As originally published in the IPC APEX EXPO Proceedings.

No-Clean Flux Residue and Underfill Compatibility Effects on Electrical Reliability

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No-clean soldering processes dominate the commercial electronics manufacturing world. With the explosion of growth in handheld electronics devices, manufacturers have been forced to look for ways to reinforce their assemblies against the inevitable bumps and drops that their products experience in the field. One method of reinforcement has been the utilization of underfills to "glue" certain surface mount devices (SMDs) to the PCB. This provides additional mechanical strength over and above the soldered connections. Bumped SMDs attached to the PCB with a no-clean soldering process offer the unavoidable scenario of the underfill coming in contact with a flux residue. This may or may not create a reliability issue. No-clean solder paste flux chemistries can vary. Some have halogens and others do not. Some have standard residues and others have residues optimized for pin probing. There are also a number of underfill chemistries on the market. Furthermore, underfill curing conditions vary depending on whether the SMDs are exposed on the surface of the PCB or underneath an RF shield. This paper will discuss an experiment designed to measure the electrical reliability of various combinations of underfill and no-clean flux residues, as measured with J-STD-004B SIR (IPC-TM-650 2.6.3.7).

<u>Procedural Backgroup and Set-Up</u>

For the experiment, a matrix of three different Pb-Free, no-clean solder pastes and four different underfills were used. The individual materials (solder pastes and underfills) were tested by themselves, as well, in order to establish the baseline performance for each.

The solder pastes are described as the following:

1) Halogen-containing with a standard residue
2) Halogen-free with a standard residue
3) Halogen-free with a residue optimized for pin-probing

Note: All pastes contained the SAC305 alloy (96.5%Sn 3.0%Ag 0.5%Cu)

The four underfills are described by the respective manufacturers as follows:

1) Underfill A – is a reworkable underfill encapsulant for CSP and BGA encapsulation that cures quickly at low temperature. It is capable of flowing quickly across distances of 750 mils and greater. This encapsulant exhibits excellent adhesion to organic substrates.
2) Underfill B - is a reworkable underfill encapsulant for CSP and BGA encapsulation that cures quickly at low temperature. It is capable of flowing quickly across distances of 750 mils and greater. This encapsulant exhibits excellent adhesion to organic substrates.
3) Underfill C - is a reworkable underfill encapsulant for CSP and BGA encapsulation that cures quickly at low temperature. It is capable of flowing quickly across distances of 750 mils and greater. This encapsulant exhibits excellent adhesion to organic substrates.
4) Underfill D – reworkable epoxy underfill is designed for CSP and BGA applications. It cures quickly at moderate temperatures to minimize stress to other components, and when cured provides excellent mechanical stress protection for solder joints.

Note: The author's company does not manufacture underfills. These underfills were sourced from two world class underfill manufacturers and the individual chemistries were selected for this experiment based upon their popularity.

Since the experiment seeks to measure the "compatibility" of the no-clean solder pastes residues and underfills based on surface insulation resistance (SIR) performance, the IPC-B-24 SIR test coupon was used as the test vehicle. Each test coupon contains four SIR patterns. Two IPC-B-24 SIR test coupons (a total of eight SIR patterns) were prepared and tested for each individual material and solder paste/underfill combination.

Furthermore, an additional objective of understanding what impact "entrapment" under an RF shield has on the SIR performance of such combinations was incorporated into the experiment. Two SIR patterns, patterns B and D, on each IPC-B-24 SIR test coupon were covered with RF shields. Every IPC-B-24 SIR test coupon, whether using solder paste alone, underfill alone, or a solder paste/underfill combination, was prepared with the RF shields affixed in place - both during solder paste reflow and underfill curing. The RF shields were cleaned with isopropyl alcohol before being used. Figures 1 and 2 are photographs of the RF shields that were used.

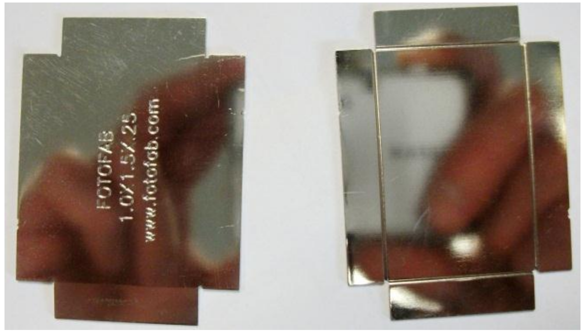


Figure 1 - Unfolded RF Shield

Figure 2 - Folded RF Shield

The following photograph (Figure 3) shows the location of the RF shields and thermocouples as used for establishing the solder paste reflow profile and underfill cure profiles.

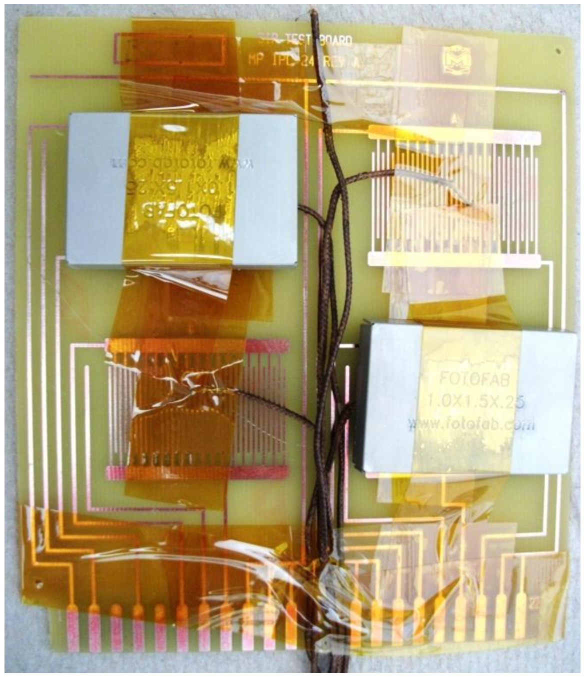


Figure 3 - IPC-B-24 SIR Test Coupon showing location of thermocouples and RF shields

Figure 4 shows the profile used to reflow the three solder pastes. The thermocouples, identified in the reflow profile as TC 2 and TC 5, were located on the SIR patterns under the RF shields. Those identified as TC 3 and TC 4 were located on the exposed SIR patterns. The exposed SIR patterns achieved a peak temperature of ~249°C and the SIR patterns covered with the RF shields achieved a peak temperature of ~244°C.

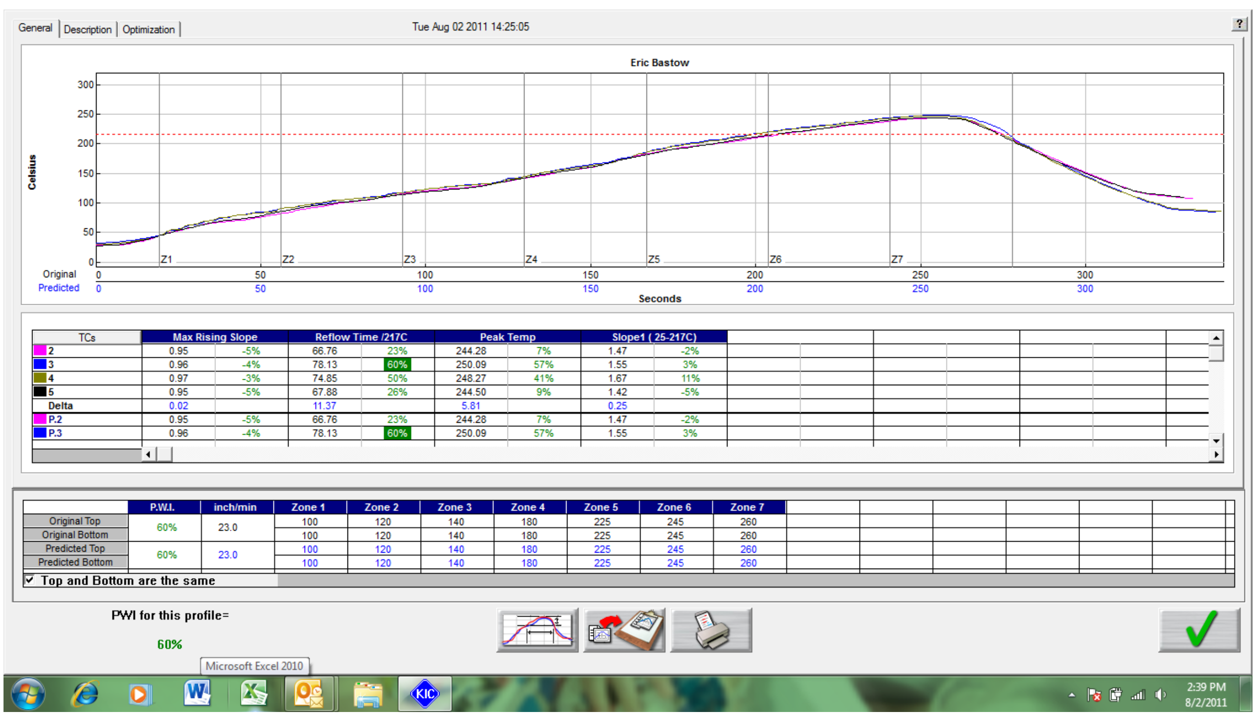


Figure 4 - Solder Paste Reflow Profile

The following were the manufacturer recommended cure cycles for the respective underfills:

1) Underfill A – 165°C for 5 minutes
2) Underfill B – 150°C for 1 to 6 minutes
3) Underfill C – 150°C for 3 to 6 minutes
4) Underfill D – 130°C for ≥ 8 minutes

Figures 5, 6, and 7 show the underfill cure profiles that were obtained using a set-up similar to what is depicted in Figure 3. For underfills B and C, the same cure profile was used (Figure 6). No care was taken to identify which thermocouples were located under the RF shields and which were located on the exposed SIR patterns. Presumably the patterns under the RF shields would have achieved a slightly lower peak temperature than those located on the exposed SIR patterns.

