Testing Printed Circuit Boards for Creep Corrosion in Flowers of Sulfur Chamber: Phase 2A

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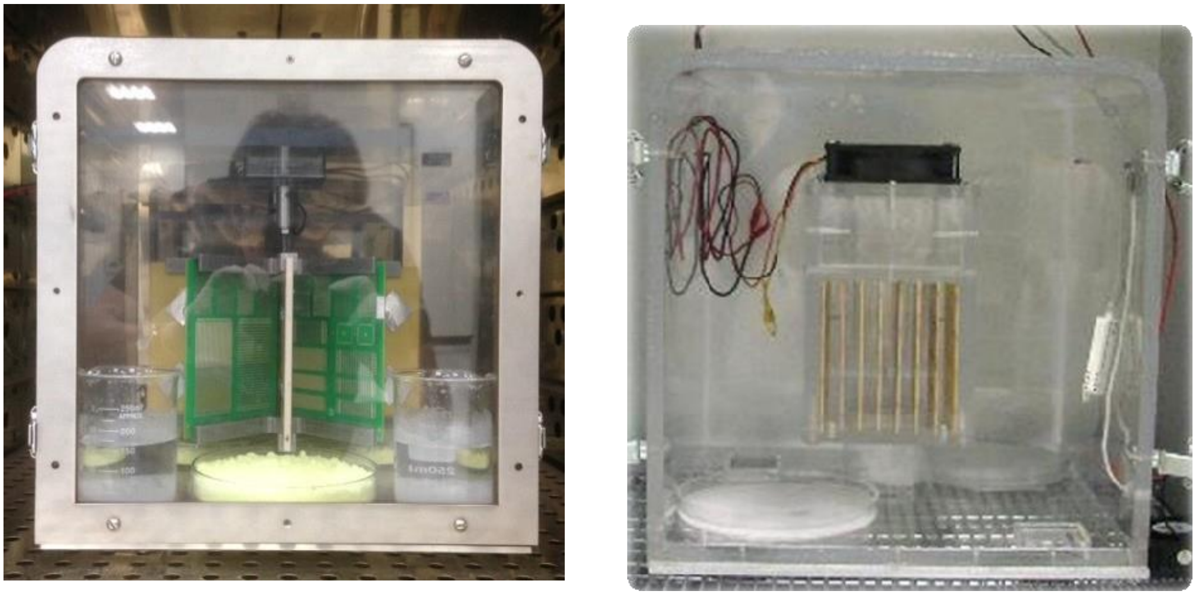
Abstract

The iNEMI technical subcommittee on creep corrosion is developing a flowers-of-sulfur (FOS) based qualification test for creep corrosion on printed-circuit boards (PCBs). In phase 1 of the project, the performances of FOS chambers of two designs were evaluated by measuring the corrosion rates of copper and silver foils. This paper deals with the phase 2A of the project in which PCBs with immersion silver (ImAg) and lead-free hot-air-surface- level (HASL) finishes soldered with rosin and organic acid fluxes were tested. The test variables were chamber temperature, type of saturated salt solution determining the relative humidity, chamber setup and particulate contamination. The results of test runs conducted at 4 laboratories involved in the round robin testing are very promising. The ImAg PCBs soldered with organic acid flux suffered the most creep corrosion in agreement with the generally agreed to field experience. There were fewer instances of creep corrosion on test PCBs with ImAg finish soldered with rosin flux and on test PCBs with lead-free HASL finish. Creep corrosion was generally associated with plated through holes (PTHs). Contaminating the test PCBs with ammonium salts contributed to more creep corrosion but made the test somewhat less discriminatory in that even test PCBs with HASL finish soldered with rosin flux suffered some creep corrosion.

1. Introduction

Creep corrosion on printed circuit boards (PCBs) is the corrosion of copper (and sometimes silver) metallization and the creeping of the corrosion products (mostly sulfide of copper and sometimes silver) on the PCB surfaces. Creep corrosion can be extensive enough to cause the electrical short circuiting of neighboring features on PCBs, such as the plated through holes (PTHs). The history of creep corrosion has been extensively covered in the literature **[1-5]**. Mixed-flowing gas (MFG) and the flowers of sulfur (FOS) are the two main tests for creep corrosion. The MFG test was developed in the 1980s for the study of electrical connector corrosion **[6]** and has been applied to the study of creep corrosion **[3, 5, 7-9**]. The FOS test has been used successfully for the qualification of miniature surface-mount resistors [10] and has recently been shown to produce well defined creep corrosion similar in morphology to that observed in the field **[11, 12].**

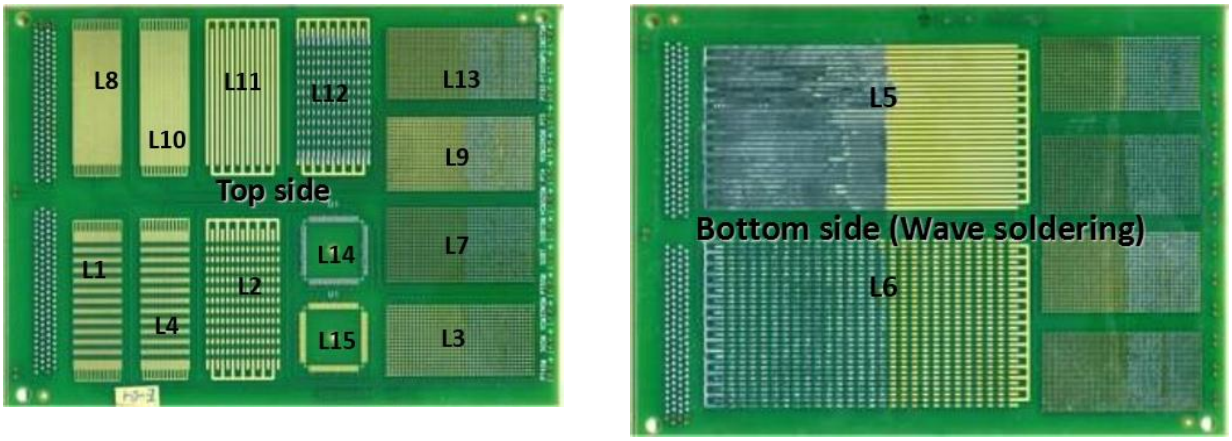


(a) **(b)**

Figure 1: FOS chambers setups (a) Paddle wheel FOS chamber with front cover in place; (b) Forced-air FOS chamber setup with front cover removed.

The iNEMI technical subcommittee on creep corrosion is developing a FOS based qualification test for creep corrosion on PCBs. The low cost and the easy of control of the test variables are the main motivation for developing the FOS-based creep corrosion qualification test. Two FOS chambers designed and developed in the phase 1 of the iNEMI project, described in a recent paper **[12**] are shown in **Figure 1**. The sulfur vapors are produced by a bed of sulfur in the bottom of the chamber. At 60^{o}C the sulfur concentration in the chamber is about 0.6 ppm **[13**]. Humidity, controlled in the 80-82% range at 60^{o}C, is provided by saturated salt solutions of KCl or KNO_3,

The paddle wheel setup rotating at 20 revolutions/minute (RPM) has an air velocity of about 0.1 m/s over the test PCBs. The forced air setup can generate air velocities in the 0.5-2 m/s range depending on the blower speed. The performance of the two setups was tested at 60^{o}C with the chambers loaded with brown epoxy boards, in place of the test PCBs. The brown epoxy boards were chosen purely because of their availability. The temperature and the humidity reached steady state values typically within 2 hours. In the paddle wheel setup at 20 revolutions/minute, the silver corrosion rate was relatively insensitive to humidity at approximately 2000 A/day; whereas, the copper corrosion rate was quite dependent on humidity, increasing from about 3000 to 6000 A/day as the relative humidity was raised from 45 to 96%. In the forced air setup, with air velocity of 1 m/s, the silver and copper corrosion rates had wide scatter with no clear dependence on relative humidity: the silver and copper corrosion rate was in the range 4000-8000 and 6000-12000 A/day, respectively.



(a) (b)

Figure 2: (a) Top side; (b) bottom side, the wave soldering side.

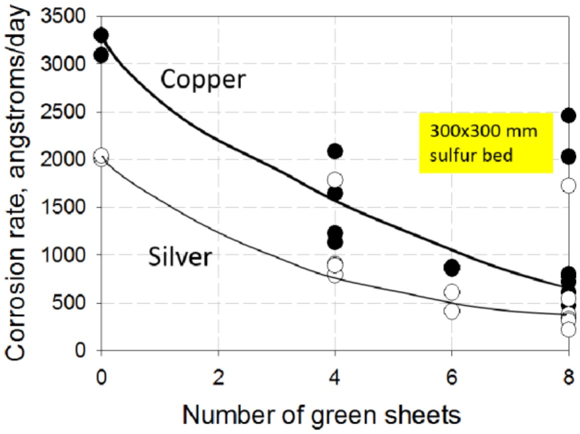


Figure 3: Copper and silver corrosion rates as a function of PCB loading. The total number of boards, the sum of the brown epoxy boards and the PCBs (green sheets) was 8 in each of the runs.

Air velocity had a dramatic effect on the corrosion rates: Copper corrosion rate rose from about 2000 to 12000 A/day as the air velocity was raised from zero to 1.3 m/s. Silver corrosion rate was similarly influenced by air velocity, though its corrosion rates were somewhat lower.

Phase 1 of the study examined the role ammonium based ionic contamination on creep corrosion. A means was developed to apply controlled concentrations of ammonium based ionic contamination on selected areas of the test PCBs. New circuit boards from a lot that suffered creep corrosion in Asian geographies, high in sulfur- bearing gaseous pollution, were tested in a FOS chamber at 60°C, 82% relative humidity using KNO_3 saturated salt solution, and 1m/s air velocity, with and without the ammonium based ionic contamination. After 3 days of testing the ionically contaminated PCB suffered creep corrosion whereas the non-contaminated PCB did not.

This paper describes the phase 2A of the project. The objective of this phase is to optimize the FOS test conditions for PCB creep corrosion qualification. The optimization test runs studied the following variables:

- Temperature: 50 versus 60°C;
- Humidity: KCl versus KNO_3 saturated salt solutions;
- Chamber setup: Paddle wheel versus forced air;
- Flux: Rosin versus organic acid
- PCB surface finish: Immersion silver (ImAg) versus Pb-free hot air surface level (HASL); and
- Ionic contamination: Mixture of $(NH_4)_2SO_4$, NH_4HSO_4, NH_4NO_3 and NH_4Cl;

2. Experimental procedure and results

The flowers of sulfur chamber is a 300-mm cube with a front-loading door sealed with a silicone coated rubber gasket. Humidity was maintained using a saturated salt solution contained in two beakers with 100-mm diameter. Sulfur concentration was maintained by sulfur contained in two beakers with 80-mm diameter or to increase the sulfur bed area, the sulfur was spread over the entire bottom of the chamber. Temperature in the chamber was maintained at 50 or 60°C with as little temperature fluctuations as possible. There were two approaches for mounting the test specimens in the chamber and for stirring the air: One used a paddle wheel as shown in **Figure 1a**, with 8 paddles, to mount the 8 test PCBs and move the air; the other was a forced air setup that used a blower to draw the air over 8 stationary test PCBs, as shown in **Figure 1b.** The paddle wheel had a rotations per minute (RPM) limit of 25. The paddles did not move the air as readily as one's intuition might expect. At the maximum possible RPM, fluid flow simulation estimates the air velocity over the specimens to be about 0.1 m/s. The air velocity over PCBs in computer racks is in the range 0.5-2 m/s. To achieve these higher airflow velocities, a new insert was designed and built, as shown in **Figure 1b**. In this setup, a blower draws air from the front of the setup that has 8 test PCBs. The action of pulling the air up through the setup and having the air take a 180 degrees turn results in quite a uniform air flow across the 8 test PCBs. Air velocities of up to 2 m/s can be achieved. The air velocity is controlled by the speed of the blower which is controlled by the dc voltage input to its electric motor.

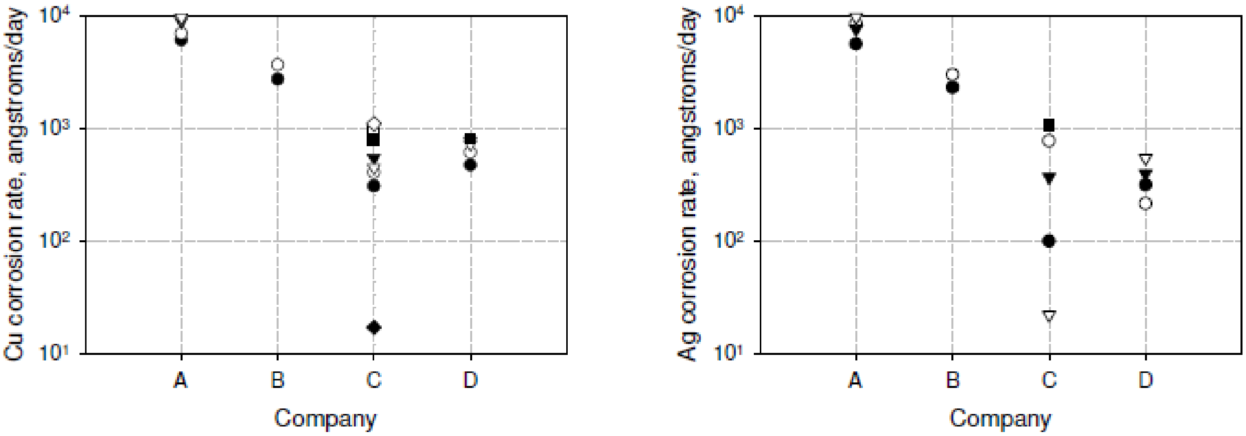


Figure 4: Copper and silver corrosion rates in the first test run at the four companies.

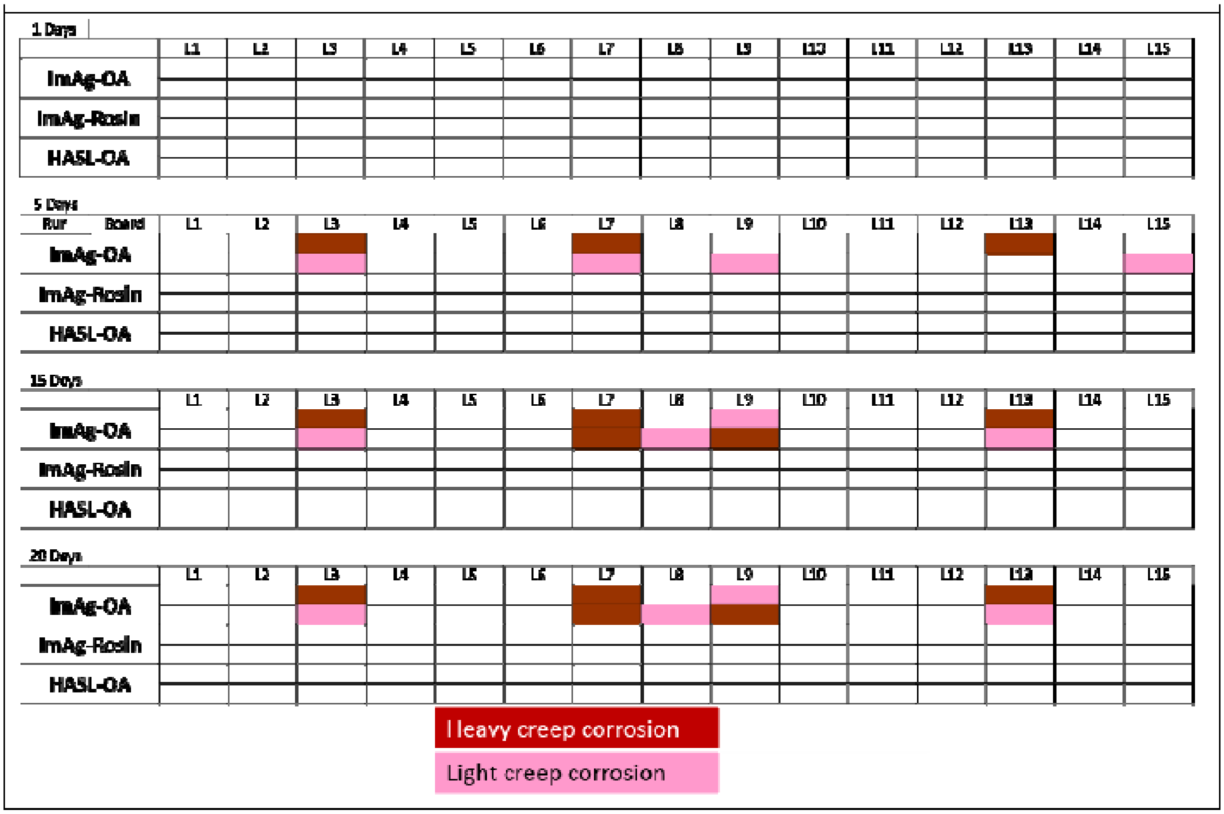
The tests, in round robin fashion, were conducted in 4 laboratories. Three test runs are reported here. The remaining test runs will be reported in a subsequent paper. The test PCBs used in this study, shown in **Figure 2**, have been described in detail in three earlier papers by the same team **[5, 9, 12]**. The test boards had either ImAg or Pb-free HASL finishes and were soldered using either rosin or organic acid fluxes.

2.1 First test run:

The first FOS tests were run under the following 4 conditions:

1. Company A: KNO_3 saturated solution in forced-air FOS chamber (1 m/s) at 60°C with no ionic contamination;
2. Company B: KNO_3 saturated solution in paddle wheel FOS chamber (20 revolutions/minute) at 60°C with no ionic contamination
3. Company C: KCl saturated solution in paddle wheel FOS chamber (20 revolutions/minute) at 50°C with no ionic contamination; and
4. Company D: KNO_3 saturated solution in paddle wheel FOS chamber (20 revolutions/minute) at 60°C with ammonium salt ionic contamination.

Table 1: First run in company C. KCI saturated salt solution, 20RPM paddle wheel FOS setup at 50oC with no salt contamination.



1 Days

	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
ImAg-OA															
ImAg-Rosin															
HASL-OA															

5 Days

Run Board	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
ImAg-OA			🟫				🟫						🟫		
			🟪				🟪		🟪						🟪
ImAg-Rosin															
HASL-OA															

15 Days

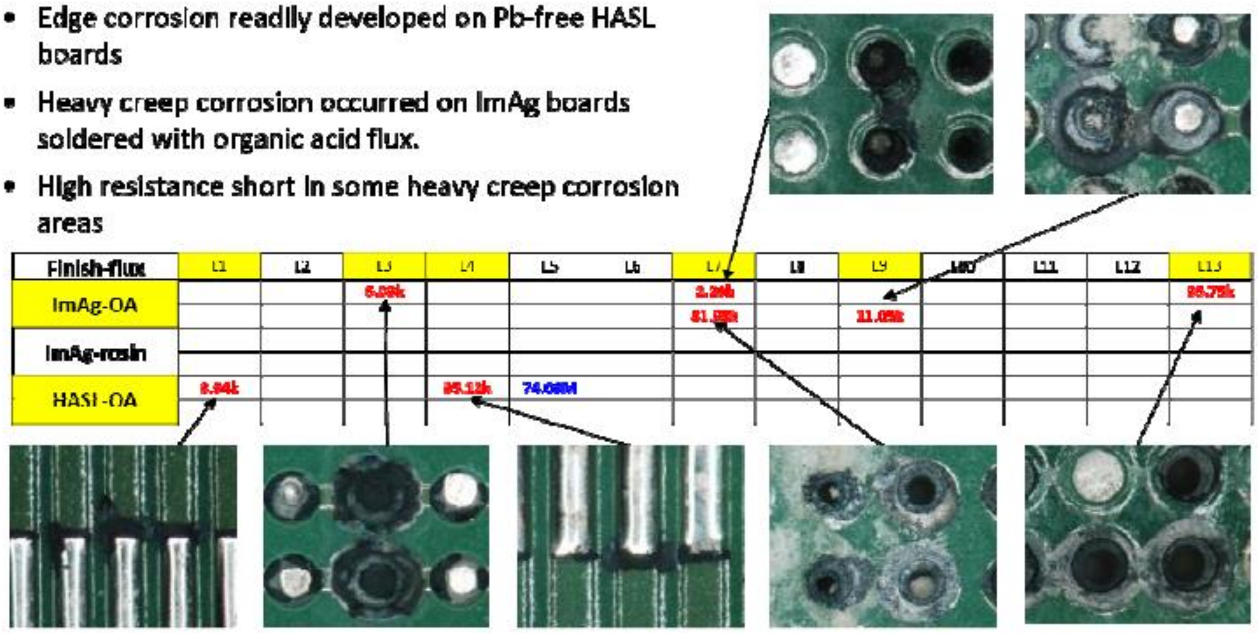
	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
ImAg-OA			🟫				🟫		🟪				🟫		
			🟪				🟫	🟪	🟫				🟪		
ImAg-Rosin															
HASL-OA															

20 Days

	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
ImAg-OA			🟫				🟫		🟪				🟫		
			🟪				🟫	🟪	🟫				🟪		
ImAg-Rosin															
HASL-OA															

🟫 Heavy creep corrosion

🟪 Light creep corrosion



- Edge corrosion readily developed on Pb-free HASL boards
- Heavy creep corrosion occurred on ImAg boards soldered with organic acid flux.
- High resistance short in some heavy creep corrosion areas

Finish-flux	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13
ImAg-OA			6.08k				2.20k						86.75k
							81.58k		11.05k				
ImAg-rosin													
HASL-OA	8.94k			85.12k	74.08M								

Figure 5: First test run 20 day results from company C.

