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Accelerated Corrosion Testing of DRAM Modules for Data Centers: An Improved Quantitative Method for Accurate Life Cycle Estimation

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ABSTRACT

Corrosion issues of electronic devices have been steadily reported in data centers due to gaseous chemicals introduced from outside, as free air cooling systems were utilized to reduce energy. To investigate corrosion problems in electronic products for server applications, mixed flowing gas (MFG) is widely used as an accelerated testing method. However, conventional MFG testing exhibits systematic issues that do not accurately replicate real environments and demonstrate deviations in each evaluation even under identical test conditions. Furthermore, it is difficult to precisely estimate the field environment based on test results because the ANSI/ISA-71.04 standard, which defines field corrosion classes, covers a wide range of copper reactivity. These limitations make it challenging to achieve the intended objectives, potentially leading to incorrect conclusions and decision-making. In this study, to solve these issues, we have proposed a desirable testing methodology that considers the deviations observed in MFG acceleration testing. This methodology encompasses the quantification of the test environment, the determination of an appropriate field-equivalent test duration, and the evaluation of products under suitable conditions. In addition, based on the test conditions quantified using the proposed method, we verified a conformal coating solution that enables operation even in harsh environments. By employing the precise testing methodology proposed in this study, it is anticipated to contribute to the development of products that meet customer requirements.

Key words: Corrosion, Data Center, Free Air Cooling, DRAM, Module, Accelerated Corrosion Test, Mixed Flowing Gas, MFG, ISA, G3

INTRODUCTION

As the use of IoT, cloud, AI, and big data increases rapidly due to the 4th industrial revolution, the role of datacenter as a hub, which plays a key role in processing, storing, and distributing various data, is becoming very important. In a data center with diverse computer systems, communication devices, data storages, and processing units, electronic components inevitably generate heat. This, along with the substantial power consumption during data processing and storage, results in approximately 40% of the total energy being allocated to cooling in order to regulate the high temperatures within the server room. Numerous endeavors are underway to support the global carbon net zero agenda by optimizing the energy consumption of data centers. Among these strategies, the adoption of free air cooling, as illustrated in Figure 1, is an effective method for mitigating server heat through the utilization of outdoor air. However, it has been reported that the infiltration of external air that contains corrosive chemicals into the server can initiate corrosion within electronic devices. Especially, the corrosion product known to result in electrical failures can be observed in metal components such as copper (Cu) traces, vias, or connectors. Furthermore, the occurrence of copper creep corrosion-related issues within the connectors of DRAM modules can lead to significant losses in data center [1]. As a result, the importance of effectively managing corrosion in the electronic products has been continuously grown.

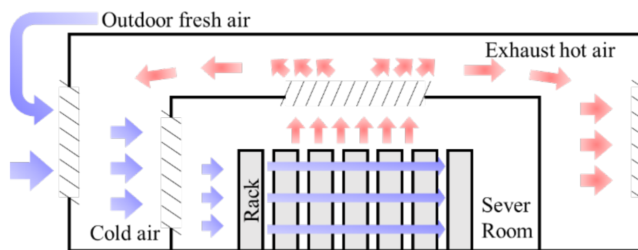


Figure 1. Schematic of direct free cooling system

The main chemical that causes corrosion failure of memory modules is sulfur-bearing gaseous such as H_2S and SO_2, which is known to generate creep corrosion in the copper components in printed circuit boards (PCB) as shown in Fig. 2 [1]. In the various previous researches, mixed flowing gas (MFG) test was conducted as an acceleration method to induce copper corrosion of PCBs and interpret mechanism [1-7]. The MFG can accelerate and evaluate copper corrosion in a complex corrosion environment with gaseous chemicals such as H_2S, SO_2, NO_2, Cl_2, and etc. Some researchers have been reported that the copper corrosion rate was measured for various conditions in order to quantify the MFG corrosion environment [2-7]. Additionally, other studies investigated field equivalent criteria by correlation between MFG accelerated test and ANSI/ISA-71.04 standard that defines corrosive environment class based on copper reactivity [6], and also corrosion behavior within electronic devices for server applications [7]. Furthermore, reviewing previous studies on MFG evaluation conducted under identical conditions, the analysis of the copper corrosion rate reveals different values as summarized in Table 1. This means that there are potential differences among MFG evaluations,

indicating the need for a quantified evaluation methodology that considers such variations.

