Understanding the Effect of Different Heating Cycles on Post-Soldering Flux Residues and the Impact on Electrical Performance

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Abstract:

There are several industry-accepted methods for determining the reliability of flux residues after assembly. The recommended methods of test sample preparation do not always closely mimic the thermal cycle experienced by an assembly. Therefore, extraction from actual assemblies has become a popular method of process control to assess consistency of post-reflow cleanliness. Every method of post-reflow flux residue characterization will depend on the reflow process followed to prepare the coupon.

This investigation will focus on the effect of thermal conditions on the remainder of active ingredients in flux residues after assembly with no-clean solder pastes. Test coupons will be processed using an IR rework station with careful monitoring of thermal profile. In order to characterize the residues, IPC standard SIR testing will be conducted as well as localized extraction, followed by ion chromatography and IC/mass spec for detailed ionic and organic acid analysis. This will essentially characterize electrical reliability, while also quantifying chemical species present in the final assembly and hopefully the relationship between the two. Results will be presented to relate thermal profile to no-clean solder paste flux residues in SnPb and Pb-free processes.

Keywords: ionic cleanliness, process control, SIR testing

Introduction:

Once a printed circuit board has been fully assembled there are many different tests to choose from for quality assurance and reliability assessment. One of the most critical areas is ionic content available to degrade electrical resistance, often referred to as cleanliness. Electronics assemblies are at risk of electrochemical migration whenever there is voltage, moisture, metal, and ionic species present. Voltage and copper will always be present in the circuit; moisture can be controlled, but operational environmental conditions are sometimes unpredictable. This leaves the factor of ionic contamination that is available to moisture and voltage as critical for control of electrochemical reliability.

Logic would follow that testing every assembly for electrochemical reliability would also be critical. With traditional industry testing, this is very difficult. The ideal test would be quick, repeatable, and easily conducted on every assembly. Test requirements already exist in IPC J-standard-004 that have proven very effective at determining electrochemical reliability over many historical studies, namely surface insulation resistance (SIR) testing and electrochemical migration (ECM) testing. In IPC J-standard-001,the resistivity of solvent extract (ROSE) test is used to test the cleaning process. Each one of these tests has a drawback to easy utilization for quality assurance, whether it is test coupon preparation or time to test; they just are not easy to conduct on a large number of assemblies.

This gap in industry testing has led to the development of new tests for ionic cleanliness assessment, focused on more user-friendly tests to characterize assemblies for quality assurance. One method that has gained popularity is localized extraction followed by IC [1] . This method uses cool steam directed through a small nozzle, which condenses on the chosen board and component surfaces to dissolve any ionic species. The nozzle then extracts the solution of water and ionic species back into the test cell for testing. Current is passed through the extract and the time to reach a level of continuity is measured. The extract is then tested using ion chromatography to diagnose which ionic species are present and to quantify them.

This type of testing is particularly useful for identifying potential causes of failure once a problem has been identified on an assembly. Additionally, if an ionic risk factor has been identified, the test is useful for continued spot checking the potential risk factors in problem areas on that assembly, such as low standoff components, high thermal mass areas, sections with selective soldering, and assemblies that are cleaned. Most importantly, once an ionic risk factor has been identified as the cause of electrical failures, localized extraction can easily be incorporated into a quality assurance protocol to verify consistency in test results over time and over many assemblies.

Localized extraction will dissolve any soluble ionic species left on the board. Common sources for ionic material on circuit boards are widely varied, including board fabrication and plating residues, residues from human interaction, flux residues, etc. This encompasses intentionally-added chemicals as well as unintentional contamination. Considering this, whenever unacceptable results are encountered, it is an invitation to investigate what changed in the process and the bill of materials. During process development, a “normal” range of results should be defined, but when results fall outside of the expected range, there can be many potential reasons.

This study focuses on process changes affecting the level of ionic species present in flux residues, which can lead to different levels of electrochemical reliability and ionic cleanliness. Typically, fluxes for SMT solder pastes can be split into two categories: water-soluble and no-clean. Water-soluble pastes are classified per IPC J-standard-004 as “M” or “H” activity, which are characterized by copper corrosion, copper mirror, and SIR and ECM testing. These flux residues must be cleaned for an electrochemically reliable assembly. No-clean solder pastes are characterized as “L” activity. They are designed to balance enough fluxing capacity for soldering while consuming the ionic species during the soldering process. This will leave a residue that is benign and will not contribute to electrochemical migration. Although the name implies that these residues cannot be cleaned, it is common practice to clean these residues using a cleaning solution which helps to also dissolve non-polar species, although cleaning is not required.

These two categories of flux pose different challenges: for water-soluble pastes, it is critical to verify that flux residues have been completely removed during the cleaning process; for no-clean pastes, it is critical to verify that the flux has been properly processed to supplier recommendations. This study will investigate the impact of each of these challenges on SIR testing and localized extraction followed by IC.

Experimental Design:

The test coupon design (shown in Figure 1) used was a 68-pin LCC with a SIR pattern underneath. This component design has enough thermal mass to allow a range for reflow profiling. The component height and bottom terminations represent a typical assembly where flux residues and other contaminants can become entrapped under the component. Once the coupons had been assembled, they were installed in the humidity chamber at 40°C and 90% RH as described in IPC TM650-2.6.3.7. There is a slight deviation because the boards were not fixtured and had varied orientations with respect to the air flow (Figure 2). The company running the chambers has ensured that no condensation was evident on the SIR coupons during the testing. According to the IPC standard, passing patterns maintain a resistance higher than $10^8\Omega$ for the entirety of the testing. The results will be reported as pass or fail based on this limit.

Coupons were tested with localized extraction and IC before and after SIR testing. During localized extraction, the nozzle is much smaller than the component and can comply with the height difference between the component and board as shown in Figure 1.