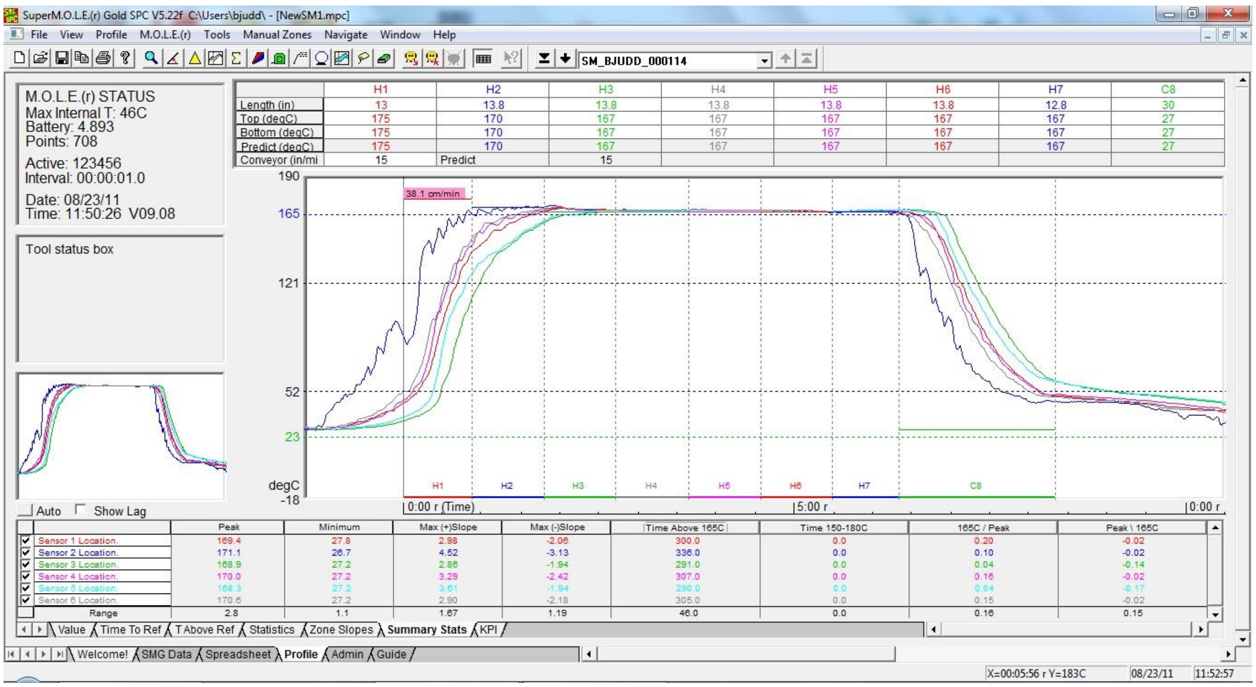


Figure 5 - Cure Profile used for Underfill A

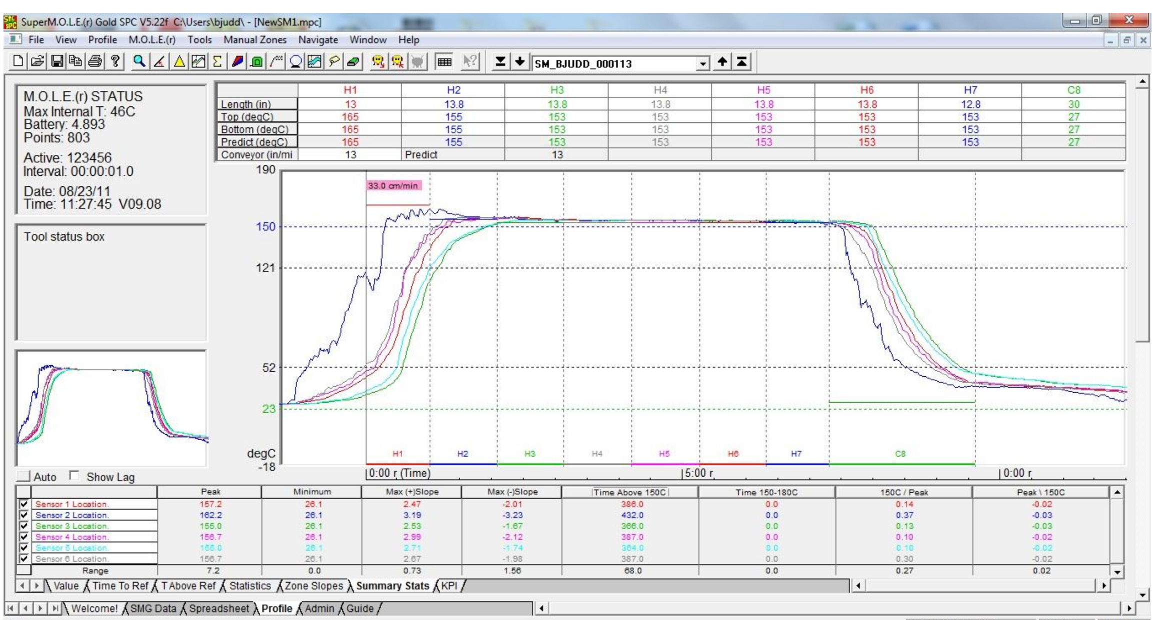


Figure 6 - Cure Profile used for Underfills B and C

Figure 7 - Cure Profile used for Underfill D

Procedure

For the two SIR test coupons prepared for each solder paste, the paste was stencil printed onto the test coupons using a stencil that is in accordance with the IPC prescribed stencil parameters. Then an RF shield was affixed over patterns B and D on each of the two SIR test coupons (see Figure 8). The SIR test coupons were then submitted to the reflow profile depicted in Figure 4. Figure 9 shows the SIR test coupon after it was reflowed. Figure 10 shows the reflowed SIR test coupon with the RF shields removed.

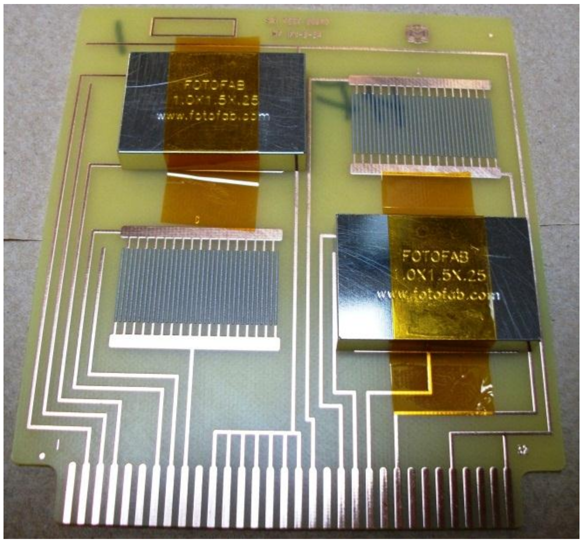


Figure 8 - SIR Test Coupon Showing Printed Paste and RF Shields Affixed Over Patterns B and D

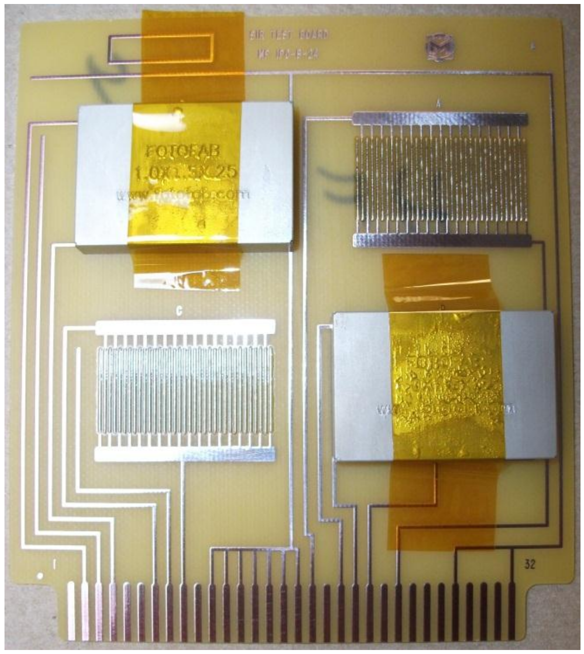


Figure 9 - Pasted SIR Test Coupon after Reflow

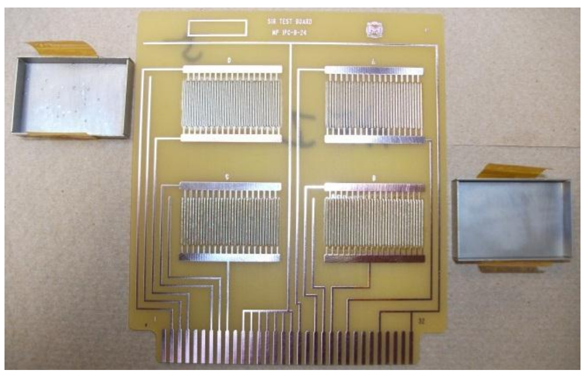


Figure 10 - Pasted and Reflowed SIR Test Coupon with RF Shields Removed

For the two SIR test coupons prepared for each underfill, the underfill was dispensed onto the test coupons (see Figure 11). The underfill was then mechanically moved around to cover the entire SIR pattern with a razor blade (see Figure 12). Next, an RF shield was affixed over patterns B and D on each of the two SIR test coupons (see Figure 13). The SIR test coupons were then submitted to the specific cure profile as prescribed by the underfill manufacturer (Figures 5, 6, and 7). Figures 14 and 15 show the cured underfill SIR test coupons with RF shields affixed and removed, respectively.

