Does Thermal Cycling Impact the Electrical Reliability of a No-Clean Solder Paste Flux Residue

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No-clean solder pastes are widely used in a number of applications that are exposed to wide variations in temperature during the life of the assembled electronics device. Some have observed that cracks can and do form in flux residue and have postulated that this is the result of or exacerbated by temperature cycling. Furthermore, the potential exists for the flux residue to soften or liquefy at elevated temperatures, and even flow if orientated parallel to gravity. In situations, such as in automotive electronics, where significant temperature cycling is a reality and high reliability is a must, , concern sometimes exists that the cracking and possible softening or liquefying of the residue may have a deleterious effect on the electrical reliability of the flux residue. This paper will attempt to address this concern.

For this work, two commercially available SAC305 Type 4 no-clean solder pastes, one halogen-free (ROL0) and the other halogen-containing (ROL1), will be examined. In accordance with IPC J-STD-004B, these solder pastes will be printed and reflowed, using the same common air reflow profile, on to IPC-B-24 SIR test boards. After reflow, each solder paste will have boards set aside for constant room temperature exposure, -40°C to +125°C temperature cycling and -55°C to +175°C temperature cycling. For the two temperature cycling scenarios, boards will be orientated both perpendicular and parallel to gravity in the temperature cycling chamber. Upon completion of the temperature cycling, the boards will be submitted to Surface Insulation Resistance (SIR) testing per IPC-TM-650 2.6.3.7. The SIR readings will be plotted for each scenario and compared.

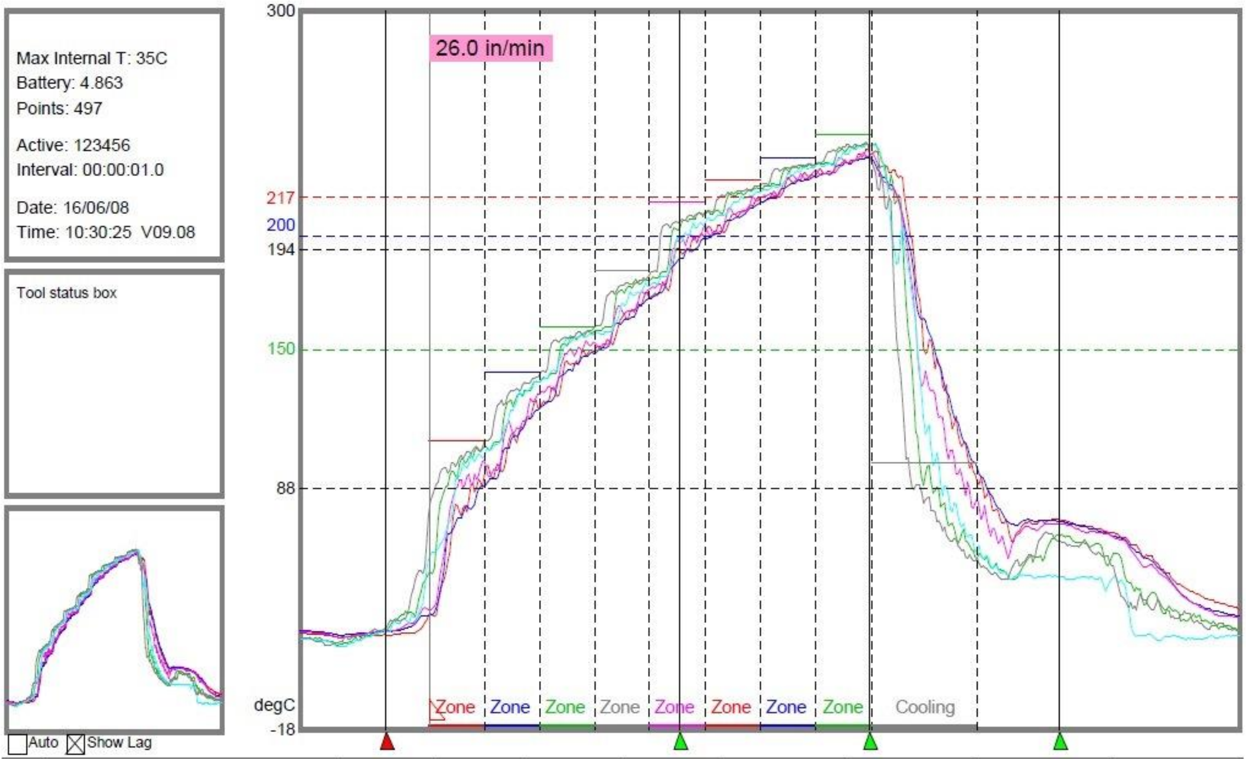
Please note that this work will focus on the cumulative effects of temperature cycling. This experiment does not attempt to look at the effects of temperature cycling in situ.

Table 1 shows the matrix of boards prepared and tested. All boards were prepared in accordance with IPC-TM-650 2.6.3.3. Two boards were prepared for each paste per scenario as well as two boards per paste that saw no temperature cycling. The boards that were not temperature cycled were prepared at the same time as the boards for temperature cycling, but were kept at room temperature. For each temperature cycling and solder paste scenario, two boards were prepared for horizontal orientation and two boards for vertical orientation inside the temperature cycling chamber. In addition, two bare (no solder paste) control boards that saw no temperature cycling were included.

Table 1 – SIR Test Matrix

SIR Test Matrix					
	Temperature Cycling				
		Chamber Orientation			
		Horizontal		Vertical	
Solder Paste	None	-40C to +125C	-55C to +175C	-40C to +125C	-55C to +175C
Halogen Free (ROL0)	2	2	2	2	2
Halogen Containing (ROL1)	2	2	2	2	2
Controls	2				
Total	22				

Figure 1 shows the air reflow profile that was used to reflow all the boards. (Control boards were not reflowed.)



	Summary Stats	Peak	Minimum	Max (+)Slo	Max (-)Slo	Time Above	Time 150-200C	30C / Peak	Peak \ 30C
¤	Sensor 1 Location.	238.3	22.8	4.94	-6.85	72.0	57.0	0.91	-1.08
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¤	Sensor 6 Location.	241.1	19.4	4.94	-12.90	87.0	57.0	0.85	-1.22
	Range	6.7	5.0	1.79	7.78	26.0	2.0	0.06	0.52

Figure 1 – Air Reflow Profile

As mentioned previously, two temperature cycling conditions were used: -40°C to +125°C and -55°C to +175°C. Table 2 shows the approximate dwell times and number of cycles completed. The boards were in the temperature cycling chambers for ~13 days. For the -55°C to 175°C temperature cycling condition, the boards saw ~535 cycles. For the -40°C to 125°C temperature cycling condition, the boards saw ~153 cycles.

Table 2 – Temperature Cycling Parameters

Temperature Cycling Parameters		
Profile	Dwell (Minutes)	Cycles Completed
-40°C to +125°C	5	~153
-55°C to +175°C	10	~535

Figure 2 shows the orientation of the boards in the -40°C to +125°C chamber as photographed at the completion of the temperature cycling. The vertically-orientated boards can be seen in the metal rack on the left. The rack was orientated so that the flow of air could pass between the boards.

Figure 2 - Orientation of the Boards in the -40°C to +125°C Chamber

Figure 3 shows the orientation of the boards in the -55°C to +175°C chamber as photographed at the completion of the temperature cycling. The vertically-orientated boards can be seen in the metal rack on the left. The rack was orientated so that the flow of air could pass between the boards.

Figure 3 - Orientation of the Boards in the -55°C to +175°C Chamber

It was observed that the metal rack and vertically-orientated boards had been disturbed inside the chamber during the temperature cycling (see Figure 4). When and how this happened is unknown. One board had fallen out of the rack and was lying horizontally on the metal grill below. This board was labeled so that it could be identified as the fallen board.

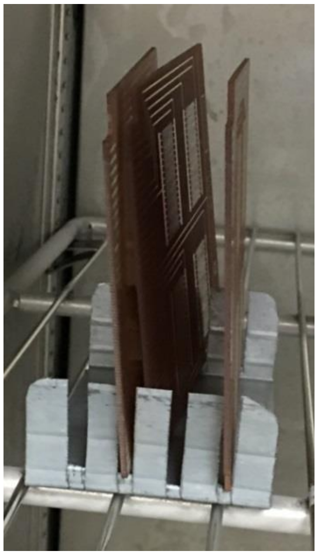

Figure 4 – Disturbed Vertically-Orientated Boards in the -55°C to +175°C Chamber

The boards that underwent the -55°C to +175°C temperature cycling had darkened considerably compared to the boards from the -40°C to +125°C chamber (see Figure 5). However, other than the discoloration, there appeared to be no damage to the boards.

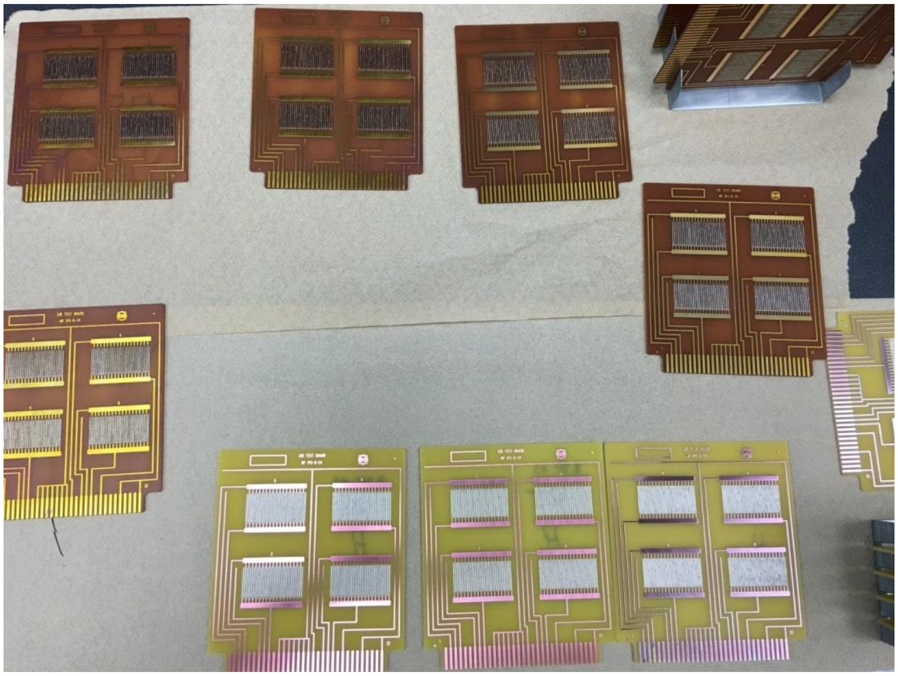

Figure 5 – Discoloration of Boards from the -55°C to +175°C Chamber

After temperature cycling and prior to SIR testing, the boards were examined for cracking in the flux residue. This is because some in the industry have either experienced or postulated cracking of the flux residue due to temperature cycling. Furthermore, it is said that this cracking in the residue can compromise the electrical reliability of the flux residue. Figures 6 through 15 are photographs of the flux residue on the SIR patterns under magnification.