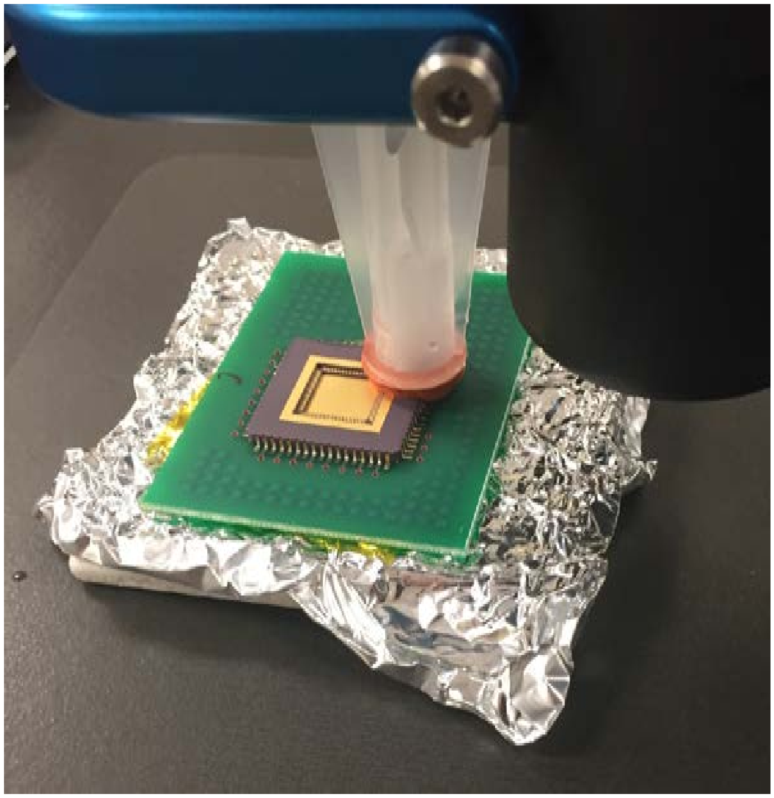

Figure 1: Test coupon in the process of localized extraction

Figure 2: SIR coupons in chamber before the start of testing

This testing was designed to show how each test works with several different types of flux residues. Since these boards and components were from the same manufacturer, it was expected that there would not be a large variation in contaminants when received. Therefore, extraction focused just on the variable of the flux residue's contribution to ionic cleanliness. The matrix of materials is referenced in Table 1. The testing was broken up into three groups: 1) the water-soluble grouping was tested to show how the results vary for washed and unwashed assemblies; 2) the SnPb no-clean and 3) Lead-free no-clean groups were tested to investigate the difference between legacy, halogenated, and newer halogen-free materials. The solder pastes were manually stencil-printed onto the coupons, ensuring consistent volumes.

Fluxes with the classification "L" are typically referred to as "no-cleans" meaning that the flux residues are expected to be benign after reflow processing. This is achieved through a balance between low activity, which is expected to be consumed during soldering, and rosin's encapsulation character. In flux residues, rosin acts to prohibit humidity from interacting with any residual ionic material, disabling the pathway for electrochemical migration. It follows that because localized extraction uses water as the sole solvent, it should mimic the worst-case intrusion of humidity on the assembly to assess how much ionic material may escape.

Table 1: Solder Paste Selections

Grouping	Material	Flux Classification	Description
Water-soluble	WU	ORH0	Unwashed SAC305 halogen-free water-soluble solder paste
	WW	ORH0	Washed SAC305 halogen-free water-soluble solder paste
Pb-free no-clean	H	ROL1	SAC305 no-clean solder paste
	HF	ROL0	SAC305 no-clean halogen-free solder paste
SnPb no-clean	N	ROL0	Sn63/Pb37 no-clean halogen-free solder paste
	L	ROL1	Sn63/Pb37 RMA legacy solder paste

For each solder paste/reflow profile combination, six coupons were assembled. Three were tested for ionic cleanliness immediately after assembly, whereas the other three were subjected to SIR testing followed by ionic cleanliness testing.

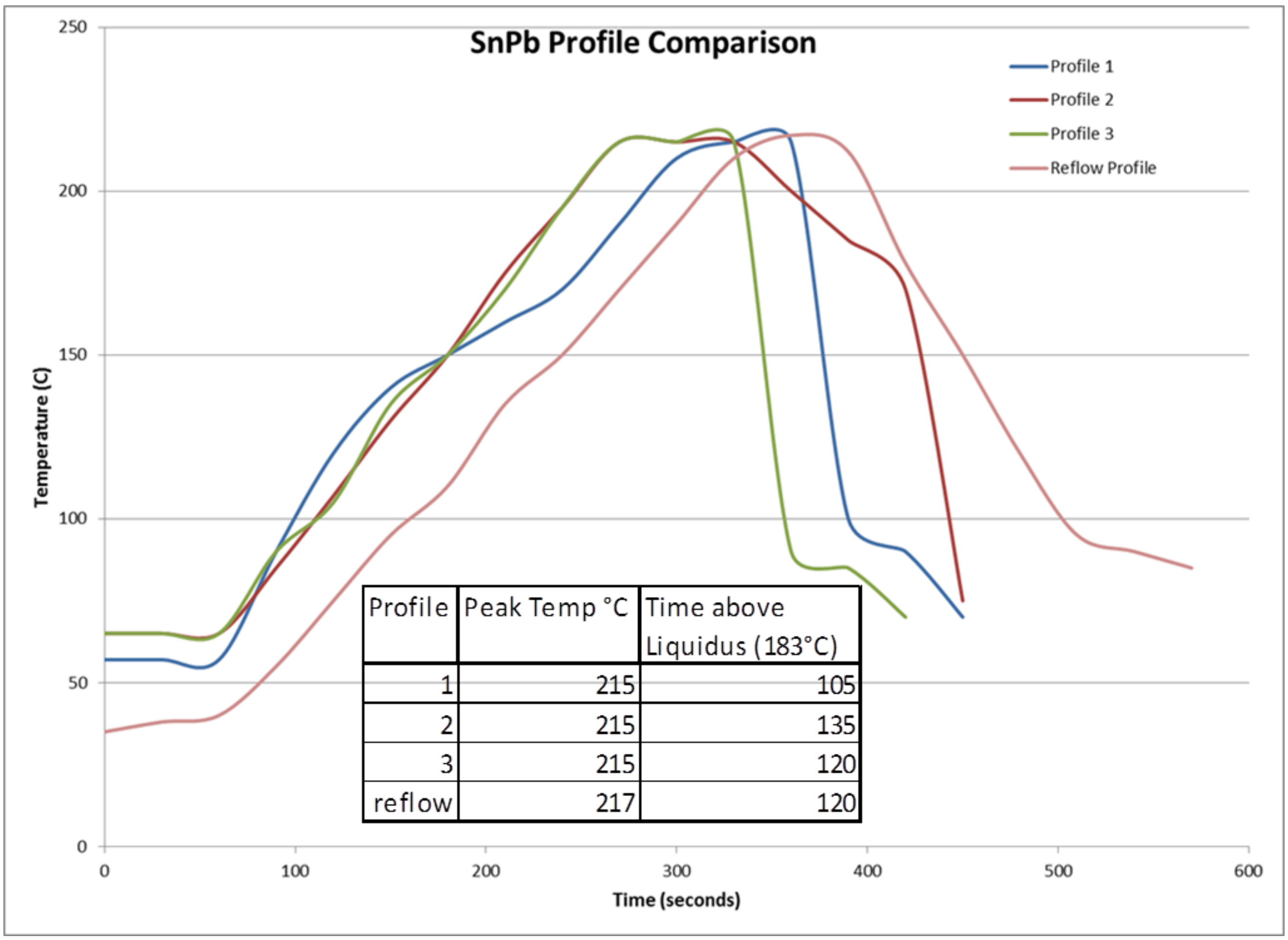

Figure 3: SnPb profiles for reflow oven and rework station

Typically, assemblies are completed using convection reflow. In previous work, it was anecdotally observed that assemblies completed using a rework station with directed IR heating and a faster cooling rate exhibited higher levels of ionic residues. To test this observation, heating profiles were developed for both the lead-free materials and SnPb materials. SAC305 has a melting range of 217-220°C, and Sn63 is eutectic, melting at 183°C. Both sets of four profiles followed the same path of logic: reflow profile, simulated reflow profile on rework station with natural (fast) cooling (Profile 1), lower peak with natural cooling (Profile 3), and lower peak with extended cooling (Profile 2). The profiles shown in Figures 3 and 4 were measured by a profiler for the reflow oven case and by the attached thermocouple on the rework station. The rework station takes less time to start ramping, thus the profiles have been slightly shifted for ease of peak and TAL comparisons.

