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A facility for mixed flowing gas testing of and experimentation with power electronic components and systems

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Abstract

Corrosion phenomena have been found to inflict new types of failures on power electronics. Currently, the precise corrosion mechanisms and effects causing problems are largely unknown. A facility dedicated for environmental reliability and lifetime testing of power electronic components and systems is presented.

Introduction

The increasing use of power electronic devices such as frequency converters in solar, wind and automotive applications, has led to the diversification of the environmental conditions the devices are exposed to. The topical matters keeping up this trend are the electrification of vehicles and ambitions of increasing the energy efficiency of systems. This trend has increased the number of devices put into environments that are more and more extreme in terms of their environmental conditions. In particular, humid environments with chemically active compounds, for example water treatment plants, mining and paper industry plants, have been found to be problematic by field experience. Such environments can cause corrosion, eventually leading to the failure of the converter. Corrosion is manifested e.g. as dendritic growth in insulations (Fig. 1) which leads to a short circuit. The reliability of power electronics has been the subject of many publications. Present literature does not, however, fully discuss corrosion phenomena and related reliability issues.

Today a common climatic accelerated aging testing method for power electronic switch components is the high humidity, high temperature and high voltage reverse bias (H3TRB) test, where corrosion is induced into the devices under test by controlled humidity, temperature and bias voltage [1, 2, 3]. While this testing method does allow studying aging phenomena in humid environments, it does not include controlling the amount of impurities and ion concentrations in the exposure air. Because of this, the test does not simulate environments with corrosive gases present. With no control on the impurities, the test results may vary and even contradict each other [4].

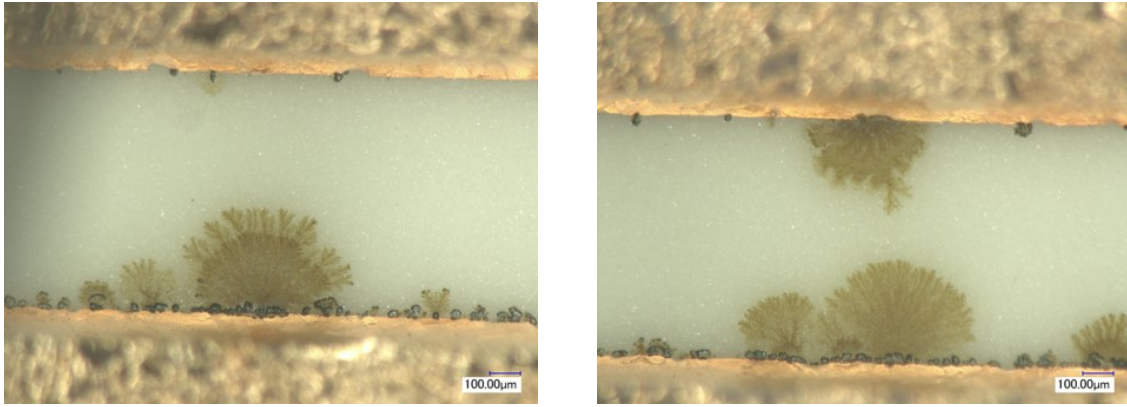


Fig. 1: Dendrite growth on an IGBT module aluminum oxide substrate. Module was recovered from a water treatment plant.

Corrosion test conditions using pollutant gases have evolved from single gas tests with high concentrations to mixed flowing gas (MFG) tests carried out with multiple corrosive gases at low concentrations [5]. While single gas tests are still used alongside MFG tests [6], MFG tests achieve high acceleration factors with lower gas concentrations because of synergistic reactions between the gases [7]. MFG tests can be run with similar humidity and electrical conditions as H3TRB, albeit at lower temperatures because of issues with exhausting and transporting moisture-laden gas to external analytical equipment without condensation [5]. The gases used in MFG tests are hydrogen sulfide H_2S , sulfur dioxide SO_2 , chlorine Cl_2 and nitrogen dioxide NO_2 [8]. Some standardized test conditions such as all Battelle tests use three gases leaving out SO_2 , as when developing these standards, it was found that adding SO_2 to the mix did not significantly affect copper corrosion [5]. It is also stated that SO_2 may be included to account for materials not present in the original Battelle tests. This means that SO_2 should be present when testing materials other than copper, for example power semiconductor switches.