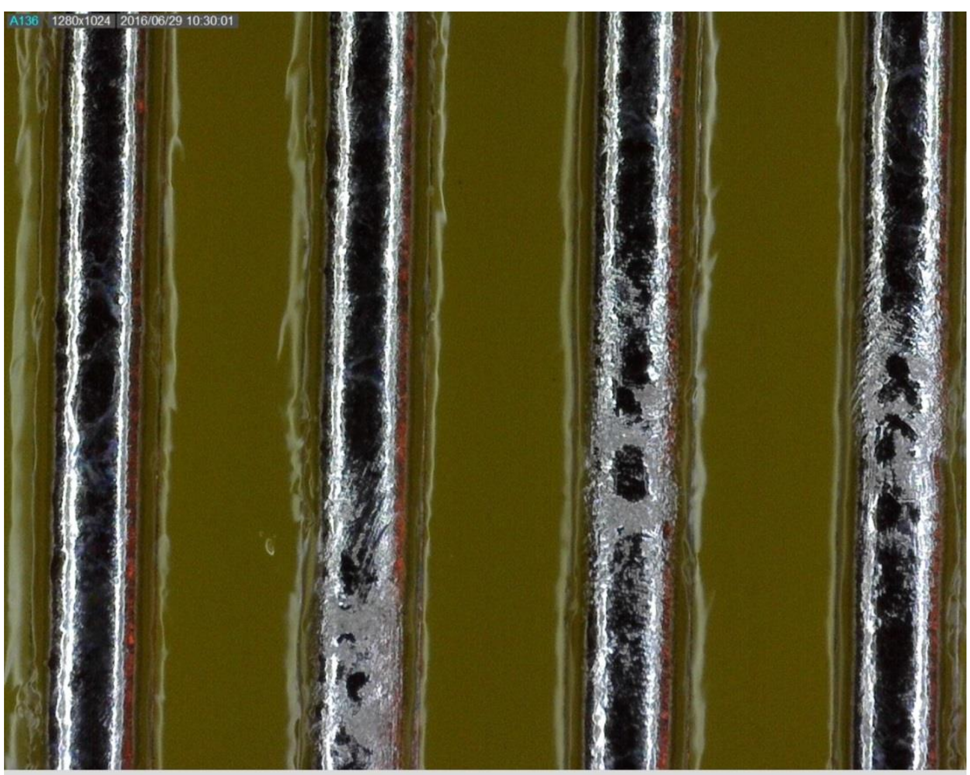

Figure 6 - Halogen-Free – No Thermal Cycling

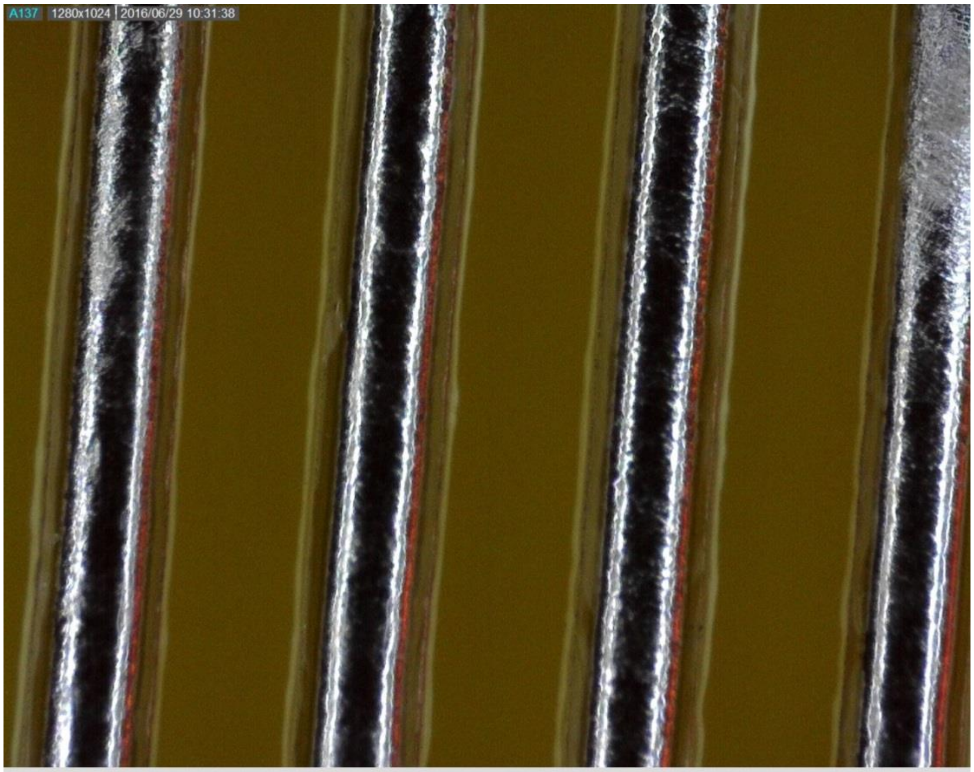

Figure 7 - Halogen-Containing – No Thermal Cycling

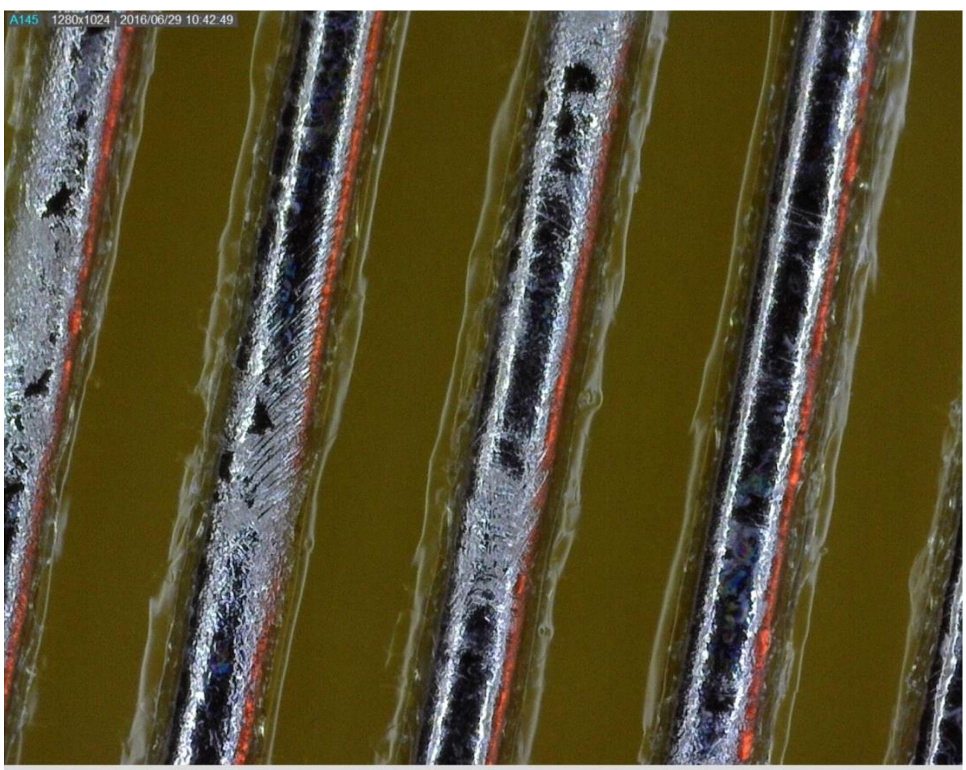

Figure 8 - Halogen-Free - -40°C to +125°C Thermal Cycling – Horizontal Orientation

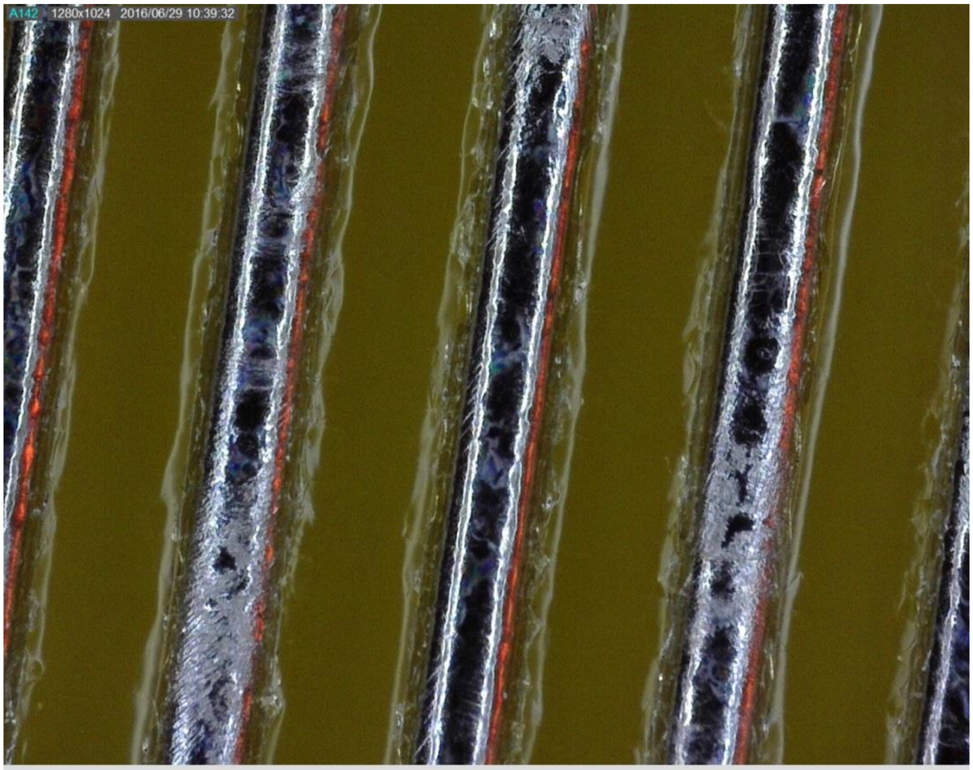

Figure 9 - Halogen-Free - -40°C to +125°C Thermal Cycling – Vertical Orientation

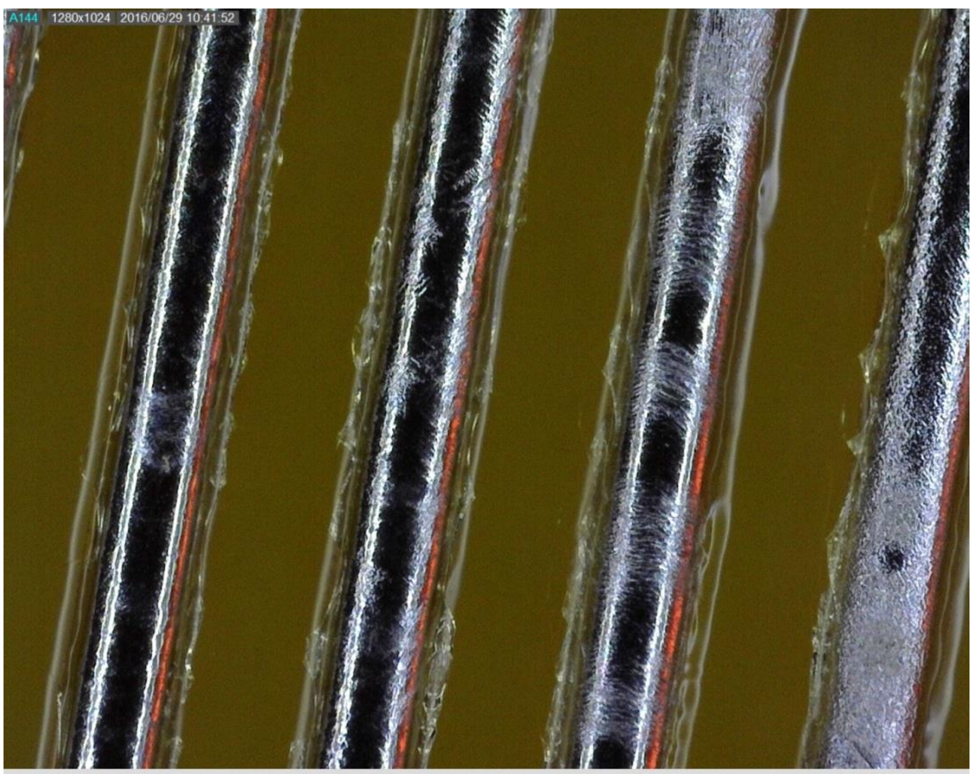

Figure 10 - Halogen-Containing - -40°C to +125°C Thermal Cycling – Horizontal Orientation