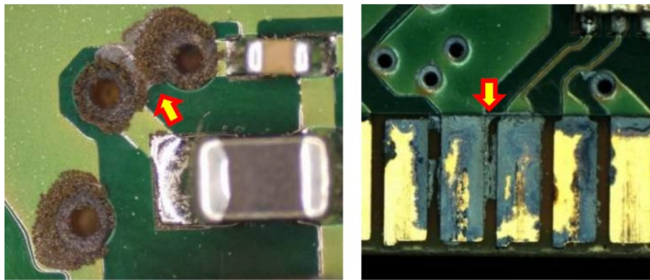


Figure 2. Copper corrosion in memory module PCB

Table 1. Comparison of Cu corrosion rate in references [3-6]

Ref	Cu Corrosion Rate [Å/day]	Temp. [°C]	RH [%]	Gas Conc. [ppb]			
				H_2S	SO_2	NO_2	Cl_2
iNEMI	15400	40	70-75	1700	200	200	20
Alcatel-Lucent	6000	40	70	1700	200	200	20
CALCE	11960	40	70	1700	200	200	30

In this study, MFG test environment was measured according to various conditions. Quantitative corrosion conditions and criteria were established using copper corrosion thickness, aligning with the ANSI/ISA71.04 standard as summarized in Table 2. The deviations were identified among equipment and testing, suggesting a proposal to enhance the evaluation procedure for minimizing variations. Furthermore, the corrosion behavior of memory modules was studied via the established MFG environment as well as potential corrosion behavior and mechanisms that can occur in harsh corrosion environments were also analyzed. Through the investigation, a conformal coating solution that can be adequately applicable in various field conditions even exceeding the specified requirements was introduced.

Table 2. Classification by Cu corrosion thickness in ANSI/ISA-71.04-2013 [8]

Class	Severity	Copper Corrosion Thickness [Å/month]
G1	Mild	< 300
G2	Moderate	300–1000
G3	Harsh	1000–2000
GX	Severe	> 2000

EXPERIMENTAL METHOD

In order to quantify the accelerated corrosion environment for each MFG test condition, the copper corrosion rate was calculated based on the weight change using pure copper coupon as a test vehicle. The WK3-340/0-BSB model manufactured from Weiss was used as the MFG test equipment, and the target temperature, humidity and gas concentration were set for each condition including 30 minutes buffer duration to form a sufficiently corrosive atmosphere. As shown in Table 3, in order to investigate various corrosion environment according to the concentration of H_2S, relative humidity, and test facilities, the experiment was designed by splitting the conditions from 1200 ppb to 1700 ppb for H_2S concentration, 60-90% for relative humidity, and A to C for MFG chamber.

Table 3. MFG acceleration test condition

No	Temp. [°C]	RH [%]	Gas Concentration [ppb]				Equipment
			H_2S	SO_2	NO_2	Cl_2	
1	40	75	1200	200	200	20	A
2	40	60	1700	200	200	20	A
3	40	75	1700	200	200	20	A
4	40	90	1700	200	200	20	A
5	40	75	1200	200	200	20	B
6	40	75	1700	200	200	20	B
7	40	75	1200	200	200	20	C
8	40	75	1700	200	200	20	C

The test period for each evaluation condition was set to three days, and nine copper coupons were prepared for each evaluation. The coupons purchased from Goodfellow were oxygen-free copper with 99.95% purity and 25 mm × 25 mm × 0.5 mm dimension. The coupons in the evaluation chamber were arranged as described in Fig. 3, and the weight change before and after evaluation was measured using microbalance. After the test and measurement, for thickness analysis, cross-sectional image of a copper foil was obtained from scanning electron microscopy (SEM) and composition of the coupon was investigated by energy-dispersive X-ray spectroscopy (EDX) for identification of corrosion layer.