Previously, mixed flowing gas testing has been mostly used for printed circuit boards and small components, motivated by the increasing number of failures associated with the RoHS directive taking effect in 2006 [9] [10]. Despite the long history of the method in many electronics applications, it has not made a breakthrough in component testing for power electronics. However, an increasing interest towards corrosion issues has been taken by industrial electronics manufacturers [11]. While many papers on MFG tests on small components and printed circuit boards exist, the papers do not describe the test system in detail.

Creating the appropriate test conditions requires carefully selected instruments for dosing the chemicals and analyzing the resulting gas concentrations. The test chambers are, in principle, typical environmental test chambers capable of producing a desired air temperature and humidity, that also are built to withstand the corrosive gas mixture used in the experiments. It is also necessary to monitor the gas concentrations for the purposes of occupational safety in order to avoid poisoning the persons carrying out the experiments.

Methods

To reduce the time needed to complete the experimental facility, the entire test facility is to be constructed of readily available systems and equipment. A major part of the challenge in choosing and procuring the equipment is defining the requirements for each element in the system. For producing the desired test conditions, two separate but connected problems are identified: how to dose the gases appropriately into the test chamber while also controlling the humidity and temperature, and how to verify that the resulting conditions satisfy the requirements.

The test setup is realized according to the the example system introduced in IEC 60068-2-60 [12]. The setup consists of a modified climatic chamber with an internal exposure chamber, gas dosing unit and gas