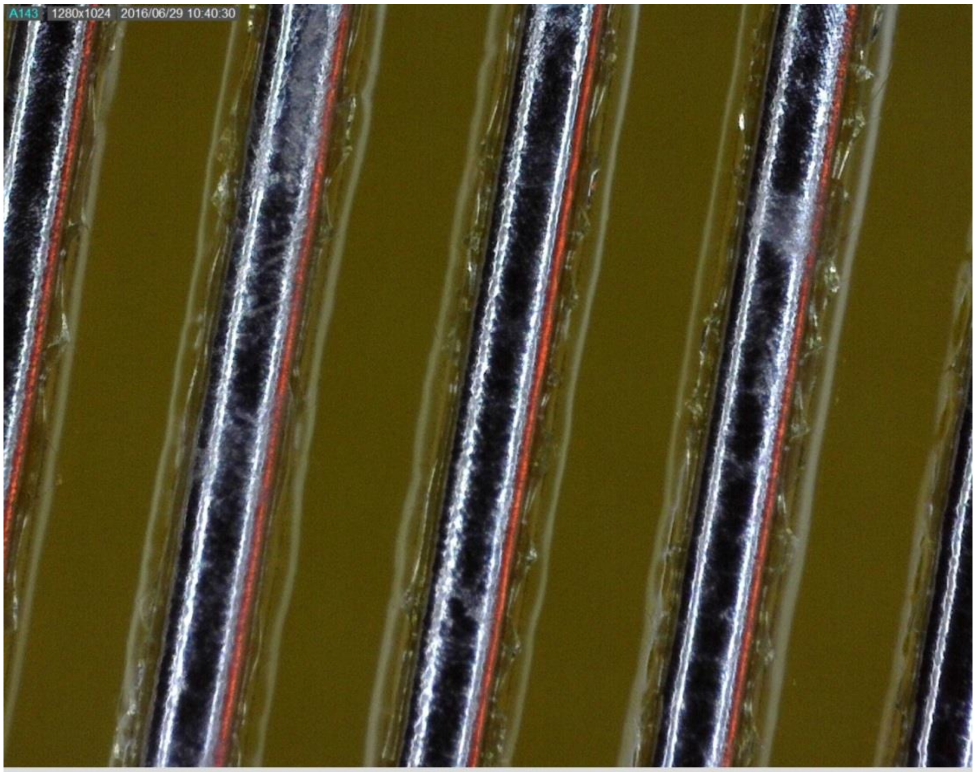

Figure 11 - Halogen-Containing - -40°C to +125°C Thermal Cycling – Vertical Orientation

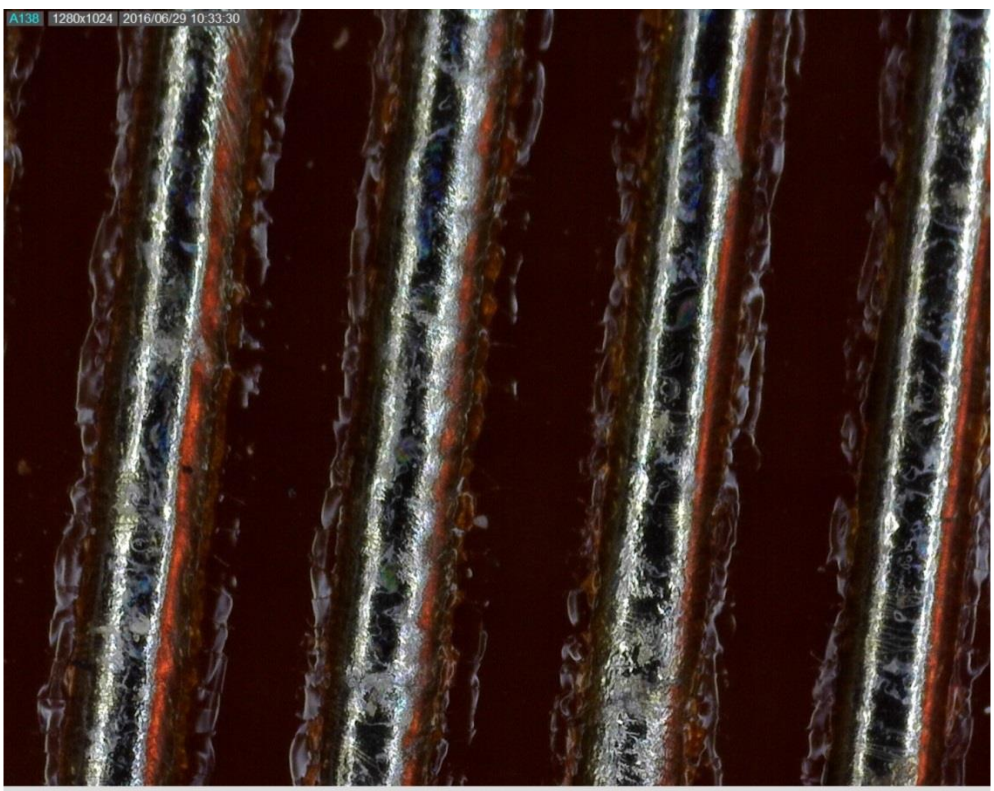

Figure 12 - Halogen-Free - -55°C to +175°C Thermal Cycling – Horizontal Orientation

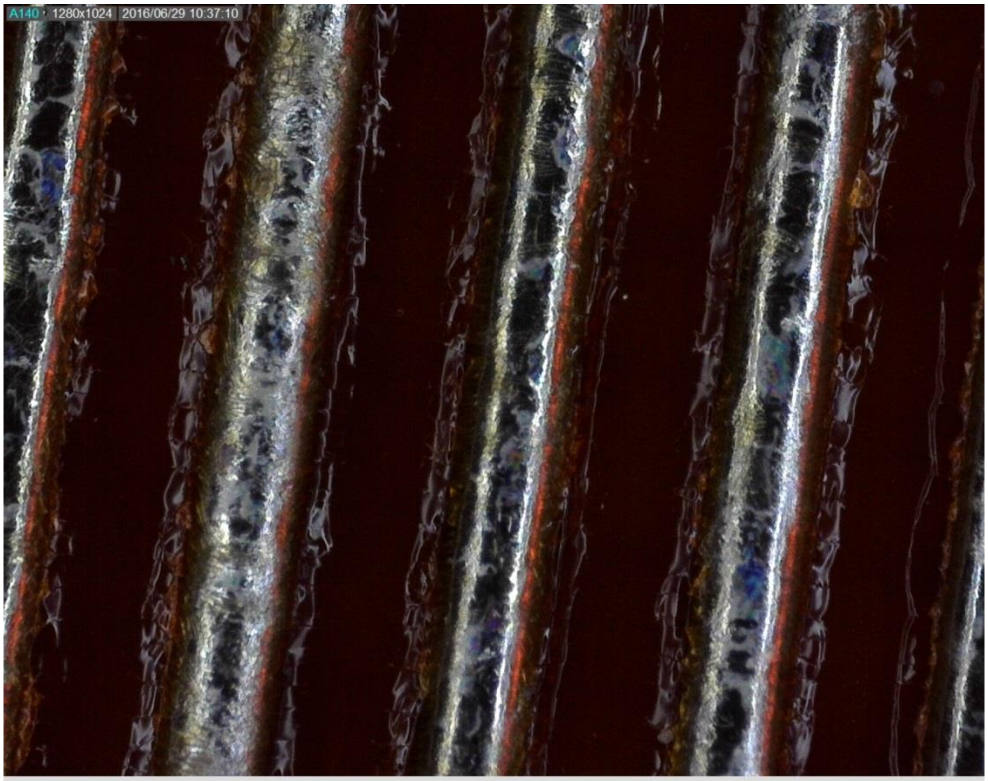

Figure 13 - Halogen-Free - -55°C to +175°C Thermal Cycling – Vertical Orientation

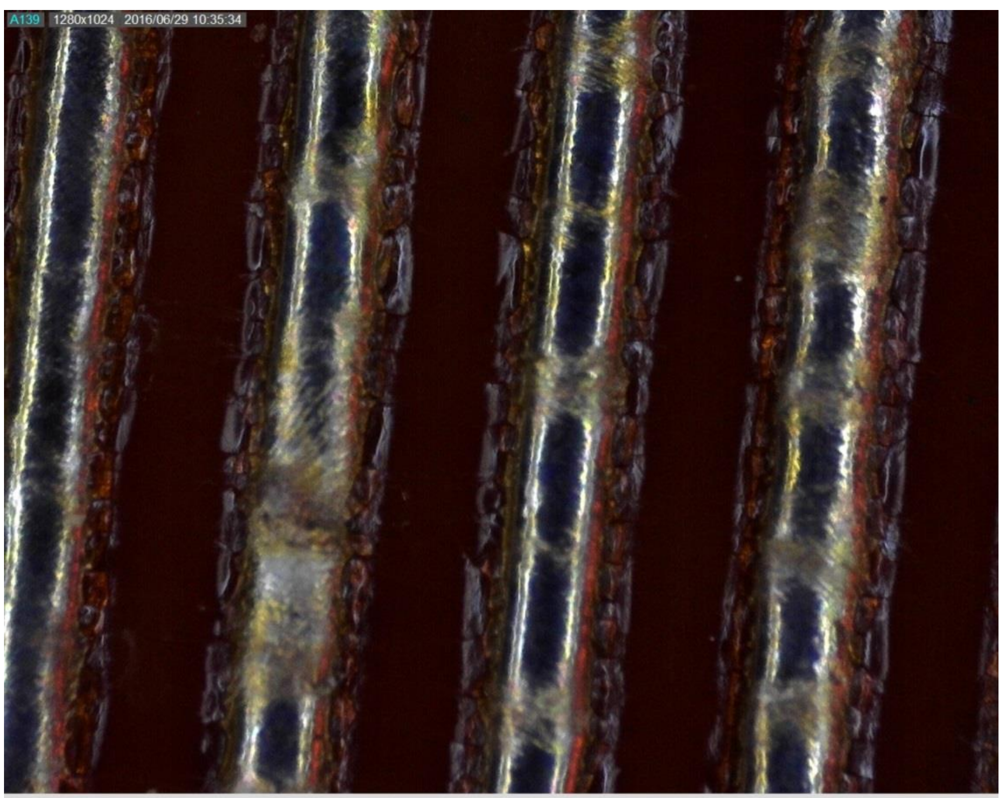

Figure 14 - Halogen-Containing - -55°C to +175°C Thermal Cycling – Horizontal Orientation

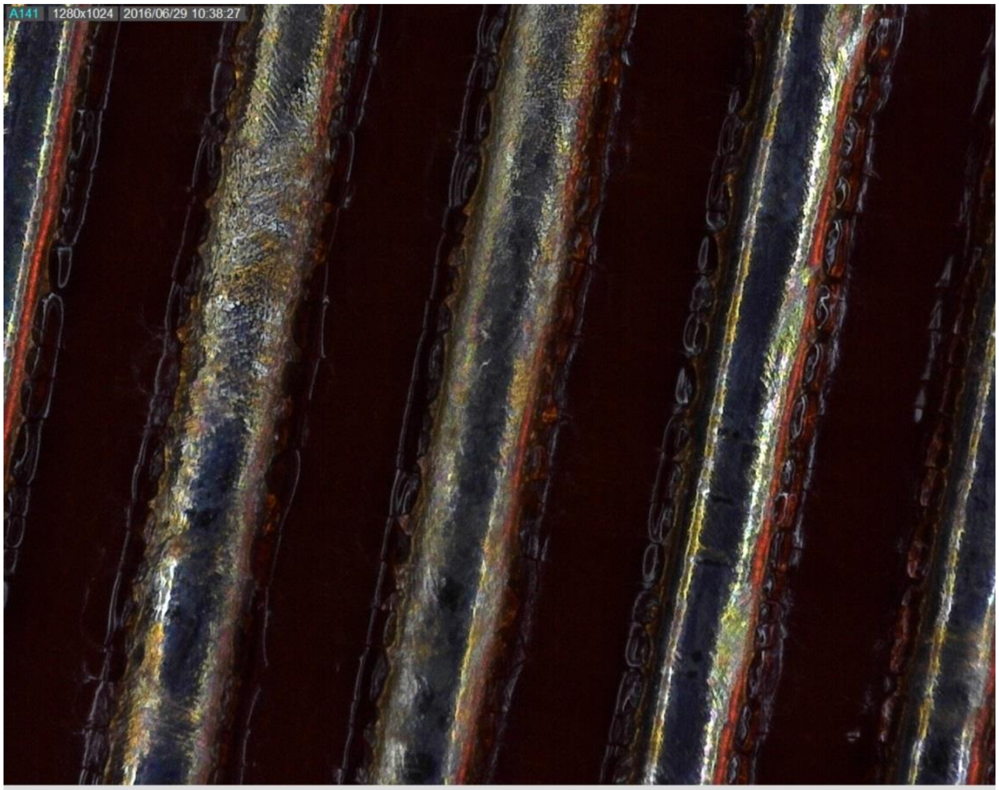

Figure 15 - Halogen-Containing - -55°C to +175°C Thermal Cycling – Vertical Orientation

Using a different microscope with different lighting, it was possible to capture a better image of what the cracking looks like in the samples that were cycled -55°C to +175°C (see Figure 16).