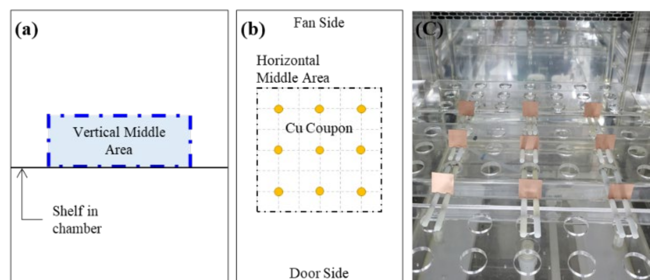


Figure 3. Copper coupon placement (a) in MFG chamber, (b) on shelf, and (c) real photograph

In this study, mass gain method was used, which is a quick and easy method for quantitative calculation of copper corrosion thickness. Equation (1) defined as follows was used to convert the weight into thickness data.

$$T = \frac{\Delta w}{A} \frac{1}{\rho_{Cu_2S}} \left(\frac{M_{w,Cu_2S}}{M_{w,S}} \right) \times 10^2 \quad (1)$$

Where T, Δw, A, ρ_{Cu2S}, and Mw represent copper corrosion thickness, weight change before and after the test, area of copper specimen, density of Cu_2S, and atomic molar mass of chemicals, respectively. The copper corrosion rate derived from the accelerated MFG test was matched with the 30-day reactivity level specified in ANSI/ISA-71.04-2013 standard. This enabled the calculation of test durations equivalent to real-field environment, corresponding to the ISA class of G1, G2, G3, and GX.

Ten samples of memory modules per each condition were prepared for product level test equivalent to 10-year of G2 class and G3 class. The evaluation was performed by placing modules in the active area of the MFG chamber as shown in Figure 4, and the electrical pass or fail was confirmed from an operation test of the module. In order to protect areas vulnerable to corrosion, conformal coating was utilized as an improvement method in this study. The polyurethane acrylate (PUA) based material was dispensed and cured to cover the gold fingers to prepare an improvement sample that can be operated even in G3 harsh environment.

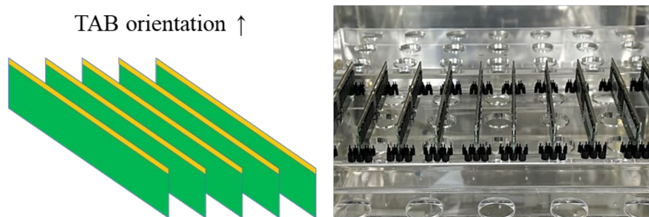


Figure 4. Placement of memory module in MFG chamber

RESULT AND DISCUSSION

The copper corrosion rate for various accelerated MFG test conditions using pure copper coupon are summarized in Table 4. First, in order to verify the logic for calculation of copper corrosion rate using weight gain, SEM and EDX analysis were performed by sectioning the coupon evaluated under No. 3 condition. As shown in Fig. 5, the delamination was formed in the interface between copper substrate and copper sulfide (Cu_2S) layer, which was result from adhesion loss of the heterogeneous layers. Through the analysis of point and line composition in each region, it was confirmed that copper and sulfur were exclusively detected in the outermost layer, while only copper atom were identified in the inner layer. From this, it was confirmed that the outer, middle, and inner layers correspond to Cu_2S, delamination, and copper substrate, respectively. Moreover, the cumulative thickness of Cu_2S after three-day MFG test was measured as 25,000 Å (2.5 um), similar to 24270 Å based on weight gain, meaning that the logic used for calculating corrosion thickness through weight change and density is valid.