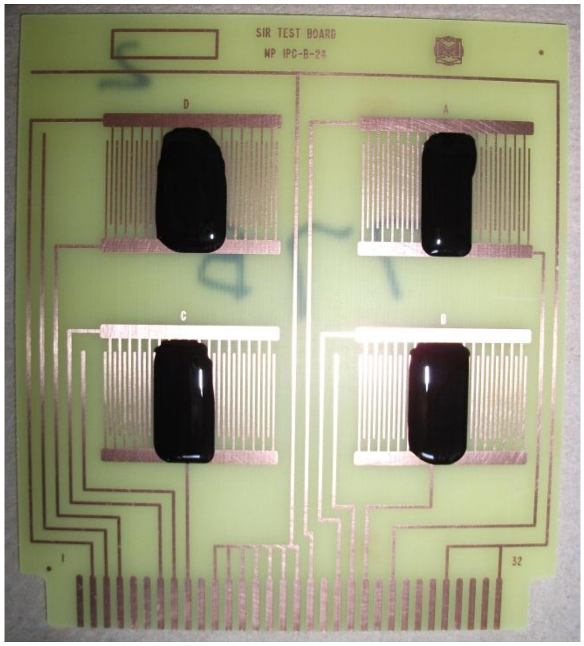


Figure 11 - Dispensed Underfill on the SIR Test Coupon

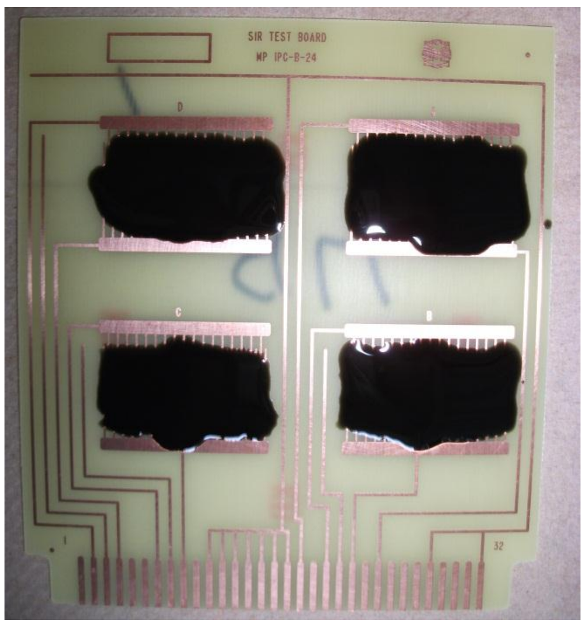


Figure 12 - Smeared Underfill Covering Entire SIR Pattern

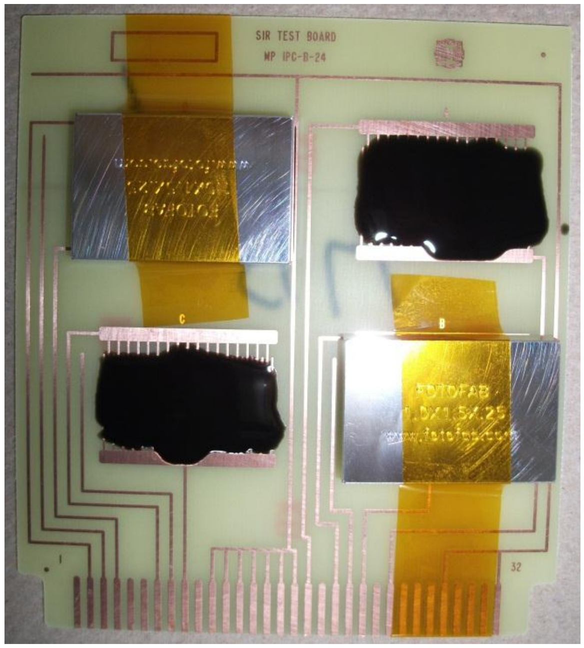


Figure 13 - Underfill Covered SIR Test Board with RF Shields Affixed

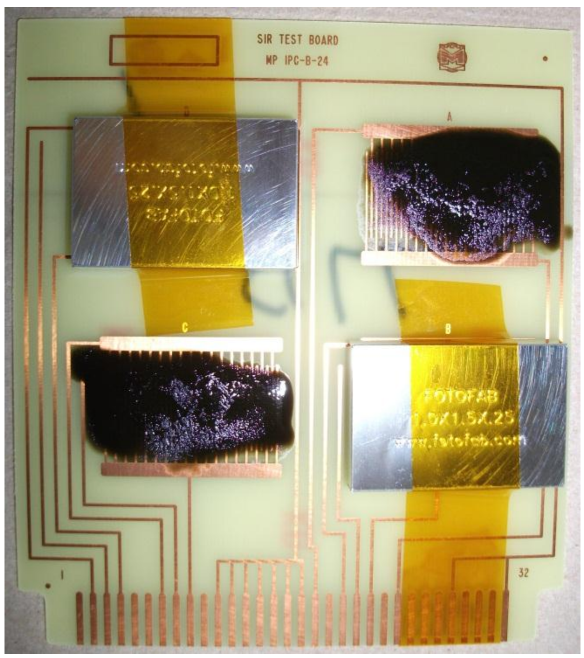


Figure 14 - Cured Underfill Test Coupon with RF Shields Affixed

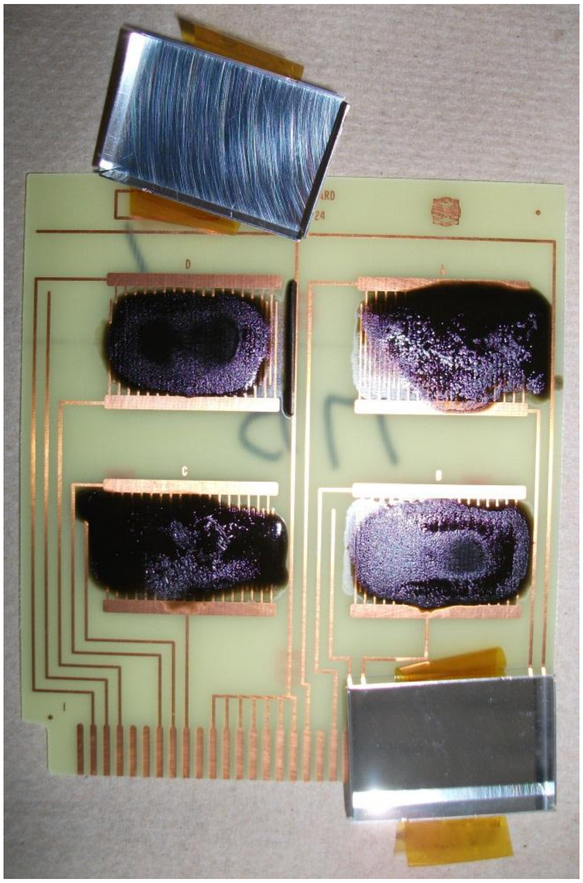
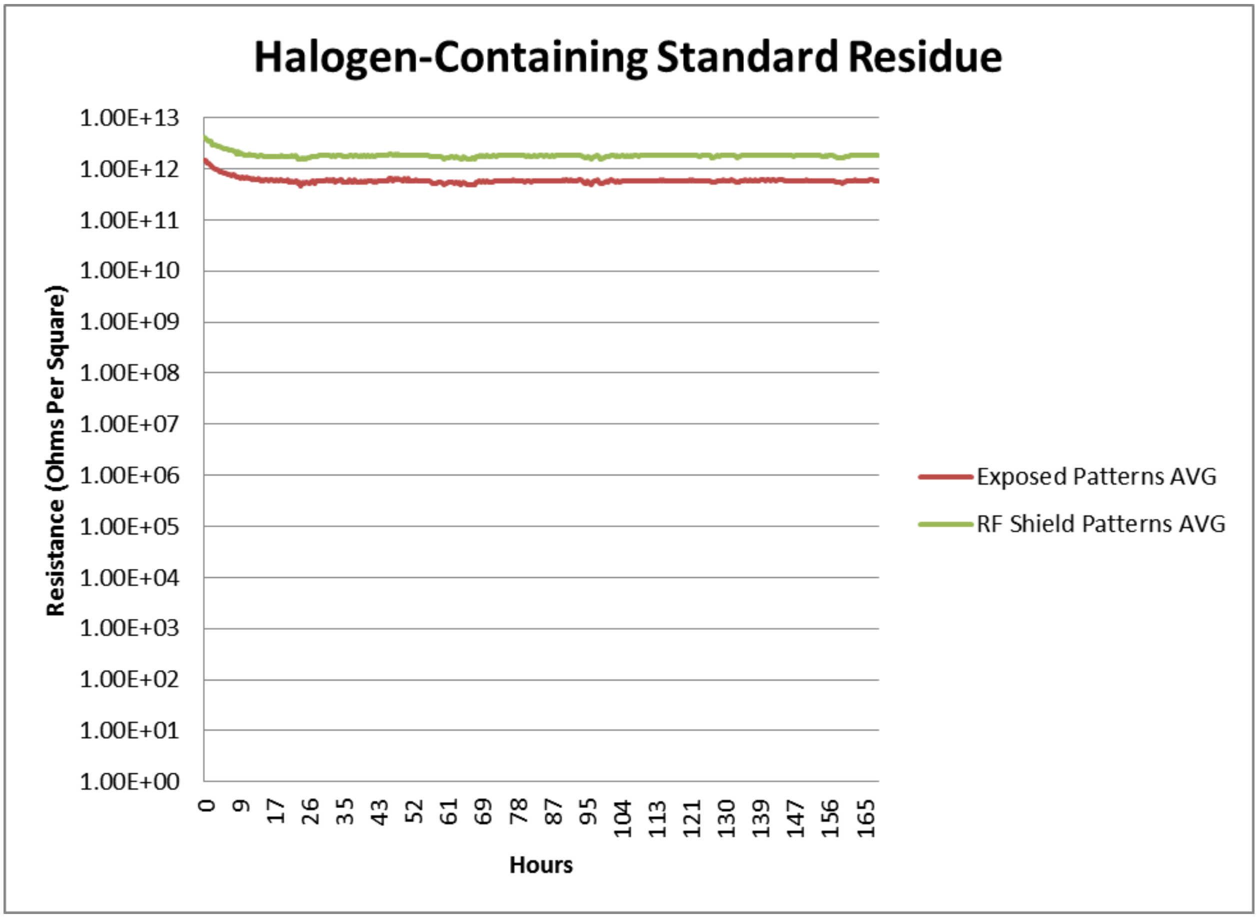


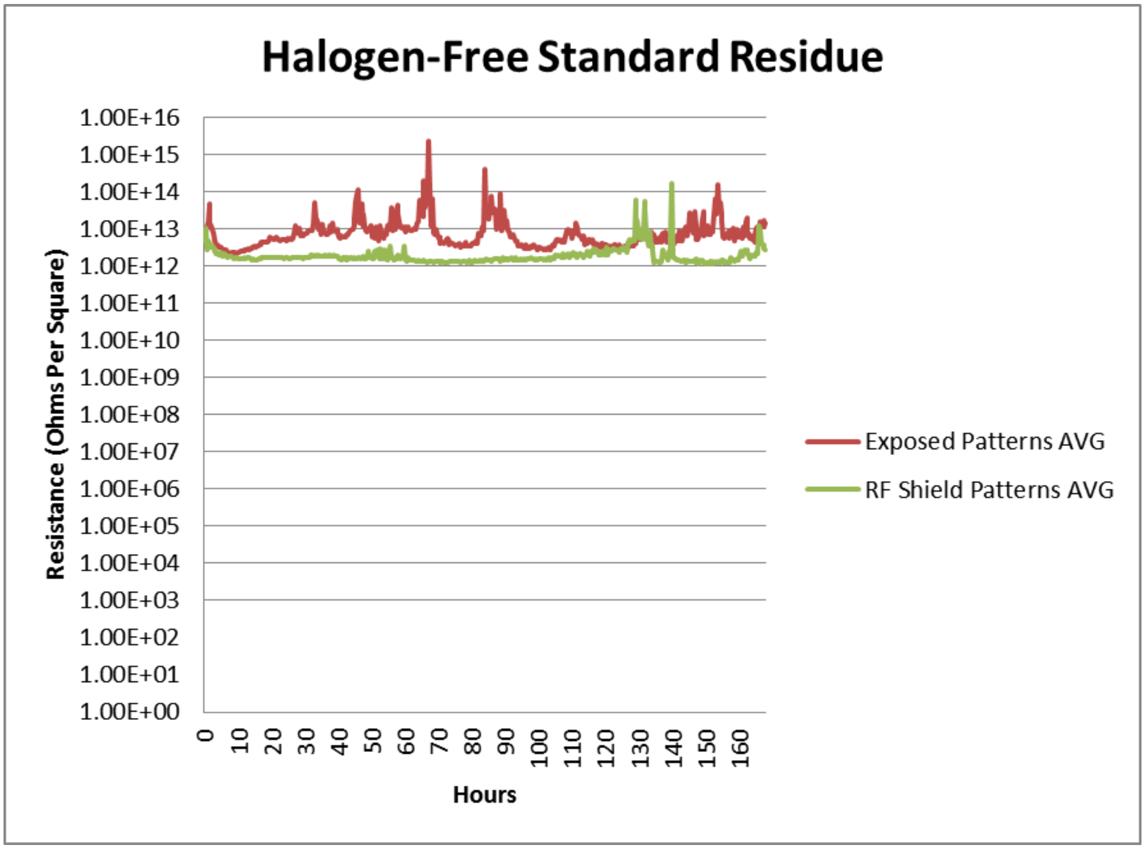
Figure 15 - Cured Underfill SIR Test Coupon with RF Shields Removed

For the two SIR test coupons prepared for each solder paste/underfill combination, the solder paste was printed and reflowed in the same manner as the SIR test coupons prepared with solder paste only. Then the RF shields were removed and underfill was applied to each SIR pattern in the same manner as the SIR test coupons prepared with underfill only. The RF shields were reaffixed to their original locations and the SIR test coupon was submitted to the appropriate underfill cure profile.

Upon completion of the preparation of all the SIR test coupons (solder paste only, underfill only and solder paste/underfill combination) all RF shields were removed. The SIR test coupons were then tested per the SIR test conditions and methods as prescribed per J-STD-004B. SIR measurements were taken every 20 minutes. The SIR measurements for the four exposed SIR patterns were averaged, and the SIR measurements for the four RF shield covered SIR patterns were averaged (from the two SIR test coupons prepared for each material or combination) and graphed as a function of resistance versus time. Following are the graphs. (Given the highly resistive nature of the flux residues and underfills, taking measurements at low voltage is subject to a certain amount of system "noise". From time to time upward and/or downward spikes will be observed in the graphs. In such cases, one should focus on the general trend of the graph instead of the "noise".)

Results


Halogen-Containing Standard Residue
Resistance (Ohms Per Square)
1.00E+13
1.00E+12
1.00E+11
1.00E+10
1.00E+09
1.00E+08
1.00E+07
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
0
9
17
26
35
43
52
61
69
78
87
95
104
113
121
130
139
147
156
165
Hours
Exposed Patterns AVG
RF Shield Patterns AVG