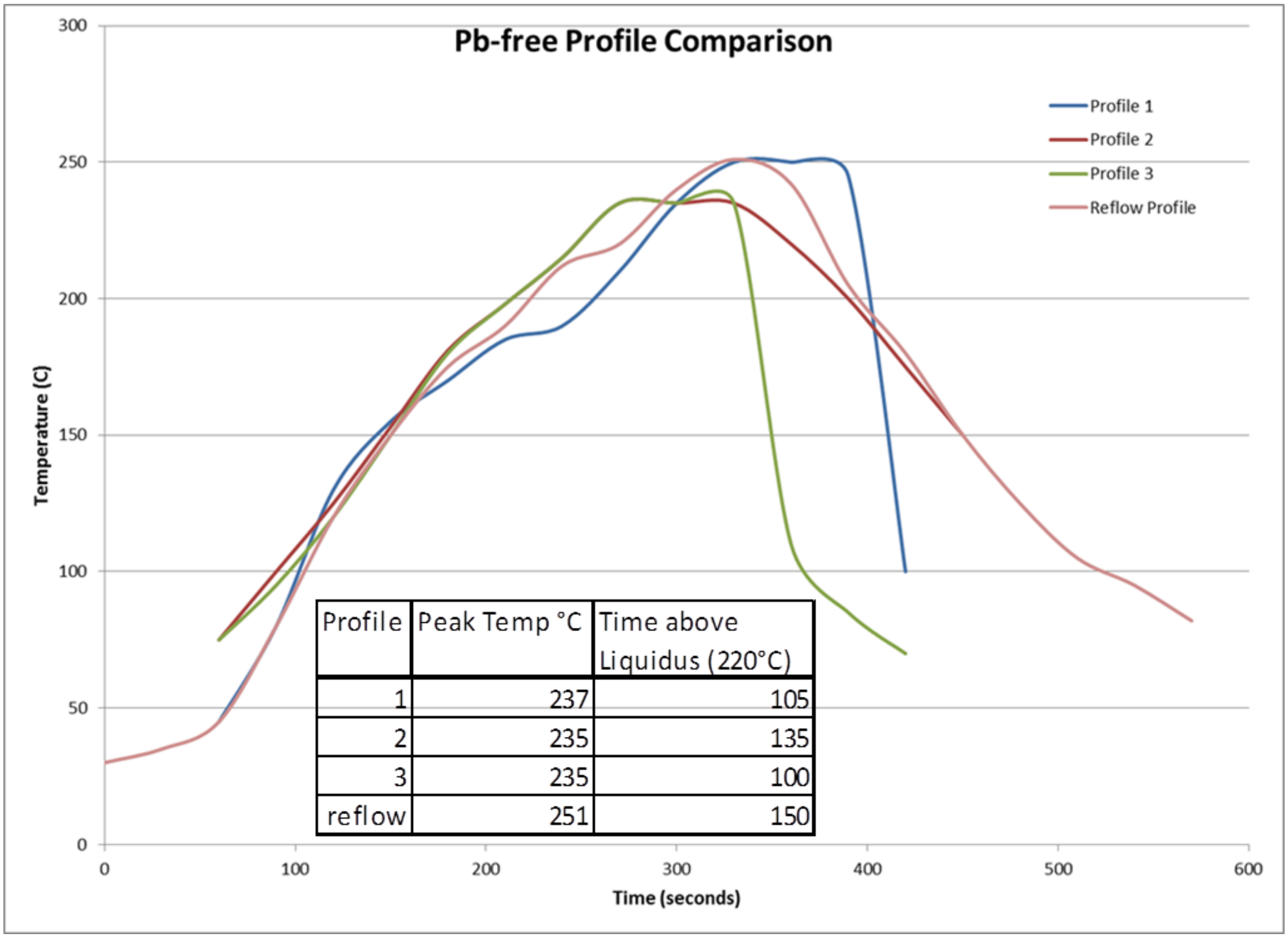

Figure 4: Lead-free profiles for reflow oven and rework station

There are three types of results reported in this study: SIR results (pass/fail based on resistance), cleanliness extraction (pass/fail based on resistivity of effluent), and IC results with measurement of ionic species. It is expected that the highest levels of ionic contamination will be present in the WU data set (see Table 1). All no-clean materials should pass, although less heating may affect the results. Details of the rework station profiles used are shown in Appendix A.

Results and Discussion:

Two sets of data were collected for coupons processed in a reflow oven with pastes HF and N (see Table 1) to verify that when heated as recommended, the results passed, as noted in Tables 3 and 4. All of the solder pastes used passed both SIR and localized extraction testing when processed as recommended by the supplier. The next data sets focus on the impact of the shorter IR heated profiles achieved on the rework station.

The results of SIR and localized extraction are pass or fail. The criteria are based on resistance of the circuit and resistivity of the extracted solution, respectively. For reference, detailed results have been included in the Appendix B. As tabulated in Tables 2-4, pass has been coded green and fails have been coded orange.

Table 2: Water soluble solder paste results

		Immediate Extraction			Post-SIR Extraction			SIR Results		
Material	Profile	1	2	3	1	2	3	1	2	3
WU	1	F	F	F	F	F	F	F	F	F
	2	F	F	F	F	F	F	F	F	F
	3	F	F	F	F	F	F	F	F	F
WW	1	P	P	P	P	P	P	P	P	P
	2	P	P	P	P	P	P	P	P	P
	3	P	P	P	P	P	P	P	P	P

The results for water-soluble solder paste show a clear definition where all uncleaned coupons failed both tests and all cleaned coupons passed. In fact, the flux residue is so concentrated with ions that the localized extraction test was very quickly over the current limit. There are several ionic species that are present in high concentrations on the unwashed boards. Overall, this was a very extreme comparison, as it is more likely that boards would be partially cleaned instead of completely uncleaned. This reinforces the high importance of cleaning all assemblies using water-soluble solder pastes.

Table 3: Lead-free no-clean solder paste results

		Immediate Extraction			Post-SIR Extraction			SIR Results		
Material	Profile	1	2	3	1	2	3	1	2	3
H	1	F	F	F	F	F	F	F	F	F
	2	P	P	P	P	P	P	P	P	P
	3	P	P	P	P	P	P	P	P	P
HF	1	P	P	P	P	P	P	P	P	P
	2	P	P	P	P	P	P	P	P	P
	3	P	P	P	P	P	P	P	P	P
	Reflow				P	P	P	P	P	P

No-clean solder pastes showed some variation based on profile. Paste H in Table 3 has one data set with profile 1 that failed both SIR and localized extraction. Paste HF meets the pass criteria for both tests at all conditions. Profile 1 was designed to be challenging due to uncontrolled cooling, essentially immediate once IR heat is removed. After 67 seconds at 235°C, the rework station rapidly cooled due to the absence of IR heating. The entire heating cycle was less than 5 minutes, whereas profiles 2 and 3 were slightly longer than 5 minutes. The time above 150°C was only slightly longer than 3 minutes. The reflow oven profile has a similar time above 150°C, but the ramp up and cool down were slower with the entire heating cycle taking about 9 minutes. All profiles are included for reference in the appendix.