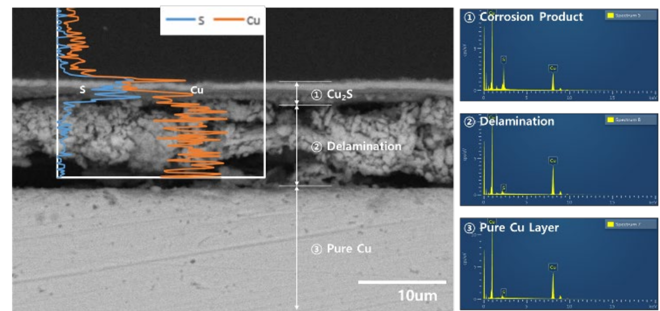


Figure 5. Cross-section and EDX analysis of test coupon

Table 4. Copper corrosion rate and field correlation

No	Average Corrosion Rate [Å/day]	Standard Deviation [Å/day]	Coefficient of Variation	Field Equivalent Test Duration		
				G1 10Y	G2 10Y	G3 10Y
1	6434	1030	0.16	6	9	28
2	6480	1203	0.19	6	9	28
3	8090	1776	0.22	4	7	22
4	11072	1681	0.15	3	5	16
5	7599	1434	0.19	5	8	24
6	8592	1388	0.16	4	7	21
7	8943	1586	0.18	4	7	20
8	9301	3310	0.36	4	6	19

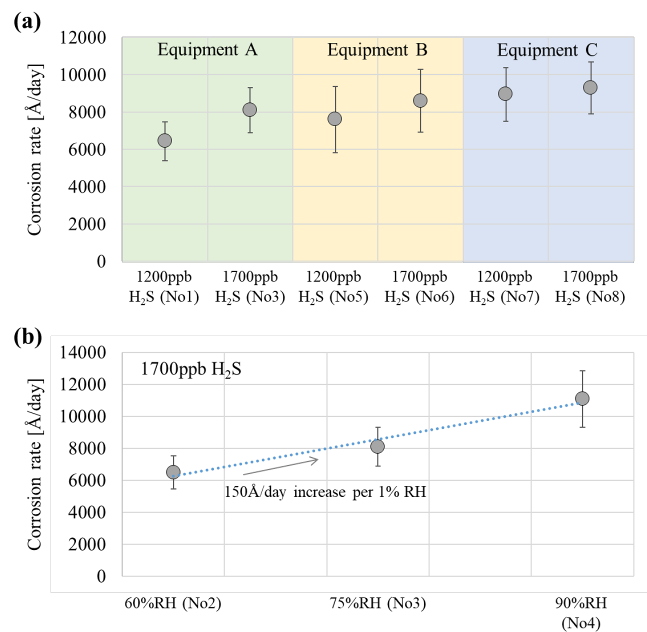
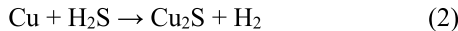


Figure 6. Analysis result of copper corrosion rate: (a) per H_2S concentration and equipment, and (b) per relative humidity

With summary described in Table 4, the results per H_2S concentration, humidity, and facilities were illustrated as shown in Fig. 6(a). As the H_2S content increased, the amount

of copper corrosion in all MFG equipment increased, and the corrosion rate increased by up to 25% at the 1700 ppb compared to 1200 ppb H_2S. Given that H_2S plays a most active role in the copper corrosion reaction among corrosive gaseous chemicals such as H_2S, SO_2, NO_2, and Cl_2, the concentration of H_2S directly influences the copper corrosion reaction. As shown in equation (2), the high concentration of H_2S as a reactant makes the chemical reaction more activated, leading to the increased generation of Cu_2S.



$$Cu + H_2S \rightarrow Cu_2S + H_2 \quad (2)$$

As shown in Fig. 6(b), maintaining a constant H_2S concentration at 1700 ppb, the copper corrosion increased from 6480 to 11072 Å/day with increase of humidity. Modeling the copper corrosion against relative humidity indicated that for every 15% increase in relative humidity, the copper corrosion rate rose by an additional 2300 Å/day. There are various researches regarding effect of relative humidity on copper corrosion [10-12], which explained the mechanism behind the increased copper corrosion attributed to relative humidity. Elevated humidity levels result in the accumulation of water layers on the surface of the copper. Consequently, the quantity of corrosive chemicals dissolved in the liquid phase on the surface increases, leading to enhance the interaction with copper, thereby activated the corrosion reaction.