Halogen-Free Standard Residue
Resistance (Ohms Per Square)
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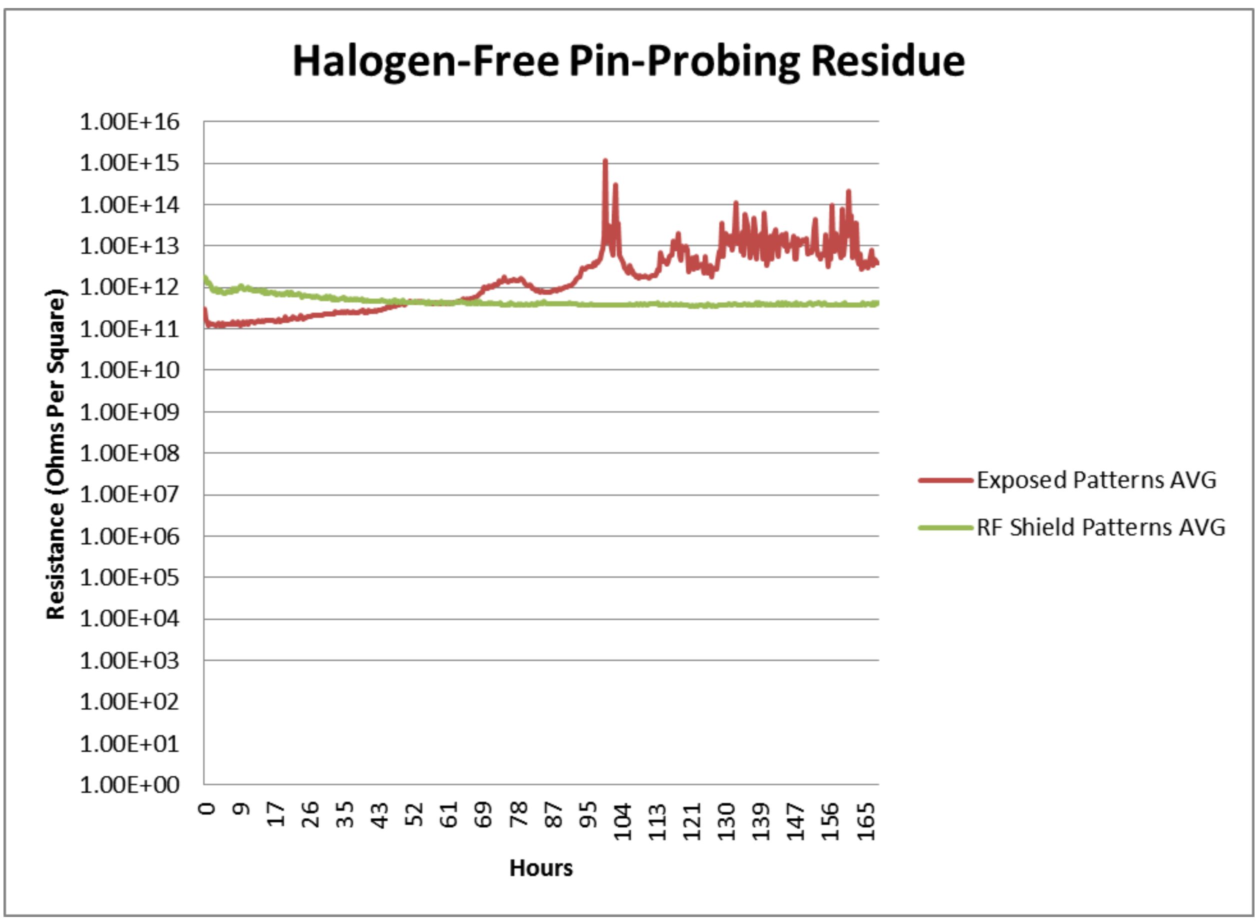
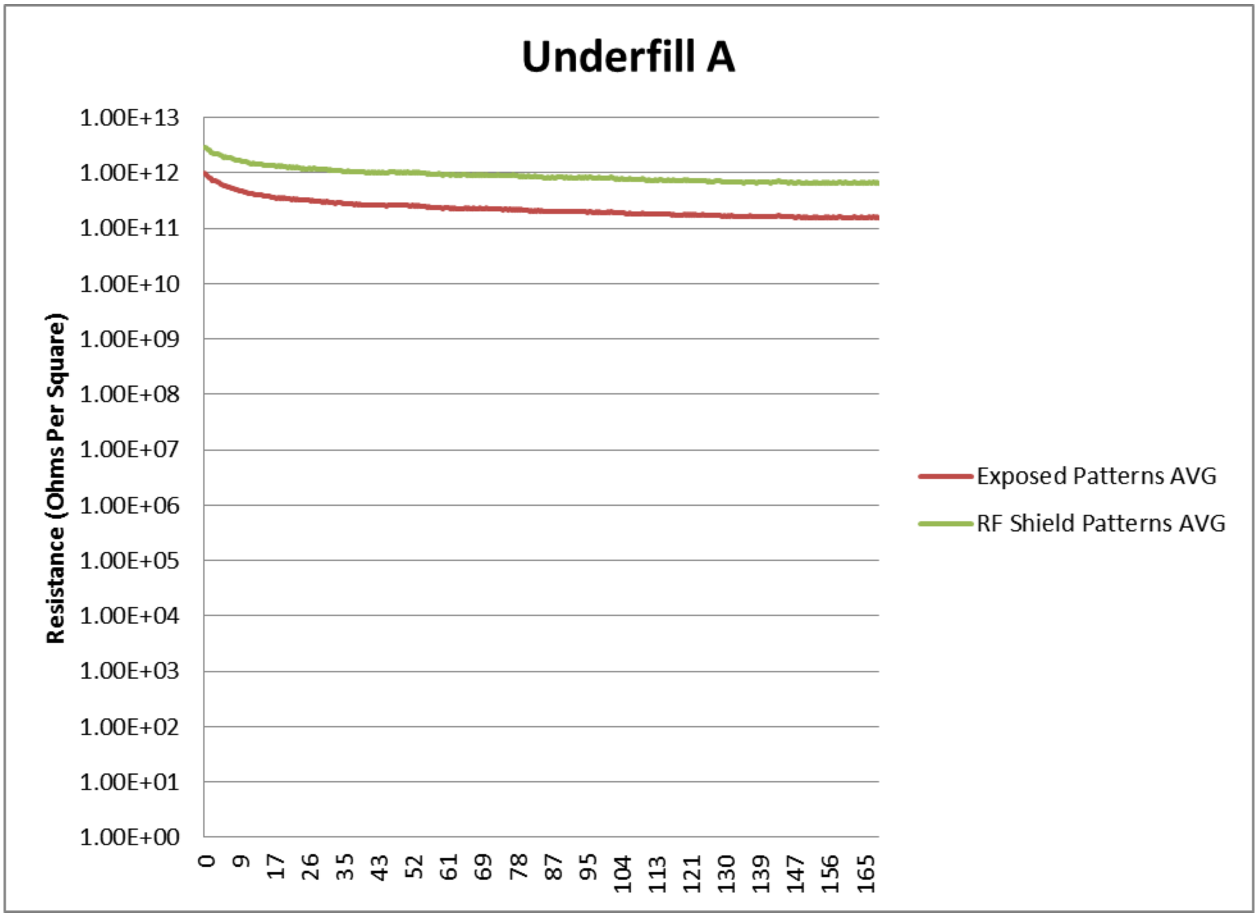
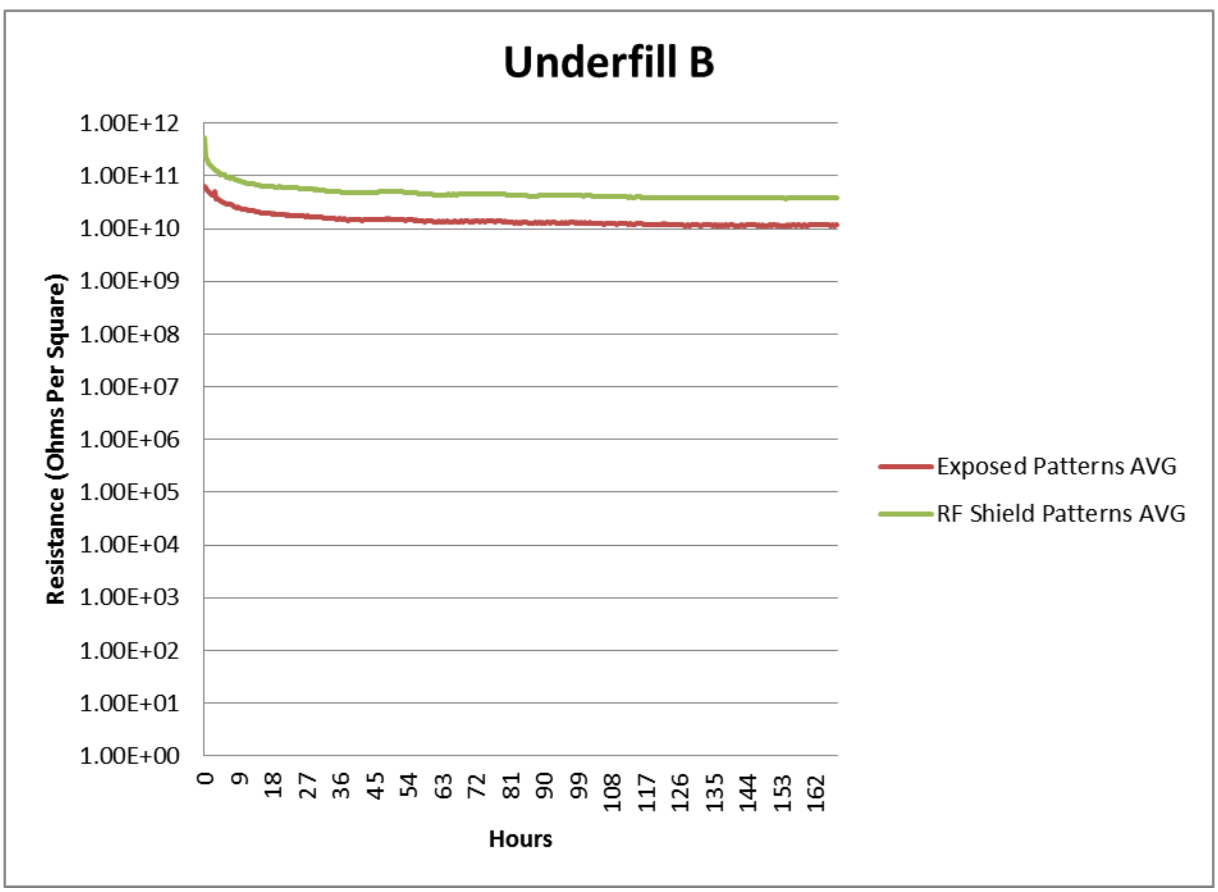
1.00E+15
1.00E+14
1.00E+13
1.00E+12
1.00E+11
1.00E+10
1.00E+09
1.00E+08
1.00E+07
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160
Hours
Exposed Patterns AVG
RF Shield Patterns AVG


Halogen-Free Pin-Probing Residue
Resistance (Ohms Per Square)
1.00E+16
1.00E+15
1.00E+14
1.00E+13
1.00E+12
1.00E+11
1.00E+10
1.00E+09
1.00E+08
1.00E+07
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
0 9 17 26 35 43 52 61 69 78 87 95 104 113 121 130 139 147 156 165
Hours
Exposed Patterns AVG
RF Shield Patterns AVG


Underfill A
1.00E+13
1.00E+12
1.00E+11
1.00E+10
1.00E+09
1.00E+08
1.00E+07
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
Resistance (Ohms Per Square)
0 9 17 26 35 43 52 61 69 78 87 95 104 113 121 130 139 147 156 165
Exposed Patterns AVG
RF Shield Patterns AVG


Underfill B
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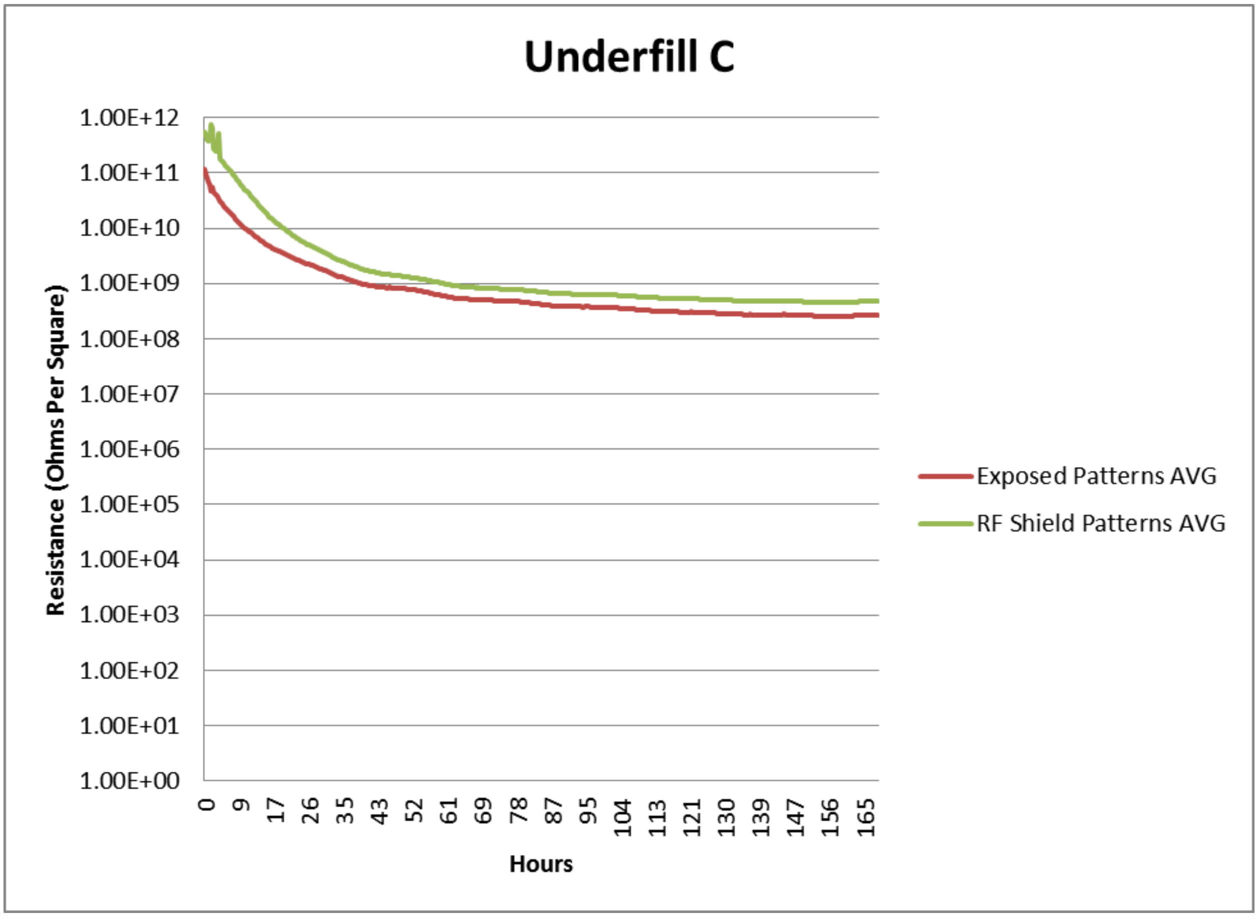
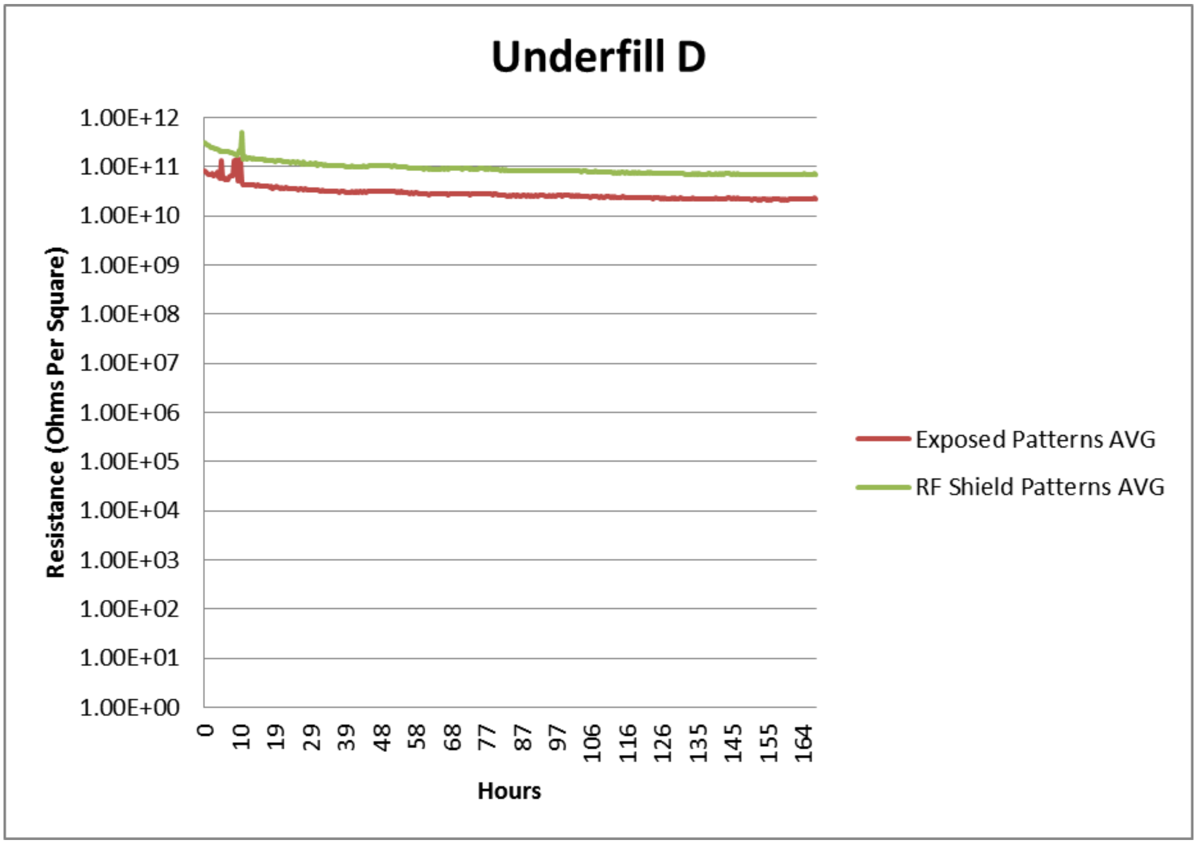
1.00E+10
1.00E+09
1.00E+08
1.00E+07
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
Resistance (Ohms Per Square)
0 9 18 27 36 45 54 63 72 81 90 99 108 117 126 135 144 153 162
Hours
Exposed Patterns AVG
RF Shield Patterns AVG



