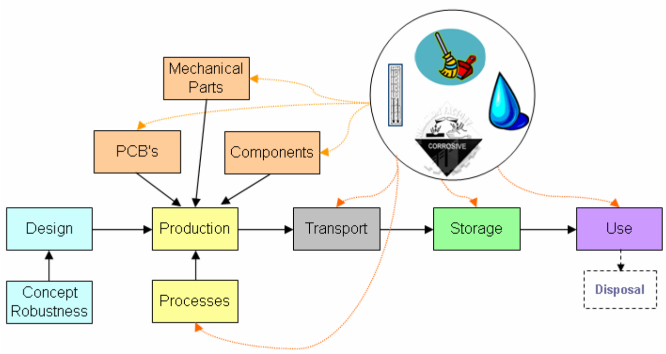

Figure 1. Development, Production, Transport and Use. In the Design phase robustness is implemented and it is indicated by orange lines, where harsh environments may occur in the later phases.

3 *EXAMPLES FROM THE FIELD*

It is necessary to analyze market failures very carefully to determine the root cause; otherwise no improvements can be made. Microscopic analysis, SEM [k] and other analysis methods are often needed, since it can be difficult to determine the root cause just by visual inspections. Furthermore, exposure in a climate chamber is often needed, since many failures have disappeared before analysis in the laboratory. The reason may be dry out of the components and PCBAs [h] or that leakage current disappears, when the PCBs are dry.

Sulphur compounds are the most common aggressive gasses, as sulphur is present in many processing industries, e.g. oil, plastic, wood and viscose. Another common aggressive gas is ammonia, which is present in among others agricultural industries. Chlorine is also found in some industries, among others the paper industry. Chlorine is more aggressive compared to ammonia and sulphur compounds. High humidity accelerates the effect of aggressive gasses, especially in conditions above 50% RH [j]. Examples of sulphur attacks on electronic components are shown in Figure 2 and 3.

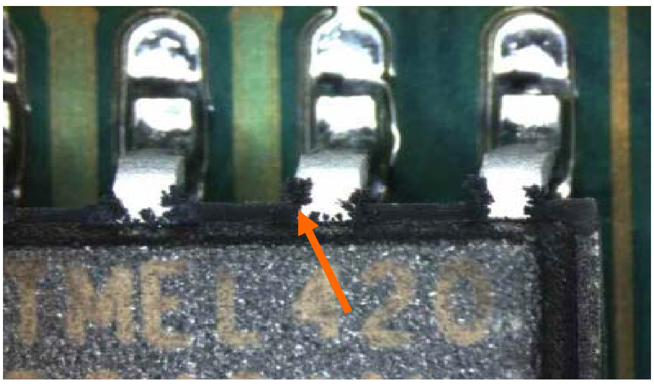

Figure 2. Sulphur attacks on IC [d] leads. The black deposit consists of copper and sulphur. Seen both in lab tests and from the market. The IC is still functioning. [4]

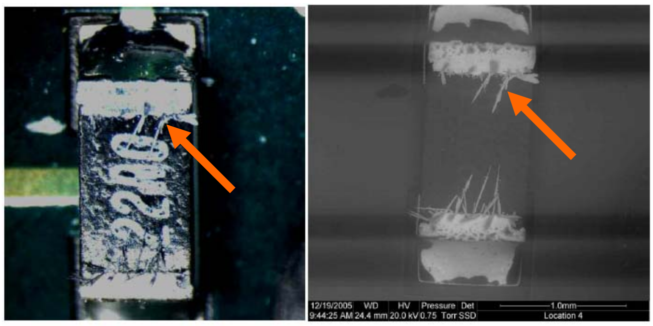

Figure 3. Sulphur attacks on a chip resistor. The 'needles' consist of Ag_2S. Seen both in lab tests and from the market. The resistor is still functioning.