When comparing the amount of corrosion across different facilities, the average copper corrosion rates for equipment A, B, and C at a 1200 ppb H_2S concentration were 6434, 7599, and 8943 Å/day, respectively, indicating differences of up to 39% between them. Additionally, at 1700 ppb H_2S concentration, it was observed that the average copper corrosion rates for equipment A, B, and C were 8090, 8592, and 9301 Å/day, respectively, with variances of up to 15%. By comparing the coefficient of variation (CV), which normalizes the deviation from the average as shown in Table 4, CV for each equipment ranged from 0.16 to 0.19 at 1200 ppb H_2S, with differences of up to 19%. Similarly, at 1700 ppb H_2S, the values varied from 0.16 to 0.36, with differences of up to 125%.

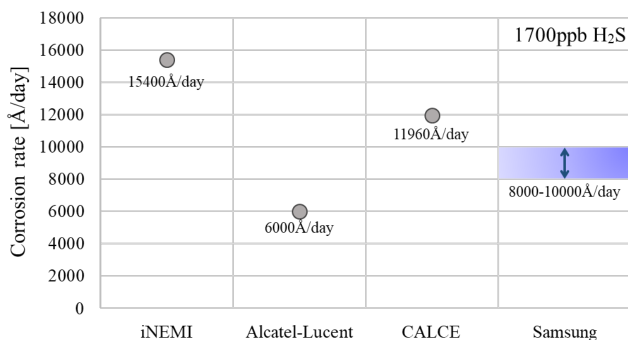


Figure 7. Comparison of MFG result (1700 ppb H_2S)

Based on the results of the MFG test conducted for each equipment, it is obvious that deviations in copper corrosion can arise due to potential fluctuations in the external environment or within facilities, even among those with the same specifications. Furthermore, when conducting the MFG test under identical conditions and comparing the studies with cases previously reported, as demonstrated in Fig. 7, the difference ranged from 25% to 93%, so it can be inferred that deviations among the tests occur in unpredictable ways. Therefore, considering deviation of the test, an evaluation platform was suggested to secure results that can accurately represent the desired corrosion environment as shown in Fig. 8. Initially, establish the conditions to accelerate the desired field environment, defining parameters such as temperature, relative humidity, and gas concentration. Subsequently, conduct corrosion measurements on copper coupon within the corresponding test environment. Next, the measurement data is analyzed for maximum, minimum, deviation, and average values to compute test criteria aligned with the targeted class and correlation outlined in the ANSI/ISA-71.04 standard. The copper corrosion range of G2 and G3 class, which corresponds to 300-1000Å/month and from 1000-2000Å/month respectively, should be considered when establish a suitable field-equivalent test duration. Using the established conditions and criteria, it is anticipated that electronic products like memory modules can be appropriately evaluated to define corrosion behavior and analyze corrosion mechanisms.