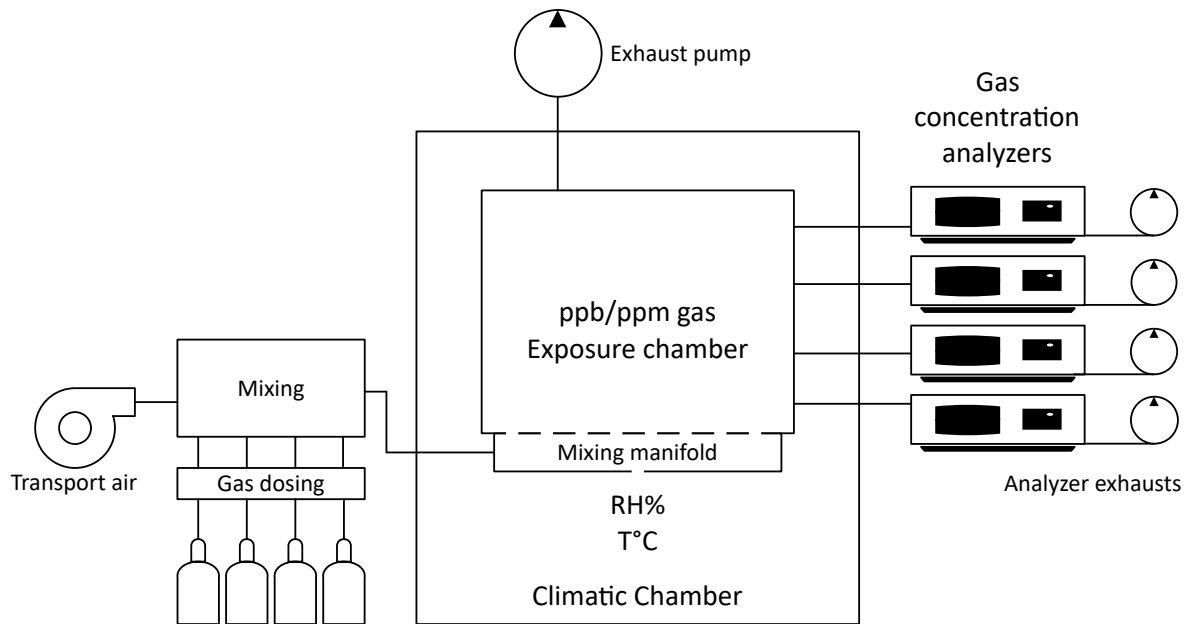


Fig. 2: Test setup with the essential components. A climatic chamber provides the desired humidity and ambient air temperature for the tests. A dosing and mixing system feeds the gases into the exposure chamber, where the devices under test are located. Gas concentration analyzers verify the test conditions.

analyzers (Fig. 2). The climatic chamber controls temperature and humidity of the system. An exposure chamber is placed inside it, into which the gases are then dosed. The exposure chamber is constructed of materials that are not harmed by the corrosive gasses. The working volume of the test system is the volume of the inner exposure chamber.

The amount of corrosive gases is controlled by mass flow controllers. The volumetric flow from the gas bottles is quite low, which means the gases would take a long time to reach the exposure chamber on their own. To mitigate this, the gases are mixed into filtered and dehumidified pressurized air called transport air. This is also the first dilution step in the gas dosing process. Transport air has a flow controller of its own.

Air flow to the exposure chamber is controlled by the exhaust system. The exhaust air pump reduces the pressure inside the exposure chamber, which allows air to diffuse into the chamber from the mixing manifold. The mixing manifold receives the mix of transport air and gases, but it also has an opening to the climatic chamber. This allows the corrosive gases to mix with temperature and humidity controlled air. This is the final dilution step. The air flowing from the mixing manifold into the exposure chamber matches the requirements in terms of temperature, humidity and gas concentrations.

The exhaust system creates a small underpressure in the exposure chamber to make sure the corrosive gases do not exit into the climatic chamber. The gas concentration analyzers sample the air from the working volume of the exposure chamber. Gas concentrations must be analyzed from the exposure chamber instead of e.g. the exhaust air because the gas concentrations decrease due to adsorption and loss by chemical reactions [5]. Measuring the exhaust air would result in smaller concentration readings than what the actual gas concentrations in the working volume are. Controlling the gas dosing based on such incorrect measurements would result in higher concentration in the working volume.

Air from the mixing manifold to the exposure chamber flows through small holes that cover the floor of the exposure chamber. The goal is to keep the flow as uniform as possible for the whole volume of the chamber. Despite this, local differences in corrosivity are possible in the chamber [12]. Local corrosivity is mapped using standard copper and silver corrosivity coupons that are spread around the exposure chamber. In addition it is also possible to use a rotating carousel structure to hang small devices from. The carousel can be used to slowly rotate the devices under test so that possible local differences in corrosivity are mitigated.

The variables affecting the gas concentrations are the exchange rate, and the flow rates of transport air, conditioned air and corrosive gases. Exchange rate – the rate at which air inside the exposure chamber is changed – is set with a valve that controls the amount of air pumped out of the exposure chamber. In standards such as the IEC 60068-2-60 the exchange rate is specified by rate of ventilations per hour, in this case 3 to 10 ventilations per hour [12]. Exchange rate is set first as it is the only variable that is directly specified in test standards. The gas concentration analyzers exhaust their sampling air out from the exposure chamber and so their flow rate needs to be added to the total exhaust flow.