Note: Three of the eight SIR patterns produced values below the IPC required minimum value of 1x10^8 ohms per square. The effect of averaging makes the plotted lines stay higher.


Underfill D
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1.00E+07
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1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
Resistance (Ohms Per Square)
0
10
19
29
39
48
58
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87
97
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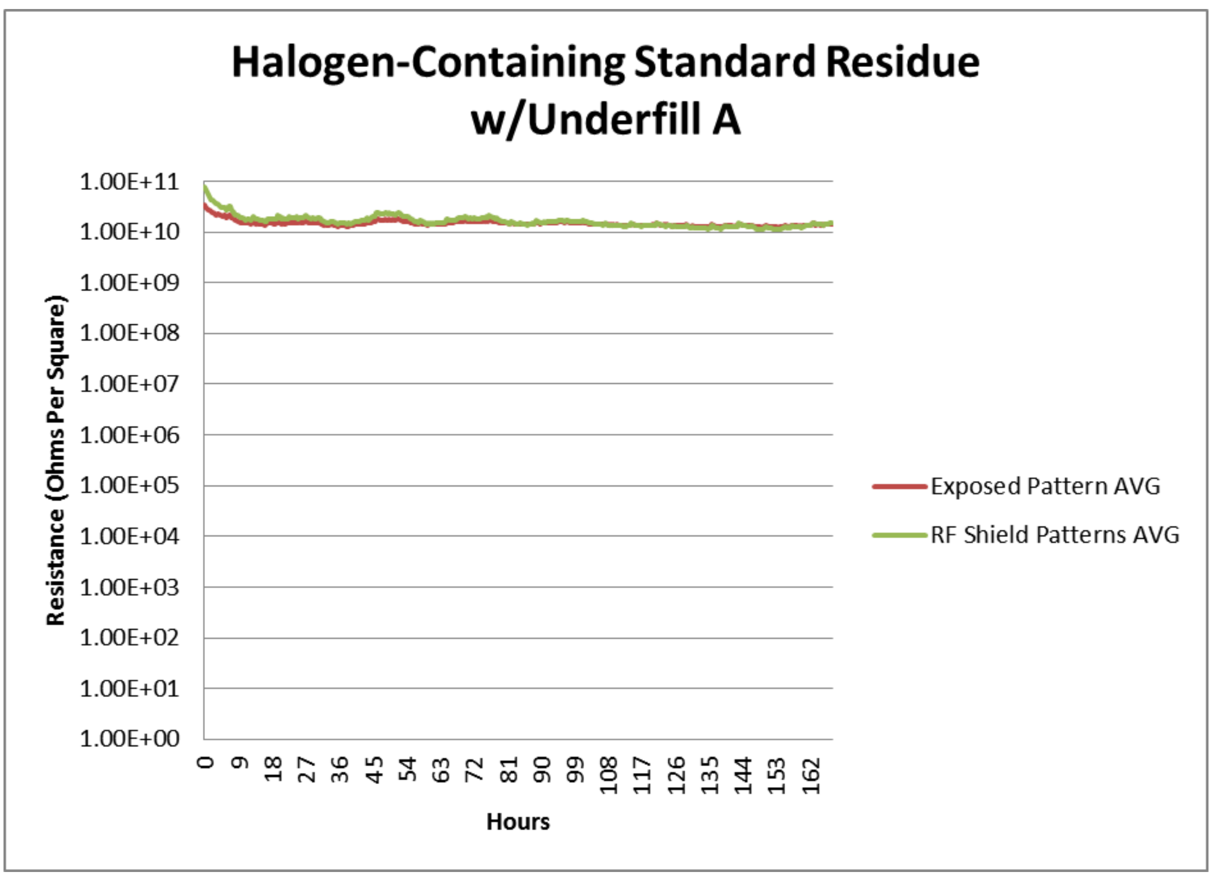
135
145
155
164
Hours
Exposed Patterns AVG
RF Shield Patterns AVG


Halogen-Containing Standard Residue w/Underfill A
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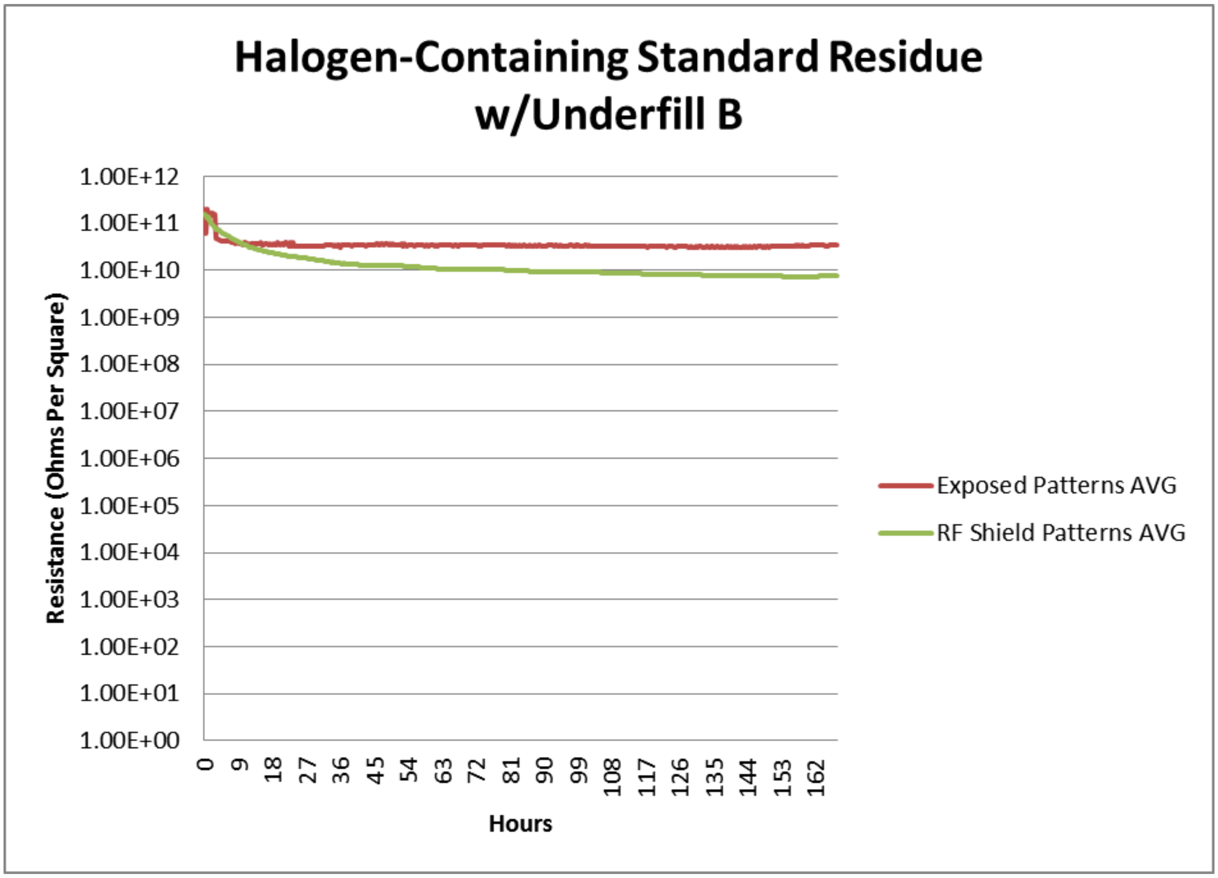
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
Resistance (Ohms Per Square)
0
9
18
27
36
45
54
63
72
81
90
99
108
117
126
135
144
153
162
Hours
Exposed Pattern AVG
RF Shield Patterns AVG