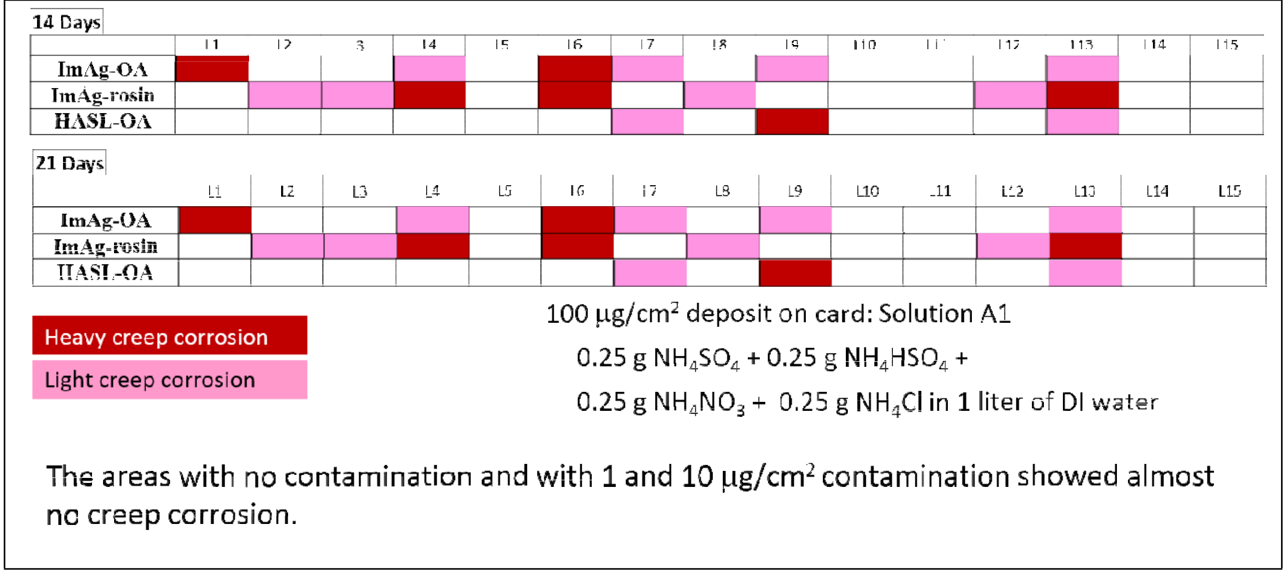
The ionic contamination was dispensed on the test PCBs from a 10 □l pipette resulting in drops with 0.1 cm^2 area. The dispensed solution had equal parts of $(NH_4)_2SO_4$, NH_4HSO_4, NH_4NO_3 and NH_4Cl in 3 concentrations: A1 solution that had 1g total salt content in 1 liter water resulted in 100 □g/cm^2 contamination on the test PCB in localized areas; A2 solution that had 0.1 g total salt content in 1 liter water resulted in 10 □g/cm^2 contamination on the test PCB in localized areas; A3 solution that had 0.01 g total salt content in 1 liter water resulted in 1 g/cm^2 contamination on the test PCB in localized areas.

The surprising observation at the start of the testing, during the first test run, was that when the FOS chambers were loaded with 3 to 6 test PCBs, the copper and silver corrosion rates dropped substantially. In the first test run the sulfur was in two beakers 100 mm in diameter. **Figure 3** shows the PCB loading effect on corrosion rates. As the mix of boards in the chamber were changed from all brown epoxy boards to all PCB boards, the copper and silver corrosion rates dropped 4 fold. The reason for this decrease in corrosion rate needs to be studied. The corrosion rate of the chamber fully loaded with 8 test PCBs increases substantially when the sulfur area is increased to cover the base of the chamber.

The copper and silver corrosion rates in the first test run at Company C and Company D are shown in **Figure 4**. The highest corrosion rates were observed by Company A because of 1 m/s air velocity afforded by the forced air setup.

Based on field experience and prior mixed flowing gas (MFG) testing, an ideal test should cause more creep corrosion on test PCBs with ImAg finish than on test PCBs with Pb-free HASL finish; and it should cause more creep corrosion on test PCBs soldered with organic acid flux than those soldered with rosin flux. The Company C test results are summarized in **Table 1.** Only the PCBs with ImAg finish soldered with organic acid flux suffered creep corrosion. The PCBs with ImAg finish soldered with rosin flux and the PCBs with HASL finish suffered with organic acid flux and rosin flux suffered no creep corrosion. The table also shows that the creep corrosion occurred early in the test and did not progress much after 5 days. This observation held true for all subsequent tests. The 20 day test results, both optical and electrical, obtained by Company C are shown in **Figure 5**.

Table 2: 1st test run in Company D: KNO3, 60oC, paddle wheel, 100 mg/cm2



14 Days

	L1	L2	3	L4	L5	L6	L7	L8	L9	L10	L1	L12	L13	L14	L15
ImAg-OA	🟥			▨		🟥	▨		▨				▨		
ImAg-rosin		▨	▨	🟥		🟥		▨				▨	🟥		
HASL-OA							▨		🟥				▨		

21 Days

	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
ImAg-OA	🟥			▨		🟥	▨		▨				▨		
ImAg-rosin		▨	▨	🟥		🟥		▨				▨	🟥		
HASL-OA							▨		🟥				▨		

🟥 Heavy creep corrosion

▨ Light creep corrosion

100 μg/cm^2 deposit on card: Solution A1

0.25 g NH_4SO_4 + 0.25 g NH_4HSO_4 +

0.25 g NH_4NO_3 + 0.25 g NH_4Cl in 1 liter of DI water

The areas with no contamination and with 1 and 10 μg/cm^2 contamination showed almost no creep corrosion.

The first run test results for Company D are shown in **Table 2**. Only some of the sites contaminated with 100 g/cm^2 ammonium salts suffered creep corrosion. All the three PCB types tested suffered creep corrosion. The areas contaminated with 10 g/cm^2, 1 g/cm^2 salts and those with no ammonium salt contamination suffered no creep corrosion.

The first run test results from the 4 companies are summarized in **Table 3**. The Company C paddle wheel setup at 50^{O}C, with KCl saturated salt solution maintaining the relative humidity at 80%, with no salt contamination on the test PCBs, gave results that most agreed with the field and MFG test experience in that only the ImAg PCBs soldered with organic acid flux suffered creep corrosion. The test results of Company A and to a lesser extent Company B were also in agreement with field and MFG experience. In contrast, Company D testing did not result in any creep corrosion in the non-contaminated areas; creep corrosion was localized to areas contaminated with 100 g/cm^2 of ammonium salts and occurred on all the three PCB types tested by Company D.

Table 3: Summary of the 1st test run at the 4 companies

Company	Setup	Salt	Temp	Dust	ImAg		HASL	HASL
					Organic acid flux	**Rosin Flux**	**Organic acid flux**	**Rosin flux**
C	Paddle Wheel	KCL	50^0	No	**2.5 HCC** **2 LCC**	**0**	**0**	**-**
B	Paddle Wheel	KNO$_3$	60^0	No	**1 HCC** **5 LCC**	**2 LCC**	**1 HCC** **3 LCC**	**0**
A	Forced Air	KNO$_3$	60^0	No	**3HCC** **4LCC**	**1 HCC** **1 LCC**		
D	Paddle Wheel	KNO$_3$	60^0	Yes	**2 HCC** **4 LCC**	**3 HCC** **4 LCC**	**1 HCC** **2 LCC**	**-**
				No	**0**	**0**	**0**	**-**

Figure 6: Setup with increased area of sulfur bed used in the 2nd run.

2.2 Second test run:

In the second FOS test runs, the area of the sulfur bed was increased to decrease the PCB loading effect. In some of the company setups, the sulfur bed practically covered the whole base of the FOS chamber, as shown in **Figure 6**. In others, the diameters of the petri dishes holding the sulfur were increased. Tests were done under the following 4 conditions:

- Company A: KCl saturated solution in forced-air FOS chamber (1 m/s) at 60^{o}C with no ionic contamination;
- Company B: KCl saturated solution in paddle wheel FOS chamber (20 revolutions/minute) at 50^{o}C with no ionic contamination;
- Company C: KNO3 saturated solution in paddle wheel FOS chamber (20 revolutions/minute) at 60^{o}C with no ionic contamination; and
- Company D: KCl saturated solution in forced-air FOS chamber (1 m/s) at 50^{o}C with ammonium salt ionic contamination.

The copper and silver corrosion rates in the second test run are listed in **Figure 7**.

Table 4 summarizes the results of the second test run. Once again, the Company C results agreed with the field and the MFG test experience: only the PCBs with ImAg finish soldered with organic acid flux suffered creep corrosion

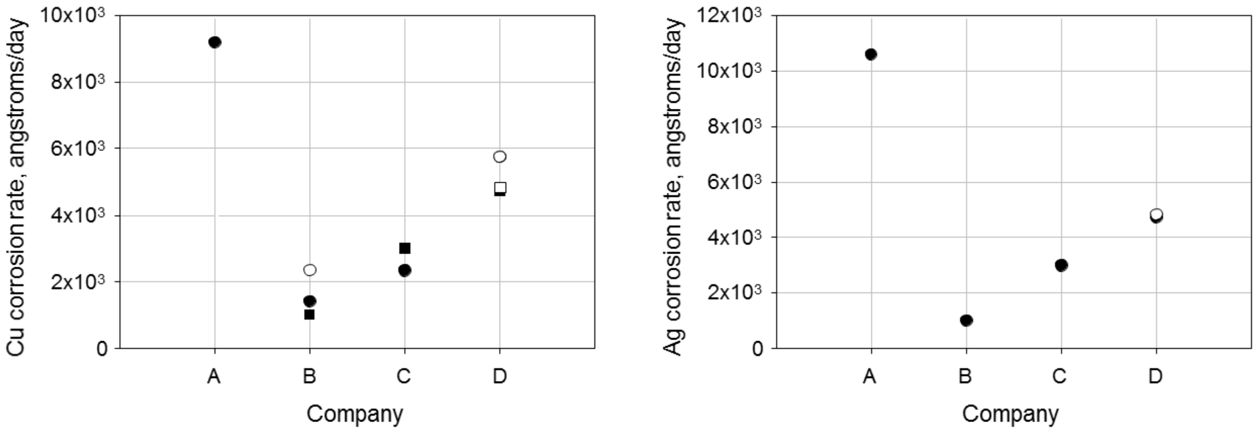


Figure 7: Copper and silver corrosion rates in the second test run at the four companies.

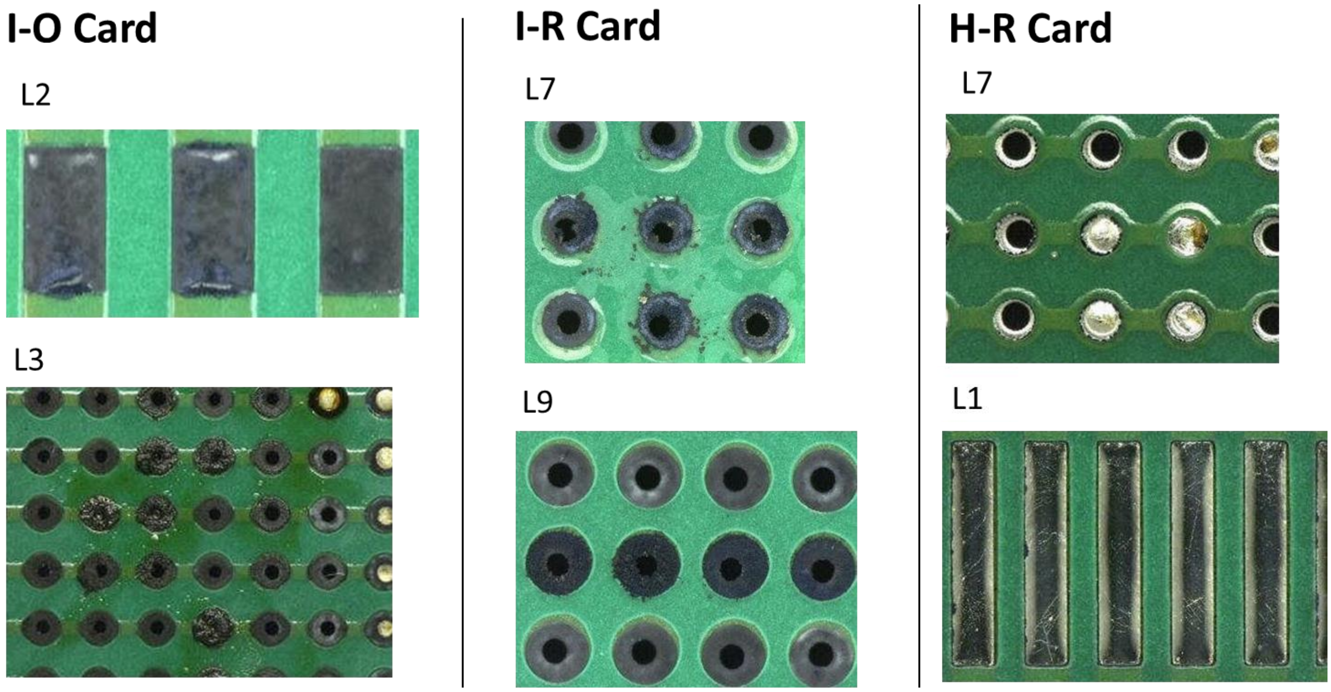


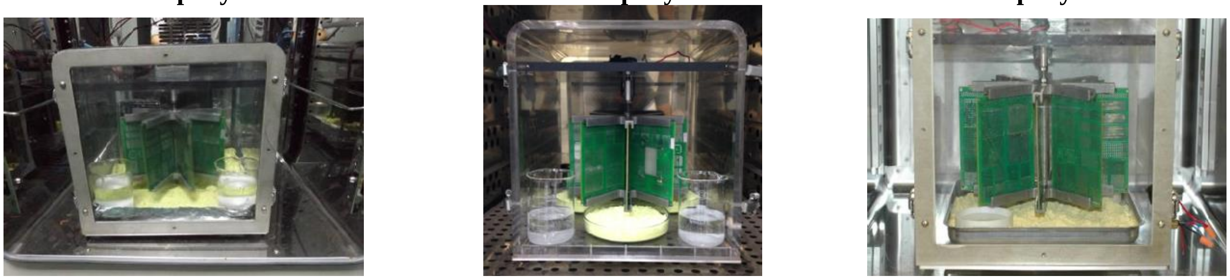
Figure 8: Company D 2nd test results.

The Company D 2nd test results are shown on **Figure 8,** which shows creep corrosion on PCBs with ImAg finish soldered with organic acid and rosin flux and no creep corrosion on PCBs with HASL finish soldered with organic acid flux. Company B was the only one that reported creep corrosion on Pb-free HASL PCBs which is not expected based on field and MFG test experience; these failing PCBs were soldered using organic acid flux.

The test results of the first and the second run show little difference between the paddle wheel and the forced air setups. There was general team consensus that creep corrosion propensity was higher in chambers with KCl saturated salt solution at 50°C compared to chambers with KNO_3 saturated salt solution at 60°C. The team settled on running the 3rd test run at 50°C and using KCl saturated salt solution. Another reason for selecting the lower chamber temperature of 50°C was because as a rule it is good practice to have the test conditions as near as possible to the actual field conditions. The KCl saturated salt solution was selected because it has chloride ions in it, though it is well understood that thermodynamics does not allow chlorine to escape from a chloride solution. If it did, the chlorine gas coming off the ocean waters would not allow life on earth as it exists today.

Table 4: Summary of the 2nd test run at the 4 companies

	Setup	Salt	Temp	Dust	ImAg		HASL	HASL
					Organic acid flux	Rosin flux	Organic acid flux	Rosin flux
C	Paddle Wheel	KNO3	60°C	No	1 HCC 4 LCC	0	0	-
B	Paddle Wheel	KCL	50°C	No	2 HCC 2 LCC	1 HCC 4 LCC	6 HCC 3 LCC	
A	Forced air	KCL	60°C	No	0 HCC 1 LCC	0 HCC 1 LCC	-	0
D	Forced air	KCL	50°C	Yes	0 HCC 2 LCC	0 HCC 2 LCC	0	-
				No	0	0	0	-



Company B

Å/day Silver	Å/day Copper
1060	1032

Company C

Å/day Silver	Å/day Copper
-184	84

Company D

Å/day Silver	Å/day Copper
866	1472

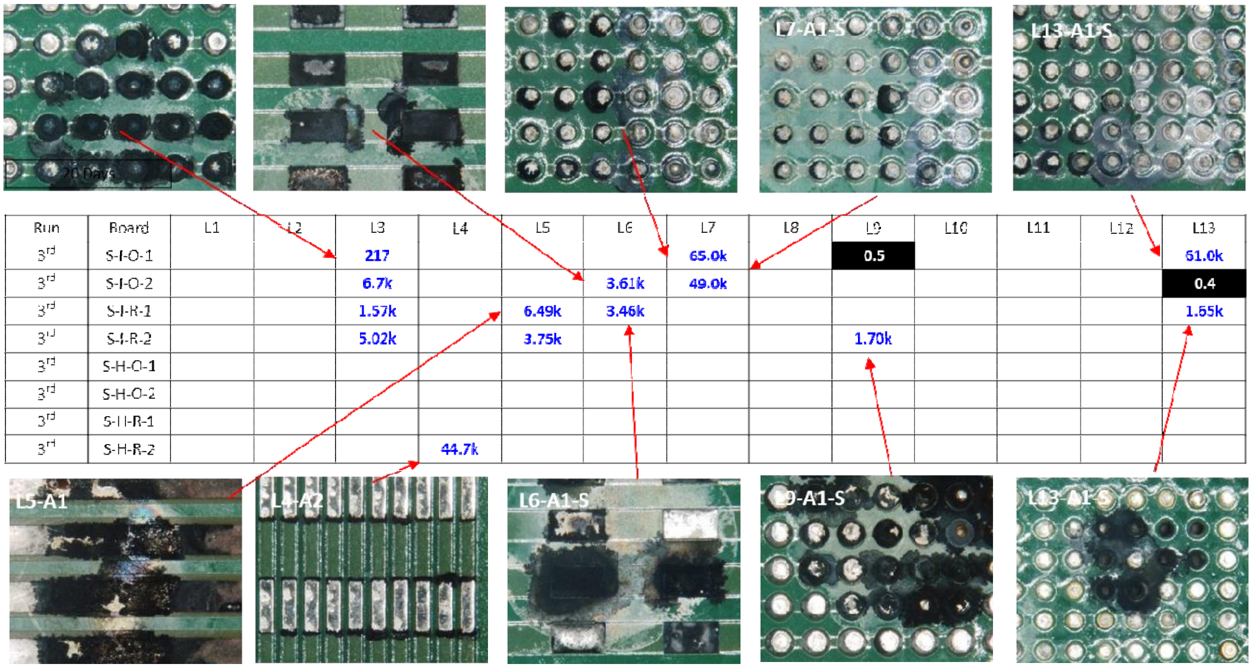
Figure 9: Copper and silver corrosion rates in the third test run.