According to the system manufacturer the air in the exposure chamber contains a mix of roughly 10 % of transport air including the corrosive gases and 90 % of conditioned air (humid and temperature controlled air inside the climatic chamber). This mix is then exhausted by the exhaust air pump and analyzers. To calculate the correct settings for gas dosing a few formulas are needed. The basis for the calculations is given by the manufacturer as

$$\dot{V}_{\text{out}} = \frac{V_{\text{EC}} r_{\text{ex}}}{60 \text{ min/h}}, \quad (1)$$

where \dot{V}_{out} is the exhaust air in litres per minute, V_{EC} is the volume of the exposure chamber in litres and r_{ex} is exchanges per hour. After the \dot{V}_{out} is calculated the transport air flow is simply $\dot{V}_{\text{Trans}} = 0.1 \cdot \dot{V}_{\text{out}}$ and the conditioned air is similarly $\dot{V}_{\text{Cond}} = 1.1 \cdot \dot{V}_{\text{out}}$. Then the mass-flow controller values \dot{V}_{Gas} in millilitres per minute can be calculated with

$$\dot{V}_{\text{Gas}} = \dot{V}_{\text{out}} \frac{C}{M}, \quad (2)$$

where C is the gas concentration wanted in the exposure chamber and M is the concentration in the gas cylinders. To achieve a desired humidity in the exposure chamber, the climatic chamber humidity setting has to be set higher. This is because the mixture of transport air and corrosive gases is dry, lowering the humidity of the air mass inside the exposure chamber.

To verify the conditions, accurate gas analyzers are required for each gas used in the experiments. For each test condition and each gas, the IEC 60068-2-60 and other standards specify a nominal gas concentration and a tolerance, e.g. (200 ± 25) ppb. The measurement uncertainty of the gas analyzer is not insignificant, and further reduces the allowed range of the displayed value (Fig. 3). Therefore, the higher the accuracy of the gas analyzer, the more forgiving the experimental system is for the gas dosing system.

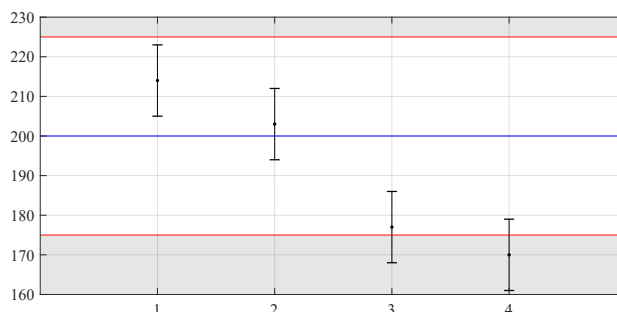


Fig. 3: Illustration of data points with uncertainty error bars reducing the range at which the displayed value can lie. In this example, the permitted range is 200 ± 25 units. The first two data points are within the specification. The third reading of the third measurement is within the specification, but conformity with the specification is unclear due to measurement uncertainty. The fourth measurement is clearly out of specification.

To compare and select gas analyzers, it was necessary to compare the measurement uncertainties. Since the instruments were not available for testing at the comparison stage, the uncertainty estimates had to rely on the manuals of the instruments. There is significant variation in how manufacturers declare the uncertainty or accuracy figures for each instrument. Some report a simple number labeled as “accuracy” or “precision”, while others provide multiple sources of uncertainty associated with the instrument itself.

For each instrument, the provided sources of uncertainty were estimated for a selected, representative reading, combined into a combined uncertainty and then into an expanded uncertainty (coverage factor $k=2.6$, confidence level 99%) according to the JCGM Guide to the Expression of Uncertainty in Measurement [13]. Uncertainties for the different analyzers were calculated and compared at different test method levels [14]. For IEC 60068-2-60 Method 4 levels uncertainties are calculated at upper concentration limit according to tolerance (Table I). As concentration levels and tolerances for IEC 60068-2-60 Method 3 are different, the tolerances and uncertainties are calculated separately for this method (Table II). Included in tables are also analyzers that were up to consideration.

Among requirements for selecting appropriate analyzers is that they have to provide real-time measurements without interrupting the exposure test. This excludes any instrument that requires manual sample extraction or otherwise opening the chamber. The analyzers that fit the description have internal or external pumps which allow for sample air extraction from the exposure chamber. Other requirements include rack-mounting and measurement range corresponding to the gas concentrations used.