Halogen-Containing Standard Residue w/Underfill B
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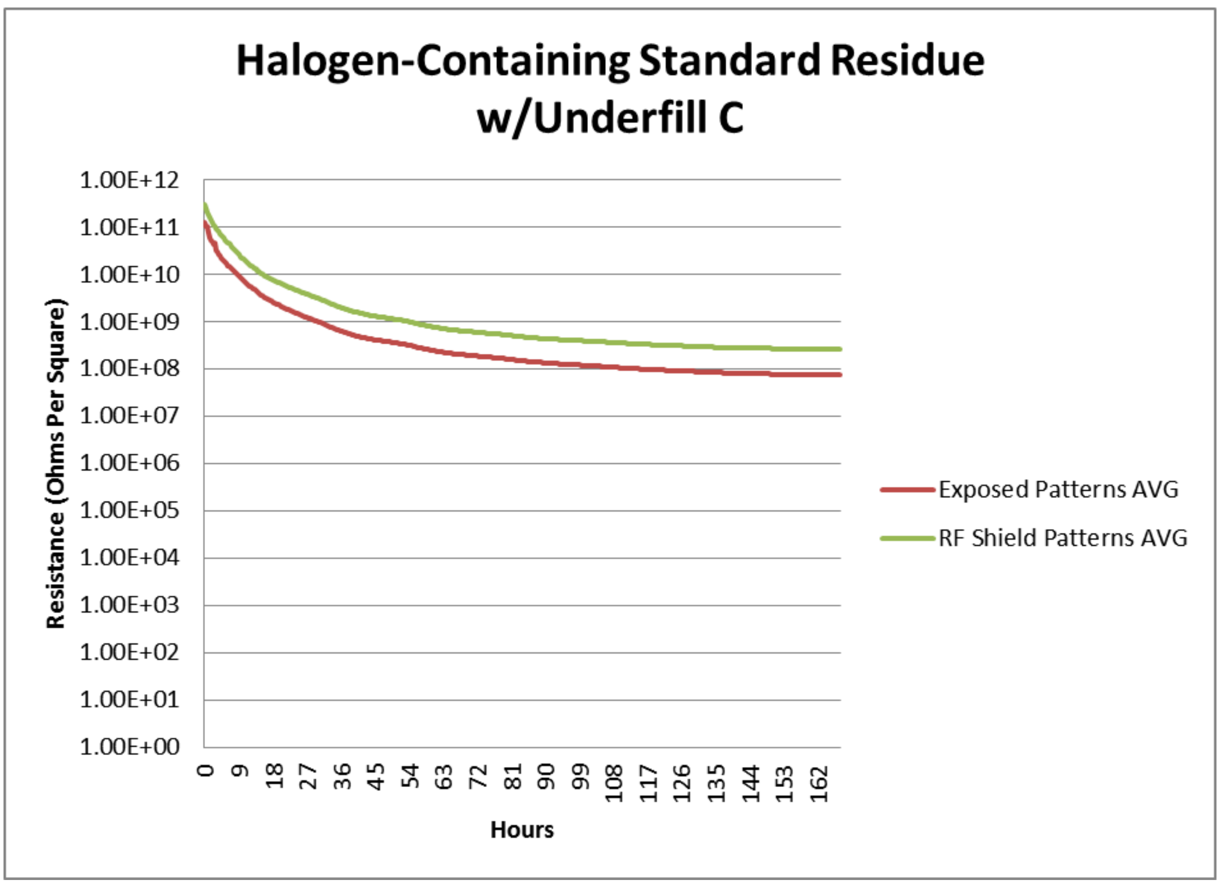
1.00E+08
1.00E+07
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
0 9 18 27 36 45 54 63 72 81 90 99 108 117 126 135 144 153 162
Hours
Exposed Patterns AVG
RF Shield Patterns AVG


Halogen-Containing Standard Residue w/Underfill C
Resistance (Ohms Per Square)
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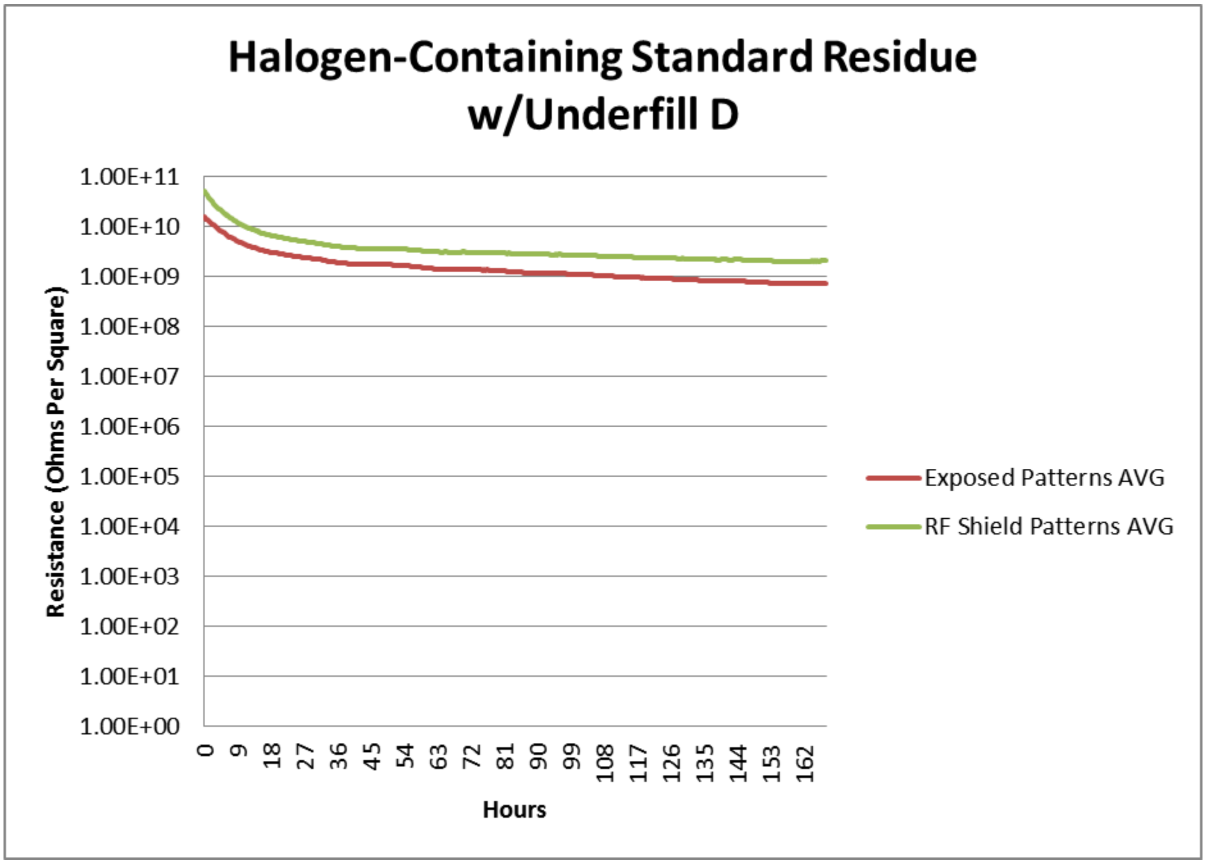
1.00E+08
1.00E+07
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
0 9 18 27 36 45 54 63 72 81 90 99 108 117 126 135 144 153 162
Hours
Exposed Patterns AVG
RF Shield Patterns AVG


Halogen-Containing Standard Residue w/Underfill D
Resistance (Ohms Per Square)
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1.00E+07
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
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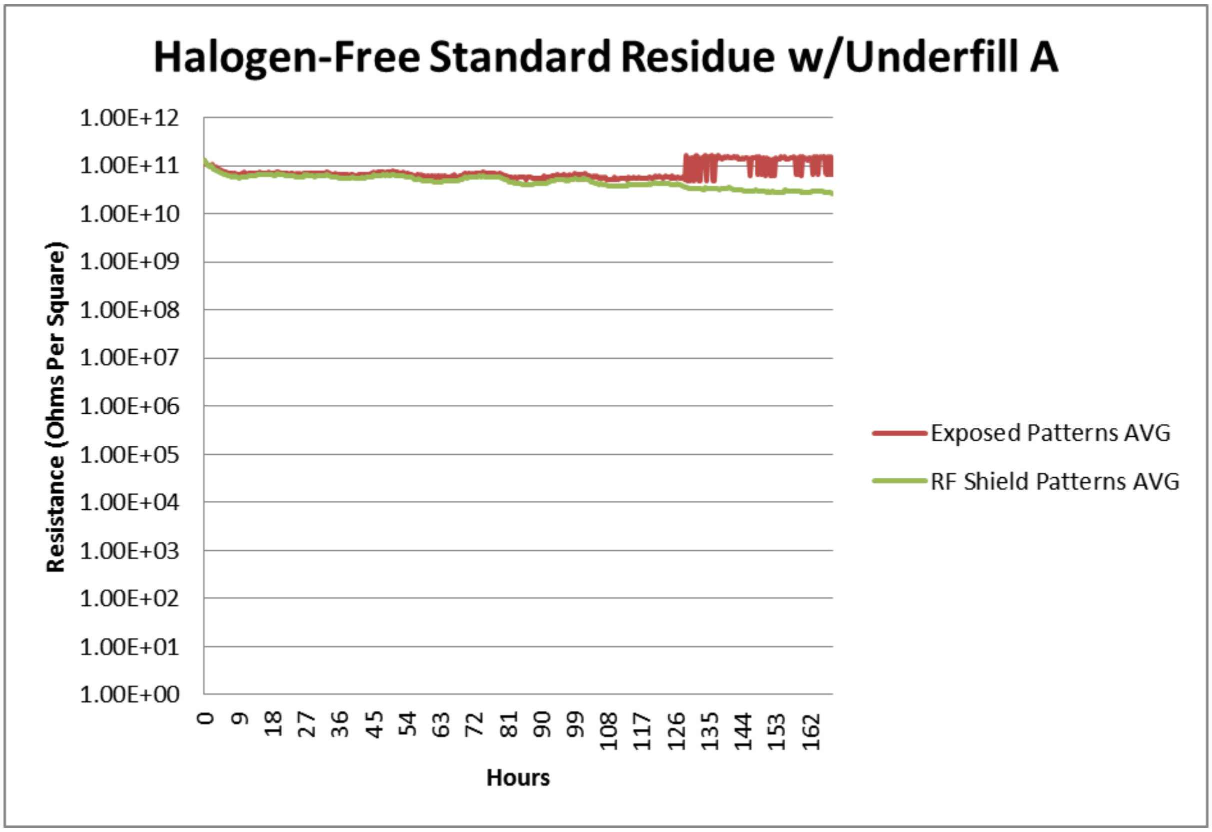
Hours
Exposed Patterns AVG
RF Shield Patterns AVG