Chemical attacks can also occur, if a high amount of flux residues from the production process are present on the PCBA. These residues can be very corrosive in the presence of high humidity or moisture. It is a common mistake that use of so-called "no-clean" fluxes will not contribute to any corrosion risk. Residues from some types of no-clean fluxes can be aggressive, if they dissolve and then become conductive. This creates a risk of leakage currents on the PCBA. Figure 4 shows an example of flux residues, which became white and conductive after exposure in high humidity at a customer.

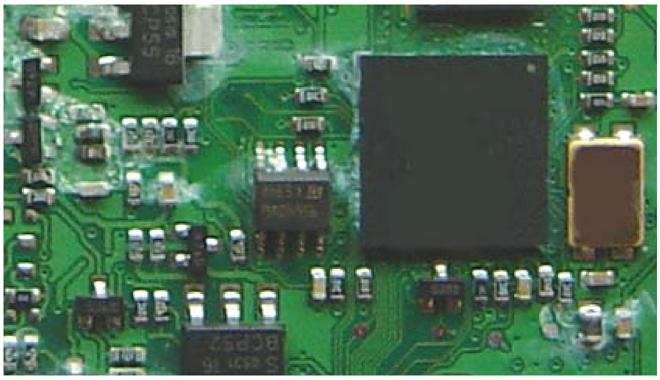

Figure 4. White residues, visible after being exposed to high humidity at a customer. The PCBA has failed.

The presence of flux residues can be detected by use of IR [f] microscopy, which identifies the organic groups in the flux. Figure 5 shows the example in Figure 4, in which the residues found on the PCBA, were analyzed by IR and compared to the applied flux. The two IR-spectra are almost identical and there is no doubt, that the residues found on the PCBA are flux residues.

More information about flux residues can be found on the Internet, among others on the 'Foresite' White Residues Homepage [13].

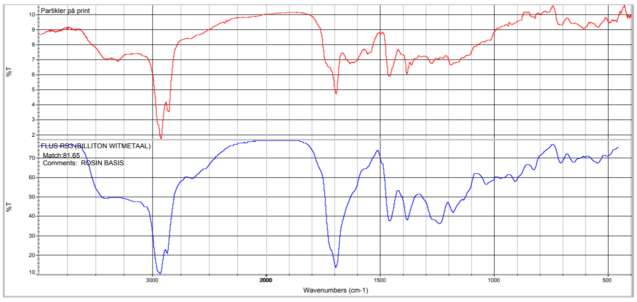

Figure 5. IR-spectra of white residues from a PCBA (upper red curve) and the applied flux (lower blue curve).

When examining corrosion failures on a PCBA, such as the one shown in Figure 4, it is common practice to use SEM-EDX [c, k] to examine the corrosion products. Figure 6 shows one example, which reveals a high amount of lead, tin and copper in the corrosion products. This observation and further information about the customer environment led to the conclusion, that corrosion of the PCBA took place in the customer environment. The failure was caused by flux residues and extreme high humidity at the customer due to a failure in the air control system.

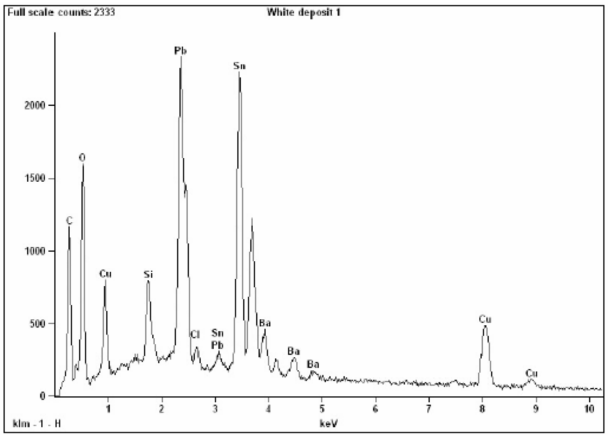

Figure 6. SEM-EDX spectra from the areas with white flux residues as seen in Figure 4.