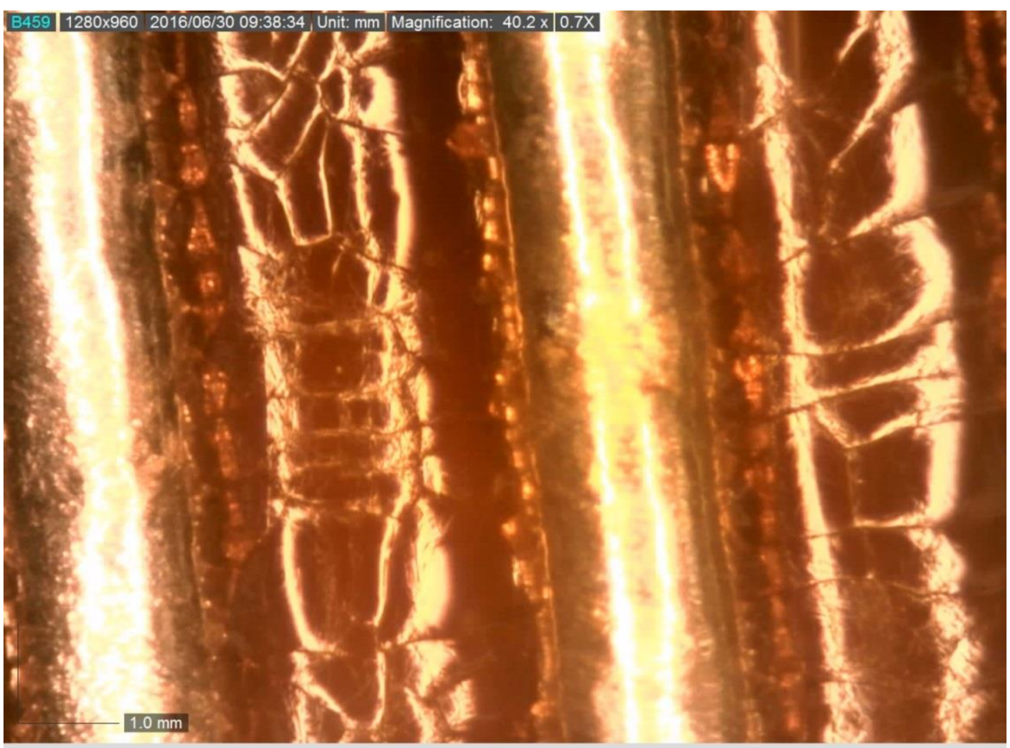

Figure 16 - Flux Cracking - -55°C to 175°C Thermal Cycling

It is important to note that the boards from the -55°C to +175°C temperature cycling chamber were at nearly room temperature when removed from the thermal cycling chamber. The boards from the -40°C to +125°C temperature cycling chamber were toward the cooler end of the cycle when they were removed. All of the boards that were temperature cycled show some amount of cracking in the flux residue, especially where it is in direct contact with the solder. It is the author's belief that at elevated temperatures above the softening point of the rosin, these cracks may "heal" and then not re-form until the cycle swings below the softening point of the rosin. It is said that cracks negatively impact the SIR performance of a flux residue. Those negative effects, should they be real, should be captured in this experiment.

There was some flow of the flux although it would probably be better to refer to it as flux "creep" or flux "migration" because it was much less dramatic than the author expected. The degree of migration was only present, to any appreciable extent, with the halogen-free solder paste. The flux migration did not seem to be sensitive to the orientation of the board as it may be more of a wicking or wetting phenomenon as opposed to a gravity-induced phenomenon. Perhaps, if more flux residue were present, gravity-induced flow may become more apparent. Figures 17 and 18 show the flux migration from -40°C to +125°C and -55°C to +175°C respectively.

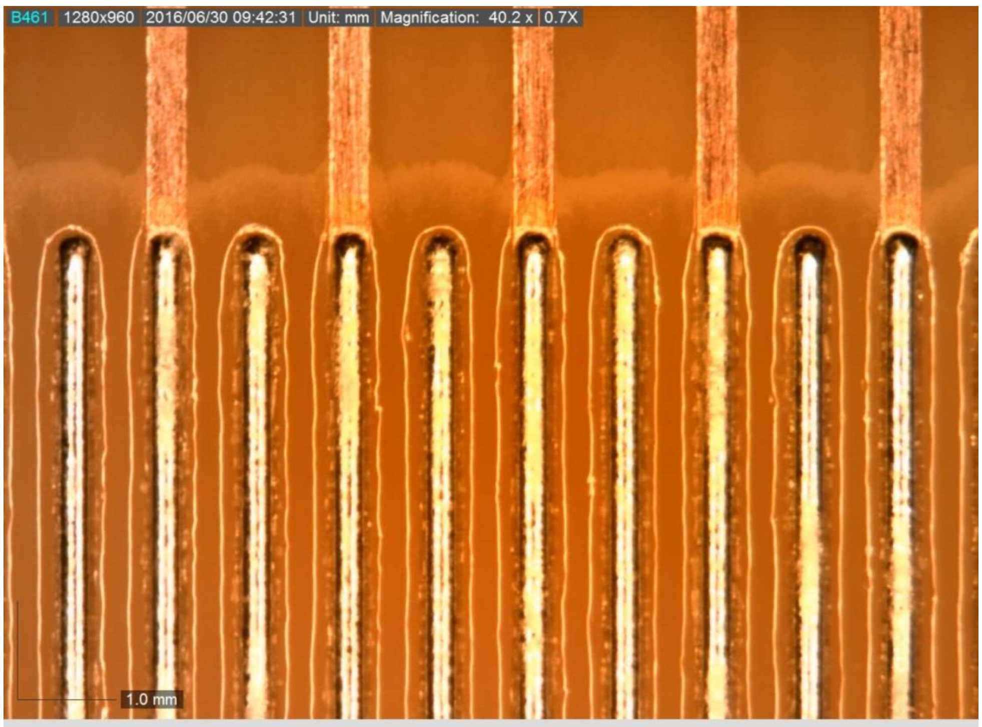

Figure 17 - Flux Migration - -40°C to +125°C

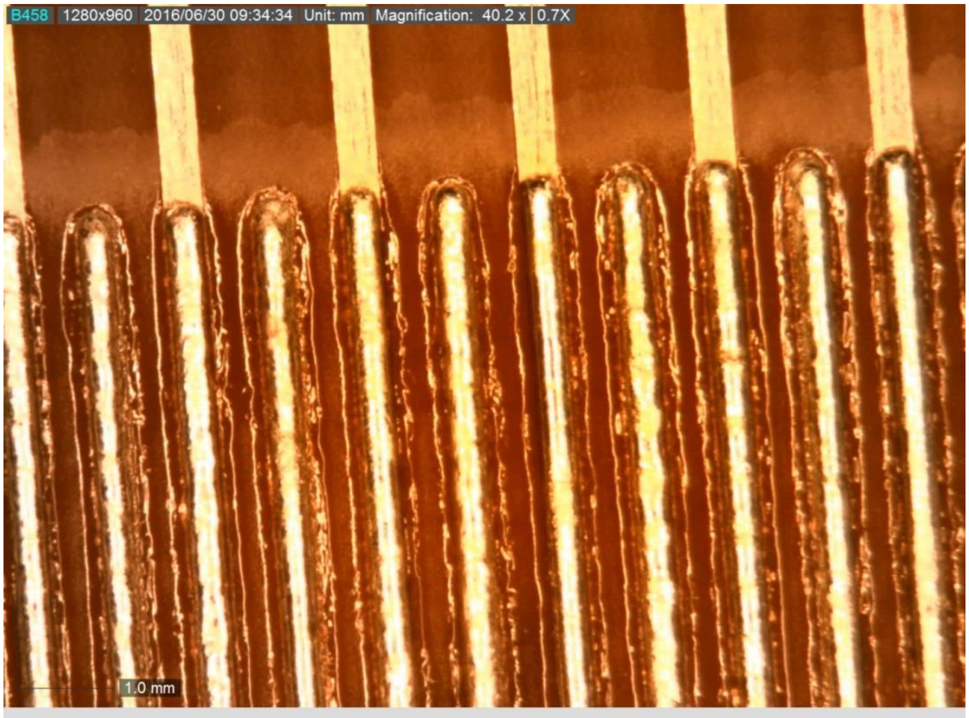

Figure 18 - Flux Migration - -55°C to +175°C

After the boards were photographed, they were submitted to SIR testing per J-STD-004B, which references IPC-TM-650 2.6.3.7. The chamber conditions are 90% RH and 40°C. A DC electrical bias is applied to produce a field strength of 25+/- 1 V/mm between adjacent parallel traces. Assuming that the surface insulation resistance is greater than 1 MΩ, this field strength corresponds to an applied voltage of 5+/- 0.2V for 0.008″ (200µ) spacing. A measurement is made at least once every 20 minutes for a duration of 168 hours (7 days or 1 week). All measurements after 24 hours must be 100MΩ or greater to constitute a "pass" per J-STD-004B – Amendment 1.

Figures 19 through 29 show the SIR results for each scenario.