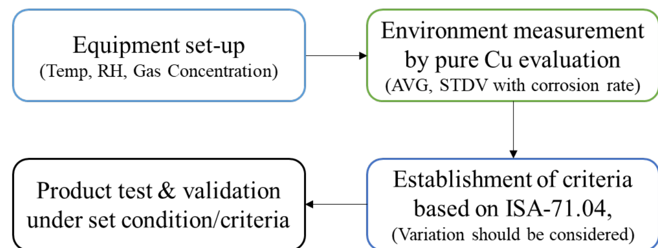


Figure 8. MFG Evaluation Platform

In order to evaluate memory module within quantified environment, as summarized in Table 5, field equivalent criteria derived from equation (3) and (4) that utilized copper corrosion rate and copper reactivity in ANSI/ISA-71.04. Corrosion in the memory module was characterized by applying the 10-year of G2 class, which adequately represents the typical data center environment, and G3 class, known for particularly harsh conditions. Following MFG test under 10-year G2 class conditions, all memory modules successfully operated in the electrical test, confirming their capability to function without long-term issues in a typical data center environment. The module has been reported to be susceptible to copper corrosion in PCB vias and tabs [1, 7]. However, as depicted in Fig 9, it was observed that corrosion did not occur in PCB vias, which are protected by solder resist, while corrosion was observed on the connector despite the nickel-gold plating that prevents direct exposure of copper.

Equivalent Field Month for 1day test

$$= \frac{\text{Measured Cu Corrosion Rate [Å/day]}}{\text{ISA Field Cu Reactivity [Å/month]}} \quad (3)$$

Test Duration for Field 10years

$$= \frac{10\ \text{[Yr]} \times 12\ \text{[Month/yr]}}{\text{Equiv. Field Month [Month/day]}} \quad (4)$$

Table 5. Field equivalent duration based on ANSI/ISA-71.04

Field Equivalent	Temp. [℃]	RH [%]	Gas Concentration [ppb]				Equivalent Test Duration [Day]
			H_2S	SO_2	NO_2	Cl_2	
G2 10Y	40	75	1200	200	200	20	10
G3 10Y	40	75	1700	200	200	20	25

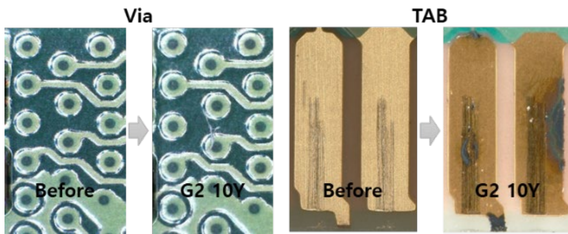


Figure 9. Visual inspection of via and tab before/after MFG

In G3 harsh environment, electrical open failure was detected from the extremely severe testing, where H_2S concentration was increased and the test duration was extended. In order to interpret the detailed failure mechanism, physical analysis was performed on the fail module, and the detailed location vulnerable to copper corrosion in the module PCB could be defined as the tab neck area. As shown in Fig. 10, it was confirmed that the structure was completely collapsed due to Cu_2S corrosion product in the copper trace. As shown in Fig. 11, the pass trace showed copper peak from EDX and maintained its shape intact, while the sulfur component is identified and the trace structure is collapsed in the case of the fail trace.