Halogen-Free Standard Residue w/Underfill A
Resistance (Ohms Per Square)
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1.00E+11
1.00E+10
1.00E+09
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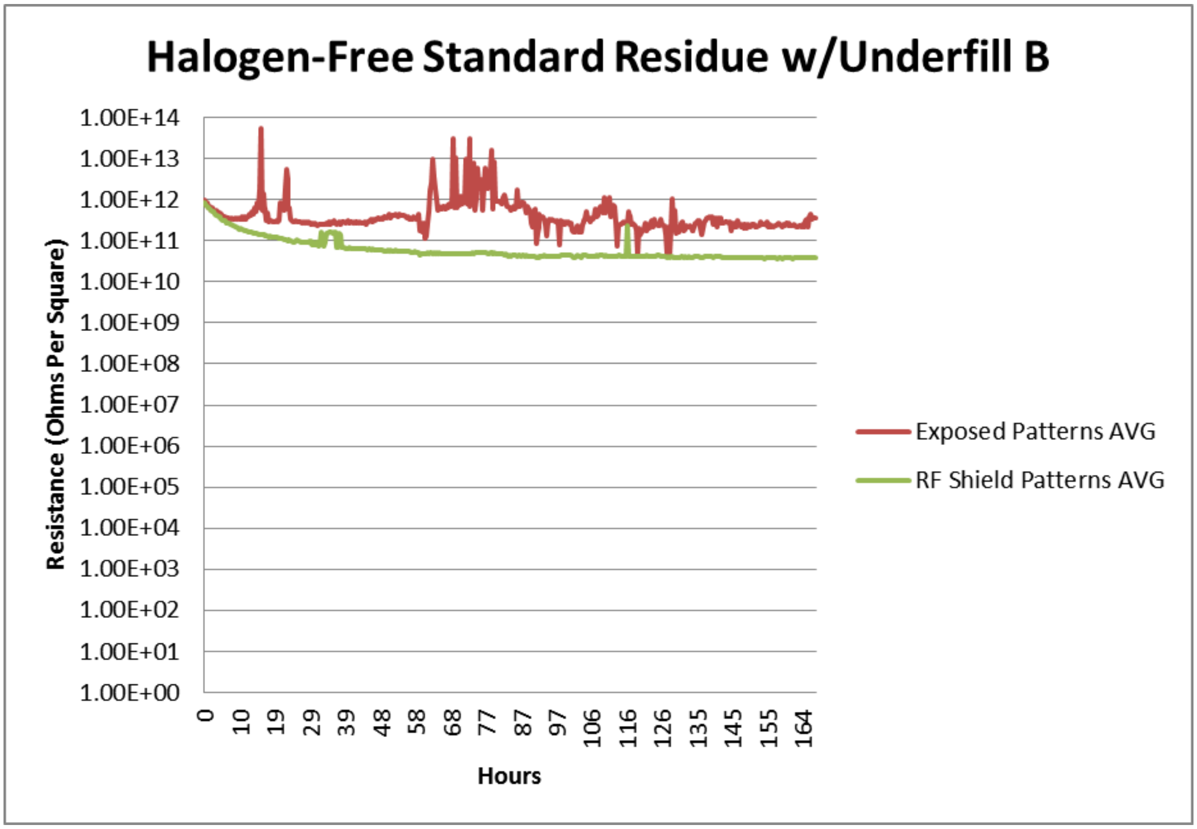
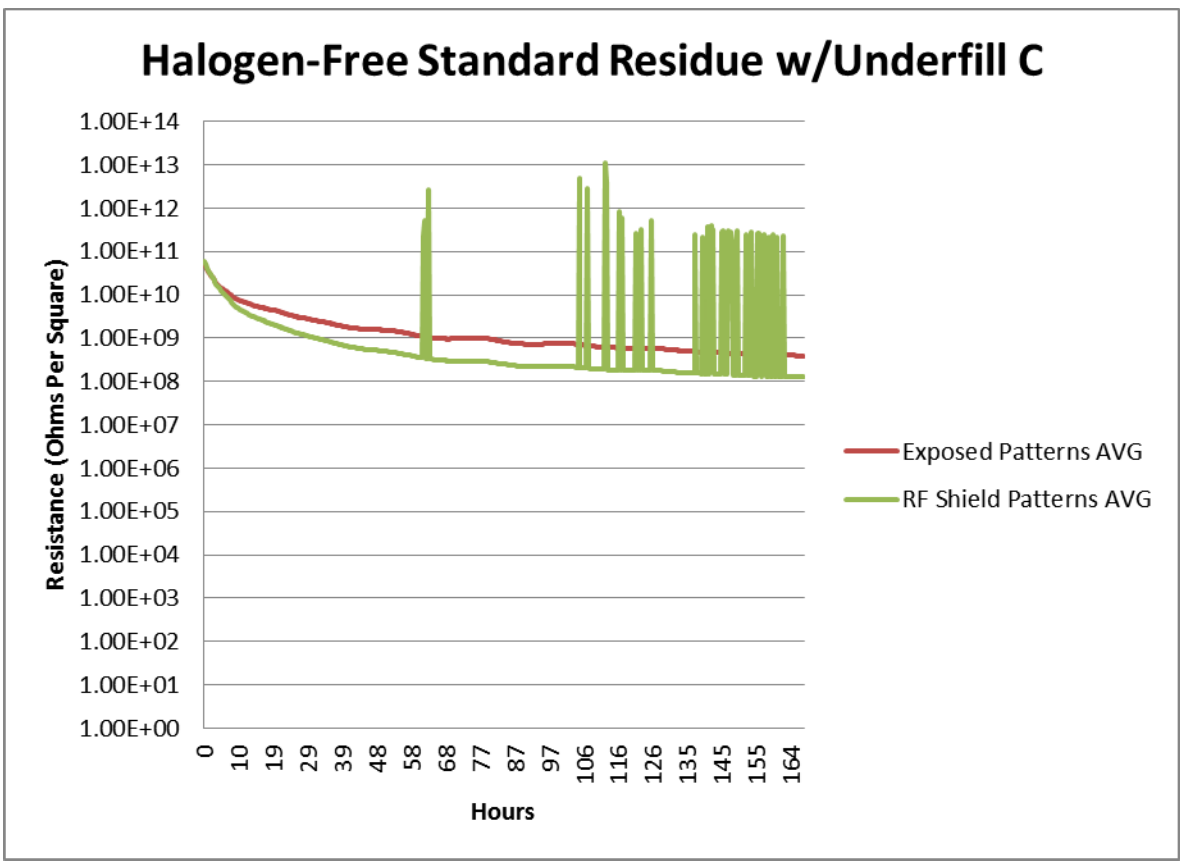
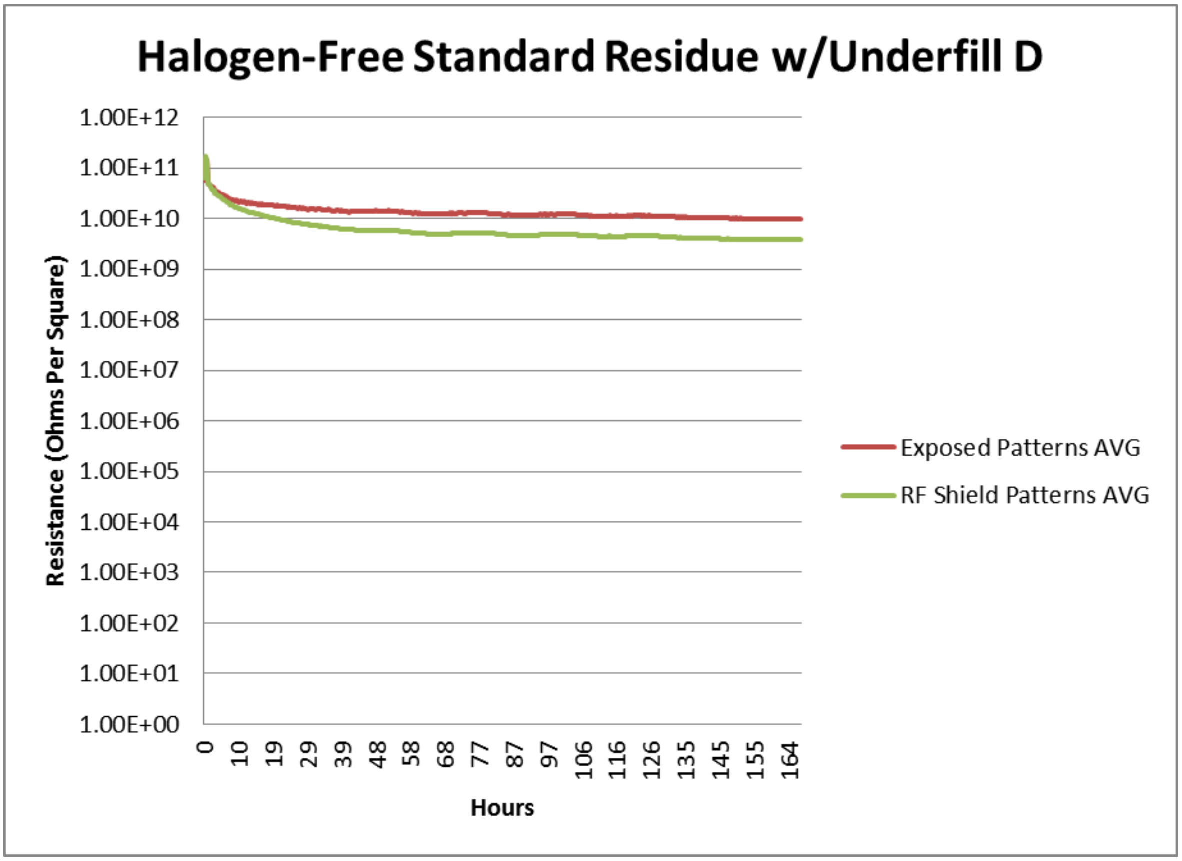
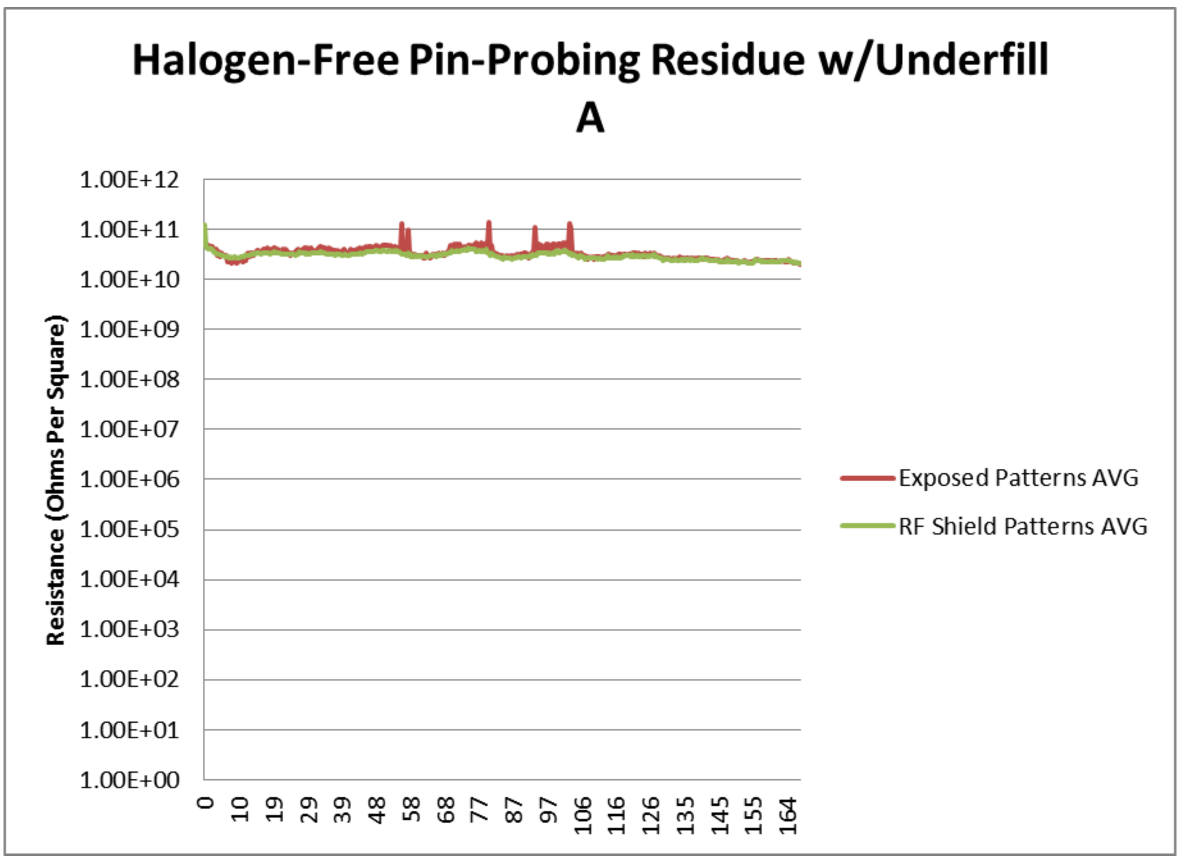
1.00E+07
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
0 9 18 27 36 45 54 63 72 81 90 99 108 117 126 135 144 153 162
Hours
Exposed Patterns AVG
RF Shield Patterns AVG





Note: One of the eight SIR patterns produced values below the IPC required minimum value of 1x10^8 ohms per square. The effect of averaging makes the plotted line stay higher.


Halogen-Free Standard Residue w/Underfill D
1.00E+12
1.00E+11
1.00E+10
1.00E+09
1.00E+08
1.00E+07
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
Resistance (Ohms Per Square)
0
10
19
29
39
48
58
68
77
87
97
106
116
126
135
145
155
164
Hours
Exposed Patterns AVG
RF Shield Patterns AVG