Results

The gas concentrations inside the exposure chamber are analyzed using external analyzers. For the measurement of sulfur dioxide and hydrogen sulfide ultraviolet fluorescence spectroscopy is used. Nitrogen dioxide is measured using chemiluminescence. Both measurement methods are affected by the high humidity in the test chamber, an effect which will have to be characterized before the actual exposure tests [14]. Chlorine is measured with a chemcassette-based method. Chosen analyzers are on a green background on Tables I and II with those up to consideration on white background.

Table I: Gas concentration analyzers with their associated combined and expanded (99%, $k = 2.6$) uncertainties calculated at IEC 60068-2-60 Method 4 levels. Analyzers on green background have been chosen for MFG gas concentration measurements and analyzers on white background were considered but were not chosen.

Gas	Analyzer	Method	Target concentration [ppb]	U [ppb]
SO ₂	Ecotech Serinus 50	UV-Fluorescence Spectroscopy	200 ± 25	± 16
SO ₂	Thermo Scientific 43i	UV-Fluorescence Spectroscopy	200 ± 25	± 16
H ₂ S	Ecotech Serinus 55	UV-Fluorescence Spectroscopy	10 ± 5	± 3
H ₂ S	Thermo Scientific 450i	UV-Fluorescence Spectroscopy	10 ± 5	± 4
NO ₂	Ecotech Serinus 40	Chemiluminescence	200 ± 20	± 9
NO ₂	Teledyne T500U	Cavity Attenuated Phase Shift	200 ± 20	± 16
Cl ₂	Honeywell SPM Flex	Chemcassette (colorimetry)	10 ± 5	± 7

Honeywell SPM Flex was found to be the most suitable for measuring chlorine gas concentrations, that also fit the other criteria of real-time measurement. For a confidence level of 99 %, the extended uncertainty exceeds the tolerances given in the standards (Tables I-II). The uncertainty is calculated based on very limited information on the performance of the instrument. For this reason, the responsibility for proper Cl₂ concentrations falls more on the mass flow controller than with other gases. It is to be noted that with a confidence level of 95% the test tolerance accuracy on Table I is met.

Table II: Combined and expanded (99%, $k = 2.6$) uncertainties U calculated at IEC 60068-2-60 Method 3 levels for gas concentration analyzers. Analyzers on green background have been chosen for MFG gas concentration measurements and analyzers on white background were considered but were not chosen.

Gas	Analyzer	Method	Target concentration [ppb]	U [ppb]
H ₂ S	Ecotech Serinus 55	UV-Fluorescence Spectroscopy	100 ± 10	± 3
H ₂ S	Thermo Scientific 450i	UV-Fluorescence Spectroscopy	100 ± 10	± 4
NO ₂	Ecotech Serinus 40	Chemiluminescence	200 ± 50	± 9
NO ₂	Teledyne T500U	Cavity Attenuated Phase Shift	200 ± 50	± 16
Cl ₂	Honeywell SPM Flex	Chemcassette (colorimetry)	20 ± 5	± 11

Power electronics switches, such as IGBT modules, are under high voltage bias in the tests to allow corrosion to take place. Both the exposure and the climatic chambers have inlets for analyzer hoses and electric cables. To keep the leakage through the inlets as little as possible panels covering the inlet holes can be customized for different amount and size of cables and hoses.

At first the test setup uses one 1000-liter climatic chamber with a 380-liter inner exposure chamber. The size of the chamber allows testing of components and small systems like printed circuit boards. The inner volume of the exposure chamber can't be filled too full or the flow of air may be restricted causing local differences in corrosivity. The system will be expanded with a larger 4200-liter climatic chamber with 1900-liter exposure chamber. The bigger volume is for testing assembled devices like frequency converters. The operating principles of the larger chamber are the same as with the smaller one.