2.3 Third test run:

As in the earlier two test runs, the test PCBs had ImAg and Pb-free HASL finishes and were soldered using organic acid and rosin fluxes. The four companies conducted the third test runs under identical conditions. All 4 companies used paddle wheel FOS chambers maintained at 50°C using KCl saturated salt solutions. All the test PCBs were contaminated with ammonium salts.

Approximately one third of each PCB area (A2) had localized spots with 10 µg/cm^2 total ammonium salt concentration, another one third of the area (A1) had 100 µg/cm^2 total ammonium salt concentration and the remaining one third of the area was without any salt contamination.

The copper and silver corrosion rates in the third test run are listed in **Figure 9**. The reason for the negative corrosion rate for silver in the Company C FOS chamber may be due to the flaking off of the corrosion product before the post-exposure mass can be measured.



Run	Board	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13
3^{rd}	S-I-O-1			217				65.0k		0.5				61.0k
3^{rd}	S-I-O-2			6.7k			3.61k	49.0k						0.4
3^{rd}	S-I-R-1			1.57k		6.49k	3.46k							1.65k
3^{rd}	S-I-R-2			5.02k		3.75k				1.70k				
3^{rd}	S-H-O-1													
3^{rd}	S-H-O-2													
3^{rd}	S-H-R-1													
3^{rd}	S-H-R-2				44.7k									

Figure 10: Company C 3^{rd} run. Creep corrosion and resulting electrical shorts.

Table 5: Summary of the 3^{rd} test run at the 4 companies

Company	Fine dust	ImAg		HASL	
		Organic acid flux	Rosin flux	Organic acid flux	Rosin flux
C	A1	3.5 HCC 6 LCC	1.5 HCC 9 LCC	0 HCC 4 LCC	0 HCC 4 LCC
	A2	0 HCC 7.5 LCC	0 HCC 8 LCC	0 HCC 6 LCC	0.5 HCC 2.5 LCC
	No	0 HCC 4.5 LCC	0 0	0 3.5 LCC	0 0.5 LCC
B	A1	9 HCC 5 LCC	10.5 HCC 2.5 LCC	6 HCC 2.5 LCC	6.5 HCC 3.5 LCC
	A2	2 HCC 7.5 LCC	3 HCC 8.5 LCC	3 HCC 4 LCC	3.5 HCC 1.5 LCC
	No	0 HCC 0.5 LCC	0 1 LCC	0 0	0.5 HCC 1 LCC
D	A1	3 HCC 5.5 LCC	4 HCC 4.5 LCC	0.5 HCC 3.5 LCC	0.5 HCC 3.5 LCC
	A2	0 0	0 0	0 0	0 0
	No	0 0	0 0	0 0	0 0

Figure 10 shows creep corrosion and the resulting electrical short circuit on areas of the test boards contaminated with 100 □g/cm^2 ammonium salts. The results are from the FOS chamber in Company C. The propensity for creep corrosion leading to electrical short circuiting is similar for both organic acid and the rosin flux soldered ImAg finished PCBs. There is only one occurrence of creep corrosion leading to electrical short circuit on the Pb-free HASL finished PCBs. This is in agreement with the field and MFG test experience.

Table 5 summarizes the results of the third test run. Test results on contaminated test PCBs are not as discriminating as those on PCBs without contamination. The ImAg finished PCBs suffered more creep corrosion that the HASL finished PCBs. The PCBs soldered with organic acid and those soldered with rosin flux suffered similar extent of creep corrosion. Heavy creep corrosion was found mostly in the areas of 100 µg/cm^2 total ammonium salt concentration; less creep corrosion was found on 10 µg/cm^2 total ammonium salt concentration and on areas free of contamination.

3. Discussions

The motivation to pursue the development of a FOS based creep corrosion qualification test is based on the following factors:

- Low cost and ease of availability of test equipment.
- Ease of control of test parameters possible because just the control of temperature in the chamber leads to sulfur concentration and humidity control.
- The S8 sulfur vapor is in the chemical form that readily attacks the copper and the silver on the PCBs.

The point must be emphasized that no other technique can match the relative humidity and sulfur vapor concentration control that a well-designed FOS chamber provides. The sulfur concentrations were not directly measured in this study. Instead, the corrosion rates of copper and silver were measured and used as a measure of the corrosivity of the atmosphere in the chamber. **Figures 4, 7 and 9** show the corrosion rates in the three test runs. What may seem to be highly scattered readings are actually quite tightly grouped compared to those from MFG test chambers.

One disadvantage of the FOS chamber is that the loading of the chamber with test PCBs decreases the corrosivity of the atmosphere in the chamber as measured by the copper and silver corrosion rates. Increasing the surface area of the sulfur bed increases the copper and silver corrosion rate as shown in **Figure 3**.

The PCBs may be absorbing the sulfur, thus, influencing the copper and silver corrosion rates. A careful study is warranted to more thoroughly characterize the mass transport kinetics in the FOS chamber. Preliminary testing indicates that the test PCBs do not give off enough volatile organic compounds (VOCs) to affect the chemistry of the air in the chamber and thus the copper and silver corrosion rates.

5. Conclusions

- In general, the test runs were quite discriminating with the tendency of creep corrosion occurring in the following decreasing order: ImAg-OA > ImAg-R > HASL-OA > HASL-R, where OA refers to soldering using organic acid flux and R refers to soldering using rosin flux.
- The presence of ammonium salts contamination made the test less discriminatory though the tendency of creep corrosion on ImAg-OA was still greater than that on HASL-R.
- The sites that suffered creep corrosion were mostly plated through holes: L3, L7, L9 and L13. Of these, L3 and L9 are not solder mask defined (NSMD); whereas, L7 and L13 are solder mask defined (SMD). Creep corrosion occurred with equal frequency at these four sites, though it is expected that there would be more corrosion in the solder mask undercut area for the SMD case leading to higher occurrences of creep corrosion.

6. References

[1] Schueller R., "Creep corrosion of lead-free printed circuit boards in high sulfur environments," SMTA Int'l Proceedings, Oct 2007.

[2] Cullen D. and O'Brien G., UL Laboratories, Implementation of immersion silver PCB surface finish in compliance with Underwriters Laboratories, IPC Printed Circuits Expo, 2004.

[3] Veale R., Rockwell International, "Reliability of PCB alternate surface finishes in a harsh industrial environment. SMTA Int'l Proceedings, 2005

[4] Mazurkiewicz P., HP Corp., "Accelerated corrosion of PCBs due to high levels of reduced sulfur gases in industrial environments," Proceedings of the 32nd ISTFA, Nov 12-16, 2006, Austin TX.

[5] Fu H., C. Chen, P. Singh, J. Zhang, A. Kurella, X. Chen, X. Jiang, J. Burlingame, S. Lee. 2012. Investigation of factors that influence creep corrosion on printed circuit boards, Pan Pacific Microelectronics Symposium, Kauai, 14-16 Feb 2012.

[6] Abbott W.H., “The development and performance characteristics of mixed flowing gas test environment,” IEEE Trans. of Component Hybrids and Manufactuirng Technology, vol. 11, no.1 . March 1988.

[7] Xu C., Smetana J., Franey J., Guerra G., Fleming D., Reents W., Willie D., Garcia A., Encinas G., Xiaodong J., “Creep corrosion of PWB final finishes: Its cause and prevention,” APEX 2009

[8] Zhao P., Pecht, M., “Field failure due to creep corrosion on components and palladium pre-plated leadframes,” Microelectronics Reliability, 43 (2003) 775-783

[9] Fu H., C. Chen, P. Singh, J. Zhang, A. Kurella, X. Chen, X. Jiang, J. Burlingame, S. Lee. 2012. Investigation of factors that influence creep corrosion on printed circuit boards – Part 2, SMTAI 2012

[10] Cole, M., L. Hedlund, G. Hutt. T. Kiraly, L. Klein, S. Nickel. P. Singh, T. Tofil, Harsh Enviroment Impact on resistor reliabiity, SMTA Int’l Conf. Proc., Oct 2010.

[11] Kondros P., Private communications, 2013.

[12] Fu, H., P. Singh, L, Campbell, J, Zhang, W. Ables, D. Lee, J. Lee, J Li, S. Zhang and S. Lee. 2014. Testing printed circuit boards for creep corrosion in flowers of sulfur chamber, Proc. IPC APEX EXPO 2014.

[13] Hindin, B., Private communications, 2010.

Qualification Test for Creep Corrosion in Flowers of Sulfur Chamber – Phase 2

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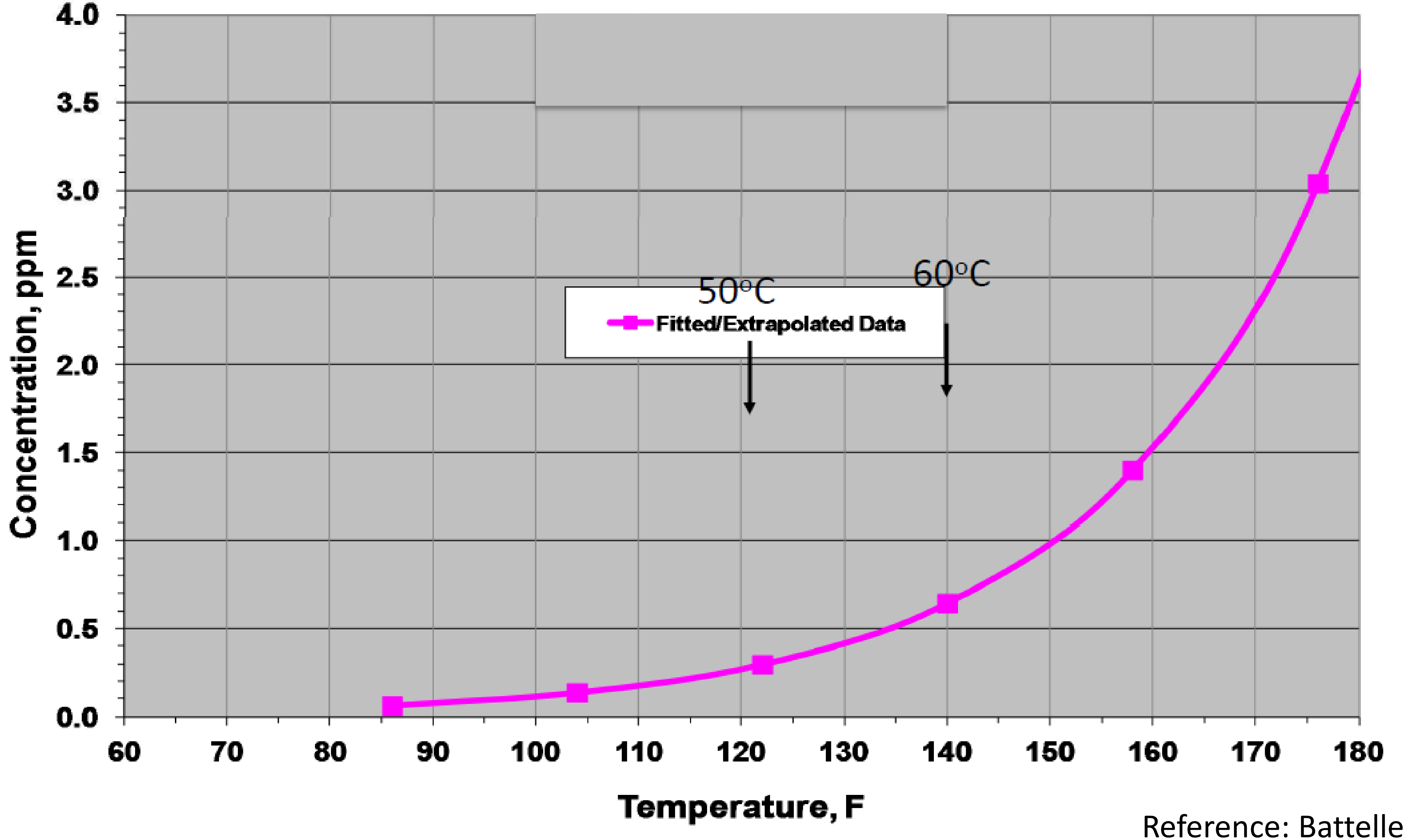
Phase 2A: Optimization Of Test Procedure Using Copper And Silver Coupons And PCB Test Boards

- Three formal runs at 4 laboratories.
- Variables include:
  - Temperature: 50^{o}C, 60^{o}C
  - Humidity (saturated salts): KCl, KNO_3
  - Test chamber: Paddle wheel, forced air setup
  - Flux: Rosin, organic acid
  - Surface finish: ImAg, Pb-free HASL
  - Contamination: NH_4SO_4, NH_4HSO_4, NH_4NO_3 and NH_4Cl in three concentrations
- Summary of the 3 test runs
- Open issues and work in progress.

Relative humidities over saturated salt solutions

Salt	Temperature °C							
	15	20	25	30	35	40	50	60
	Relative Humidity%							
Potassium sulfate K_2SO_4	97	97	97	96	96	96	96	96
Potassium nitrate KNO_3	94	93	92	91	89	88	85	82
Potassium chloride KCl	87	86	85	84	83	82	81	80
Ammonium sulfate $(NH4)_2SO_4$	81	81	80	80	80	79	79	78
Sodium chloride NaCl	76	76	75	75	75	75	75	75

Concentration of Sulfur Vapor (S_8) by Volume vs Temperature



Reference: Battelle

Phase 2A

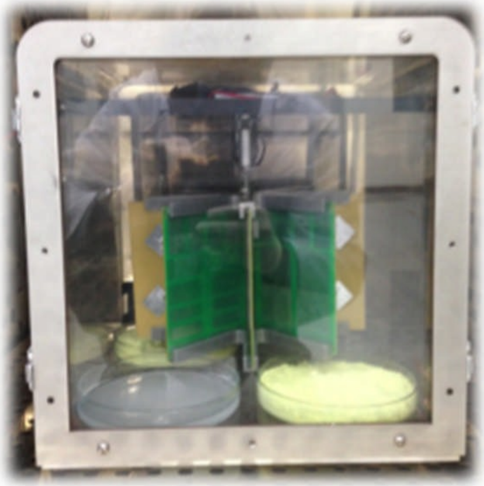
1st Run

Plan for the 1st run

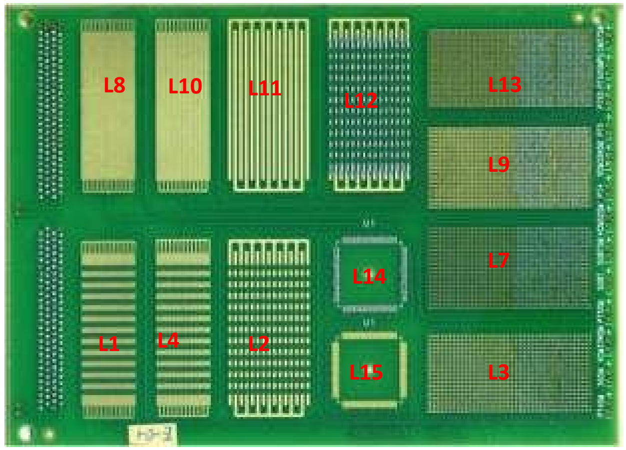
	Finish type	Flux type	Salt	Temprature °C	Contamination	Setup	Company
Baseline	ImAg	Organic Acid	KNO_3	60	No	Forced air 1 m/s	A
		Rosin Flux					
	Pb-free HASL	Rosin Flux					
Baseline	ImAg	Organic Acid	KNO_3	60	No	Paddle wheel 20 RPM	B
		Rosin Flux					
	Pb-free HASL	Organic Acid					
humidity/ temperature	ImAg	Organic Acid	KCl	50	No	Paddle wheel 20 RPM	C
		Rosin Flux					
	Pb-free HASL	Organic Acid					
Contamin- ation	ImAg	Organic Acid	KNO_3	60	NH4SO4, NH3HSO4, NH4NO3, NH4Cl	Paddle wheel 20 RPM	D
	ImAg	Rosin Flux					
	Pb-free HASL	Organic Acid					

The 1st run: Some observations

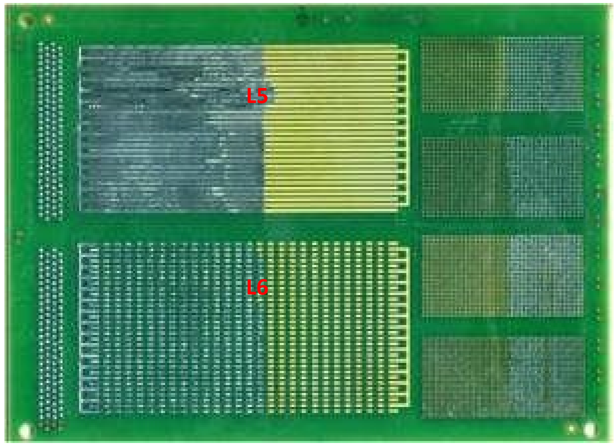
- Corrosion rates on copper and silver foils were lower than expected.
- Creep corrosion observed to occur somewhat more readily at 50°C compared with 60°C.
- Creep corrosion is quite evident in 5 days.