4 EXAMPLES OF CONTAMINATION FROM SUPPLIERS

As components, protective layers in/on parts and distances between conducting parts are getting smaller and smaller; it becomes increasingly important to be sure that no process residues remain, when PCBs and components arrive at the final assembly process and of course also after own processing. The contamination can originate from process related residues such as flux and dry etches or as fingerprints from incorrect handling. These process residues may cause corrosion, leakage currents and other failures, when exposed to a humid environment.

At Danfoss contamination levels on new PCBs are examined on a regular basis by a cleanliness test [1]. The contaminants present on the PCB surface are dissolved in a solution of isopropanol and deionized water. The contaminated solution is following analyzed by IC [e], which determines the amount of various ionic contaminants. Table 1 shows the results from one cleanliness test of a PCB and it is especially the high concentration of chloride, which is critical for corrosion resistance in this example. The recommended limit is 1,56 μg/cm^2 NaCl equivalent according to IPC J-STD-001D [5]. Different concentrations of ionic contaminants are converted into sodium chloride equivalents. The test method is described in IPC-A-600F [6].

Table 1. Cleanliness analysis of a PCB.

Parameter	Concentration (μg/cm^2)	Detection limit (μg/cm^2)
Fluoride	< 0.003	< 0.003
Chloride	5.4	< 0.005
Nitrite	< 0.004	< 0.004
Bromide	0.48	< 0.005
Nitrate	< 0.006	< 0.006
Phosphate	< 0.008	< 0.008
Sulphate	0.60	< 0.008
Sodium	0.55	< 0.02
Ammonium	1.03	< 0.02
Potassium	1.30	< 0.03
Magnesium	< 0.03	< 0.03
Calcium	3.80	< 0.03
Conductivity/area (μS/cm/cm^2)	0.11	< 0.008

It is important to specify a degree of cleanliness from the suppliers – especially as more and more low-cost electronic components and PCBs are used in industrial products. In the agreement with the supplier, it also shall be stated which corrective actions shall be taken, if the specifications are not met. It is not an unknown phenomenon that some PCBs contain visible signs of fingerprints and a high amount of residues from production processes. These are all contaminants, which lowers the corrosion immunity of the final product.

5 HOW TO MEASURE CUSTOMER ENVIRONMENTS

It is possible to measure temperature, humidity and air quality at customers, but as customers often are located world wide, it is time consuming to visit just some of them. It is also possible to find information about outdoor climate in literature and on the Internet, but the outdoor climate may not be the same as the customer's indoor environment. Instead small humidity and temperature loggers [2] can be sent to the customers together with metal coupons in order to evaluate the aggressiveness of the customer environment. The normal procedure is to use both copper and silver coupons, since these two metals have different corrosion mechanisms. The loggers and metal coupons shall be placed in the customer environment for 30 days, before they are returned for analysis.

The following analysis of the metal coupons gives useful information about the corrosivity of the user environment. ECR [b] analysis is used to determine the thickness of the corrosion products on the metal coupons. Besides thickness, the ECR method also gives some information about the chemical composition of the corrosion products. The thickness of the corrosion products on the copper coupons corresponds to a severity class according to ISA-S71.04-1985 [7]. This standard concerns the effect of airborne contaminants including gasses. According to the standard, the environment can be categorized into four classes named G1, G2, G3 and Gx. Table 2 describes the criteria for the four classes in ISA-S71.04-1985.

Table 2. Severity levels according to ISA-S71.04-1985.

Severity level	Copper reactivity after 30 days	Class description
G1 Mild	< 300 Å	Corrosion is not a factor influencing product reliability.
G2 Moderate	< 1000 Å	The effects of corrosion are measurable and may influence the equipment reliability.
G3 Harsh	< 2000 Å	There is a high probability of corrosive attack and special designed equipment should be considered.
Gx Severe	≥ 2000 Å	Corrosion will occur if the equipment is not designed and packed properly.