Table 4: Tin-lead no-clean solder paste results										
		Immediate Extraction			Post-SIR Extraction			SIR Results		
Material	Profile	1	2	3	1	2	3	1	2	3
N	1	F	F	F	F	F	F	F	F	F
	2	P	P	P	P	P	P	P	P	P
	3	F	F	F	F	F	F	F	F	F
	Reflow				P	P	P	P	P	P
L	1	P	P	F	F	P	P	P	P	F
	2	P	P	P	P	P	P	P	P	P
	3	P	F	F	P	F	P	P	F	F

SnPb no-clean pastes also yielded passing results for reflow in an oven and profile 2, which featured controlled cooling to make a shape more similar to the reflow oven profile. Paste L exhibited some variation with the quick cool profiles, whereas the N paste was always negatively affected by quick cooling.

Looking more closely at the profiles achieved using the rework station, it was not clear why sometimes profile 1 failed, but profile 3 passed. Profile 3 was designed to have a lower peak and quick cooling. More investigation would be required to determine which aspect of profiling is the determining factor: overall heating time, peak temperature, time above liquidus, time above 150°C, or cooling rate. It was clear that controlled cooling similar to what is experienced in a reflow oven is preferred.

Summary/ Conclusions:

This study investigated three points: whether SIR and localized extraction results correlate, how water-soluble solder pastes perform in testing before and after cleaning, and how no-clean flux residues vary depending on the reflow process. First, the two test methods produced the same pass/fail results for all samples. Both differentiated when conditions deviated from the confirmed process, whether it was the cleaning process or the reflow process.

Water-soluble flux residues must always be cleaned from assemblies. The results dramatically demonstrated that the ionic species left after reflow will interact with the copper in the circuit and lead to electrochemical failures. When using this process on partially-cleaned assemblies, the variation in results will be more subtle but still indicate when something in the cleaning process has changed and the residues are not removed to a reliable level.

No-clean flux residues of all solder pastes tested passed both SIR and localized extraction tests when reflowed in convection ovens and when the cooling was controlled on the IR rework station as recommended. There was more variation on samples which cooled quickly when IR heating was removed

**Acknowledgements: **

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References

[1] Steve Shoda, Terry Munson, Cleanliness Assessment Correlation to Electronics Hardware Reliability, IPC APEX 2007

Appendix A: Rework station profiles

	PreHeat	Soak	Reflow	Cool Down
Top Heater	181	235	235	
Bottom Power	2	2	2	2
Time	122	91	32	90
Dwell Time	0	35	1	

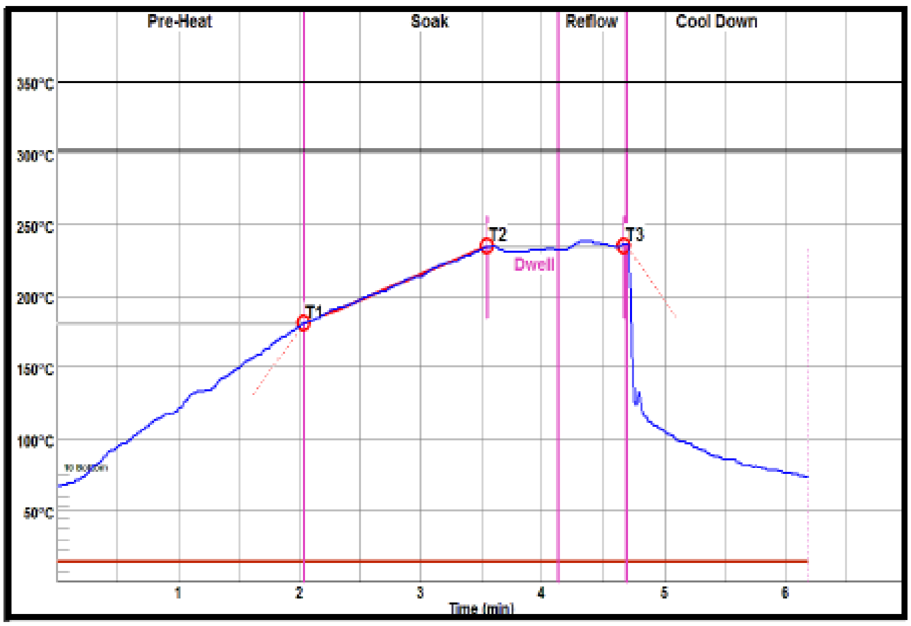

Figure A1: Pb-free standard profile 1

	PreHeat	Soak	Reflow	Cool Down
Top Heater	181	235	151	
Bottom Power	2	2	2	2
Time	122	91	111	90
Dwell Time	0	66	66	

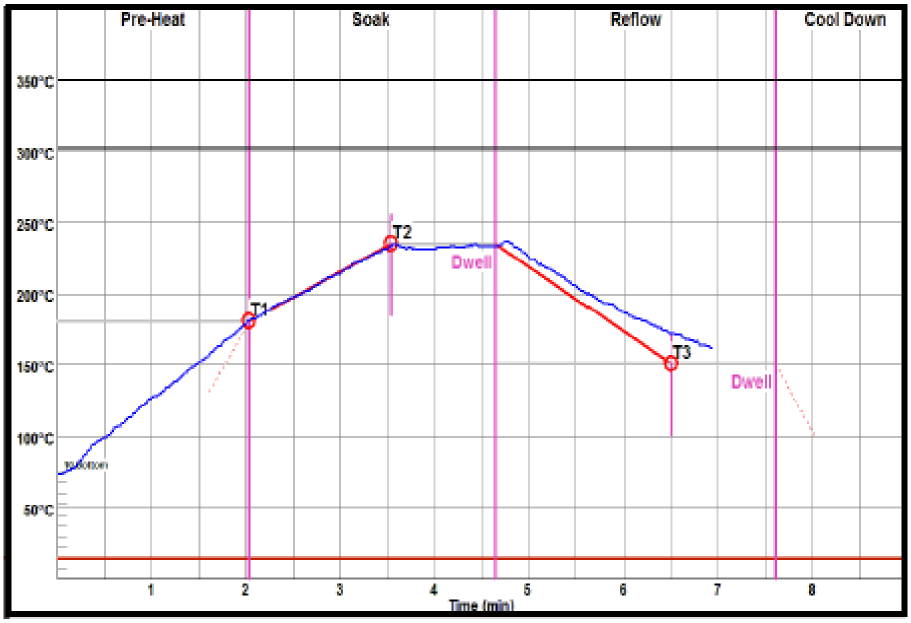

Figure A2: Pb-free profile 2 – Lower peak, controlled cooling

	PreHeat	Soak	Reflow	Cool Down
Top Heater	181	235	235	
Bottom Power	2	2	2	2
Time	122	91	32	90
Dwell Time	0	35	1	