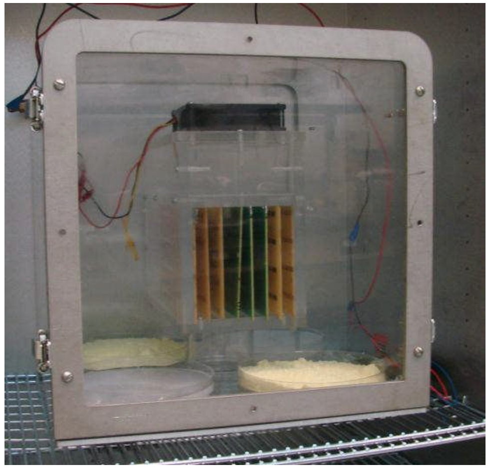


Top side



Bottom side (Wave soldering)

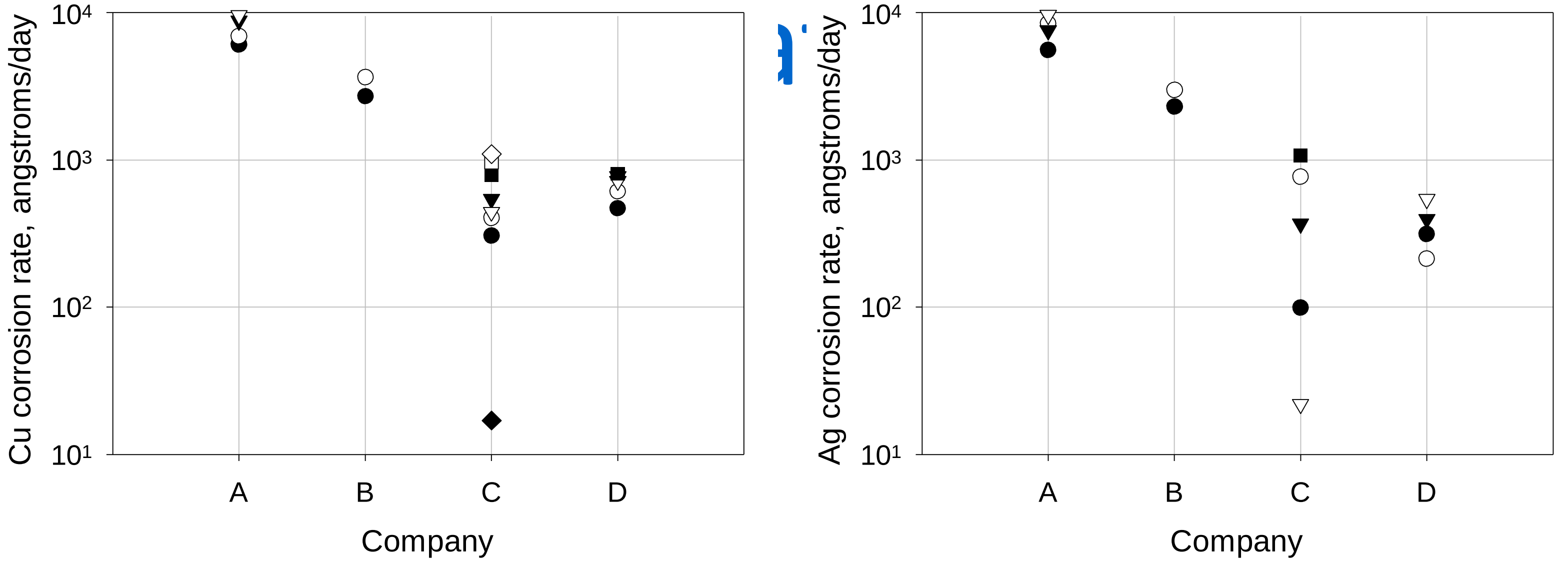




The 15 regions of the PCB test boards

L1	SMD	linear
L2	SMD	linear
L3	NSMD	PTH
L4	SMD	linear
L5	NSMD	linear
L6	SMD	linear
L7	SMD	PTH
L8	NSMD	linear
L9	NSMD	PTH
L10	NSMD	linear
L11	SMD	linear
L12	SMD	linear
L13	SMD	PTH
L14	?	?
L15	NSMD	linear

Run #1: Copper and silver corrosion



Company	Setup	Saturated salt	Temp	%RH	Speed	PCB/Dummy
A	Forced air	KNO_3	60^{o}C		1m/s	3/5
B	Paddle wheel	KNO_3	60^{o}C		20 PRM	3/5
C	Paddle wheel	KCl	50^{o}C		20 RPM	6/2
D	Paddle wheel	KNO_3	60^{o}C		20 PRM	3/5

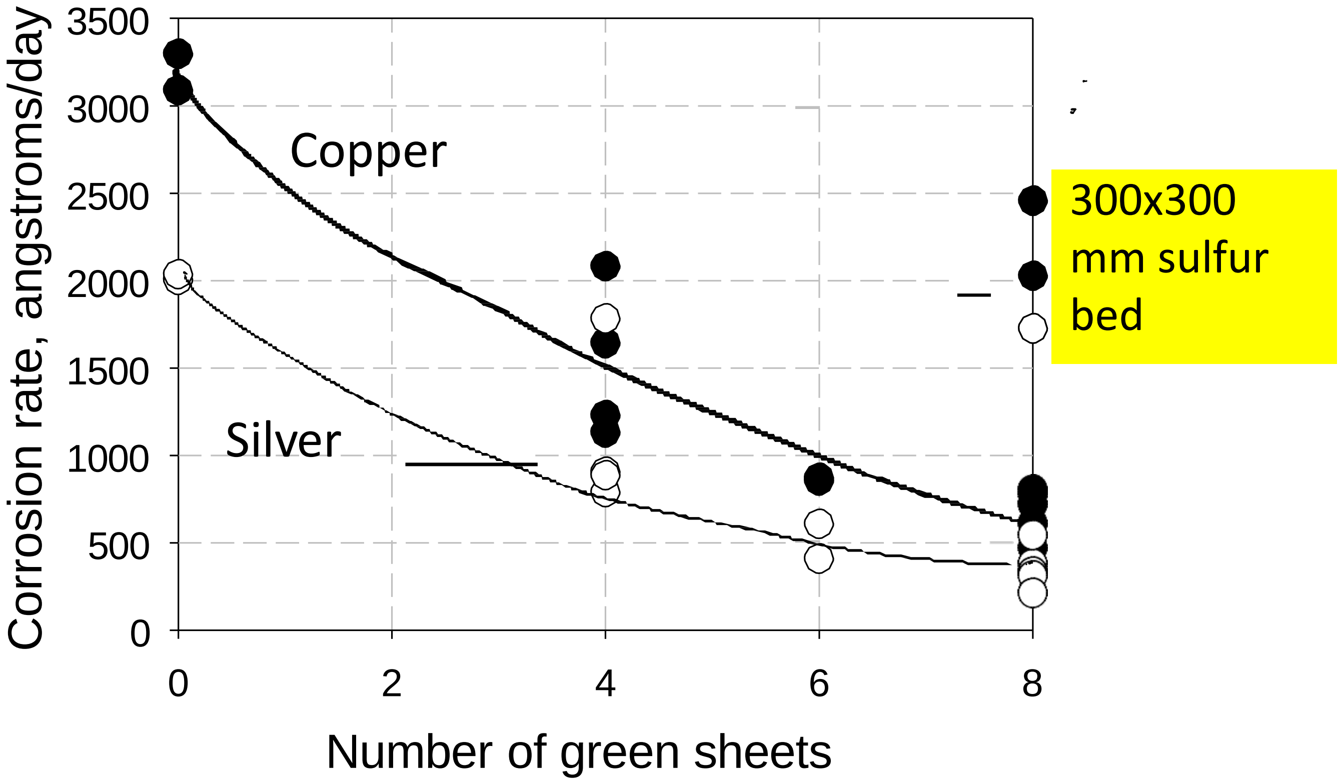
Company D: Corrosion rates as a function of PCB loading

The solder mask was probably absorbing the sulfur?

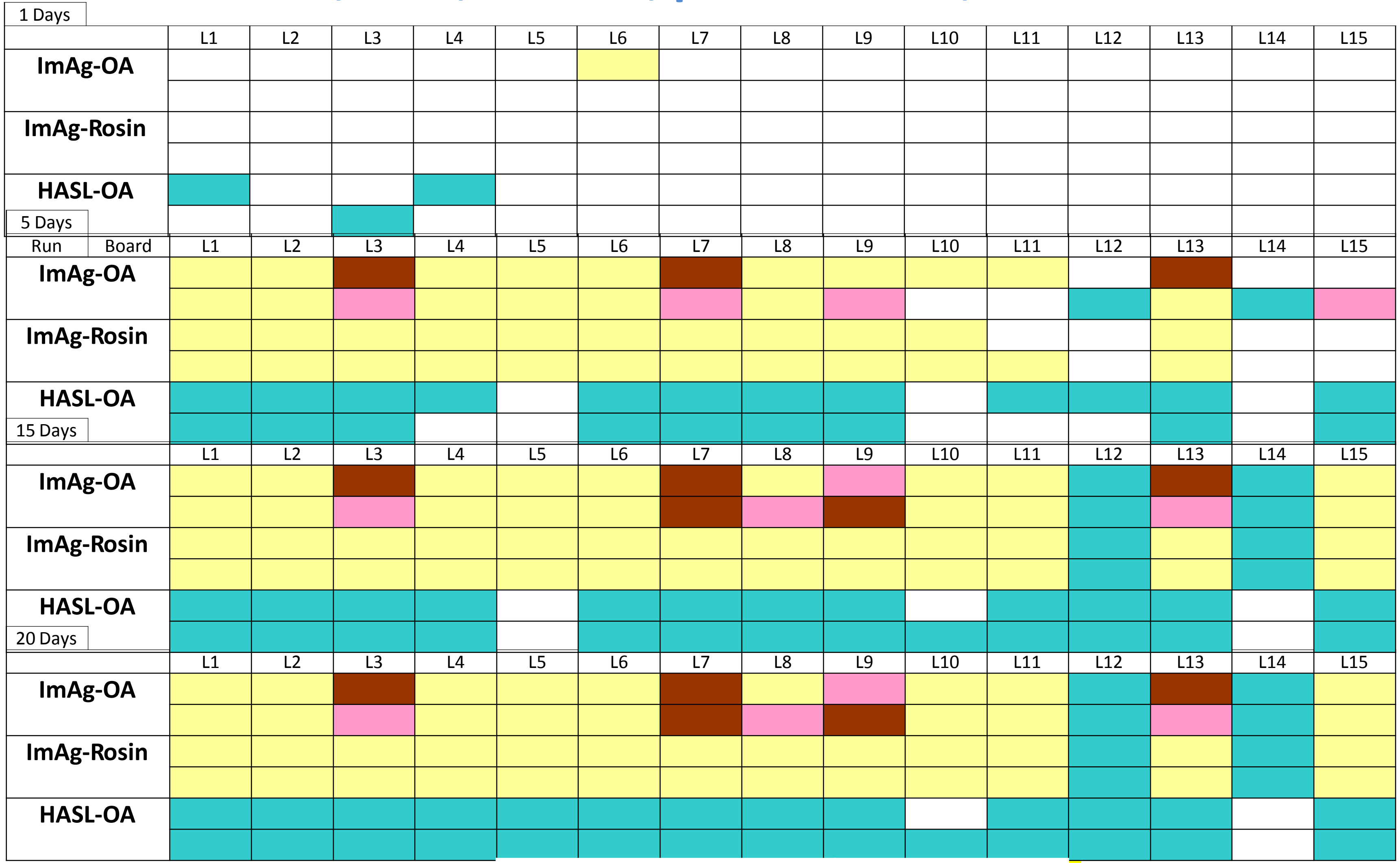
No evidence of PCBs giving off VOCs.

Increasing the area of the sulfur bed increases the Cu and Ag corrosion rates substantially.

The total number of PCBs and brown epoxy sheets was kept constant at 8. KNO3, 60°C, paddle wheel, 20 RPM.



1^{st} run in Co C: KCl, $50^{o}C$, 20 RPM, paddle wheel, no contamination



1 Days

	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
ImAg-OA						🟨									
ImAg-Rosin															
HASL-OA	🟦			🟦											
			🟦												

5 Days

Run Board	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
ImAg-OA	🟨	🟨	🟥	🟨	🟨	🟨	🟥	🟨	🟨	🟨	🟨		🟥		
	🟨	🟨	🟪	🟨	🟨	🟨	🟪	🟨	🟪			🟦	🟨	🟦	🟪
ImAg-Rosin	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨			🟨		
	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨		🟨		
HASL-OA	🟦	🟦	🟦	🟦		🟦	🟦	🟦	🟦		🟦	🟦	🟦		🟦
	🟦	🟦	🟦			🟦	🟦	🟦	🟦				🟦		🟦

15 Days

	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
ImAg-OA	🟨	🟨	🟥	🟨	🟨	🟨	🟥	🟨	🟪	🟨	🟨	🟦	🟥	🟦	🟨
	🟨	🟨	🟪	🟨	🟨	🟨	🟥	🟪	🟥	🟨	🟨	🟦	🟪	🟦	🟨
ImAg-Rosin	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟨	🟦	🟨
	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟨	🟦	🟨
HASL-OA	🟦	🟦	🟦	🟦		🟦	🟦	🟦	🟦		🟦	🟦	🟦		🟦
	🟦	🟦	🟦	🟦		🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦		🟦

20 Days

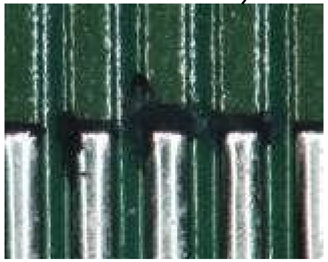
	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
ImAg-OA	🟨	🟨	🟥	🟨	🟨	🟨	🟥	🟨	🟪	🟨	🟨	🟦	🟥	🟦	🟨
	🟨	🟨	🟪	🟨	🟨	🟨	🟥	🟪	🟥	🟨	🟨	🟦	🟪	🟦	🟨
ImAg-Rosin	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟨	🟦	🟨
	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟨	🟦	🟨
HASL-OA	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦		🟦	🟦	🟦		🟦
	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦		🟦

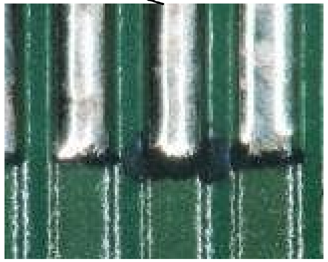
🟥 Heavy creep corrosion	🟨 Corrosion
🟪 Light creep corrosion	🟦 Edge corrosion

1st run in Company C: 20 day test results

- Edge corrosion readily developed on Pb-free HASL boards
- Heavy creep corrosion occurred on ImAg boards soldered with organic acid flux.
- High resistance short in some heavy creep corrosion areas

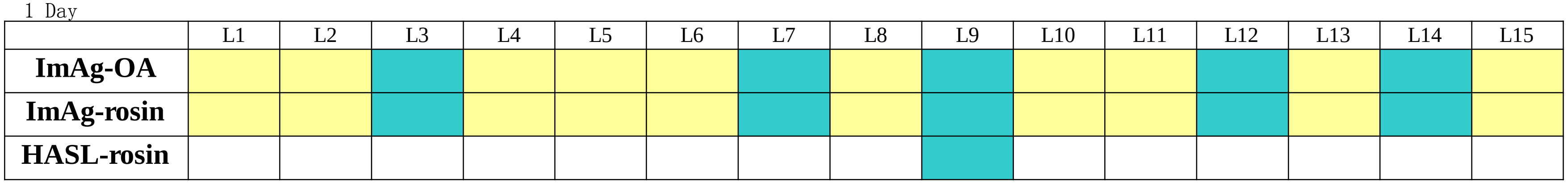
Finish-flux	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13
ImAg-OA							5.03k	2.29k					35.75k
								81.98k	11.05k				
ImAg-rosin													
HASL-OA	3.94k			35.12k	74.09M								





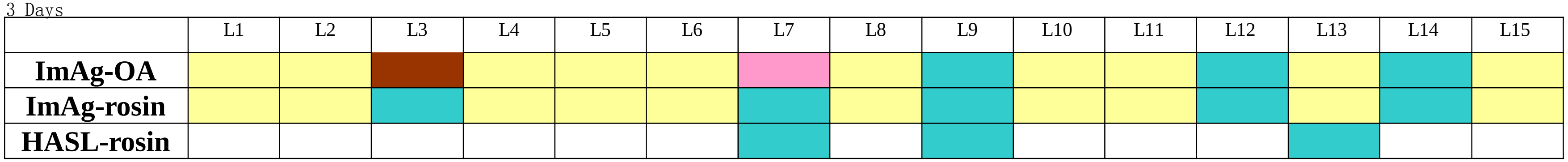
- *I-O: ImAg, organic acid flux*
- *I-R: ImAg, rosin flux*
- *H-O: Pb-free HASL, organic acid flux*

1st run in Co A: KNO$_3$, 60^{o}C, 1m/s, force air, no contamination



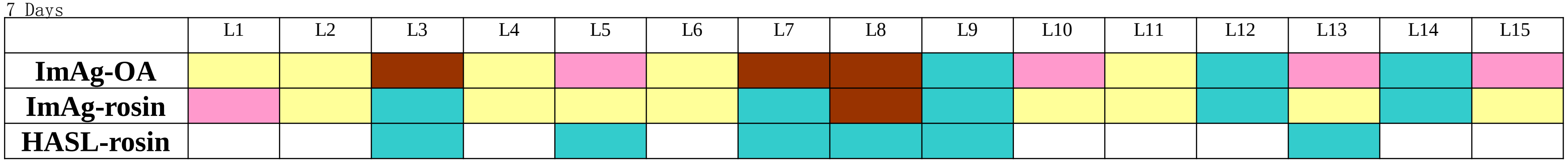
1 Day

	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
ImAg-OA	🟨	🟨	🟦	🟨	🟨	🟨	🟦	🟨	🟦	🟨	🟨	🟦	🟨	🟦	🟨
ImAg-rosin	🟨	🟨	🟦	🟨	🟨	🟨	🟦	🟨	🟦	🟨	🟨	🟦	🟨	🟦	🟨
HASL-rosin									🟦						



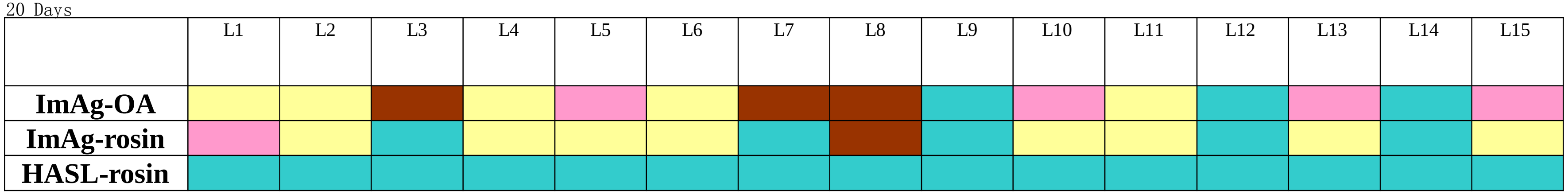
3 Days

	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
ImAg-OA	🟨	🟨	🟥	🟨	🟨	🟨	🟪	🟨	🟦	🟨	🟨	🟦	🟨	🟦	🟨
ImAg-rosin	🟨	🟨	🟦	🟨	🟨	🟨	🟦	🟨	🟦	🟨	🟨	🟦	🟨	🟦	🟨
HASL-rosin							🟦		🟦				🟦		



7 Days

	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
ImAg-OA	🟨	🟨	🟥	🟨	🟪	🟨	🟥	🟥	🟦	🟪	🟨	🟦	🟪	🟦	🟪
ImAg-rosin	🟪	🟨	🟦	🟨	🟨	🟨	🟦	🟥	🟦	🟨	🟨	🟦	🟨	🟦	🟨
HASL-rosin			🟦		🟦		🟦	🟦	🟦				🟦		



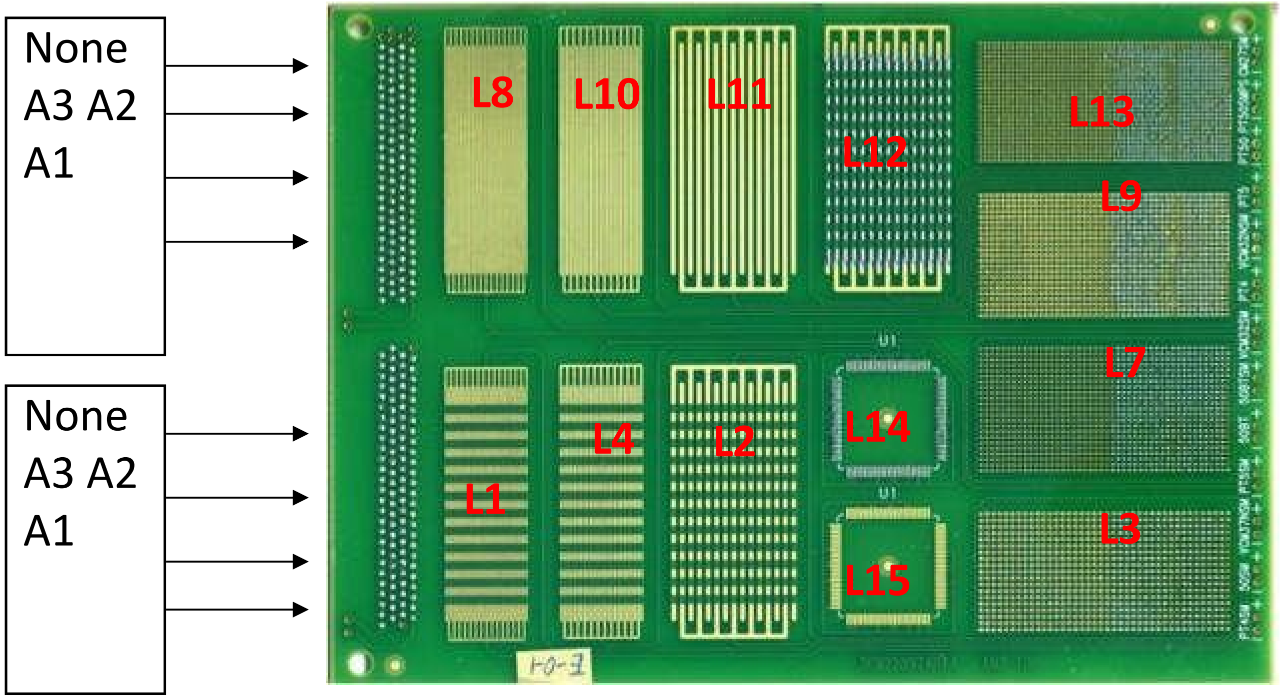
20 Days

	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
ImAg-OA	🟨	🟨	🟥	🟨	🟪	🟨	🟥	🟥	🟦	🟪	🟨	🟦	🟪	🟦	🟪
ImAg-rosin	🟪	🟨	🟦	🟨	🟨	🟨	🟦	🟥	🟦	🟨	🟨	🟦	🟨	🟦	🟨
HASL-rosin	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦

🟥 Heavy creep corrosion	🟨 Corrosion
🟪 Light creep corrosion	🟦 Edge corrosion

Adding contamination

- Each pattern was divided into quarters. Salt contamination was applied to the quarters, except to area labeled None. The salt solutions contain equal amounts of NH_4SO_4, NH_4HSO_4, NH_4NO_3 and NH_4Cl.
- A1 contains 100 μg/cm^2, A2 contains 10 μg/cm^2 and A3 contains 1 μg/cm^2



None
A3 A2
A1

None
A3 A2
A1

How to deposit 10 $\mu g/cm^2$ salt on a test board?