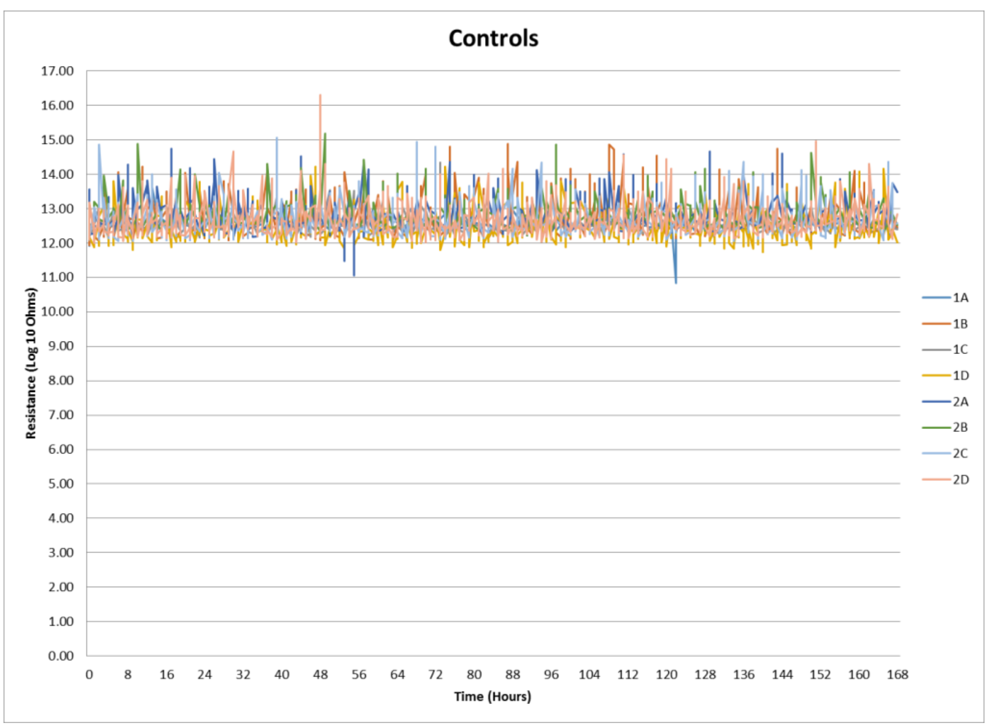

Figure 19 – Controls SIR Results

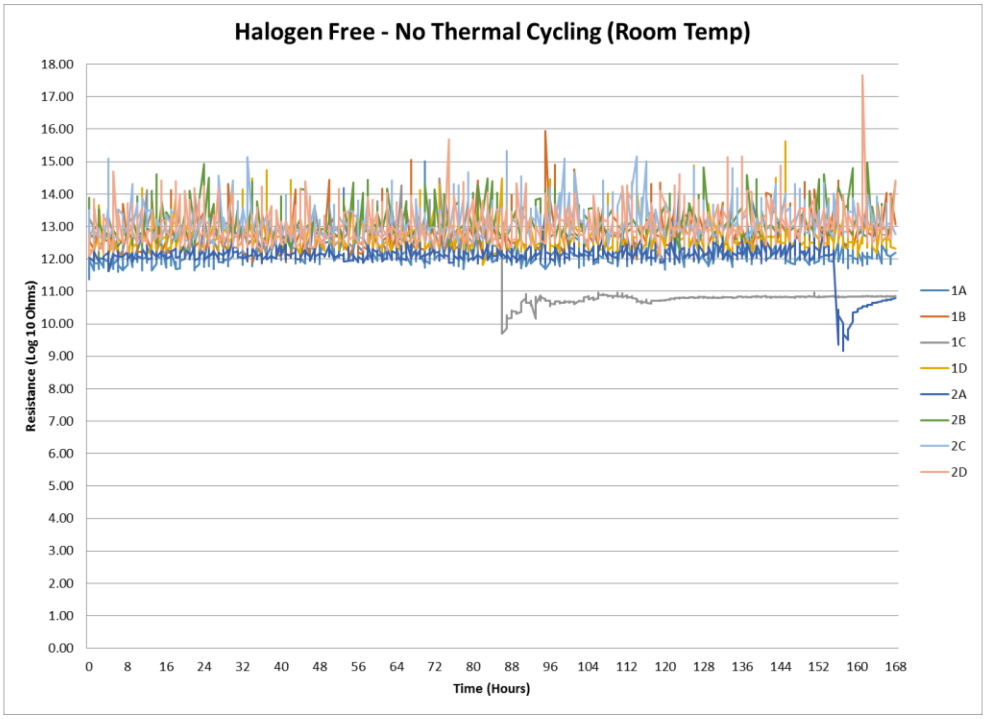

Figure 20 – Halogen-Free – No Thermal Cycling (Room Temperature) SIR Results

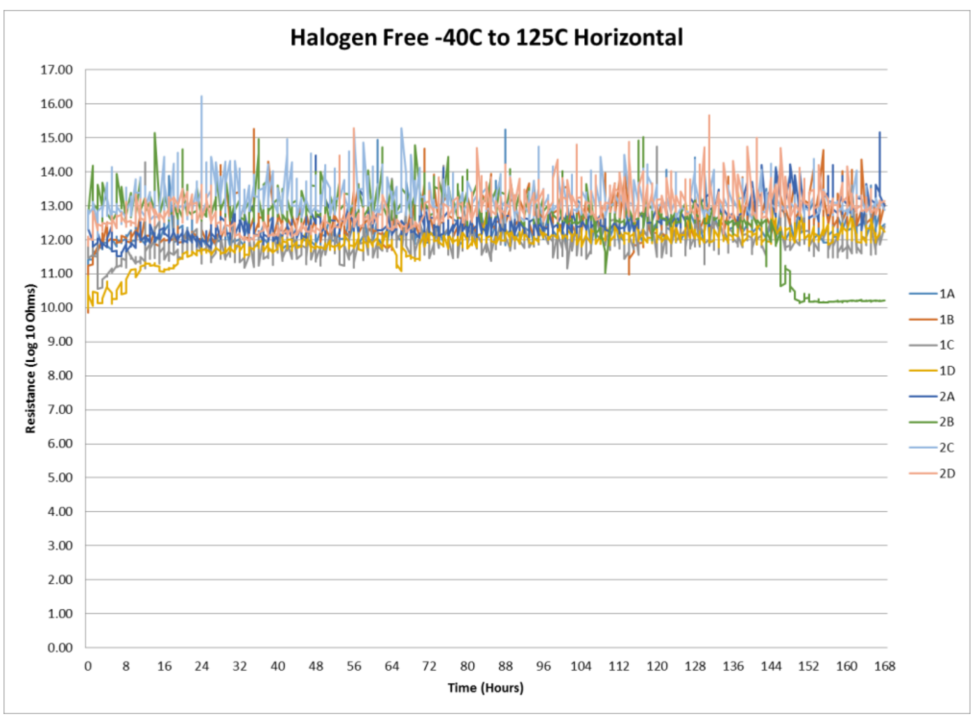

Figure 21 – Halogen Free -40°C to 125°C Horizontal SIR Results

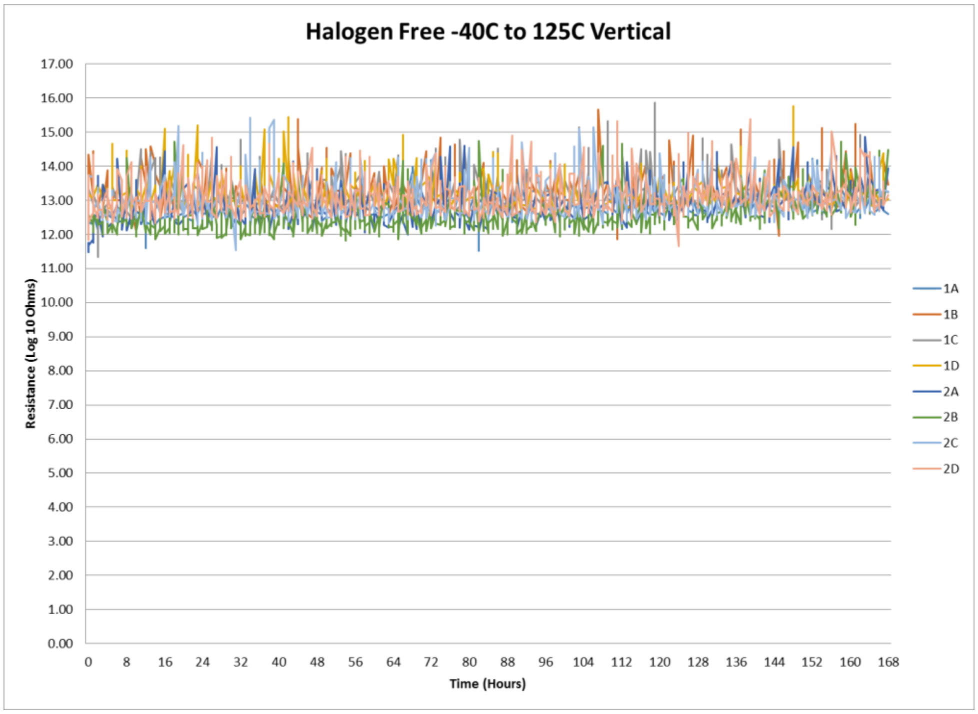

Figure 22 – Halogen-Free -40°C to 125°C Vertical SIR Results

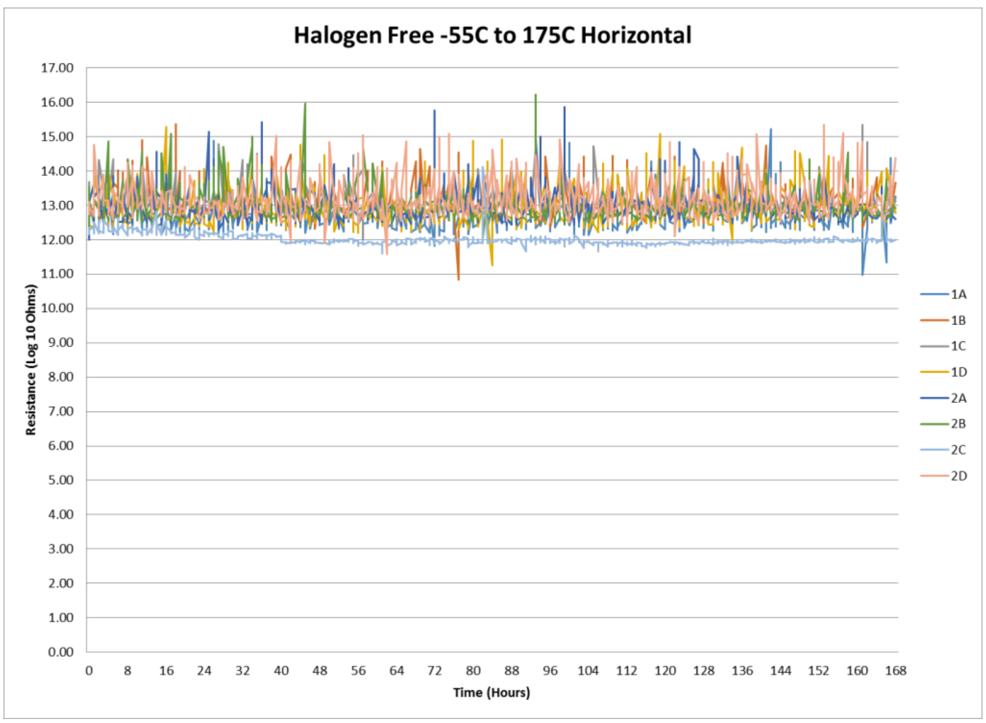

Figure 23 – Halogen-Free -55°C to 175°C Horizontal SIR Results

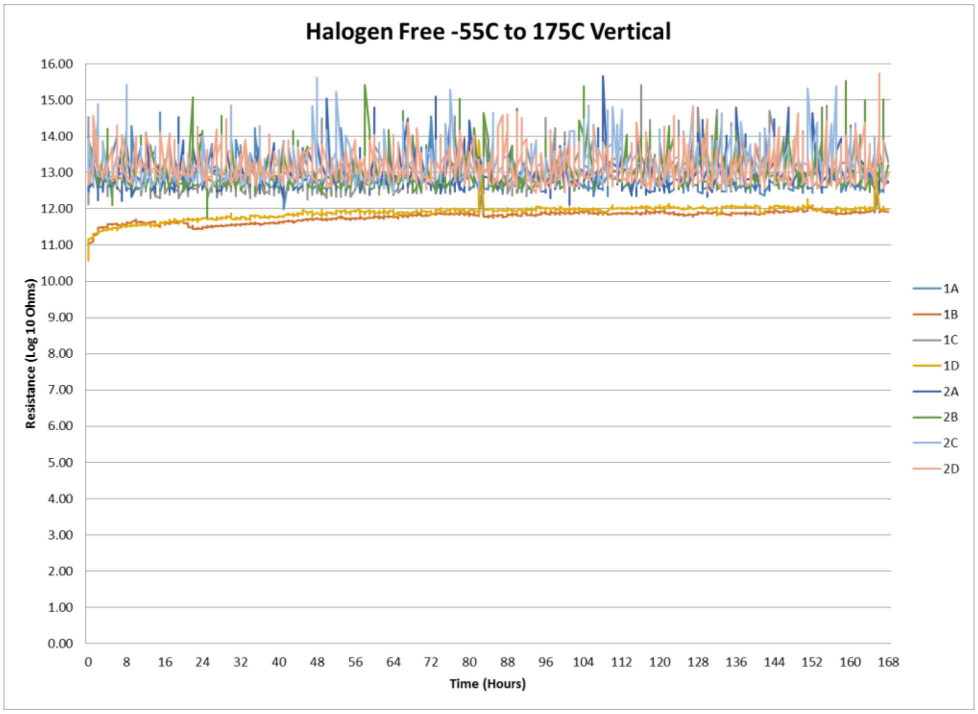

Figure 24 – Halogen-Free -55°C to 175°C Vertical SIR Results

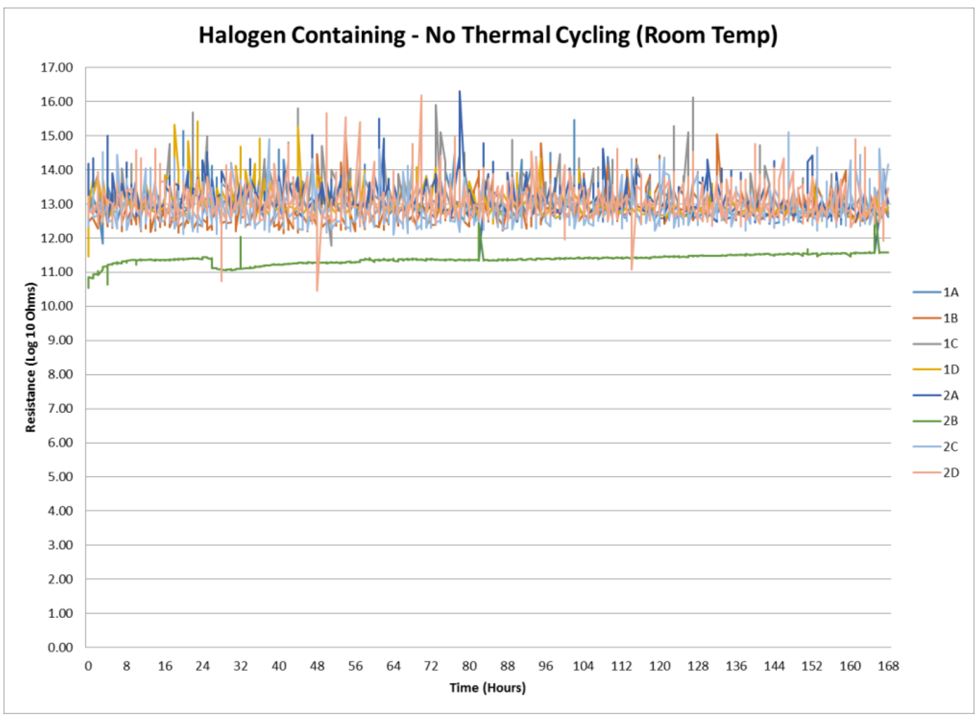

Figure 25 – Halogen-Containing – No Thermal Cycling (Room Temperature) SIR Results

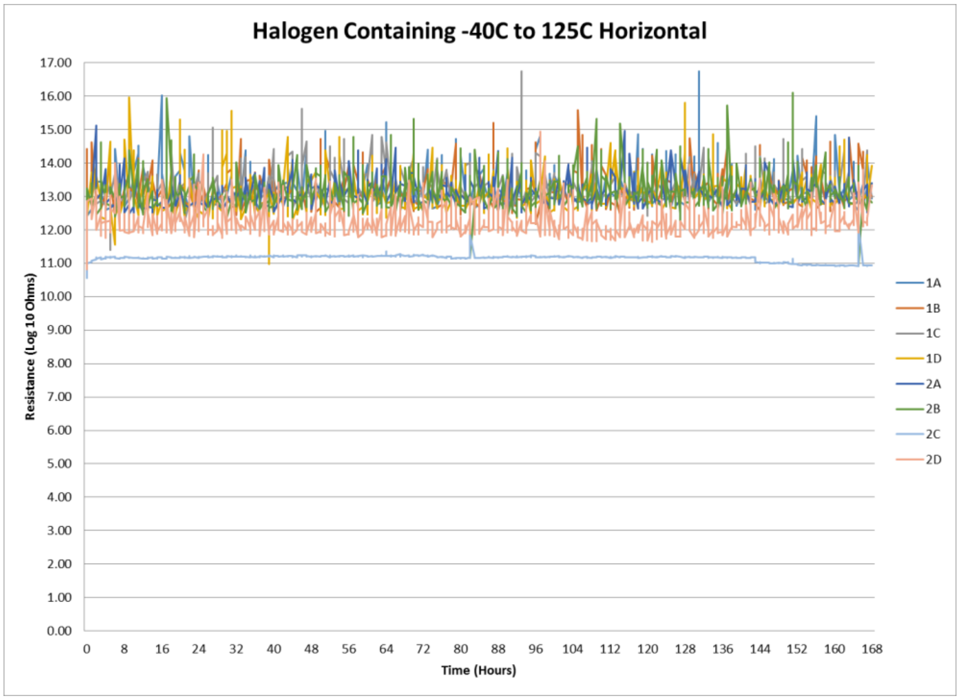