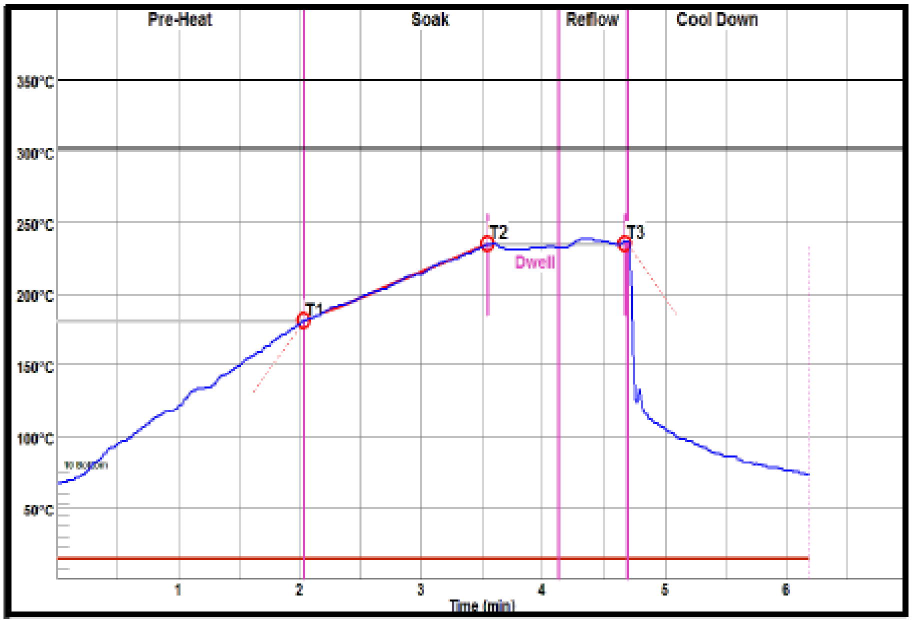

Figure A3: Pb-free profile 3 – Lower peak, quick (uncontrolled) cool

	PreHeat	Soak	Reflow	Cool Down
Top Heater	120	160	215	
Bottom Power	2	2	2	2
Time	61	77	95	90
Dwell Time	0	21	60	

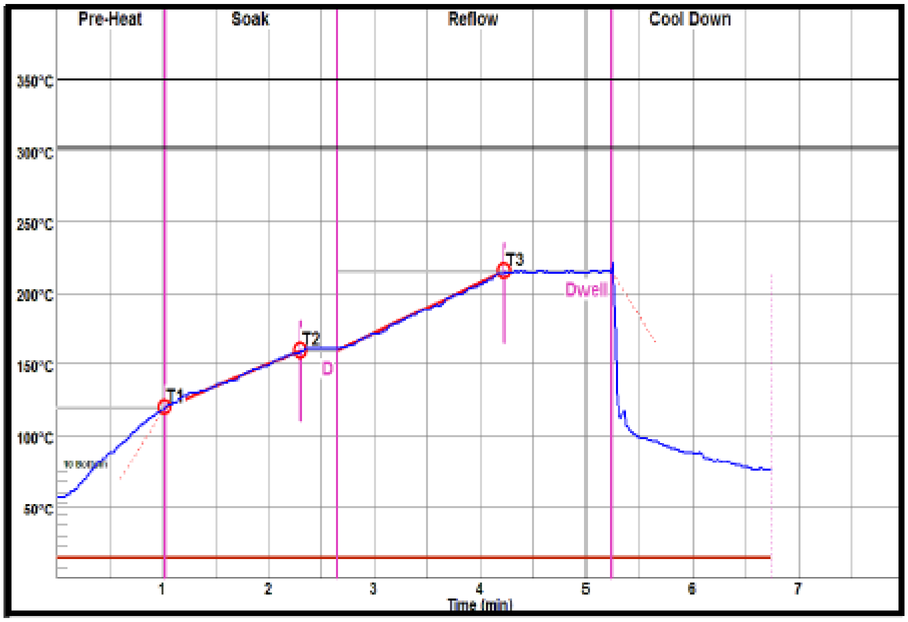

Figure A4: SnPb standard profile 1

	PreHeat	Soak	Reflow	Cool Down
Top Heater	150	215	130	
Bottom Power	2	2	2	2
Time	120	88	90	90
Dwell Time	0	60	1	

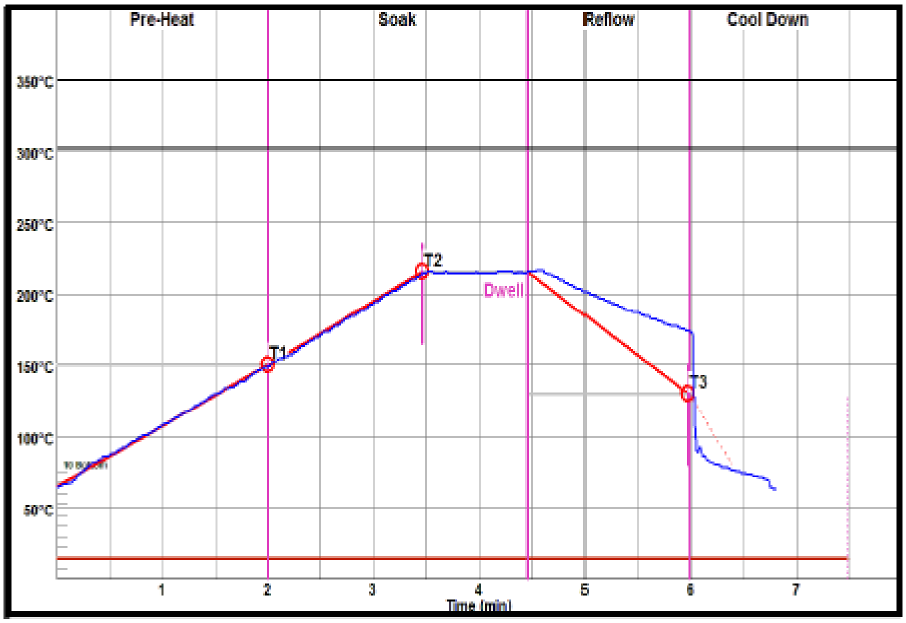

Figure A5: SnPb profile 2: Lower peak, controlled cool

	PreHeat	Soak	Reflow	Cool Down
Top Heater	150	215	215	
Bottom Power	2	2	2	2
Time	120	88	30	90
Dwell Time	0	30	1	