Volume of drops = 10 μl

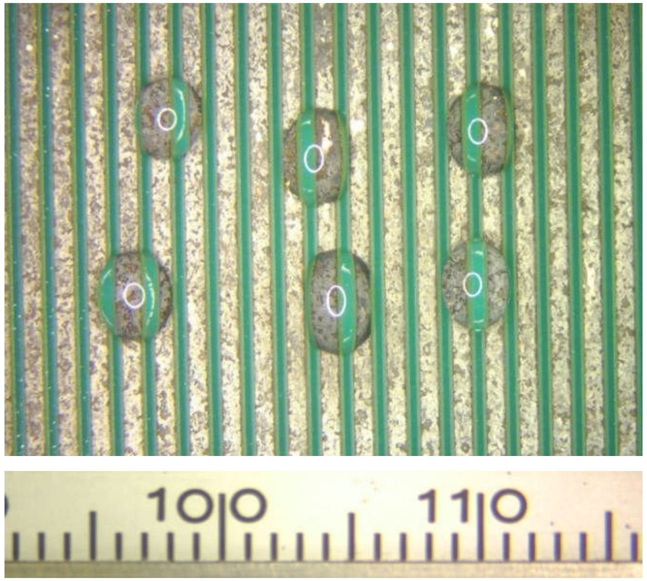
Area of drop = $\nu(0.35/2)^2$ = 0.096 cm^2 1 cm^2 to have $10\text{x}10^{-6}$ g salt

0.096 cm^2 to have $0.096\text{x}10\text{x}10^{-6}$ g salt

10 μl of solution to have $0.096\text{x}10\text{x}10^{-6}$ g salt

1 liter of solution to have $(0.096\text{x}10\text{x}10^{-6})(1/10\text{x}10^{-6})$ g 1 liter of solution to have 0.096 g salt

1 liter to have 0.96 g salt for 100 $\mu g/cm^2$ 1 liter to have 0.096 g salt for 10 $\mu g/cm^2$ 1 liter to have 0.0096 g salt for 1 $\mu g/cm^2$



1st run in Company D: KNO$_3$, 60^{o}C, paddle wheel, 100 µg/cm^2 contamination

14 Days

	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
ImAg-OA	🟥	🟦	🟨	🟪	🟨	🟥	🟪	🟦	🟪	🟨	🟨		🟪		
ImAg-rosin	🟦	🟪	🟪	🟥	🟦	🟥	🟨	🟪	🟦	🟨	🟨	🟪	🟥		
HASL-OA	🟦	🟦	🟦			🟩	🟪	🟨	🟥				🟪		

21 Days

	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
ImAg-OA	🟥	🟦	🟨	🟪	🟨	🟥	🟪	🟦	🟪	🟨	🟨		🟪		
ImAg-rosin	🟦	🟪	🟪	🟥	🟦	🟥	🟨	🟪	🟦	🟨	🟨	🟪	🟥		
HASL-OA	🟦	🟦	🟦			🟩	🟪	🟨	🟥				🟪		

🟥 Heavy creep corrosion	🟨 Corrosion
🟪 Light creep corrosion	🟩 Edge corrosion

100 µg/cm^2 deposit on card: Solution A1

0.25 g NH$_4$SO$_4$ + 0.25 g NH$_4$HSO$_4$ +

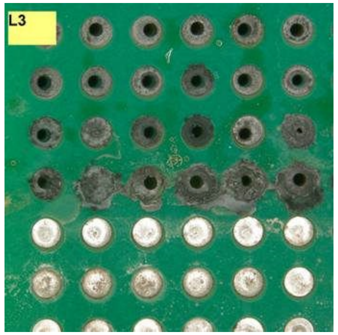
0.25 g NH$_4$NO$_3$ + 0.25 g NH$_4$Cl in 1 liter of DI water

The areas with no contamination and with 1 and 10 µg/cm^2 contamination showed almost no creep corrosion.

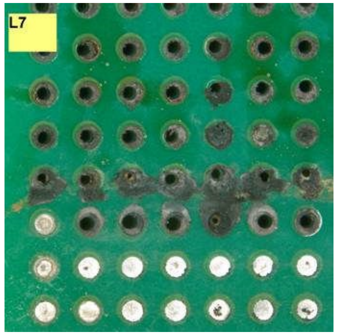
1st test run in Company D: 21 day results, 100 $\mu g/cm^2$ contamination

ImAg-OA

L3

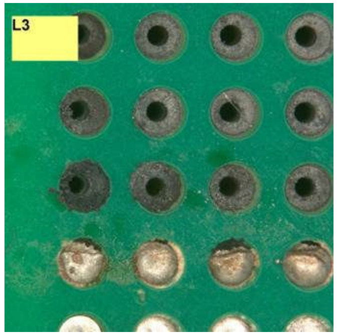


L7

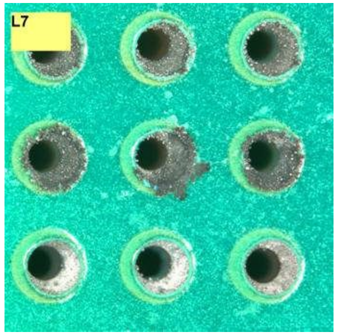


ImAg-Rosin

L3



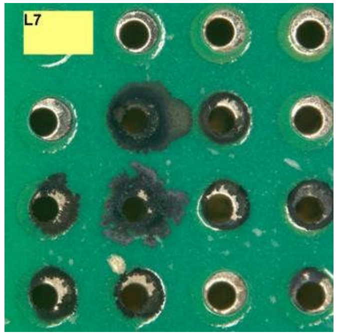
L7



HASL-OA

L3

L7



Summary: 1st run results

Company	Setup	Salt	Temp	Dust	ImAg		HASL	HASL
					Organic acid flux	Rosin flux	Organic acid flux	Rosin flux
C	Paddle Wheel	KCL	50°C	No	2.5 HCC 2 LCC	0	0	-
B	Paddle Wheel	KNO_3	60°C	No	1 HCC 5 LCC	2 LCC	1 HCC 3 LCC	
A	Forced Air	KNO_3	60°C	No	3HCC 4 LCC	1HCC 1 LCC	-	0
D	Paddle Wheel	KNO_3	60°C	Yes	2 HCC 4 LCC	3HCC 4 LCC	I HCC 2 LCC	-
				No	0	0	0	-

HCC = heavy creep corrosion; LCC = light creep corrosion

Summary: 1st run results

- In FOS chambers loaded with PCBs, the solder mask has high absorption rate for sulfur vapors?
- Increasing the sulfur bed area increased the Cu and Ag corrosion rates substantially.
- Creep corrosion was associated mostly with the plated through holes. These are locations L3, L7, L9 and L13.
- Creep corrosion was well developed in 5 days. Additional time saw little increase in creep corrosion.
- The forced air setup gave more creep corrosion than the paddle wheel setup.
- 50°C, KCl sat salt solution (81%RH) with 20 RPM paddle wheel was felt to be the optimum condition for creep corrosion.
- Company D test run generated creep only in the 100 μg/cm^2 areas.

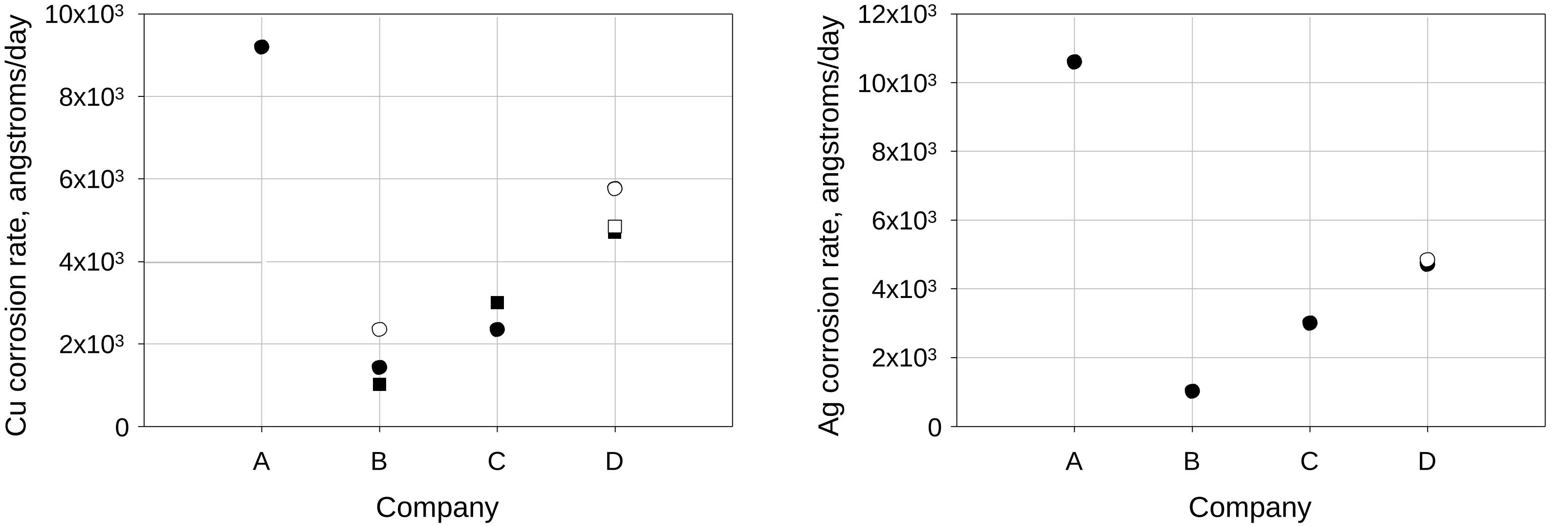
Phase 2

2nd Run

Plan for the 2nd run

	Finish type	Flux type	Salt	Temp °C	Contamination	Setup	Co
Baseline	ImAg	Organic Acid	KNO_3	60	No	Paddle wheel 20 RPM	A
	ImAg	Rosin flux					
	Pb-free HASL	Organic Acid					
Study humidity/ temperature	ImAg	Organic Acid	KCl	50	No	Paddle wheel 20 RPM	B
	ImAg	Rosin flux					
	Pb-free HASL	Organic Acid					
Study humidity/ temperature	ImAg	Organic Acid	KCl	60	No	Forced air 1 m/s	C
	ImAg	Rosin flux					
	Pb-free HASL	Rosin flux					
Study contamination	ImAg	Organic Acid	KCl	50	NH_4SO_4, NH_3HSO_4, NH_4NO_3, NH_4Cl	Forced air 20 RPM	D
	ImAg	Rosin flux					
	Pb-free HASL	Organic Acid					

Run #2 copper and silver corrosion rates



Company	Setup	Saturated salt	Speed	Temp	PCB/Dummy
A	Forced air	KCl	1 m/s	60°C	6/2
C	Paddle wheel	KNO_3	20 RPM	60°C	6/2
D	Forced air	KCl	1 m/s	50°C	6/2
B	Paddle wheel	KCl	20 RPM	50°C	6/2

2nd run in Co C: KNO$_3$, 60°C, 20 RPM, paddle wheel, no contamination

0 Days

	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
ImAg-OA													⬛		
ImAg-R															
HASL-OA															

3 Days

	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
ImAg-OA	🟨	🟨	🟪	🟨	🟪	🟪	🟪	🟨	🟪	🟨	🟨	🟦	⬛	🟦	🟨
ImAg-R	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟨	🟦	🟨
HASL-OA	🟦	🟦	🟦	🟦	🟨	🟦	🟨		🟦	🟦	🟦		🟨		🟨

7 Days

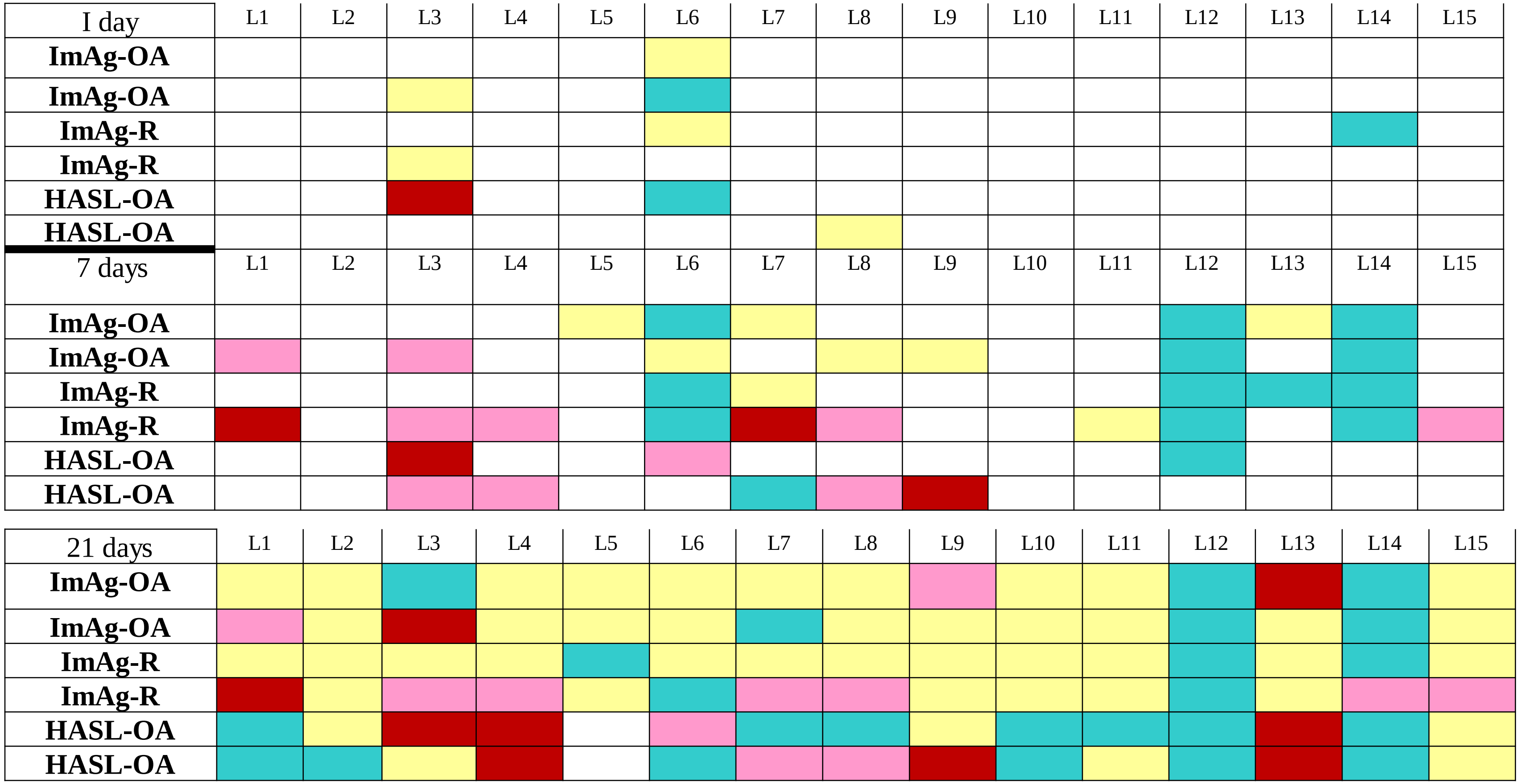
	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
ImAg-OA	🟨	🟨	🟪	🟨	🟪	🟪	🟪	🟨	🟫	🟨	🟨	🟦	⬛	🟦	🟨
ImAg-R	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟨	🟦	🟨
HASL-OA	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦		🟦		🟦

21 Days

	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
ImAg-OA	🟨	🟨	🟪	🟨	🟪	🟪	🟪	🟨	🟫	🟨	🟨	🟦	⬛	🟦	🟨
ImAg-R	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟨	🟦	🟨
HASL-OA	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦

🟥 Heavy creep corrosion	🟨 Corrosion
🟪 Light creep corrosion	🟦 Edge corrosion

2nd test run Company B: KCl, 50°C, 20 RPM, paddle wheel, no contamination



I day	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
ImAg-OA						🟨									
ImAg-OA			🟨			🟦									
ImAg-R						🟨								🟦	
ImAg-R			🟨												
HASL-OA			🟥			🟦									
HASL-OA								🟨							

7 days	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
ImAg-OA					🟨	🟦	🟨					🟦	🟨	🟦	
ImAg-OA	🟪		🟪			🟨		🟨	🟨			🟦		🟦	
ImAg-R						🟦	🟨					🟦	🟦	🟦	
ImAg-R	🟥		🟪	🟪		🟦	🟥	🟪			🟨	🟦		🟦	🟪
HASL-OA			🟥			🟪						🟦			
HASL-OA			🟪	🟪			🟦	🟪	🟥						

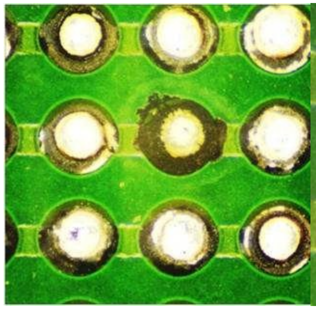
21 days	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
ImAg-OA	🟨	🟨	🟦	🟨	🟨	🟨	🟨	🟨	🟪	🟨	🟨	🟦	🟥	🟦	🟨
ImAg-OA	🟪	🟨	🟥	🟨	🟨	🟨	🟦	🟨	🟨	🟨	🟨	🟦	🟨	🟦	🟨
ImAg-R	🟨	🟨	🟨	🟨	🟦	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟨	🟦	🟨
ImAg-R	🟥	🟨	🟪	🟪	🟨	🟦	🟪	🟪	🟨	🟨	🟨	🟦	🟨	🟪	🟪
HASL-OA	🟦	🟨	🟥	🟥		🟪	🟦	🟦	🟨	🟦	🟦	🟦	🟥	🟦	🟨
HASL-OA	🟦	🟦	🟨	🟥		🟦	🟪	🟪	🟥	🟦	🟨	🟦	🟥	🟦	🟨