ISA-S71.04-1985 is not the only international standard which attempts to categorize the environment. Another example is IEC 60721-3-3 [11], which is widely used for environmental characterization, but the concentration limits of aggressive gasses in this standard are high compared to ISA-S71.04-1985. Thus there is very little correlation between ISA-S71.04-1985 and IEC 60721-3-3. The only correlation between these two standards is that neither of them are test standards – they can only be used to describe environmental conditions and NOT how to test according to a specific severity class.

The ISA-S71.04-1985 standard also gives information about how to prepare metal coupons. The classification is defined as corrosion layer on Cu. Danfoss also uses Silver coupons as they give a more detailed picture of the corrosivity in the location to be measured.

6 *WHY USE OUR OWN GAS TESTS?*

As electronic products are placed in almost all kinds of industries and harsh environments, it is necessary to test the ability of the products to operate in these environments. In order to make improvements to the design and choice of materials and components, it is necessary to make accelerated tests, which show same failures as on the market. In the late nineties, the only "supplier" (Danfoss was able to find) of mixed gas tests was in the US, and it was very time consuming to have testing done there due to a long transportation time and custom clearance. Therefore Danfoss searched for a test facility inside Europe.

It was only possible to have a single gas test done according to IEC 60068-2-43 [8]. After this test, none of the Test Specimens failed and there was almost no evidence of them being attacked by the hydrogen sulfide present in the test chamber. But failures similar to those at customer facilities could be provoked if a Prohesion test was added after this test. Furthermore a cyclic humidity added after the two other tests, revealed the most robust product.

Therefore, we came up with the idea of designing our own aggressive gas test. The requirements were: It should be fast and show the same failures as in the dyeing industry in tropical countries. After some experiments with either too harsh or too mild gas mixtures, the aggressive tests were carried out in a sub 3 test: 1) Prohesion [9], 2) Aggressive gas and 3) Cyclic humidity. At the moment three different types of aggressive gasses are used: sulphur, chlorine and ammonia. A flow diagram of the Danfoss test procedure is shown in figure 7.

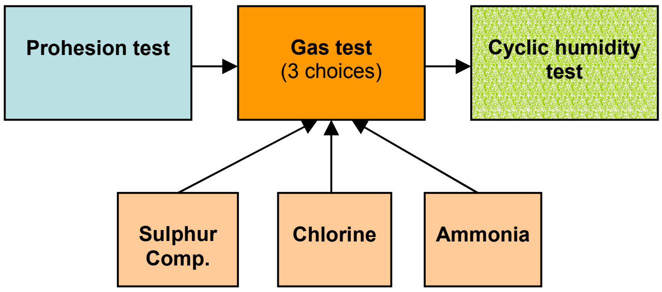

Figure 7. Flow diagram of the 'Aggressive sub 3 test'.

The Prohesion test is a mild salt spray test performed according to ASTM G 85 – Annex A5 [9]. The products are exposed to a mist containing 0.05% sodium chloride and 0.35% ammonium sulphate. The Prohesion test varies between "wet" and "dry" conditions in intervals of 60 minutes, and the normal test duration is 6 hours, corresponding to 3 cycles. Figure 8 shows the Prohesion chamber used at Danfoss.

Figure 8. Prohesion chamber used at Danfoss.

All three types of gas test (sulphur, chlorine and ammonia) are performed in a 60 liter sealed and acid proof tub as shown in figure 9. The conditions of each of the three gas test are described in table 3. Establishing of 75% RH is done by a saturated water solution (0,05% NaCl + 0,35% ammonium sulphate + water [15]) in the bottom of the chamber in Figure 9.

Figure 9. Aggressive gas test chamber used at Danfoss.

Table 3. Test conditions of the gas tests used at Danfoss.