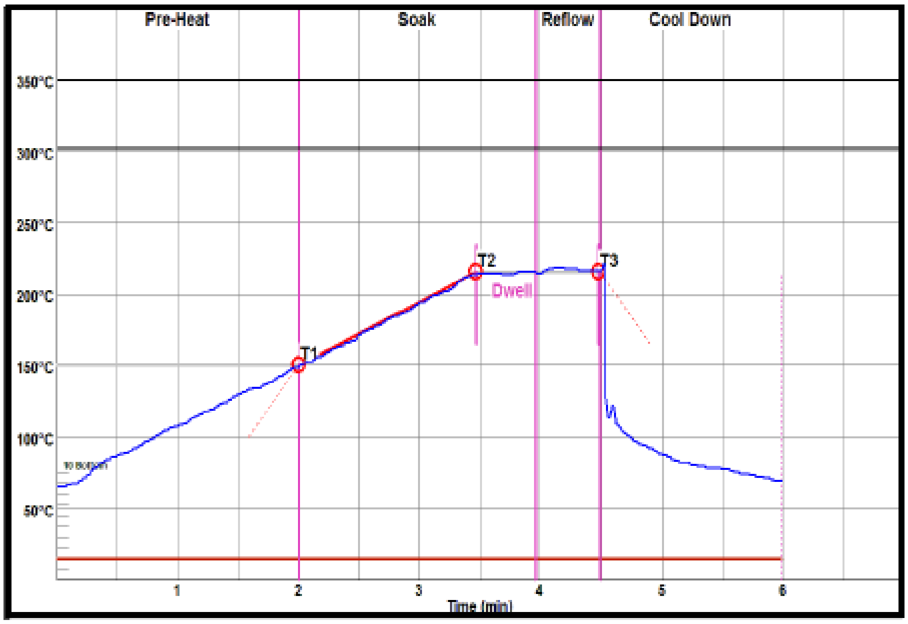

Figure A6: SnPb profile 3 – Lower peak, quick (uncontrolled) cool

Appendix B: Localized extraction/IC results

Paste	Profile	Test	F	ACETATE	FORMATE	Cl^-	NO_2^-	Br^-	NO_3^-	PO_4^{-3}	SO_4^{-2}	WOA	MSA	Li^+	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Results	Time(sec)
WU	1	After SIR	0	165.62	97.13	4.44	0	11.12	14.77	0	11.96	310.16	0	0	96.67	13.42	0	0	0	Fail	1
WU	1	After SIR	0	162.01	126.21	2.73	0	14.54	14.36	0	14.62	346.26	0	0	101.05	16.40	0	0	0	Fail	1
WU	1	After SIR	0	164.25	102.62	2.25	0	12.86	13.99	0	12.70	307.55	0	0	98.97	20.47	0	0	0	Fail	2
WU	1	Before SIR	0	171.04	99.87	5.85	0	10.78	14.77	0	10.54	295.64	0	0	95.03	12.05	0	0	0	Fail	1
WU	1	Before SIR	0	181.01	118.77	4.05	0	24.05	14.89	0	12.79	348.47	0	0	104.06	13.31	0	0	0	Fail	2
WU	1	Before SIR	0	184.74	104.05	2.98	0	23.03	14.81	0	10.67	306.71	0	0	107.37	10.05	0	0	0	Fail	1
WU	3	After SIR	0	112.54	56.65	3.24	0	12.05	0.98	0	8.54	176.62	0	0	54.21	8.98	0	0	0	Fail	11
WU	3	After SIR	0	121.05	51.04	3.15	0	14.07	2.04	0	9.06	212.35	0	0	31.91	9.25	0	0	0	Fail	8
WU	3	After SIR	0	98.98	49.98	3.06	0	12.35	1.06	0	7.41	206.54	0	0	48.05	9.64	0	0	0	Fail	13
WU	3	Before SIR	0	121.65	52.06	2.54	0	19.87	1.51	0	8.32	185.57	0	0	35.26	7.98	0	0	0	Fail	9
WU	3	Before SIR	0	112.04	49.98	2.36	0	14.69	1.31	0	9.16	194.87	0	0	31.24	8.15	0	0	0	Fail	8
WU	3	Before SIR	0	104.04	51.24	3.16	0	11.04	1.36	0	7.04	202.06	0	0	42.15	9.36	0	0	0	Fail	11
WU	2	After SIR	0	105.25	32.26	2.87	0	8.36	6.65	0	5.15	151.65	0	0	35.65	7.54	0	0	0	Fail	19
WU	2	After SIR	0	98.78	22.98	2.07	0	7.04	5.71	0	5.35	163.26	0	0	31.05	6.59	0	0	0	Fail	15
WU	2	After SIR	0	104.05	30.15	2.71	0	7.07	6.19	0	4.29	187.98	0	0	28.08	7.14	0	0	0	Fail	17
WU	2	Before SIR	0	102.15	29.45	2.53	0	6.98	6.13	0	5.19	201.06	0	0	24.08	6.98	0	0	0	Fail	12
WU	2	Before SIR	0	79.98	21.16	2.62	0	8.41	6.82	0	5.06	158.04	0	0	31.05	6.35	0	0	0	Fail	18
WU	2	Before SIR	0	87.05	23.18	2.24	0	7.48	7.12	0	5.71	163.25	0	0	30.18	7.14	0	0	0	Fail	15

Figure B1: Paste WU

Paste	Profile	Test	F	ACETATE	FORMATE	Cl^-	NO_2^-	Br^-	NO_3^-	PO_4^{-3}	SO_4^{-2}	WOA	MSA	Li^+	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Results	Time(sec)
WW	1	After SIR	0	2.77	0.79	0.70	0	0.96	0.74	0	0.73	18.04	0	0	1.24	1.05	0	0	0	Pass	180
WW	1	After SIR	0	1.84	0.98	1.99	0	0.96	1.06	0	0.97	19.54	0	0	1.67	1.36	0	0	0	Pass	178
WW	1	After SIR	0	1.64	0.87	1.04	0	0.85	0.40	0	0.33	18.78	0	0	1.09	1.04	0	0	0	Pass	180
WW	1	Before SIR	0	1.77	0.95	0.97	0	0.79	1.19	0	0.87	19.74	0	0	1.31	1.21	0	0	0	Pass	178
WW	1	Before SIR	0	2.05	0.98	0.95	0	0.48	0.93	0	0.17	18.24	0	0	1.41	1.09	0	0	0	Pass	180
WW	1	Before SIR	0	2.01	0.79	1.63	0	1.89	0.85	0	0.24	19.65	0	0	1.26	1.19	0	0	0	Pass	179
WW	3	After SIR	0	2.02	0.54	0.26	0	1.04	0.52	0	0.35	15.64	0	0	0.98	0.57	0	0	0	Pass	180
WW	3	After SIR	0	1.91	0.63	0.21	0	1.15	0.04	0	0.26	14.21	0	0	0.79	0.36	0	0	0	Pass	180
WW	3	After SIR	0	1.83	0.54	0.25	0	1.46	1.23	0	0.35	12.65	0	0	0.97	0.52	0	0	0	Pass	180
WW	3	Before SIR	0	1.99	0.29	0.29	0	1.24	1.58	0	0.29	15.07	0	0	0.83	0.27	0	0	0	Pass	180
WW	3	Before SIR	0	1.91	0.35	0.19	0	1.36	1.47	0	0.35	16.05	0	0	0.87	0.32	0	0	0	Pass	180
WW	3	Before SIR	0	1.81	0.24	0.31	0	1.51	1.04	0	0.22	16.27	0	0	0.98	0.36	0	0	0	Pass	180
WW	2	After SIR	0	0.87	0.21	0.31	0	0.98	0.87	0	0.16	11.14	0	0	0.78	0.24	0	0	0	Pass	180
WW	2	After SIR	0	0.98	0.29	0.26	0	0.87	0.96	0	0.26	10.53	0	0	0.81	0.21	0	0	0	Pass	180
WW	2	After SIR	0	0.52	0.24	0.26	0	0.95	0.82	0	0.25	9.98	0	0	0.87	0.26	0	0	0	Pass	180
WW	2	Before SIR	0	0.67	0.21	0.22	0	0.83	0.78	0	0.35	10.50	0	0	0.59	0.25	0	0	0	Pass	180
WW	2	Before SIR	0	0.29	0.22	0.35	0	0.67	0.81	0	0.24	8.74	0	0	0.67	0.27	0	0	0	Pass	180
WW	2	Before SIR	0	0.38	0.25	0.54	0	0.81	0.97	0	0.16	9.09	0	0	0.81	0.21	0	0	0	Pass	180