Figure 26 – Halogen-Containing -40°C to 125°C Horizontal SIR Results

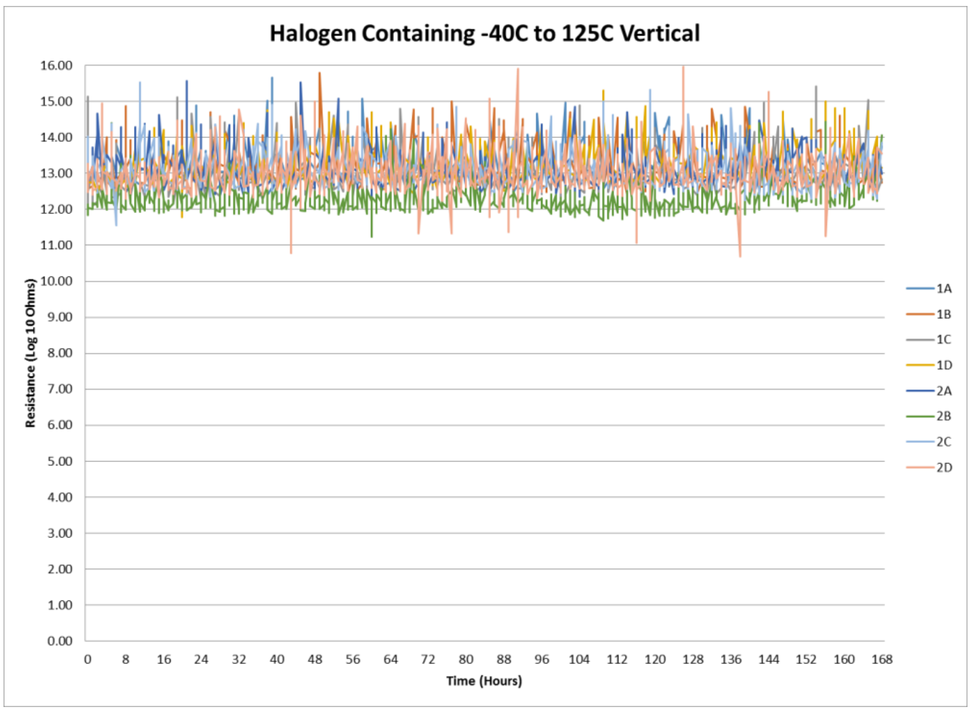

Figure 27 – Halogen-Containing -40°C to -125°C Vertical SIR Results

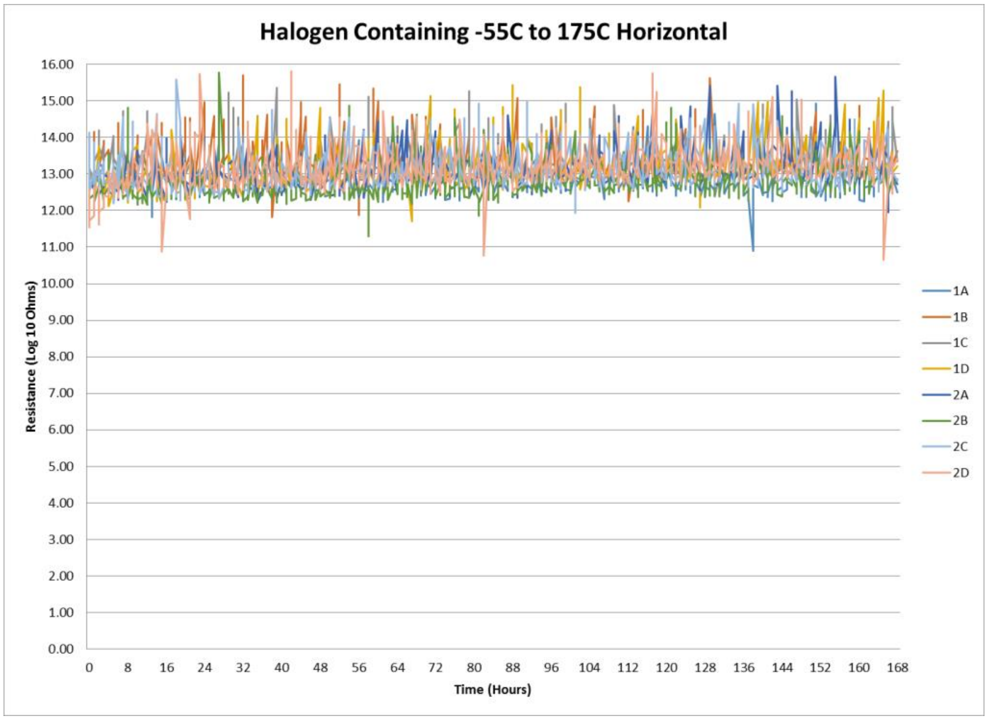

Figure 28 – Halogen-Containing -55°C to 175°C Horizontal SIR Results

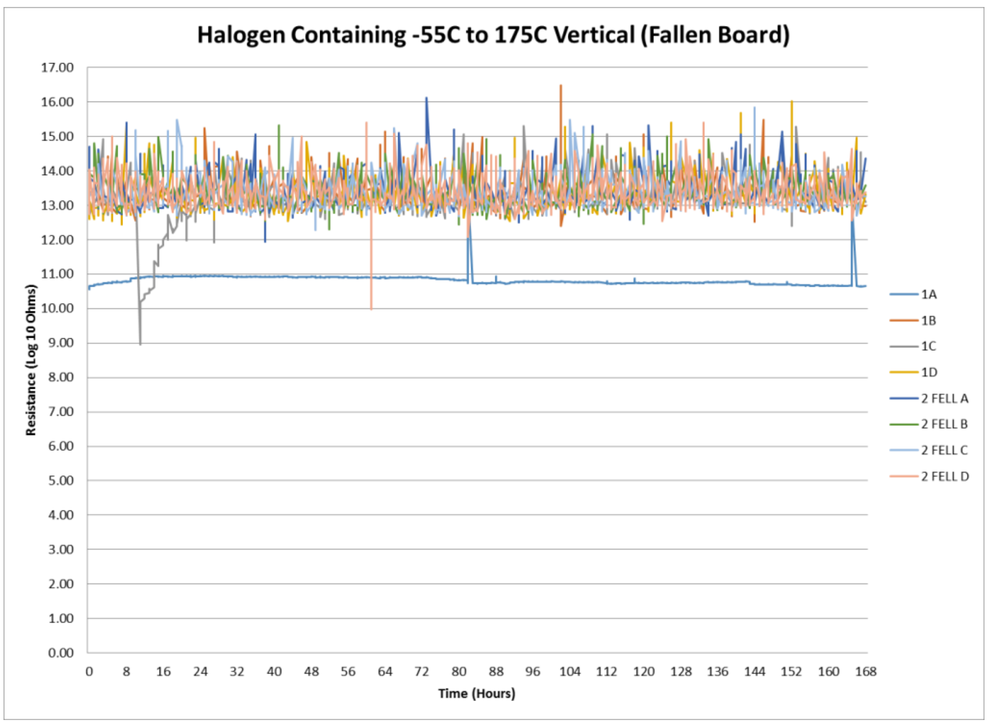

Figure 29 – Halogen-Containing -55°C to 175°C Vertical (with Fallen Board) SIR Results

After critical examination of Figures 19 through 29, we can clearly see that all SIR values exceed the minimum J-STD-004B value of 1 x 10^8 Ohms and the lowest value achieved was 1 x $10^{8.96}$ Ohms, nearly one order of magnitude higher than the minimum J-STD-004B value of 1 x 10^8 Ohms (see Pattern 1C of Figure 29 at ~ 11 hours).