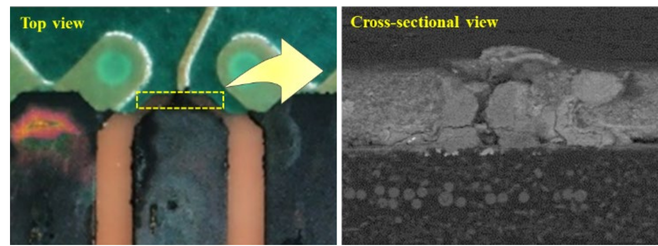


Figure 10. Physical analysis of failure module tab

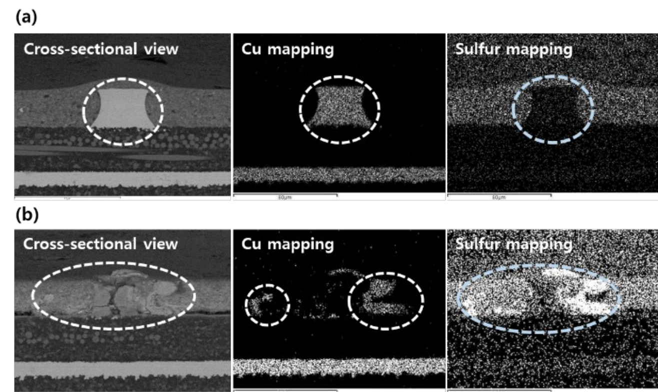


Figure 11. Cross-sectional analysis result: (a) pass, and (b) fail

Based on the analysis results the failure mechanism could be described in detail as shown in Fig. 12. The micro-pores were inevitably generated at the interface between PSR and nickel-gold passivation layer that cover the copper pattern, as a result of the manufacturing process. These micro-pores provided a pathway for infiltration of H_2O and corrosive chemicals, leading to the production of Cu_2S through the copper corrosion reaction. The crystal structure of Cu_2S applied physical stress to the original copper trace, eventually causing structural collapse and resulting in electrical open failure.

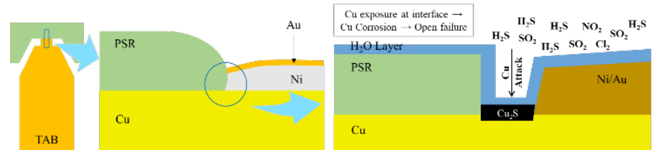


Figure 12. Cu corrosion mechanism at tab neck

Through module-level test, we identified susceptible location to copper corrosion and analyzed the failure mechanisms. Based on the detail analysis, conformal coating was verified in order to propose a solution that can enhance long-term reliability even under harsh environment of G3 class or beyond. The selection of the coating material is most important. Especially, silicone based materials, which can accelerate corrosion by absorbing sulfur compound, were excluded based on the previous study [9]. Memory modules coated with polyurethane acrylate (PUA) were prepared for the highly accelerated MFG evaluation. Despite of a long-term accelerated corrosion evaluation equivalent to 10-year G3 class, as shown in Fig. 13, it is confirmed that the conformal coating effectively prevented the penetration of gaseous chemicals. As a result, the tab neck was not corroded because it was protected from sulfur attack to the exposed cooper. In the electrical test of DRAM modules, all samples

successfully passed, verifying the effectiveness of the conformal coating. The conformal coating to prevent copper exposure, can completely inhibit the corrosion reaction by blocking the corrosion path. Moreover, the coating suggested in this study, which can be used easily and quickly, is anticipated to be effectively utilized to the products required in various environments as a reasonable solution.

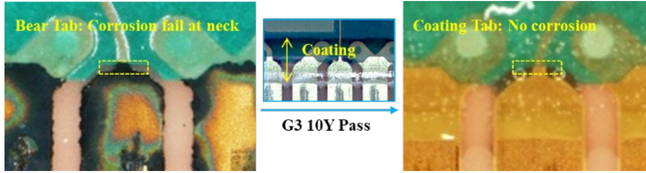


Figure 13. Appearance analysis of bare and coated tab neck after MFG test (G3 class 10 years)

CONCLUSION

In this study, a quantitative investigation was conducted on the MFG accelerated test that can effectively represent corrosion environments of data center. The copper corrosion rate under various conditions was measured, and the test criteria was established by adopting the field environment defined in the ANSI/ISA-71.04 standard. Upon estimating and analyzing the accelerated corrosion environment, it was verified that the variation existed across tests and equipment. In order to improve conventional MFG testing method, the quantitative evaluation platform considering deviation was proposed. Through the suggested process, it is anticipated that a highly consistent test can be performed by establishing acceleration test conditions and field-equivalent criteria. By evaluating memory module products for data center applications based on the evaluation platform, vulnerable region and mechanism of copper corrosion in the G3 harsh environment could be defined. In addition, it was possible to contribute to securing products that can be used in various environments by verification of conformal coating solution. Through this study, we anticipate that the proposed quantitative methodology will facilitate establishment of proper test criteria for product qualification, as well as appropriate analysis of corrosion behavior and mechanisms in product. Furthermore, by the improvement solutions, we aim to contribute to the development of products that align with various field requirements.

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