Figure B2: Paste WW

Paste	Profile	Test	F	ACETATE	FORMATE	Cl^-	NO_2^-	Br^-	NO_3^-	PO_4^{-3}	SO_4^{-2}	WOA	MSA	Li^+	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Results	Time(sec)
H	1	After SIR	0	**5.26**	0	1.05	0.03	1.51	0	0	0.65	**34.07**	0	0	**6.33**	1.84	0	0	0	**Fail**	89
H	1	After SIR	0	**4.46**	0	0.98	0	1.08	0	0	0.51	**33.12**	0	0	**4.05**	1.69	0	0	0	**Fail**	92
H	1	After SIR	0	**7.25**	0	0.78	0	1.54	0	0	0.52	**34.29**	0	0	**7.30**	1.88	0	0	0	**Fail**	80
H	1	Before SIR	0	**4.47**	0	1.02	0	1.37	0	0	0.57	**34.50**	0	0	**3.72**	1.74	0	0	0	**Fail**	92
H	1	Before SIR	0	**3.83**	0	0.51	0	1.08	0	0	0.42	**32.83**	0	0	**3.70**	1.91	0	0	0	**Fail**	94
H	1	Before SIR	0	**4.65**	0	0.89	0	0.98	0	0	0.06	**33.56**	0	0	**4.03**	1.77	0	0	0	**Fail**	89
H	3	After SIR	0	1.81	0	1.51	0	2.61	0	0	0.45	21.35	0	0	1.17	0.65	0	0	0	Clean	180
H	3	After SIR	0	1.79	0	1.25	0	2.11	0	0	0.34	20.71	0	0	1.45	0.93	0	0	0	Clean	180
H	3	After SIR	0	0.98	0	1.62	0	2.05	0	0	0.65	19.87	0	0	1.35	0.65	0	0	0	Clean	180
H	3	Before SIR	0	1.50	0	1.25	0	2.36	0	0	0.54	21.21	0	0	1.25	0.65	0	0	0	Clean	180
H	3	Before SIR	0	1.03	0	1.36	0	1.98	0	0	0.62	19.54	0	0	1.36	0.65	0	0	0	Clean	180
H	3	Before SIR	0	1.24	0	1.54	0	2.43	0	0	0.35	22.31	0	0	1.25	0.65	0	0	0	Clean	180
H	2	After SIR	0	1.38	0	0.60	0	1.32	0	0	1.52	13.17	0	0	0.91	0.82	0	0	0	Clean	180
H	2	After SIR	0	1.21	0	0.65	0	1.05	0	0	0.98	15.24	0	0	1.10	0.54	0	0	0	Clean	180
H	2	After SIR	0	1.64	0	0.81	0	1.66	0	0	1.21	13.60	0	0	0.87	0.62	0	0	0	Clean	180
H	2	Before SIR	0	2.04	0	0.68	0	1.54	0	0	1.06	16.35	0	0	1.24	0.35	0	0	0	Clean	180
H	2	Before SIR	0	1.87	0	0.57	0	1.29	0	0	1.69	12.35	0	0	1.35	0.51	0	0	0	Clean	180
H	2	Before SIR	0	1.69	0	0.63	0	1.21	0	0	1.24	15.32	0	0	1.06	0.44	0	0	0	Clean	180

Figure B3: Paste H

Paste	Profile	Test	F	ACETATE	FORMATE	Cl^-	NO_2^-	Br^-	NO_3^-	PO_4^{-3}	SO_4^{-2}	WOA	MSA	Li^+	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Results	Time(sec)
HF	1	After SIR	0	2.35	0	0.54	0	0.54	0	0	0.26	22.32	0	0	1.87	0	0	0	0	Pass	172
HF	1	After SIR	0	2.16	0	0.69	0	0.62	0	0	0.54	21.36	0	0	2.15	0	0	0	0	Pass	180
HF	1	After SIR	0	2.04	0	0.51	0	0.55	0	0	0.37	23.11	0	0	1.81	0	0	0	0	Pass	163
HF	1	Before SIR	0	2.62	0	0.64	0	0.08	0	0	0.48	22.80	0	0	1.98	0	0	0	0	Pass	169
HF	1	Before SIR	0	2.51	0	0.29	0	0.28	0	0	0.51	20.65	0	0	1.41	0	0	0	0	Pass	180
HF	1	Before SIR	0	2.65	0	0.35	0	3.20	0	0	0.66	23.73	0	0	1.87	0	0	0	0	Pass	171
HF	3	After SIR	0	1.46	0	0.44	0	0.47	0	0	0.41	18.68	0	0	1.87	0	0	0	0	Pass	180
HF	3	After SIR	0	1.36	0	0.65	0	0.68	0	0	0.25	17.69	0	0	1.36	0	0	0	0	Pass	180
HF	3	After SIR	0	1.25	0	0.58	0	0.29	0	0	0.36	18.54	0	0	1.54	0	0	0	0	Pass	180
HF	3	Before SIR	0	1.09	0	0.62	0	0.35	0	0	0.52	16.35	0	0	1.69	0	0	0	0	Pass	180
HF	3	Before SIR	0	1.54	0	0.35	0	0.29	0	0	0.57	17.41	0	0	1.62	0	0	0	0	Pass	180
HF	3	Before SIR	0	1.69	0	0.57	0	0.54	0	0	0.55	18.21	0	0	1.77	0	0	0	0	Pass	180
HF	2	After SIR	0	1.24	0	0.51	0	0.63	0	0	0.64	13.65	0	0	0.87	0	0	0	0	Pass	180
HF	2	After SIR	0	1.21	0	0.27	0	0.52	0	0	0.46	14.24	0	0	0.81	0	0	0	0	Pass	180
HF	2	After SIR	0	1.36	0	0.35	0	0.44	0	0	0.29	13.26	0	0	0.57	0	0	0	0	Pass	180
HF	2	Before SIR	0	1.05	0	0.26	0	0.58	0	0	0.35	12.54	0	0	0.95	0	0	0	0	Pass	180
HF	2	Before SIR	0	1.65	0	0.38	0	0.57	0	0	0.41	11.64	0	0	0.58	0	0	0	0	Pass	180
HF	2	Before SIR	0	1.27	0	0.44	0	0.65	0	0	0.47	12.09	0	0	0.67	0	0	0	0	Pass	180
HF	Reflow	After SIR	0	0.87	0	0.33	0	1.21	0	0	0.35	9.98	0	0	1.21	0	0	0	0	Pass	180
HF	Reflow	After SIR	0	0.95	0	0.26	0	1.36	0	0	0.37	9.51	0	0	1.06	0	0	0	0	Pass	180
HF	Reflow	After SIR	0	0.87	0	0.35	0	1.51	0	0	0.33	9.69	0	0	1.25	0	0	0	0	Pass	180