	Sulphur	Chlorine	Ammonia
Active gas	0.5% H_2S 0.5% SO_3	0.01% Cl_2	0.5% NH_3
Humidity	75%RH	75%RH	75%RH
Temperature	Room temp.	Room temp.	Room temp.
Duration	6 hours	0.5 hours	8 hours
Power on Test Specimen	ON	ON	ON

The last sub-test in the Danfoss test is exposure in cyclic humidity [14], in which the temperature changes from 25°C to 50°C at a humidity level of 89 to 95 %RH. The normal cycle time is 24 hours and the power on the test specimen is switched On 12 hours and Off 12 hours. Condensation with visible water flow shall be avoided. The test duration depends on which gas is used in the gas test.

A mixed gas test at Battelle [3] has also been used as a supplement to the aggressive Danfoss tests described above. The Battelle test is performed according to ASTM B827-92 [10]. The test conditions are described in Table 4. Other levels of concentrations can also be made by Battelle. The test from Battelle is only used in a limited extent by Danfoss due long transport times and the costs involved. The Battelle test shown in table 4, is the Battelle method for testing according to ISA-S71.04-1985, level Gx.

Table 4. Test conditions for the Battelle test. Duration 20 days.

H_2S	NO_2	Cl_2	RH	Temp.
200 ppb [i]	200 ppb	50 ppb	75 %	50°C

7 *COMPARISON BETWEEN AGGRESSIVE GAS TESTS*

A direct comparison of the aggressiveness of the various gas tests described in section 6 is difficult. Both Danfoss gas tests and the Battelle test have very aggressive test conditions and a comparison with the severity levels of corrosion rates in ISA S71.04-1985 shows that both gas tests can be classified as Gx (i.e. severe conditions). However, there is a huge difference in the test duration and gas concentrations present in the Danfoss gas test and the Battelle test, but in some cases the damages on electronics are identical.

It is a big challenge to design a gas test, which corresponds to the chemical environmental conditions at the customer site or specifications like IEC-60721-3-3. Knowledge about how different gasses interact with each other and electronic products is still limited, and it is therefore difficult to specify the perfect test conditions.

An attempt to evaluate the corrosivity of the Battelle test was made by exposing 6 panels with metal coupons for various exposure times – 2 panels were exposed for 7 days, 2 panels for 14 days and finally 2 panels for 21 days. Unfortunately, the corrosion products on the metal coupons were too thick to be measured by the ECR method, and only the weight gain could be used to describe the corrosion rate of copper and silver in the Battelle test. Figure 10 illustrates weight gain of silver and copper coupons as a function of time.

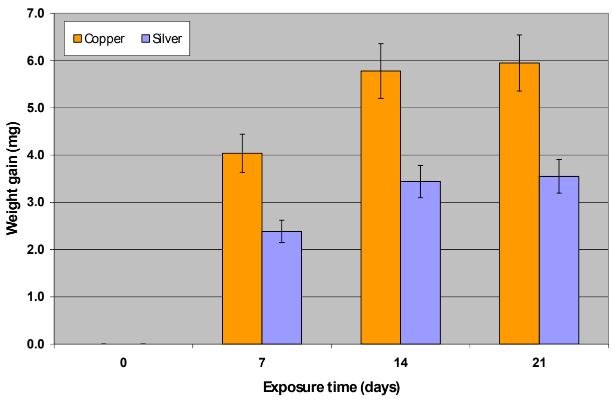

Figure 10. Weight gain of copper and silver due to corrosion in the Battelle test. Copper: orange/left, silver: blue/right.

As illustrated in Figure 10, the Battelle test is more aggressive to copper than silver. It also seems like the corrosion of both metals starts to stabilize after 14 days of exposure. Therefore, it is not correct to consider the corrosion of copper and silver as linear in severe environments (Gx environments). This observation is in contrast to ISA-S71.04-1985, which states that the corrosion of copper in a Gx environment can be expressed by the following linear expression.

$$X_{30} = X_t * (30 / t)$$

Where X_{30} equals the film thickness after 30 days and X_t the film thickness after time t.