🟥 Heavy creep corrosion	🟨 Corrosion
🟪 Light creep corrosion	🟦 Edge corrosion

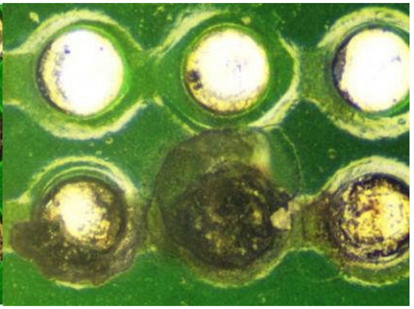
2nd test run in Co B:
20 Days results

I-O Card

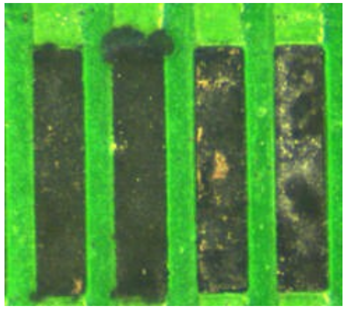
L9



L13



L1



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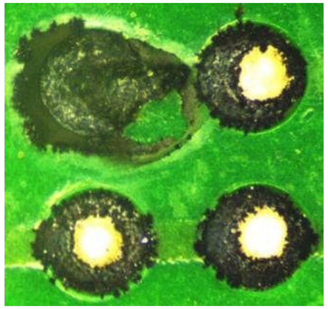
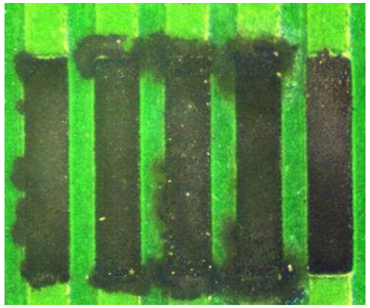
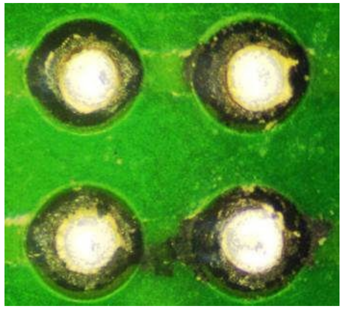


I-R Card

L1



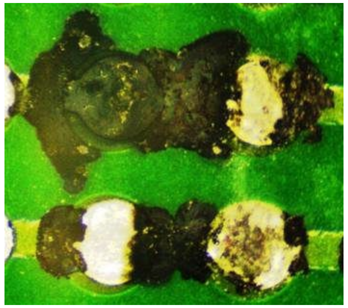
L3



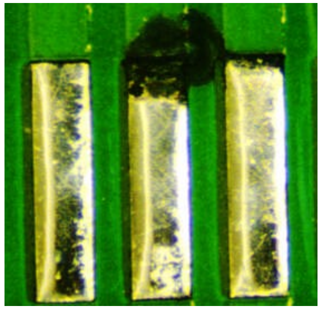
L8

H-O Card

L3



L4



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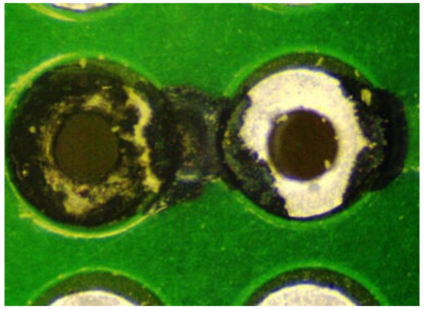

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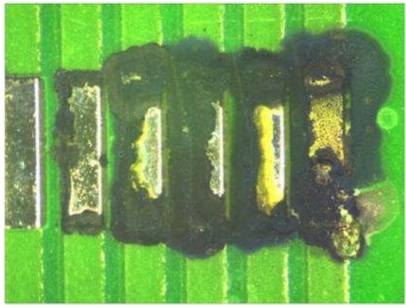
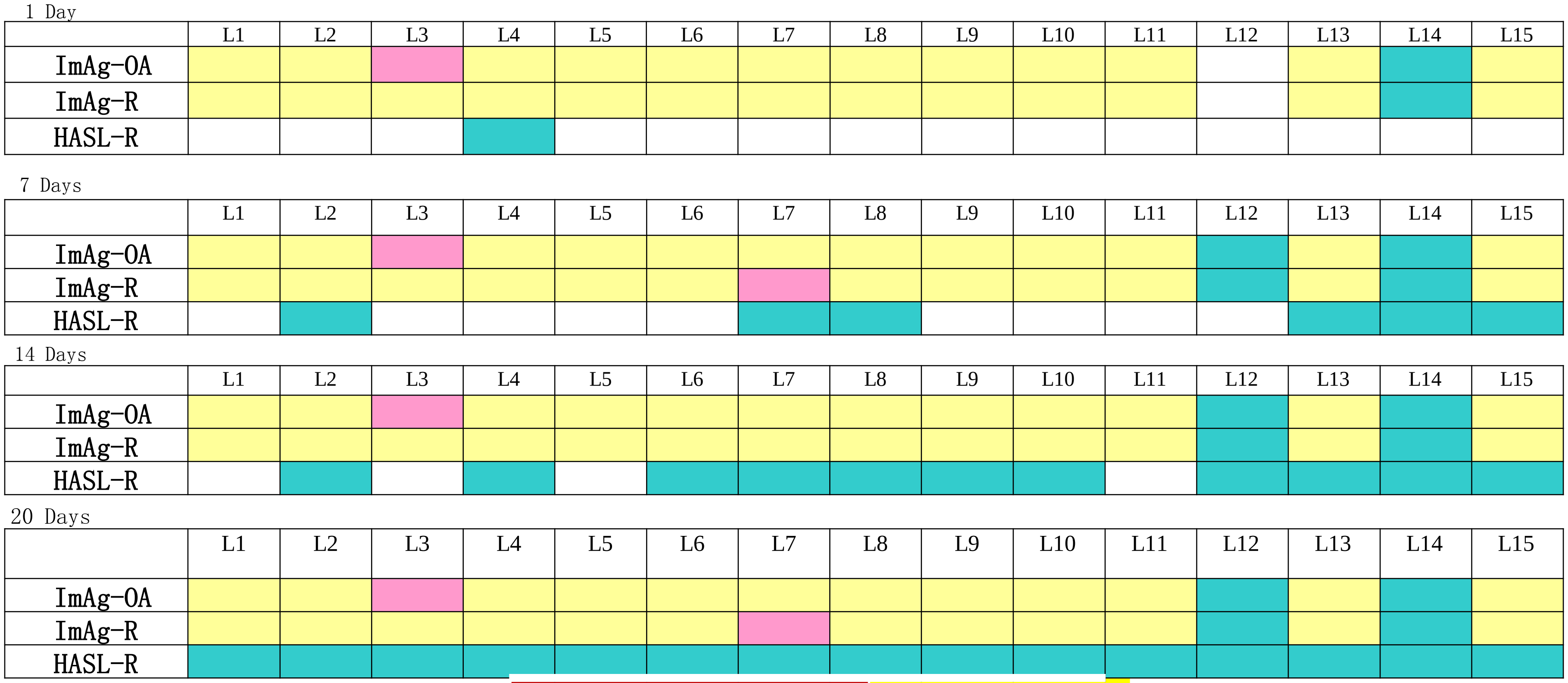


L13

2nd test run in Company A: KCl, 60oC, force air at 1m/s, no contamination



1 Day

	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
ImAg-OA	🟨	🟨	🟪	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨		🟨	🟦	🟨
ImAg-R	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨		🟨	🟦	🟨
HASL-R				🟦											

7 Days

	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
ImAg-OA	🟨	🟨	🟪	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟨	🟦	🟨
ImAg-R	🟨	🟨	🟨	🟨	🟨	🟨	🟪	🟨	🟨	🟨	🟨	🟦	🟨	🟦	🟨
HASL-R		🟦					🟦	🟦					🟦	🟦	🟦

14 Days

	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
ImAg-OA	🟨	🟨	🟪	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟨	🟦	🟨
ImAg-R	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟨	🟦	🟨
HASL-R		🟦		🟦		🟦	🟦	🟦	🟦	🟦		🟦	🟦	🟦	🟦

20 Days

	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
ImAg-OA	🟨	🟨	🟪	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟨	🟦	🟨
ImAg-R	🟨	🟨	🟨	🟨	🟨	🟨	🟪	🟨	🟨	🟨	🟨	🟦	🟨	🟦	🟨
HASL-R	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦

🟥 Heavy creep corrosion	🟨 Corrosion
🟪 Light creep corrosion	🟦 Edge corrosion

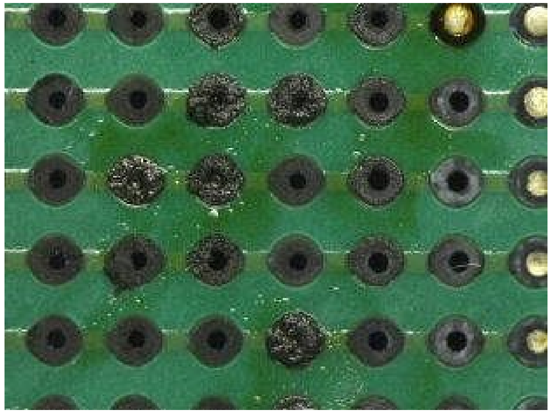
No high resistance short detected

2nd test run in Company A: KCl, 60°C, 1m/s, force air, no contamination, 20 day result

I-O Card

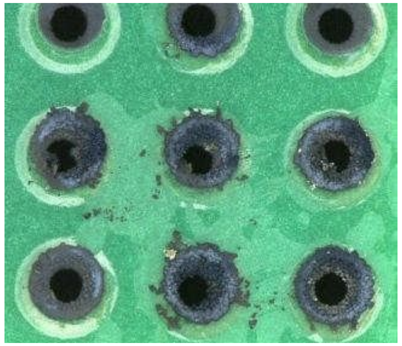
L2

L3

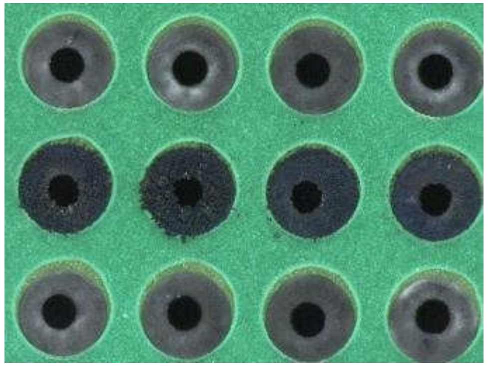


I-R Card

L7

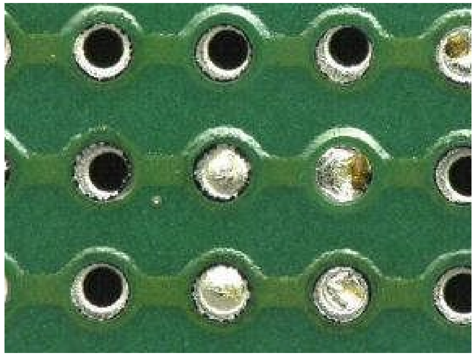


L9

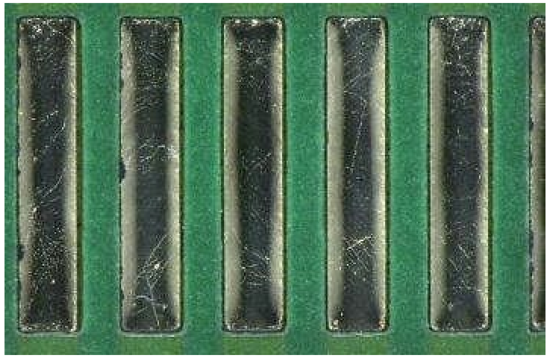


H-R Card

L7

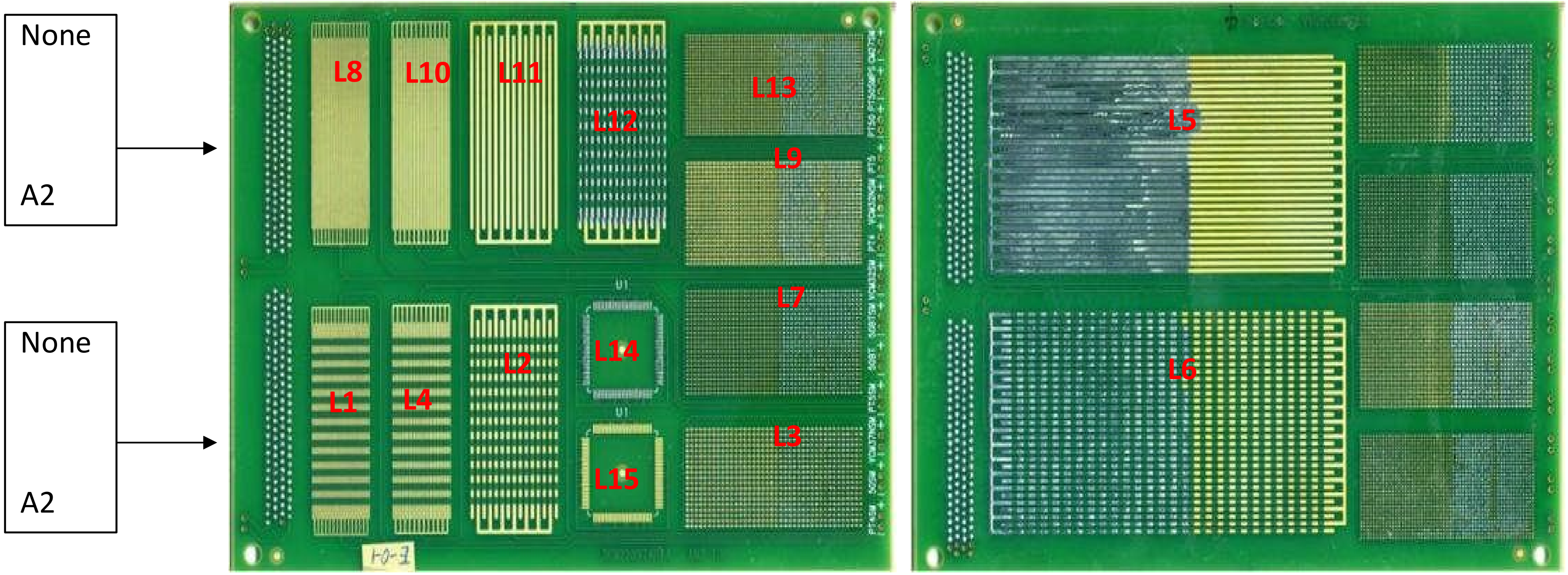


L1



Adding contamination

Each pattern was divided in half. Salt contamination was applied to one half of each pattern. The salt solution contains equal amounts of NH_4SO_4, NH_4HSO_4, NH_4NO_3 and NH_4Cl. A2 contains 10 $\mu g/cm^2$



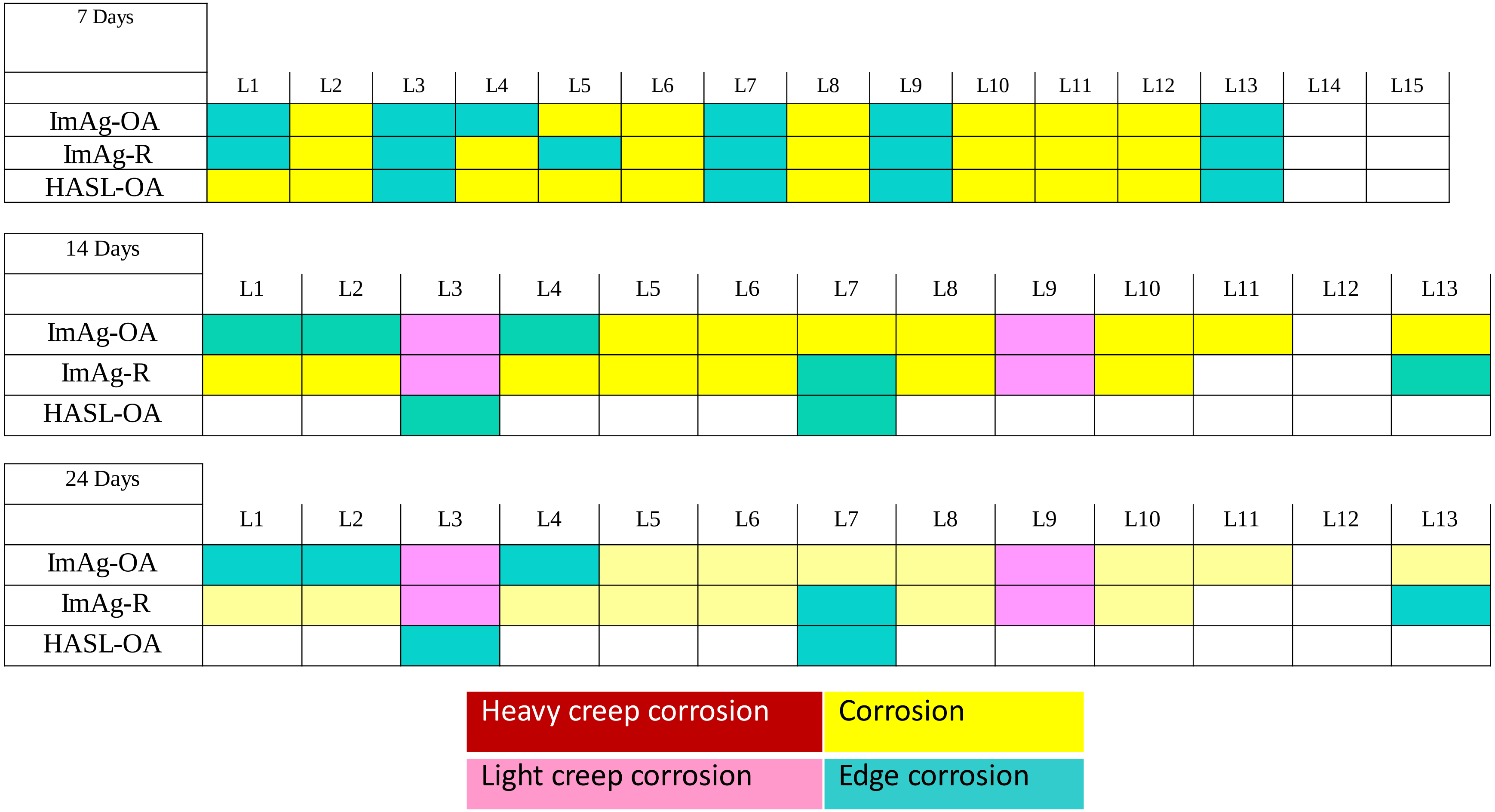
None

A2

None

A2

2nd test run in Company D: Forced air setup, 1m/s, KCL, 50°C, with contamination (creep mainly on 100 μg/cm^2)



7 Days	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
ImAg-OA	🟦	🟨	🟦	🟦	🟨	🟨	🟦	🟨	🟦	🟨	🟨	🟨	🟦		
ImAg-R	🟦	🟨	🟦	🟨	🟦	🟨	🟦	🟨	🟦	🟨	🟨	🟨	🟦		
HASL-OA	🟨	🟨	🟦	🟨	🟨	🟨	🟦	🟨	🟦	🟨	🟨	🟨	🟦		

14 Days	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13
ImAg-OA	🟦	🟦	🟪	🟦	🟨	🟨	🟨	🟨	🟪	🟨	🟨		🟨
ImAg-R	🟨	🟨	🟪	🟨	🟨	🟨	🟦	🟨	🟪	🟨			🟦
HASL-OA			🟦				🟦						