Validation

The system performance was evaluated using gas concentration analyzers. First the parameters including the corrosive gas flow rates were set according to calculations by user manual. The test was conducted at 30°C temperature and 40% relative humidity. The target concentration for both NO₂ and SO₂ gases was 200 ppb.

Control parameters for transport air, conditioned air and corrosive gases were calculated from (1) and (2). With these parameters both gas concentrations became steady at around 140% of the intended value (Table III). The initial corrosive gas flow rates were corrected based on measurements and the concentrations became steady very close to the target value of 200 ppb.

Table III: Average gas concentrations inside exposure chamber and associated standard deviations per test run. Standard deviation expresses the variation in the concentrations over the observation period. Expanded (99%, $k = 2.6$) measurement uncertainty U for NO₂ analyzer Ecotech Serinus 40 and SO₂ analyzer Ecotech Serinus 50.

Measurement	Concentration [ppb]	U [ppb]
NO ₂ uncorrected	291.2 ± 3.3	±9.0
SO ₂ uncorrected	283.1 ± 2.0	±15.4
NO ₂ corrected	198.1 ± 0.6	±8.2
SO ₂ corrected	194.8 ± 0.9	±15.4

One of the reasons for higher-than-expected uncorrected values is the coarse scale of the exchange rate and conditioned air valves that affect all gas concentrations. For example the target for exchange rate

valve was 1.14 m³/min and closest scale increments are 1 m³/min and 1.2 m³/min. However this does not account for the whole error as the possible deviation is in this case less than 20%.

Other observations

From using the test system a few practical observations of possible problems in similar MFG test setups were made. The H₂S concentration measurement is based on a process where the analyzer first removes SO₂ from the sampling air, converts the remaining H₂S into SO₂ and finally measures the SO₂. The H₂S to SO₂ converter was poisoned by chlorine gas that was present in the sampled air mix. In this case 20 ppb concentration over a few days was enough to poison the converter. Poisoning reduces the conversion efficiency drastically, leading to lowered concentration readings. Readings of over 90% less than the actual concentration were observed.

Humidity in the air mix is known to affect gas concentration measurements using UV-Fluorescence spectroscopy and chemiluminescence methods [15, 16]. To keep the gas concentrations repeatable between tests with different humidity targets, they are measured before increasing humidity in the exposure chamber. The ideal relative humidity range for measurements is not specified but it should be kept constant between tests.

When running tests with higher than ambient temperatures it is possible that the humid air condenses on the analyzer sampling tubes. One possible point where condensation occurs is metal connectors on the sampling lines. The probability of this happening can be reduced by starting the tests with low humidity and letting the sample lines warm up before increasing the humidity to desired value. If the ambient temperature is lower than the dew point of sample air, the sample lines can be heated or water condensation traps used in addition.

Conclusions

A system for Mixed Flowing Gas (MFG) tests built out of readily available instruments is described. The system can be used for research of corrosion-related failure modes of power electronic components. The tests carried out with the setup complement the more common H3TRB tests that are limited to failure modes in humid environments with no pollutants.

The requirements for equipment on a mixed flowing gas test system are hard to meet due to very small gas concentrations. This leads to fewer options especially for gas concentration analyzers. In the case of chlorine the measurements extended uncertainty (99%, $k = 2.6$) is larger than the allowed error in the example test methods from IEC 60068-2-60. The importance of gas concentration measurements is shown in the validation section: Without measurements the gas concentration values can deviate considerably from the target values. Measurements also help test repeatability by minimizing the effect of human error. In the case of this test setup two of the four parameters controlling the resulting gas concentrations are prone to such errors.

Mixed flowing gas tests require fine control of exposure parameters and managing system consisting of many devices, but they are far from impossible to conduct properly with thorough and attentive work. The practical capabilities and effects of mixed flowing gas tests on power semiconductors and assembled devices is determined in further work.