For ease of comparison and to detect any meaningful trend in the SIR data, the values for each scenario were averaged and then placed in a single graph, side by side (see Figure 30). It can be argued that averaging SIR data is not wise. However, the emphasis of this paper is to look at the general effect of temperature cycling and not meant to be a point by point analysis of the SIR values.

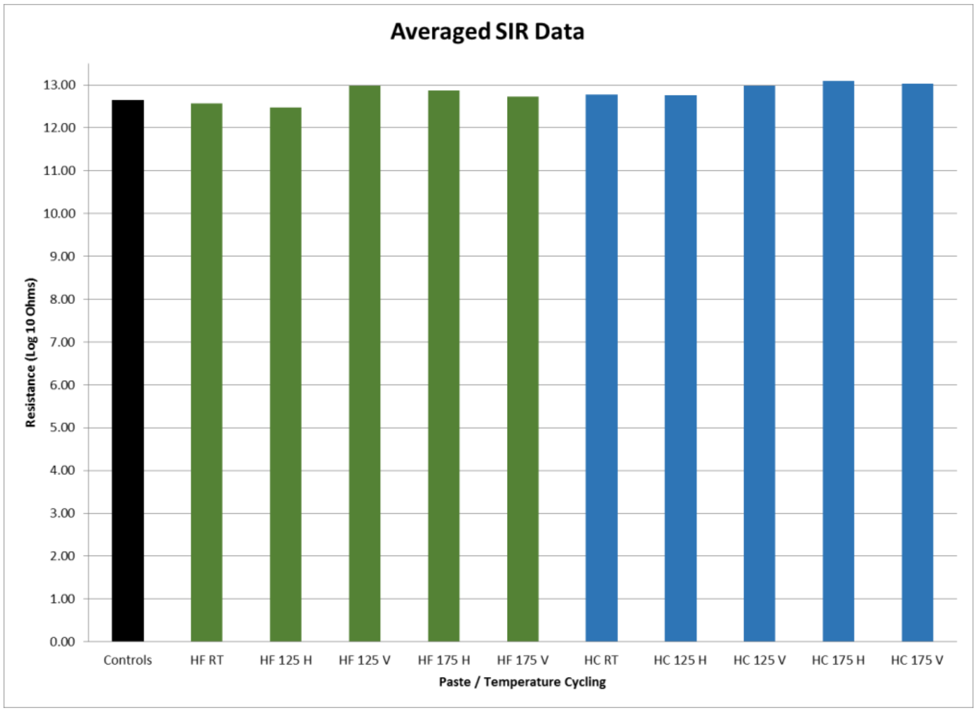

Figure 30 – Averaged SIR Results

Key for Figure 30:

- HF = Halogen-Free Solder Paste
- HC = Halogen-Containing Solder Paste
- RT = Room Temperature - No Thermal Cycling
- 125 = -40°C to 125°C Thermal Cycling
- 175 = -55°C to 175°C Thermal Cycling
- H = Horizontal Orientation During Thermal Cycling
- V = Vertical Orientation During Thermal Cycling

A few things are immediately evident when viewing the data this way.

1) The averaged SIR values of all scenarios are virtually identical.
2) The averaged SIR values of the temperature cycled pastes are virtually identical to their respective room temperature scenarios.
3) All of the scenarios produced average SIR values that are comparable to or higher than the controls.
4) All of the averaged SIR values are at least 4 orders or magnitude higher than the minimum J-STD-004B requirement of 1×10^8 Ohms.
5) There is no meaningful difference between how the halogen-free and halogen-containing solder paste formulations respond to temperature cycling.
6) The orientation of the boards, horizontal and vertical, did not have any impact on the SIR values.
7) The number of cycles and range of the temperature cycling has no meaningful impact on the averaged SIR values.
8) Even with the inclusion of (a) pattern(s) that exhibited noticeably lower values than the rest of the patterns for a given scenario, the impact to the average was minimal. For example, see pattern 1A in Figure.

These results are no surprise to the author. Knowing that both of these temperature cycling regimes are likely high enough to soften or even liquefy the flux residue, it is the author's belief that each time the residue experienced the hot side of the cycle, the cracks would have the opportunity to "heal" and re-encapsulate. Therefore, the exposure of the residual activators and activator/metal oxide by-products in the flux residue caused by the cracking either does not really happen to any significant degree or the residue readily re-encapsulates them. It would be interesting to know if the cracking in the residue is the result of CTE mismatch between the various materials in and on the SIR board, or that the residue is simply drying and/or burning off and reducing in volume, or some combination of both.

Orientating the boards so that they were parallel to gravity did not seem to cause any substantial "flow" of the flux residue when the thermal cycle exceeded the softening point of the rosin. Any "flow" that did occur seemed to be more of a wetting or wicking action of the flux across the surface of the board. Keep in mind that there is no solder mask on the SIR test boards. They are bare FR4.

The results of this experiment suggest that thermal cycling and the resulting cracks that form in the flux residue pose no deleterious threat to the electrical reliability of a ROL0 or ROL1 flux residue.

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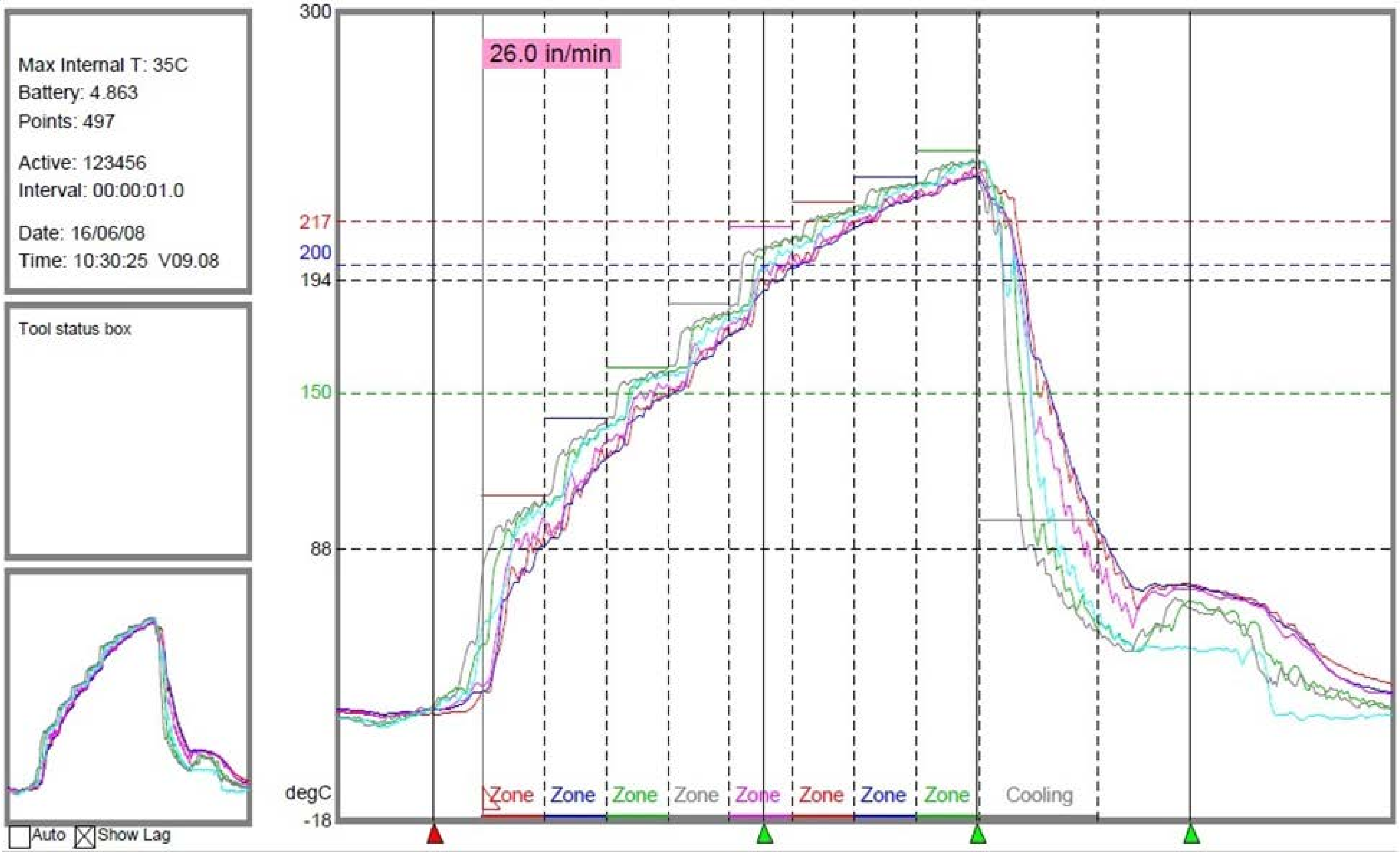