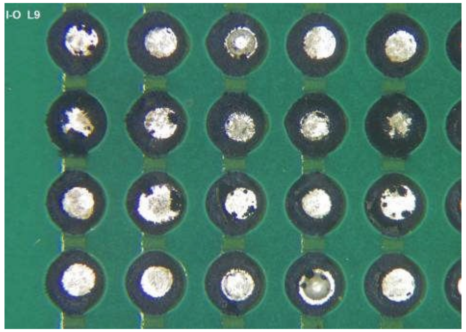
24 Days	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13
ImAg-OA	🟦	🟦	🟪	🟦	🟨	🟨	🟨	🟨	🟪	🟨	🟨		🟨
ImAg-R	🟨	🟨	🟪	🟨	🟨	🟨	🟦	🟨	🟪	🟨			🟦
HASL-OA			🟦				🟦						

🟥 Heavy creep corrosion	🟨 Corrosion
🟪 Light creep corrosion	🟦 Edge corrosion

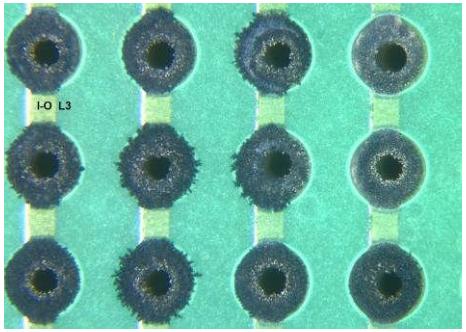
2nd test run in Company D: 24 days results

I-O Card

L9

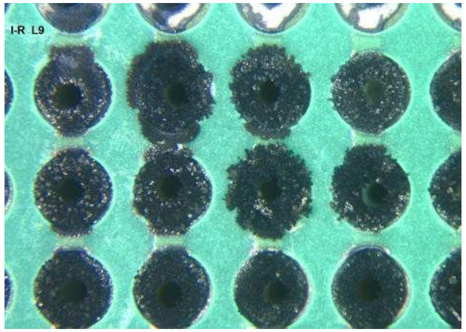


L3

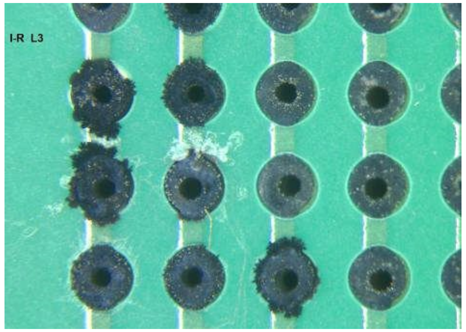


I-R Card

L9

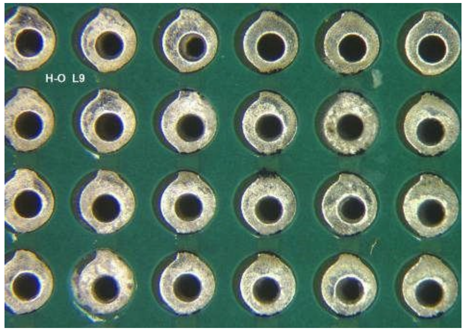


L3

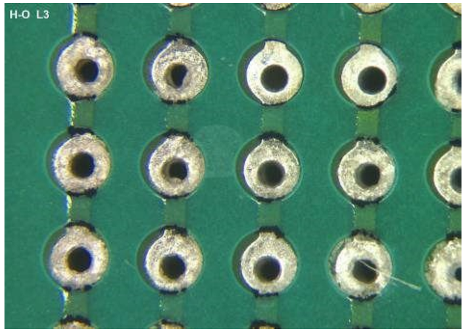


H-O Card

L9



L3



Conclusion: 2nd run of phase 2

- Increasing the sulfur bed area increases the Cu and Ag corrosion rates substantially.

	Setup	Salt	Temp	Dust	ImAg		HASL	
					Organic acid flux	Rosin flux	Organic acid flux	Rosin flux
C	Paddle Wheel	KNO3	60°C	No	1 HCC 4 LCC	0	0	-
B	Paddle Wheel	KCL	50°C	No	2 HCC 2 LCC	1 HCC 4 LCC	6 HCC 3 LCC	
A	Forced air	KCL	60°C	No	0 HCC 1 LCC	0 HCC 1 LCC	-	0
D	Forced air	KCL	50°C	Yes	0 HCC 2 LCC	0 HCC 2 LCC	0 HCC 0 LCC	-
				No	0	0	0	-

HCC = heavy creep corrosion; LCC = light creep corrosion

1st and 2nd run summary

Run #	Site	Setup	Salt	Temp	Fine dust	ImAg		HASL	
						Organic acid flux	Rosin flux	Organic acid flux	Rosin flux
1st run	C	Paddle Wheel	KCL	50ºC	No	2.5 HCC 2 LCC	0	0	-
	B	Paddle Wheel	KNO3	60ºC	No	1 HCC 5 LCC	2 LCC	1 HCC 3 LCC	
	A	Forced air	KNO3	60ºC	No	3HCC 4 LCC	1HCC 1 LCC	-	0
	D	Paddle Wheel	KNO3	60ºC	Yes	2 HCC 4 LCC	3HCC 4 LCC	I HCC 2 LCC	-
					No	~~0~~	~~0~~	~~0~~	-
C	C	Paddle Wheel	KNO3	60ºC	No	1 HCC 4 LCC	0	0	-
	B	Paddle Wheel	KCL	50ºC	No	2 HCC 2 LCC	1 HCC 4 LCC	6 HCC 3 LCC	
	A	Forced air	KCL	60ºC	No	0 HCC 1 LCC	0 HCC 1 LCC	-	0
	D	Forced air	KCL	50ºC	Yes	0 HCC 2 LCC	0 HCC 2 LCC	0 HCC 0 LCC	-
					No	~~0~~	~~0~~	~~0~~	-

1st and 2nd run summary (without contamination)

Setup	Salt	Temp	Co	ImAg		HASL	
				Organic acid flux	Rosin flux	Organic acid flux	Rosin flux
Paddle wheel	KCL	50ºC	C	2.5 HCC 2 LCC	0	0	-
			B	2 HCC 2 LCC	1 HCC 4 LCC	6 HCC 3 LCC	-
	KNO_3	60ºC	C	1 HCC 4 LCC	0	0	-
			B	1 HCC 5 LCC	0HCC 2 LCC	1 HCC 3 LCC	-
Forced air	KCL	60ºC	A	0 HCC 1 LCC	0 HCC 1 LCC	-	0
	KNO_3		A	3 HCC 4 LCC	1 HCC 1 LCC	-	0

- In general, the tests runs were discriminating with the frequency of creep corrosion occurrence in the following order:

ImAg-OA > ImAg-R > HASL-OA > HASL-R.

- Company C test runs were the most discriminating with only ImAg-OA creep corrosion.

Phase 2
3rd Run

Plan for the 3rd run

- Each company tested 8 test, two of each type.

ImAg	Organic Acid	KCL	50°C	A1 and A2 NH4SO4, NH3HSO4, NH4NO3, NH4Cl	Paddle wheel
	Rosin Flux				
Pb-free HASL	Organic Acid				
	Rosin Flux				

To make 100 $\mu g/cm^2$ deposit on card: Solution A1:

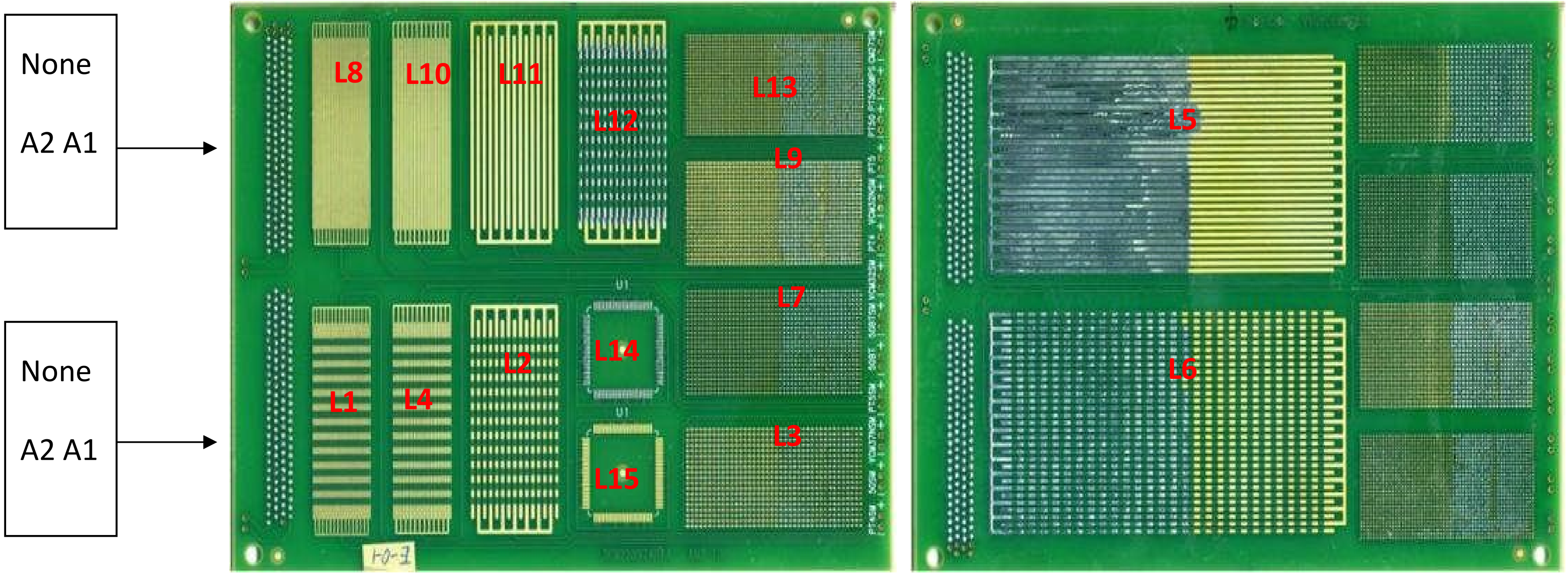
0.25 g NH_4SO_4 + 0.25 g NH_4HSO_4 + 0.25 g NH_4NO_3 + 0.25 g NH_4Cl in 1 litre of DI water.

To make 10 $\mu g/cm^2$ deposit on card: Solution A2.

Add 10 ml of solution A1 to 90 ml DI water.

Adding contamination

Each pattern was divided into 3 sections. Section A1 was contaminated with a total of 100 µg/cm² consisting of equal parts of NH_4SO_4, NH_4HSO_4, NH_4NO_3 and NH_4Cl. A2 contains a total of 10 µg/cm² contamination and the 3rd section was left with no contamination.



None

A2 A1

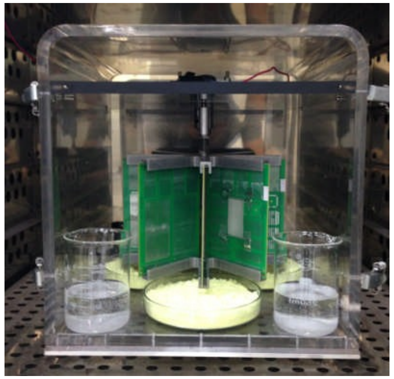
None

A2 A1

Company B

Å/day Silver	Å/day Copper
1060	**1032**

Company C



Å/day Silver	Å/day Copper
-184	**84**

Company D

Å/day Silver	Å/day Copper
866	**1472**

Company	Setup	Saturated salt	Temp	%RH	Speed	PCB/Dummy
A	Paddle wheel	KCl	50^{o}C		20 RPM	8/0
B	Paddle wheel	KCl	50^{o}C		20 PRM	8/0
C	Paddle wheel	KCl	50^{o}C		20 RPM	8/0
D	Paddle wheel	KCl	50^{o}C		20 PRM	8/0

3rd run in Company C: 20 day results

20 Days

	Salt	L1	L2	L3		L4	L5		L6		L7		L8	L9		L10	L11	L12	L13		L14	L15
		N	N	N	S	N	N	S	N	S	N	S	N	N	S	N	N	S	N	S	S	N
ImAg-OA 1	A1	🟪	🟪	🟨	🟫	🟪	🟪	🟦	🟪	🟪	🟨	🟫	🟨	🟪	🟫	🟨	🟨	🟦	🟪	🟫	🟦	🟪
	A2	🟪	🟪	🟪	🟦	🟪	🟨	🟦	🟨	🟦	🟪	🟪	🟨	🟪	🟦	🟨	🟨	🟦	🟪	🟪	🟦	🟨
	Non	🟨	🟨	🟨	🟦	🟨	🟪	🟦	🟪	🟦	🟪	🟪	🟨	🟪	🟦	🟨	🟨	🟦	🟪	🟪	🟦	🟨
ImAg-OA 2	A1	🟪	🟪	🟪	🟫	🟪	🟪	🟦	🟪	🟫	🟪	🟪	🟨	🟨	🟪	🟪	🟨	🟦	🟪	🟫	🟦	🟨
	A2	🟪	🟪	🟪	🟦	🟪	🟨	🟦	🟨	🟦	🟪	🟦	🟨	🟪	🟦	🟨	🟨	🟦	🟨	🟪	🟦	🟪
	Non	🟨	🟨	🟪	🟦	🟨	🟨	🟦	🟨	🟦	🟪	🟪	🟨	🟪	🟦	🟨	🟨	🟦	🟪	🟪	🟦	🟨
ImAg-R 1	A1	🟪	🟪	🟪	🟫	🟪	🟪		🟪		🟪	🟦	🟪	🟪	🟪	🟨	🟨	🟦	🟪		🟦	🟪
	A2	🟪	🟪	🟨	🟪	🟨	🟨		🟨		🟪	🟪	🟨	🟨	🟪	🟨	🟨	🟦	🟪	🟦	🟦	🟪
	Non	🟨	🟨	🟨	🟦	🟨	🟨		🟨		🟨	🟦	🟨	🟨	🟦	🟨	🟨	🟦	🟨	🟦	🟦	🟨
ImAg-R 2	A1	🟪	🟪	🟪	🟪	🟪	🟪		🟪		🟪	🟦	🟨	🟪	🟫	🟨	🟨	🟦	🟪	🟫	🟦	🟪
	A2	🟪	🟪	🟨	🟪	🟪	🟪		🟨		🟪	🟦	🟨	🟪	🟦	🟨	🟨	🟦	🟨	🟪	🟦	🟪
	Non	🟨	🟨	🟨	🟦	🟨	🟨		🟨		🟨	🟦	🟨	🟨	🟦	🟨	🟨	🟦	🟨	🟦	🟦	🟨
HASL-OA 1	A1	🟪	🟦	🟪	🟦	🟦	🟦	🟦	🟦	🟦	🟪	🟦	🟦	🟦	🟦		🟦		🟦	🟦		🟦
	A2	🟪	🟦	🟪	🟦	🟦	🟦	🟦	🟪	🟪	🟪	🟦	🟦	🟦	🟪		🟦		🟦	🟦		🟦
	Non	🟦	🟦	🟦	🟦	🟦	🟦	🟦		🟦	🟪	🟦	🟦	🟦	🟦		🟦		🟦	🟦		🟦
HASL-OA 2	A1	🟦	🟦	🟪	🟪	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟪	🟪	🟪		🟦		🟪	🟦		🟪
	A2	🟦	🟦	🟦	🟪	🟪	🟦	🟦	🟦	🟪	🟪	🟪	🟪	🟦	🟪		🟦		🟪	🟦		🟦
	Non	🟦	🟪	🟪	🟪	🟦	🟦	🟦	🟦	🟪	🟪	🟦	🟦	🟦	🟦		🟦		🟪	🟪		🟪
HASL-R 1	A1	🟦	🟪	🟦	🟦		🟦		🟦	🟦	🟦		🟦	🟦	🟪		🟦		🟦			🟪
	A2	🟦	🟪	🟦	🟦	🟦			🟦	🟦	🟦		🟦	🟦	🟦		🟦		🟦	🟦		🟦
	Non	🟦			🟦	🟦	🟦		🟦	🟦			🟦	🟦			🟦		🟦			🟦
HASL-R 2	A1	🟦	🟪	🟪	🟦	🟦			🟪	🟦	🟦	🟦	🟪	🟦	🟪	🟦	🟦		🟦	🟦		🟦
	A2	🟪	🟪	🟦	🟪	🟫			🟦	🟦	🟦	🟦	🟪	🟦	🟦		🟦		🟦	🟦		🟦
	Non	🟪								🟦	🟦	🟦	🟦	🟦			🟦		🟦	🟦		🟦

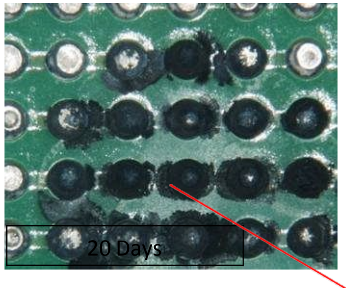
🟫 **Heavy Creep Corrosion**

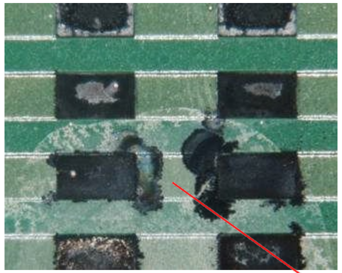
🟪 **Slight Creep Corrosion**

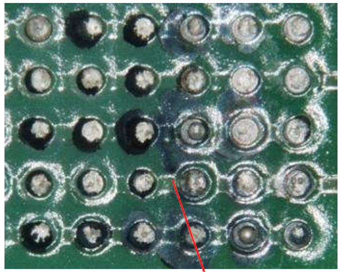
🟨 **Pad Corrosion**

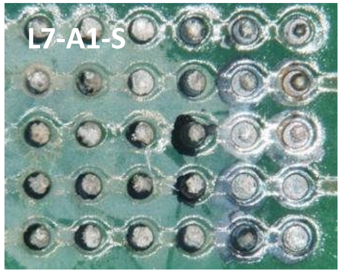
🟦 **Edge Corrosion**

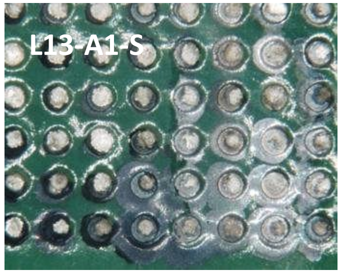
3rd run in Company C: Opens and shorts after day 20



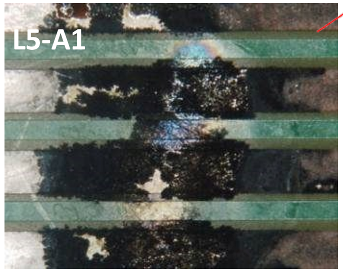


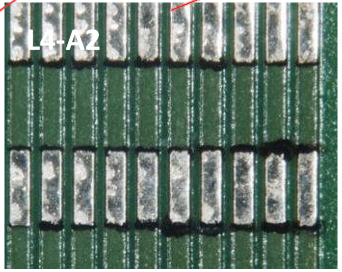


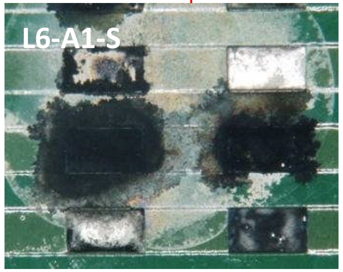


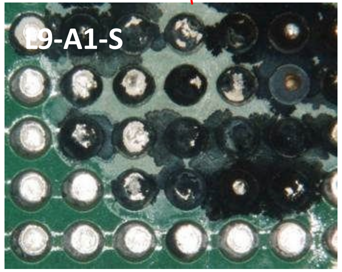


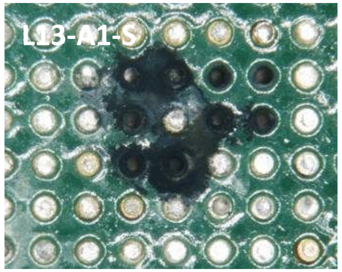
Run	Board	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13
3rd	S-I-O-1			217				65.0k		0.5				61.0k
3rd	S-I-O-2			6.7k			3.61k	49.0k						0.4
3rd	S-I-R-1			1.57k		6.49k	3.46k							1.65k
3rd	S-I-R-2			5.02k		3.75k				1.70k				
3rd	S-H-O-1													
3rd	S-H-O-2													
3rd	S-H-R-1													
3rd	S-H-R-2				44.7k									