Figure B4: Paste HF Results

Paste	Profile	Test	F	ACETATE	FORMATE	Cl^-	NO_2^-	Br^-	NO_3^-	PO_4^{-3}	SO_4^{-2}	WOA	MSA	Li^+	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Results	Time(sec)
N	1	After SIR	0	4.65	0	0.94	0	0.64	0	0	0.21	57.95	0	0	4.65	0	0	0	0	Fail	62
N	1	After SIR	0	4.59	0	0.95	0	0.58	0	0	0.26	53.65	0	0	4.51	0	0	0	0	Fail	68
N	1	After SIR	0	4.97	0	0.93	0	0.69	0	0	0.36	63.16	0	0	6.37	0	0	0	0	Fail	54
N	1	Before SIR	0	5.14	0	0.54	0	0.59	0	0	0.26	71.54	0	0	6.89	0	0	0	0	Fail	52
N	1	Before SIR	0	4.84	0	0.97	0	0.66	0	0	0.24	69.54	0	0	6.54	0	0	0	0	Fail	49
N	1	Before SIR	0	5.27	0	0.84	0	0.59	0	0	0.24	70.46	0	0	6.51	0	0	0	0	Fail	63
N	3	After SIR	0	4.21	0	0.68	0	0.41	0	0	0.39	50.21	0	0	5.21	0	0	0	0	Fail	89
N	3	After SIR	0	4.06	0	0.87	0	0.65	0	0	0.26	44.65	0	0	4.84	0	0	0	0	Fail	106
N	3	After SIR	0	3.95	0	0.92	0	0.26	0	0	0.35	51.36	0	0	5.69	0	0	0	0	Fail	93
N	3	Before SIR	0	4.11	0	0.87	0	0.35	0	0	0.29	49.35	0	0	4.89	0	0	0	0	Fail	102
N	3	Before SIR	0	4.32	0	0.95	0	0.25	0	0	0.34	52.13	0	0	4.93	0	0	0	0	Fail	94
N	3	Before SIR	0	3.87	0	0.58	0	0.66	0	0	0.70	42.35	0	0	4.15	0	0	0	0	Fail	110
N	2	After SIR	0	1.21	0	0.63	0	0.41	0	0	0.36	13.65	0	0	0.63	0	0	0	0	Pass	180
N	2	After SIR	0	1.36	0	0.54	0	0.29	0	0	0.35	18.24	0	0	0.54	0	0	0	0	Pass	180
N	2	After SIR	0	1.25	0	0.68	0	0.35	0	0	0.26	16.35	0	0	0.63	0	0	0	0	Pass	180
N	2	Before SIR	0	1.14	0	0.46	0	0.47	0	0	0.35	14.65	0	0	0.58	0	0	0	0	Pass	180
N	2	Before SIR	0	1.54	0	0.65	0	0.63	0	0	0.16	13.65	0	0	0.55	0	0	0	0	Pass	180
N	2	Before SIR	0	0.99	0	0.59	0	0.55	0	0	0.35	14.24	0	0	0.61	0	0	0	0	Pass	180
N	Reflow	After SIR	0	1.31	0	0.41	0	1.85	0	0	0.41	8.95	0	0	0.21	0	0	0	0	Pass	180
N	Reflow	After SIR	0	1.09	0	0.62	0	1.98	0	0	0.21	9.54	0	0	0.26	0	0	0	0	Pass	180
N	Reflow	After SIR	0	1.25	0	0.35	0	1.47	0	0	0.35	8.79	0	0	0.35	0	0	0	0	Pass	180

Figure B5: Paste N

Paste	Profile	Test	F	ACETATE	FORMATE	Cl^-	NO_2^-	Br^-	NO_3^-	PO_4^{-3}	SO_4^{-2}	WOA	MSA	Li^+	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Results	Time(sec)
L	1	After SIR	0	4.54	0	2.98	0	1.09	0	0	1.37	24.04	0	0	2.54	1.51	0	0	0	Pass	144
L	1	After SIR	0	3.98	0	2.69	0	1.05	0	0	1.24	22.65	0	0	2.65	1.63	0	0	0	Pass	165
L	1	After SIR	0	5.41	0	2.87	0	1.26	0	0	1.36	31.25	0	0	3.12	2.83	0	0	0	Fail	102
L	1	Before SIR	0	4.66	0	2.57	0	1.36	0	0	1.25	26.54	0	0	2.91	2.51	0	0	0	Fail	111
L	1	Before SIR	0	4.95	0	2.88	0	1.24	0	0	1.05	21.35	0	0	2.11	1.67	0	0	0	Pass	151
L	1	Before SIR	0	4.81	0	2.81	0	1.04	0	0	1.45	23.96	0	0	2.39	1.86	0	0	0	Pass	134
L	3	After SIR	0	3.65	0	2.71	0	1.20	0	0	1.89	19.98	0	0	2.15	0.87	0	0	0	Pass	169
L	3	After SIR	0	3.98	0	2.69	0	1.32	0	0	1.89	30.14	0	0	4.21	1.84	0	0	0	Fail	104
L	3	After SIR	0	3.51	0	2.61	0	1.05	0	0	1.89	27.54	0	0	3.62	2.16	0	0	0	Fail	112
L	3	Before SIR	0	2.85	0	2.54	0	1.22	0	0	1.89	23.16	0	0	2.61	0.84	0	0	0	Pass	141
L	3	Before SIR	0	4.14	0	2.84	0	1.96	0	0	1.89	28.25	0	0	4.37	3.21	0	0	0	Fail	107
L	3	Before SIR	0	2.11	0	2.59	0	1.54	0	0	1.89	17.98	0	0	2.26	0.88	0	0	0	Pass	178
L	2	After SIR	0	2.46	0	0.85	0	0.81	0	0	1.74	6.68	0	0	1.27	0.53	0	0	0	Pass	180
L	2	After SIR	0	2.31	0	0.69	0	0.63	0	0	1.31	6.21	0	0	1.05	0.46	0	0	0	Pass	180
L	2	After SIR	0	2.20	0	0.91	0	0.59	0	0	1.06	5.98	0	0	1.24	0.54	0	0	0	Pass	180
L	2	Before SIR	0	2.61	0	0.98	0	0.57	0	0	1.54	7.99	0	0	1.27	0.29	0	0	0	Pass	180
L	2	Before SIR	0	2.36	0	1.02	0	0.61	0	0	1.25	5.14	0	0	1.36	0.37	0	0	0	Pass	180
L	2	Before SIR	0	2.45	0	0.98	0	0.54	0	0	1.33	6.95	0	0	1.54	0.51	0	0	0	Pass	180

Figure B6: Paste L