8 TEST LEVELS AND APPROVAL CRITERIA

Before approval criteria and test levels can be defined, the customer environment must be known, at least to some degree.

If the climate is hot and humid, it is recommended that electronic products are placed in air conditioned rooms or shelters. If so, it is necessary to inform the customer that opening the door to the air conditioned shelter may cause condensing, if the temperature outside the shelter is very high. If it is not possible to place the electronic product in shelters or air conditioned rooms, the product shall be able to withstand high humidity, which means cyclic humidity test with condensation.

The customer application related air quality must also be known. Are there aggressive gasses in the air? Particles and dust? If no specific information is available, the following tests can be recommended:

- Cyclic humidity with condensation periods, 89 to 97% RH, 25 - 50°C, duration min. 3 weeks.
- Aggressive sub 3 test with sulphur is recommended if no specific information is available. It is normally not necessary with other aggressive gas tests, as sulphur gives a good indication of the robustness. No failures before 21 days in cyclic humidity.
- Aggressive sub 3 test with ammonia is recommended in agricultural installations. No failures before 14 days in cyclic humidity.
- Aggressive sub 3 test with chlorine is recommended in the paper industry. No failures before 7 days in cyclic humidity.
- Rapid temperature cycling to verify if the product is designed in a way, that local condensing does not occur. It should be able to withstand large temperature differences (-30 to +50°C) and 1000 cycles without any failures. Normally this test will reveal many other weaknesses.
- Dust test. The purpose is to verify areas inside the product with dust formation. Normally areas with much dust are the same areas, which are sensible to aggressive gasses.
- Dust test followed by cyclic humidity. The purpose is to verify, if condensed water is trapped in the dust located inside the test specimen.

9 'DO' AND 'DO NOT' WHEN DEALING WITH ELECTRONICS AND HARSH ENVIRONMENTS

1. Avoid forced ventilation from the surrounding air. Especially over sensitive components like small SMD components [l]. The reason is that corrosive attacks are more liable in a high airflow and the possibility for local condensing and local collections of dust are considerably increased.
2. Avoid thermally heavy components placed in the top of a product. This may lead to local condensed water which, if not controlled, may cause leakage currents and short circuits.
3. Be sure to have a 'controlled water path' out of the product. The reason is that local condensing often cannot be avoided; therefore it may be necessary to lead the water out in a controlled way.
4. Perform cleanliness tests regularly on PCBs and PCBAs. The reason is that the combination of high humidity and contaminated PCBAs can lead to failures even in clean and moderate humid environments.
5. Specify PCBAs according to IPC-A-610 rev. D [12]. Without the right specifications, you may receive a low-quality product from the supplier.
6. Specify PCBs according to IPC J-STD-001D and IPC-A-600. Also use X-ray to inspect PCBs. Without the right specifications, you may receive a low-quality product from the supplier.
7. Design the PCBAs in a way that they easily can be dip coated if necessary, and avoid 'last minute decisions' with the risk of a bad result or at best a very expensive solution.

10 FUTURE WORK

Much research is needed for future work, because of ongoing miniaturization of components, cost optimization, smaller products with need for forced cooling, smaller spaces and distances between conducting parts. But also the user pattern continues to change and the electronic functions are getter more and more complex. Furthermore it is getting more challenging to find the root cause of failures. So the conclusion is that there are many questions to answer and tasks to perform. The following is a partial list, in no particular order:

1. Clarify the interaction between aggressive gasses, humidity and particles.
2. Determine at which humidity level aggressive gasses and particles become a problem and at what gas and particle level humidity becomes a problem.
3. Define test methods which can be communicated to the

customers and suppliers and are reproducible. Preferable as international standards. The methods shall be suitable for measuring customer environments and verification of new products in laboratory tests.