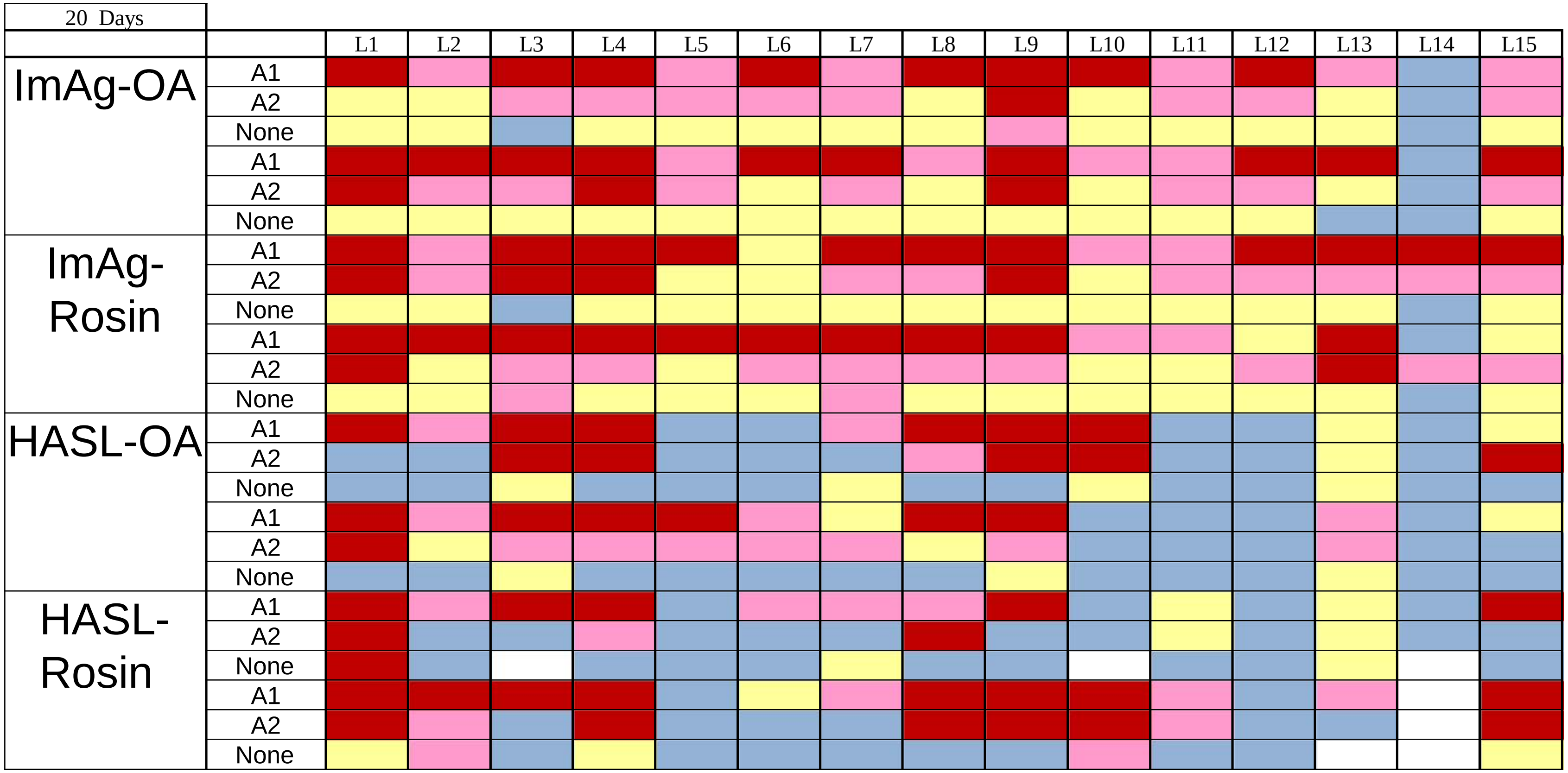








3rd run in Company B: 20 day results



20 Days		L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15
ImAg-OA	A1	🟥	🟪	🟥	🟥	🟪	🟥	🟪	🟥	🟥	🟥	🟪	🟥	🟪	🟦	🟪
	A2	🟨	🟨	🟪	🟪	🟪	🟪	🟪	🟨	🟥	🟨	🟪	🟪	🟨	🟦	🟪
	None	🟨	🟨	🟦	🟨	🟨	🟨	🟨	🟨	🟪	🟨	🟨	🟨	🟨	🟦	🟨
	A1	🟥	🟥	🟥	🟥	🟪	🟥	🟥	🟪	🟥	🟪	🟪	🟥	🟥	🟦	🟥
	A2	🟥	🟪	🟪	🟥	🟪	🟨	🟪	🟨	🟥	🟨	🟪	🟪	🟨	🟦	🟪
	None	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟦	🟨
ImAg-Rosin	A1	🟥	🟪	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟪	🟪	🟥	🟥	🟥	🟥
	A2	🟥	🟪	🟥	🟥	🟨	🟨	🟪	🟪	🟥	🟨	🟪	🟪	🟪	🟪	🟪
	None	🟨	🟨	🟦	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟨
	A1	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟪	🟪	🟨	🟥	🟦	🟨
	A2	🟥	🟨	🟪	🟪	🟨	🟪	🟪	🟪	🟪	🟨	🟨	🟪	🟥	🟪	🟪
	None	🟨	🟨	🟪	🟨	🟨	🟨	🟪	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟨
HASL-OA	A1	🟥	🟪	🟥	🟥	🟦	🟦	🟪	🟥	🟥	🟥	🟦	🟦	🟨	🟦	🟨
	A2	🟦	🟦	🟥	🟥	🟦	🟦	🟦	🟪	🟥	🟥	🟦	🟦	🟨	🟦	🟥
	None	🟦	🟦	🟨	🟦	🟦	🟦	🟨	🟦	🟦	🟨	🟦	🟦	🟨	🟦	🟦
	A1	🟥	🟪	🟥	🟥	🟥	🟪	🟨	🟥	🟥	🟦	🟦	🟦	🟪	🟦	🟨
	A2	🟥	🟨	🟪	🟪	🟪	🟪	🟪	🟨	🟪	🟦	🟦	🟦	🟪	🟦	🟦
	None	🟦	🟦	🟨	🟦	🟦	🟦	🟦	🟦	🟨	🟦	🟦	🟦	🟨	🟦	🟦
HASL-Rosin	A1	🟥	🟪	🟥	🟥	🟦	🟪	🟪	🟪	🟥	🟦	🟨	🟦	🟨	🟦	🟥
	A2	🟥	🟦	🟦	🟪	🟦	🟦	🟦	🟥	🟦	🟦	🟨	🟦	🟨	🟦	🟦
	None	🟥	🟦	⬜	🟦	🟦	🟦	🟨	🟦	🟦	⬜	🟦	🟦	🟨	⬜	🟦
	A1	🟥	🟥	🟥	🟥	🟦	🟨	🟪	🟥	🟥	🟥	🟪	🟦	🟪	⬜	🟥
	A2	🟥	🟪	🟦	🟥	🟦	🟦	🟦	🟥	🟥	🟥	🟪	🟦	🟦	⬜	🟥
	None	🟨	🟪	🟦	🟨	🟦	🟦	🟦	🟦	🟦	🟪	🟦	🟦	⬜	⬜	🟨

🟥 Heavy creep corrosion	🟨 Corrosion
🟪 Light creep corrosion	🟦 Edge corrosion

3rd run summary: Paddle wheel, KCl and 50^{o}C

Company	Fine dust	ImAg		HASL	
		Organic acid flux	Rosin flux	Organic acid flux	Rosin flux
C	A1	3.5 HCC 6 LCC	1.5 HCC 9 LCC	0 HCC 4 LCC	0 HCC 4 LCC
	A2	0 HCC 7.5 LCC	0 HCC 8 LCC	0 HCC 6 LCC	0.5 HCC 2.5 LCC
	No	0 HCC 4.5 LCC	0 0	0 3.5 LCC	0 0.5 LCC
B	A1	9 HCC 5 LCC	10.5 HCC 2.5 LCC	6 HCC 2.5 LCC	6.5 HCC 3.5 LCC
	A2	2 HCC 7.5 LCC	3 HCC 8.5 LCC	3 HCC 4 LCC	3.5 HCC 1.5 LCC
	No	0 HCC 0.5 LCC	0 1 LCC	0 0	0.5 HCC 1 LCC
D	A1	3 HCC 5.5 LCC	4 HCC 4.5 LCC	0.5 HCC 3.5 LCC	0.5 HCC 3.5 LCC
	A2	~~0~~ ~~0~~	~~0~~ ~~0~~	~~0~~ ~~0~~	~~0~~ ~~0~~
	No	~~0~~ ~~0~~	~~0~~ ~~0~~	~~0~~ ~~0~~	~~0~~ ~~0~~

3rd run summary

- Heavy creep corrosion are found mostly in the areas with A1 contamination. Less creep corrosion occurred in A2 contaminated areas and in areas free of contamination.
- Presence of dust reduced the discriminatory nature of the test:
  - The ImAg finished PCBs suffered more creep corrosion than the HASL finished PCBs.
  - The organic acid flux and the rosin flux PCBs suffered similar extent of creep corrosion.
- Corrosion tends to be developed along the edge of the contamination drops.

Overall Conclusions:

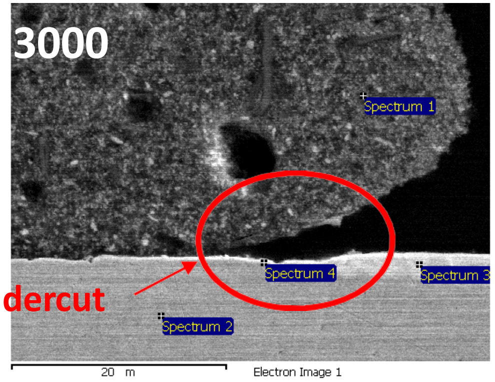
- In general, the tests runs were discriminating with the frequency of creep corrosion occurrence in the following order:
ImAg-OA > ImAg-R > HASL-OA > HASL-R.

- The presence of ammonium salt contamination reduced the discriminatory nature of the test.

- The sites that suffered creep corrosion were mostly plated through holes: sites L3, L7, L9 and L 13.

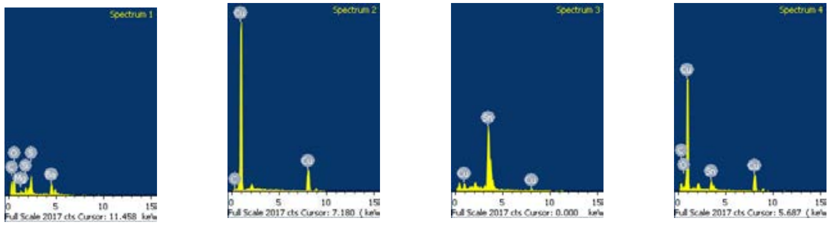
PCB Design: SolderMask Design (SMD)

❖ **Undercut Area will induced Creep Corrosion Occurrence due to Copper Exposure.**



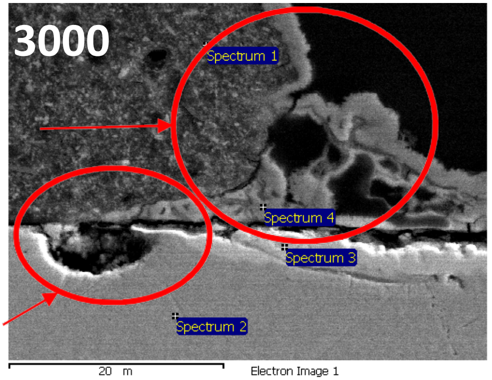
Soldermask undercut

Before FoS test



All results in weight%

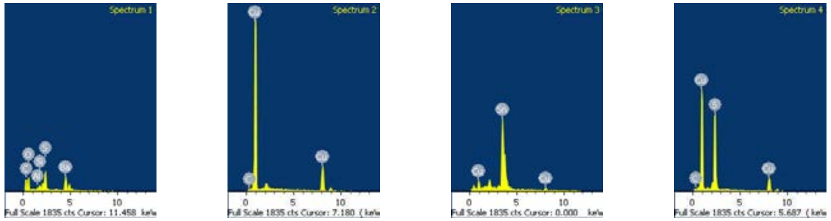
ID	C	O	Mg	Si	S	Cu	Sn	Ba
Spectrum 1	26.07	25.51	1.38	2.77	8.74			35.53
Spectrum 2	6.18					93.82		
Spectrum 3						7.02	92.98	
Spectrum 4	13.87	2.57				71.33	12.23	



Creep corrosion

Copper Cavity

After FoS test



All results in weight%

ID	C	O	Al	Si	S	Sn Cu		Ba
Spectrum 1	27.57	16.75	1.11	2.76	9.81			42.01
Spectrum 2	4.03					95.97		
Spectrum 3						11.64	88.36	
Spectrum 4	8.12				30.19	61.68		

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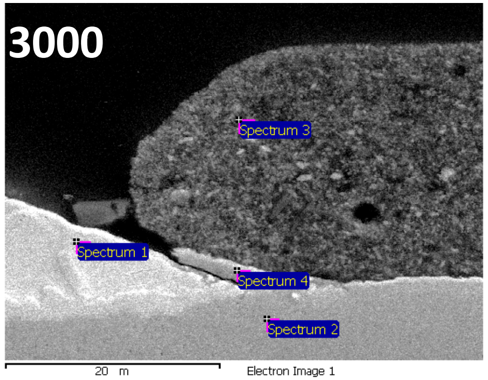
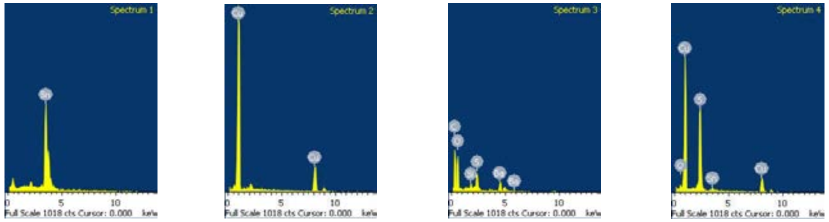
PCB Design: SolderMask Design (SMD)

- **Corrosion Product grew along Soldermask Undercut Area during FoS test.**

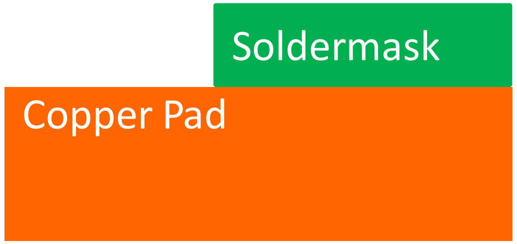


During FoS test

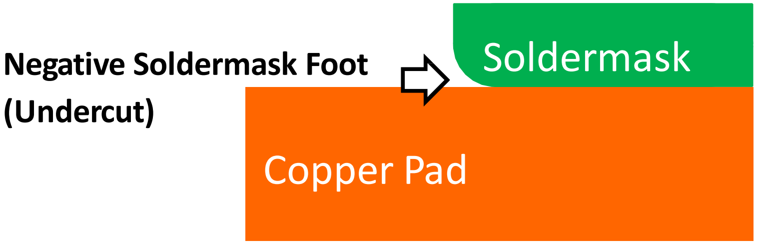


All results in weight% ID	C	O	Si	S	Cu	Sn	Ba	C
Spectrum 1						100.00		
Spectrum 2					100.00			
Spectrum 3	58.66	34.93	1.09	2.80			2.52	58.66
Spectrum 4		11.79		45.09	41.49	1.63		

- **Poor soldermask processing will induce soldermask undercut issue.**



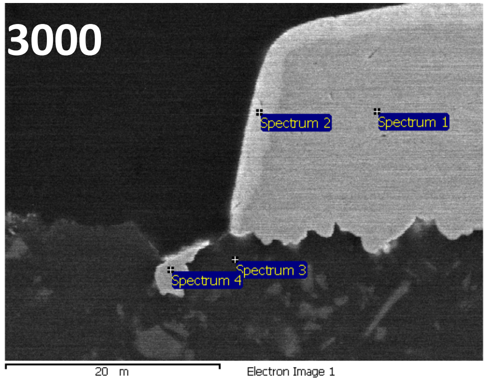
Normal Soldermask Processing



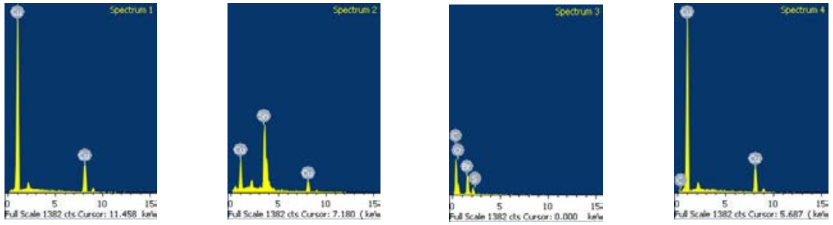
Poor Soldermask Processing

PCB Design: Non-SolderMask Design (NSMD)

- **Perfect Coverage of Surface Finish can avoid Creep Corrosion Occurrence.**

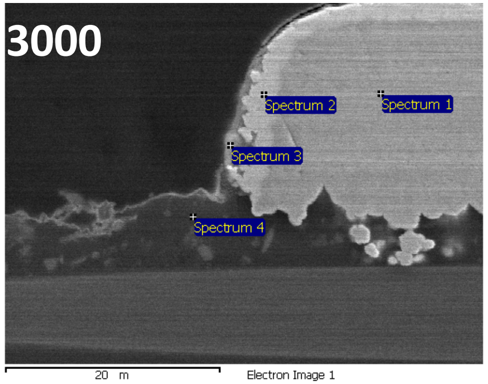


Before FoS test

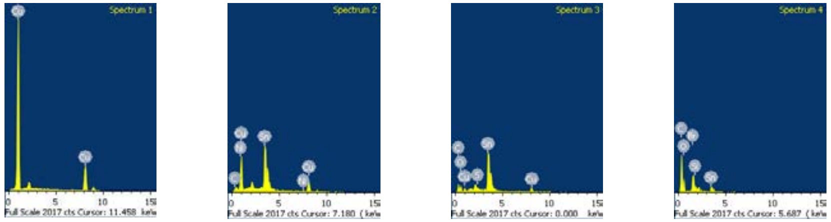


All results in weight%

ID	C	O	S	Cu	Br	Sn
Spectrum 1				100.00		
Spectrum 2				31.39		68.61
Spectrum 3	61.84	23.72	0.74		13.70	
Spectrum 4	5.08			94.92		



After FoS test



All results in weight%

ID	C	O	Si	S	Ni	Cu	Br	Sn
Spectrum 1						100.00		
Spectrum 2	2.81				2.68	35.49		59.02
Spectrum 3	8.98	13.86		1.25		14.79		61.12
Spectrum 4	54.63	24.83	1.96				10.53	8.06

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Work in progress

- The synergistic effects of chlorine on creep corrosion will be studied using Clorox as the source of chlorine gas.

- The mechanism of the influence of PCB loading on Cu and Ag corrosion rate will be studied.

- The FOS test will be verified using test boards from lots that have suffered creep corrosion in the field and from lots that did not suffer creep corrosion in the field.

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THANK YOU!

QUESTIONS?