Halogen-Free Pin-Probing Residue w/Underfill A
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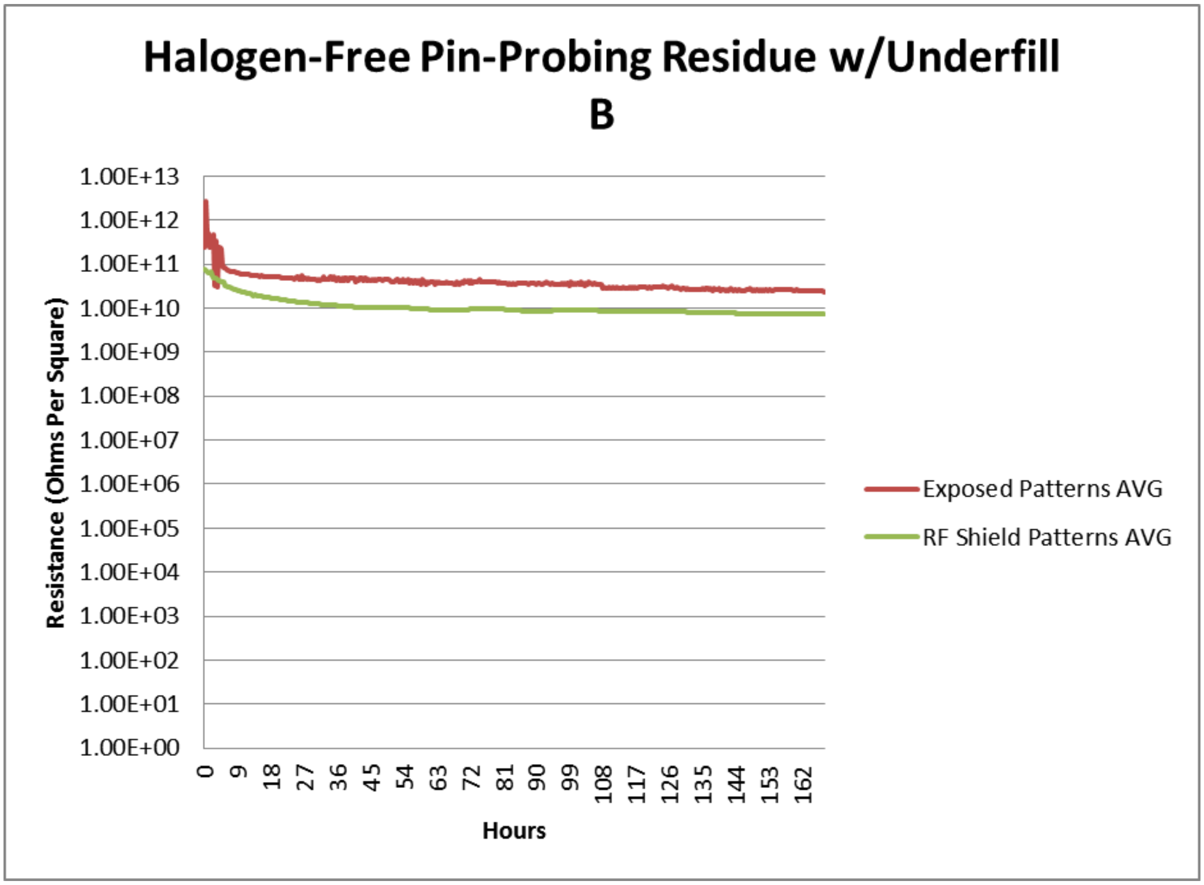
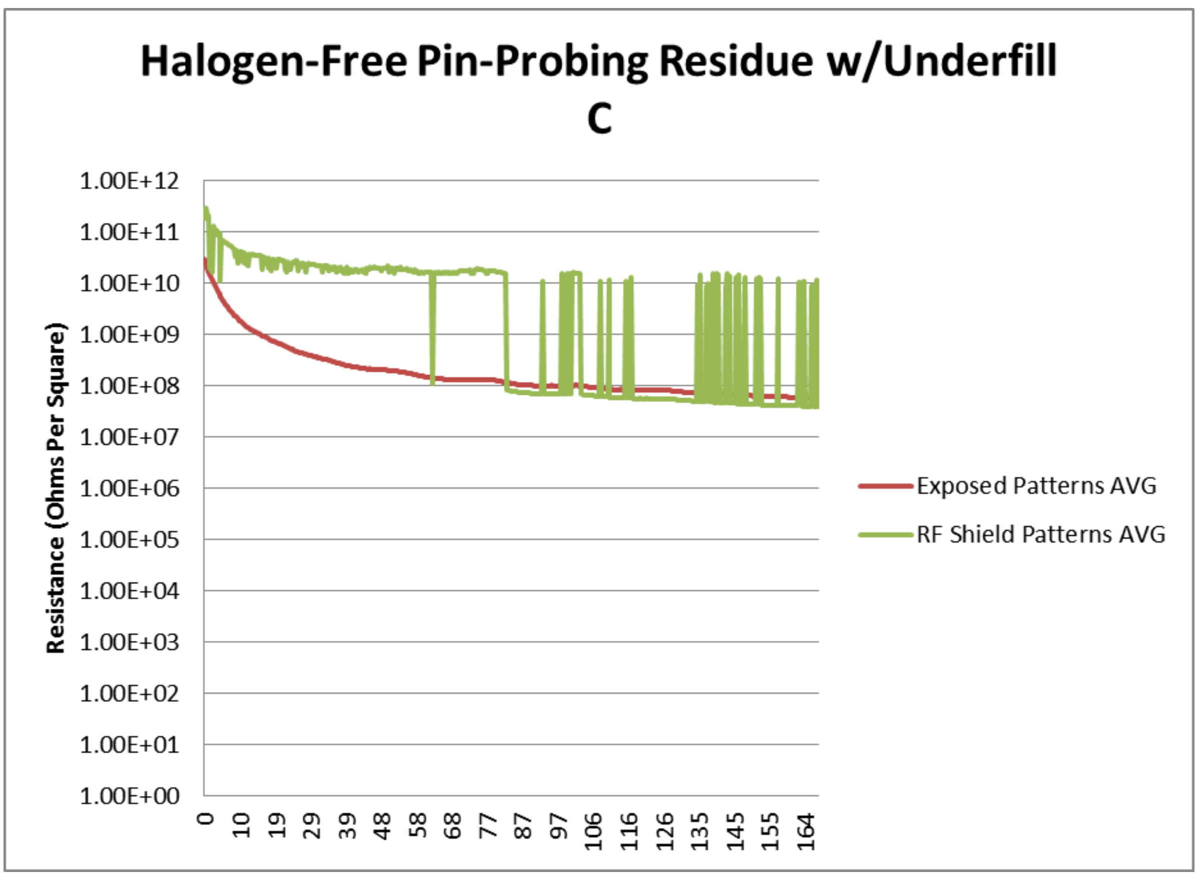
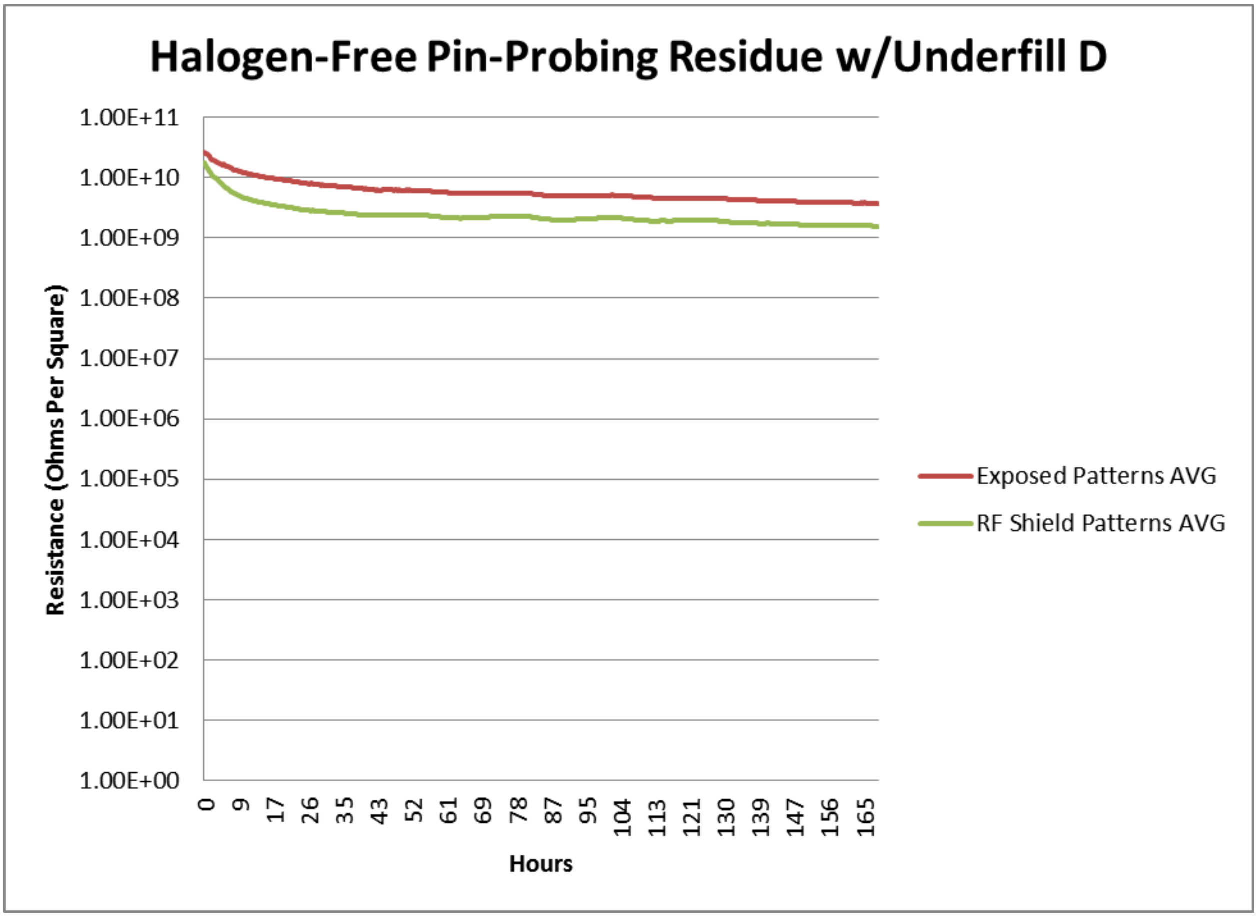
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
Resistance (Ohms Per Square)
0
10
19
29
39
48
58
68
77
87
97
106
116
126
135
145
155
164
Exposed Patterns AVG
RF Shield Patterns AVG


Halogen-Free Pin-Probing Residue w/Underfill
B
Resistance (Ohms Per Square)
1.00E+13
1.00E+12
1.00E+11
1.00E+10
1.00E+09
1.00E+08
1.00E+07
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
0 9 18 27 36 45 54 63 72 81 90 99 108 117 126 135 144 153 162
Hours
Exposed Patterns AVG
RF Shield Patterns AVG


Halogen-Free Pin-Probing Residue w/Underfill
C
Resistance (Ohms Per Square)
1.00E+12
1.00E+11
1.00E+10
1.00E+09
1.00E+08
1.00E+07
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
0 10 19 29 39 48 58 68 77 87 97 106 116 126 135 145 155 164
Exposed Patterns AVG
RF Shield Patterns AVG



Observations and Conclusions

It was observed that Underfill B produced a unique visual anomaly as can be seen in Figure 16. This anomaly was especially pronounced on the SIR patterns that were covered with RF shields. It is not known whether the underfill looked this way after curing or not until after SIR testing. None of the other underfills exhibited this sort of phenomenon.

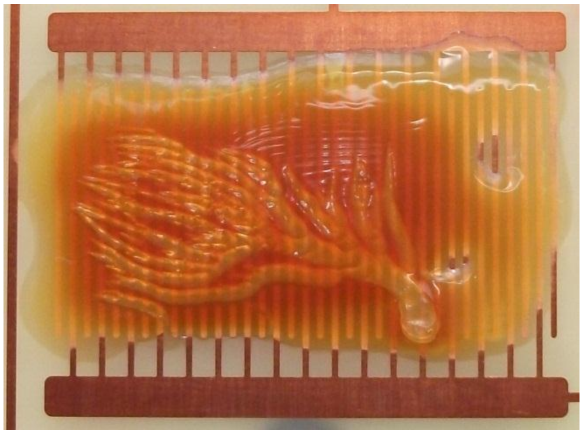


Figure 16 - Anomaly in Underfill B, Post SIR Testing (RF Shield Pattern)

In a previous work, the author studied the impact of RF shields on no-clean flux residues. In that work, the results showed that entrapping a flux residue under an RF shield consistently produced lower SIR results than residues that were fully exposed (not covered). In that work, the RF shields were larger, produced a better seal (restricted outgassing), noticeably reduced the peak temperature of the SIR patterns below the shields, and were left on the patterns during SIR testing. In this study, certain materials and combinations, especially the underfills, seemed to benefit (produce higher SIR values) when covered with an RF shield. However, in this study, the RF shields were smaller, did not create a seal (see the corners of the RF shields in Figure 2), did not significantly reduce the peak temperature of the reflow and cure profile of the SIR patterns below the shield, and were removed prior to the SIR test. Therefore, it is unclear just what sort of impact these RF shield have on the results and how well they mimic a real world scenario. The author believes that the results in the previous work are more true to reality.

Underfill C produced poor SIR results. The poor SIR performance of Underfill C was transposed onto the SIR performance of the solder paste/underfill C combinations. Based upon the shape of the graphs (decreasing SIR performance with time), it would appear that Underfill C is somehow sensitive to the SIR chamber test conditions (temperature, humidity, and/or applied voltage).

Solder paste/underfill combinations involving an underfill with good SIR performance and a solder paste with good SIR performance produced a combination with good SIR performance. No chemical “incompatibilities” between the solder paste flux vehicles and the underfills were detected. The SIR results of the solder paste/underfill combinations logically follow the SIR results of the parent materials. Keeping in mind the adage that electricity follows the path of least resistance; if one material performs poorly by itself, it will cause the combination to perform poorly regardless of the performance of the other material(s) in the combination.

If an underfill/paste combination is causing current leakage, both materials should be investigated separately to determine the culprit material. The combination should not be lightly dismissed as “incompatible”. Furthermore, one should not immediately assume that one material is the problem and not the other(s) without first investigating the materials separately.