References

- [1] J. Jormanainen, E. Mengotti, T. Batista Soeiro, E. Bianda, D. Baumann, T. Friedli, A. Heinemann, A. Vulli, and J. Ingman, "High humidity, high temperature and high voltage reverse bias - a relevant test for industrial applications," in *PCIM Europe 2018; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*, pp. 1–7, 2018.
- [2] J. Leppänen, "Humidity related failure mechanisms in power semiconductor devices," master's thesis, Aalto University, <http://urn.fi/URN:NBN:fi:aalto-201706135367>, 2017.

- [3] C. Zorn and N. Kaminski, "Acceleration of temperature humidity bias (thb) testing on igbt modules by high bias levels," in *2015 IEEE 27th International Symposium on Power Semiconductor Devices IC's (ISPSD)*, pp. 385–388, 2015.
- [4] N. L. Sbar and R. P. Kozakiewicz, "New acceleration factors for temperature, humidity, bias testing," *IEEE Transactions on Electron Devices*, vol. 26, no. 1, pp. 56–71, 1979.
- [5] W. H. Abbott, "The development and performance characteristics of mixed flowing gas test environment," *IEEE Transactions on Components, Hybrids, and Manufacturing Technology*, vol. 11, no. 1, pp. 22–35, 1988.
- [6] T. Wassermann, O. Schilling, K. Müller, A. Rossin, and J. Uhlig, "A new high-voltage h2s single noxious gas reliability test for power modules," *Microelectronics Reliability*, vol. 100-101, p. 113468, 2019. 30th European Symposium on Reliability of Electron Devices, Failure Physics and Analysis.
- [7] W. Abbott, "Effects of industrial air pollutants on electrical contact materials," *IEEE Transactions on Parts, Hybrids, and Packaging*, vol. 10, no. 1, pp. 24–27, 1974.
- [8] "Standard guide for mixed flowing gas (mfg) tests for electrical contacts," standard, American Society for Testing and Material, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States, Aug. 2013.
- [9] Ping Zhao and M. Pecht, "Mixed flowing gas studies of creep corrosion on plastic encapsulated microcircuit packages with noble metal pre-plated leadframes," *IEEE Transactions on Device and Materials Reliability*, vol. 5, no. 2, pp. 268–276, 2005.
- [10] R. Schueller, "Creep corrosion of lead-free printed circuit boards in high sulfur environments," in *SMTA International Proceedings, Orlando, FL*, vol. 21, 2007.
- [11] G. K. Morris, R. A. Lukaszewski, and C. Genthe, "Environmental contamination and corrosion in electronics: The need for an industrial standard and related accelerated test method that makes sense," in *2018 Annual Reliability and Maintainability Symposium (RAMS)*, pp. 1–7, 2018.
- [12] "Environmental testing – part 2-60: Tests – test ke: Flowing mixed gas corrosion test," standard, International Electrotechnical Commission, Geneva, CH, June 2015.
- [13] JCGM, "Jcgm 100: Evaluation of measurement data - guide to the expression of uncertainty in measurement," tech. rep., Joint Committee for Guides in Metrology, 2008.
- [14] J. Jäppinen, "Measurement of gas concentrations in an environmental mixed flowing gas test chamber," master's thesis, Lappeenranta-Lahti University of Technology LUT, <http://urn.fi/URN:NBN:fi-fe2019100731571>, 2019.
- [15] A. B. Bluhme, J. L. Ingemar, C. Meusinger, and M. S. Johnson, "Water vapor inhibits hydrogen sulfide detection in pulsed fluorescence sulfur monitors," *Atmospheric Measurement Techniques*, vol. 9, no. 6, pp. 2669–2673, 2016.
- [16] P. Visamo, "Evaluating the measurement uncertainty for nitrogen oxides in air quality measurements," Master's thesis, Lappeenranta University of Technology, Skinnarilankatu 34, 53850 Lappeenranta, Finland, 2009.