4. Determine failure mechanisms in common components due to aggressive gasses, particles and humidity.
5. Clarify the influence of contamination inside components.
6. Develop design rules regarding choice of materials, process technologies and mechanical construction.
7. Clarify the interaction between airflow, air quality, design and chemical attacks on sensitive parts.

A Danish Corrosion project named CELCORR [a] - established in August 2007 - has the purpose to research in the questions above. CELCORR is a corporation between Danish Universities and Industries, among others Danfoss.

ABBREVIATIONS

a. CELCORR: Centre for Electronic Corrosion
b. ECR: Electrolytic Cathodic Reduction
c. EDX: Energy dispersive X-ray spectroscopy
d. IC: Integrated Circuit
e. IC: Ion Chromatography
f. IR: Infrared
g. PCB: Printed Circuit Board
h. PCBA: Printed Circuit Board Assembly
i. ppb: parts per 10^9, same as µg per liter
j. RH: Relative Humidity
k. SEM: Scanning Electron Microscope
l. SMD: Surface Mounted Devices

REFERENCES

1. *Petersen Marie Louise,"Cleanliness of Chinese PCBs",* Danfoss IS-T report 2006-10550e-GB, 15-01-2007
2. http://www.geminidataloggers.com.
3. Battelle, Ohio: http://www.battelle.org
4. Pictures, analyses and graphs are all made by Danfoss.
5. IPC J-STD-001D. Joint Industry Standard. Requirements for Soldered Electrical and Electronic Assemblies.
6. IPC-A-600F. Acceptability of Printed Boards.
7. ISA-S71.04-1985. Environmental conditions for Process Measurement and Control Systems: Airborne Contaminants.
8. IEC 60068-2-43 Environmental testing Part 2-43: Tests Test Kd: Hydrogen sulphide test for contacts and connections.
9. ASTM G85 annex A5 – dilute electrolyte cyclic fog /dry test. This test is also referred to as a Prohesion test.
10. ASTM B827-92 Standard Practice for Conducting Mixed Flowing Gas Environmental Testing.
11. IEC-60721-3-3 Classification of environmental conditions Part 3-3: Classification of groups of environmental parameters and their severities. Stationary use at weather protected locations.
12. IPC-A-610 REV. D. Acceptability of Electronic Assemblies.
13. http://www.residues.com
14. IEC 60068-2-30 is used as basis, but slightly modified.
15. Laborprodukte für die Praxis. Part 3.

BIOGRAPHIES

Kirsten Stentoft, B. Sc. Electronics
Danfoss Drives A/S
Ulsnaes 1
6300 Graasten
Denmark
E-mail: Kirsten_Stentoft@Danfoss.com

Mrs. Stentoft has more than 20 years of experience working in quality in several Danfoss divisions. She has worked as specialist, manager of quality departments and manager of laboratories. Mrs. Stentoft is a professional engineer and received her B.S. in Electronics from Soenderborg Teknikum in Denmark. She is currently a reliability specialist at Danfoss Drives, where she has developed strategies for reliability testing and new test methods and criteria's for approval.

Marie Louise Petersen, M.Sc. Chemistry
Danfoss A/S
Nordborgvej 81
6430 Nordborg, Denmark
E-mail: marie_louise@danfoss.com

Marie Louise Petersen is a Consulting Engineer at Danfoss A/S and works primarily in the field of corrosion and failure analysis. She earned her master degree in Chemistry with specialty in Material Science at the Danish Technological University in Lyngby, Denmark. In her job as a Consultant she has gained a lot of interests within corrosion of electronics and introduced many new methods for evaluating the corrosion risk in electronics – for instance measurements of environmental corrosivity by the use of Electrolytic Cathodic Reduction (ECR) analysis on metal coupons. Cleanliness measurement on PCBs is another one of her fields of expertise.