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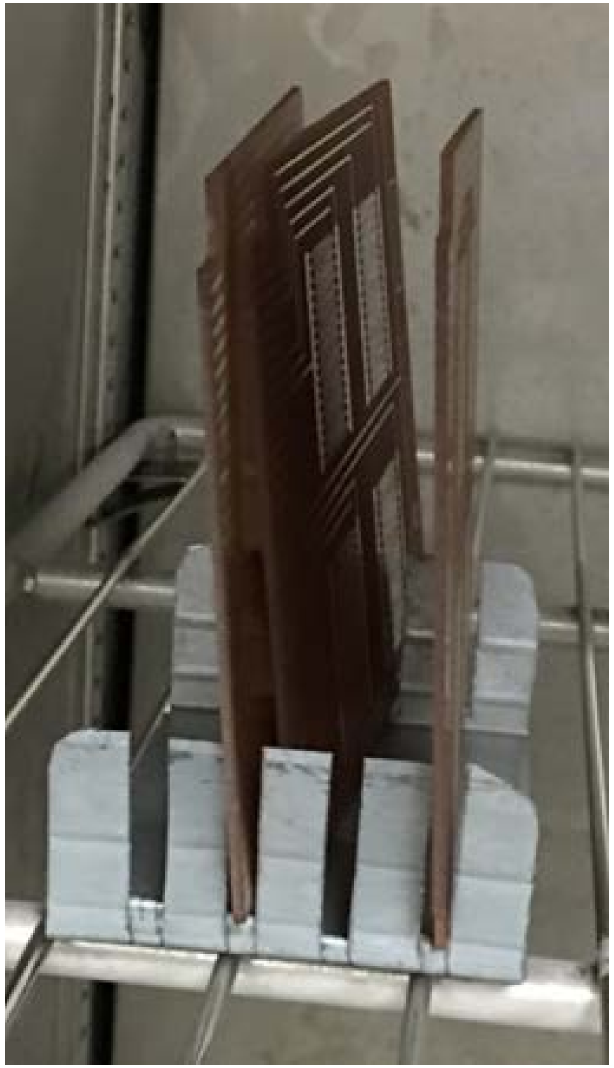
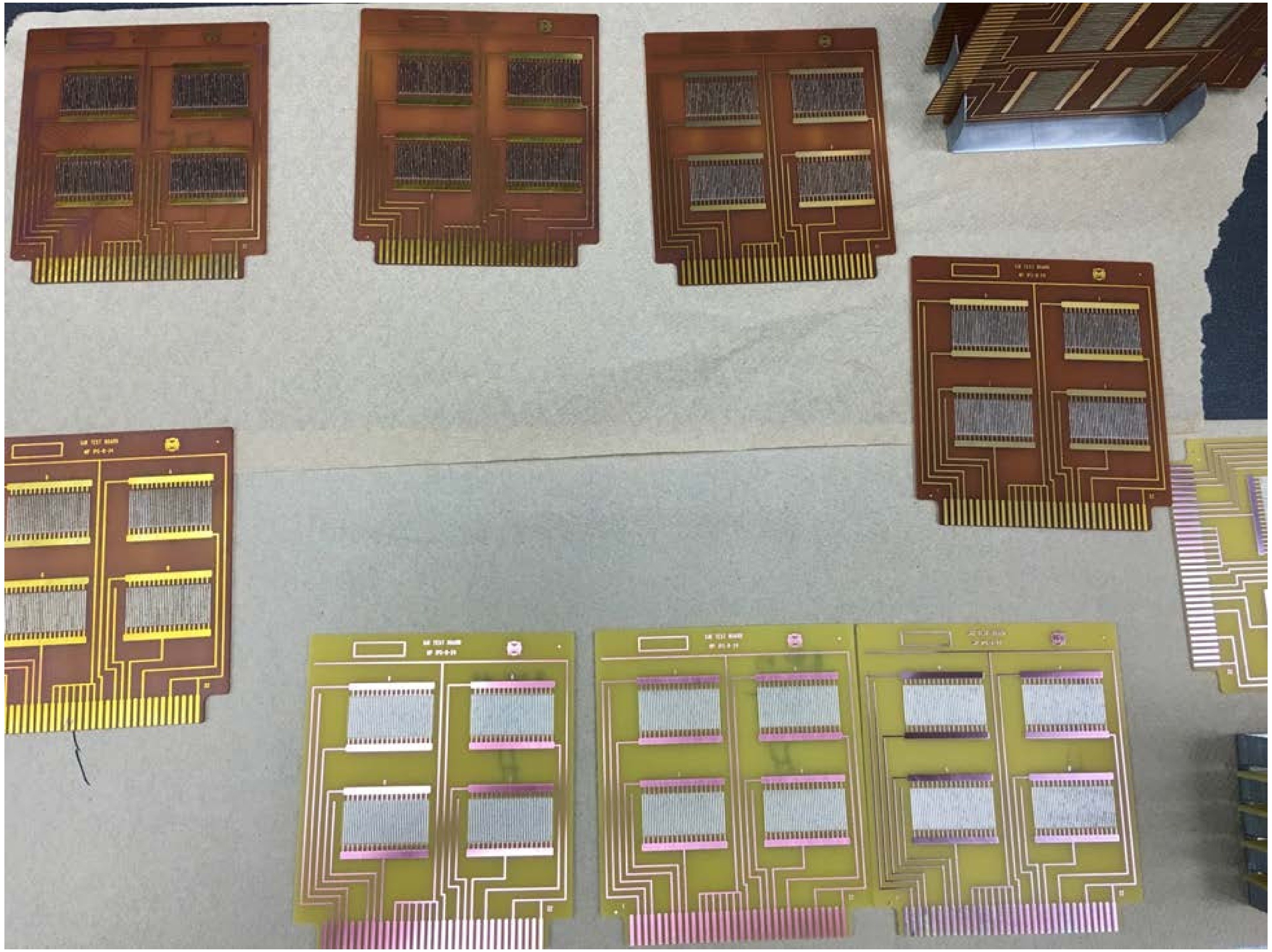
Orientation of the Boards in the -40C to +125C Chamber

Orientation of the Boards in the -55C to +175C Chamber

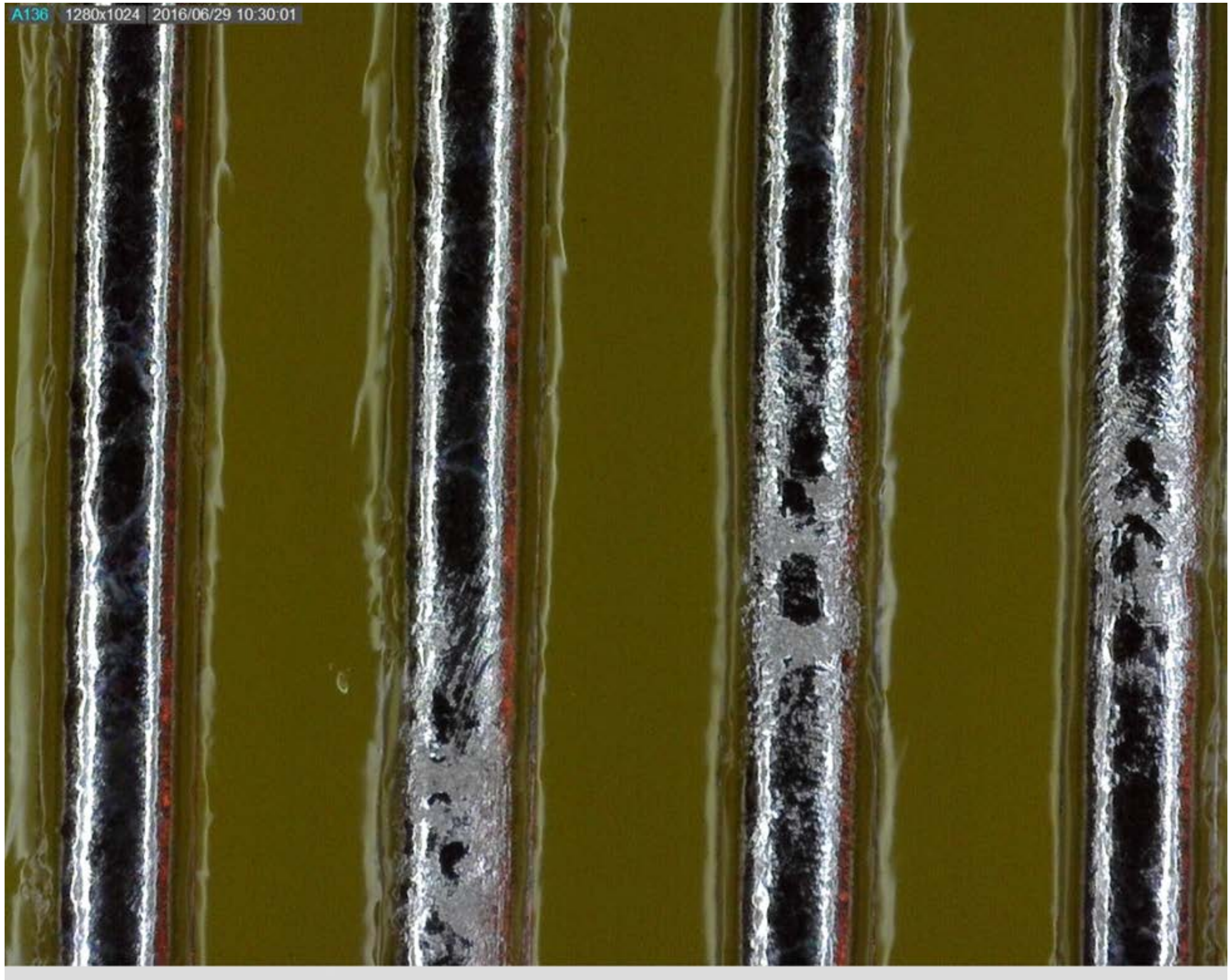
Disturbed Vertically Orientated Boards in the -55C to +175C Chamber



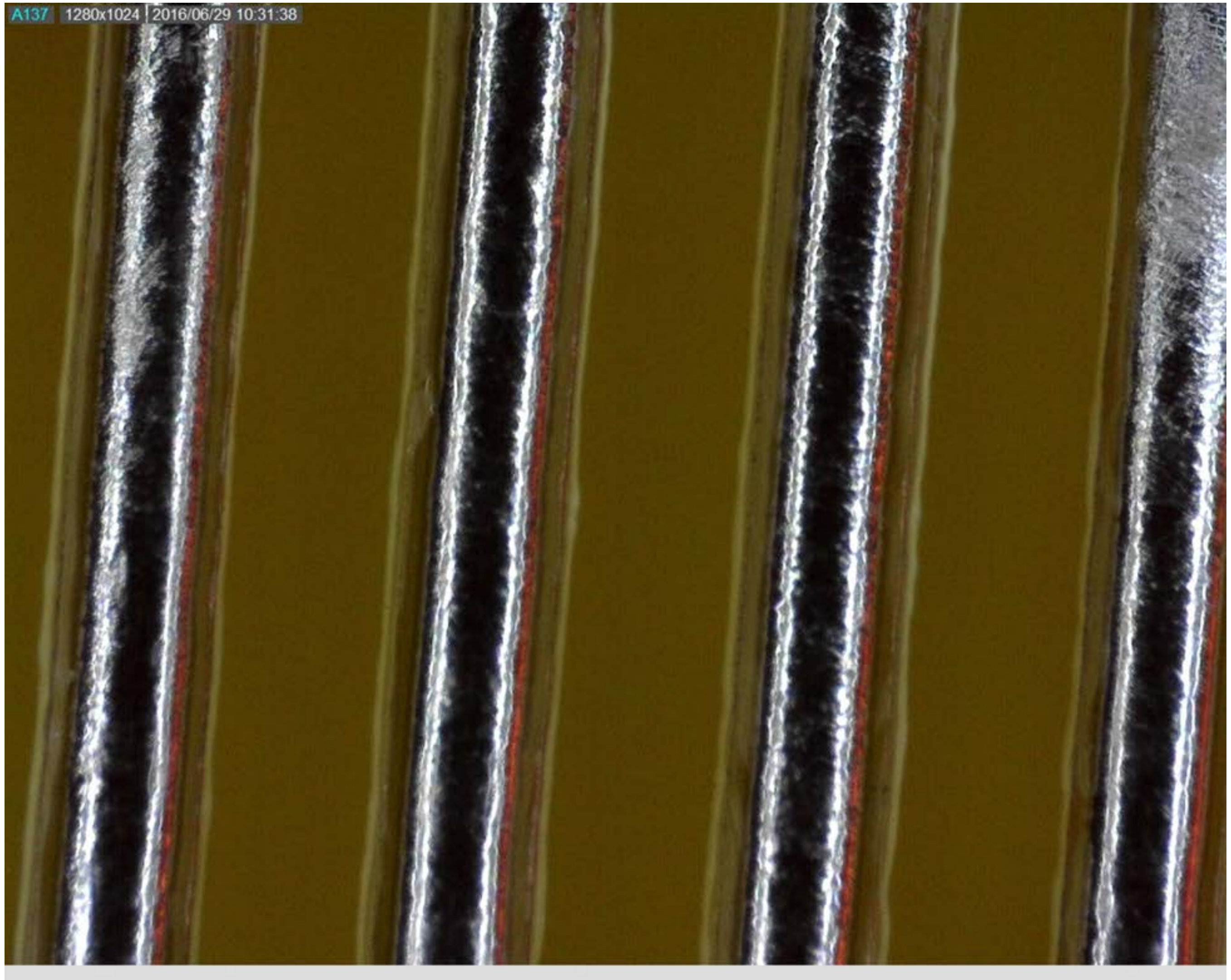
Discoloration of Boards from the -55C to +175C Chamber



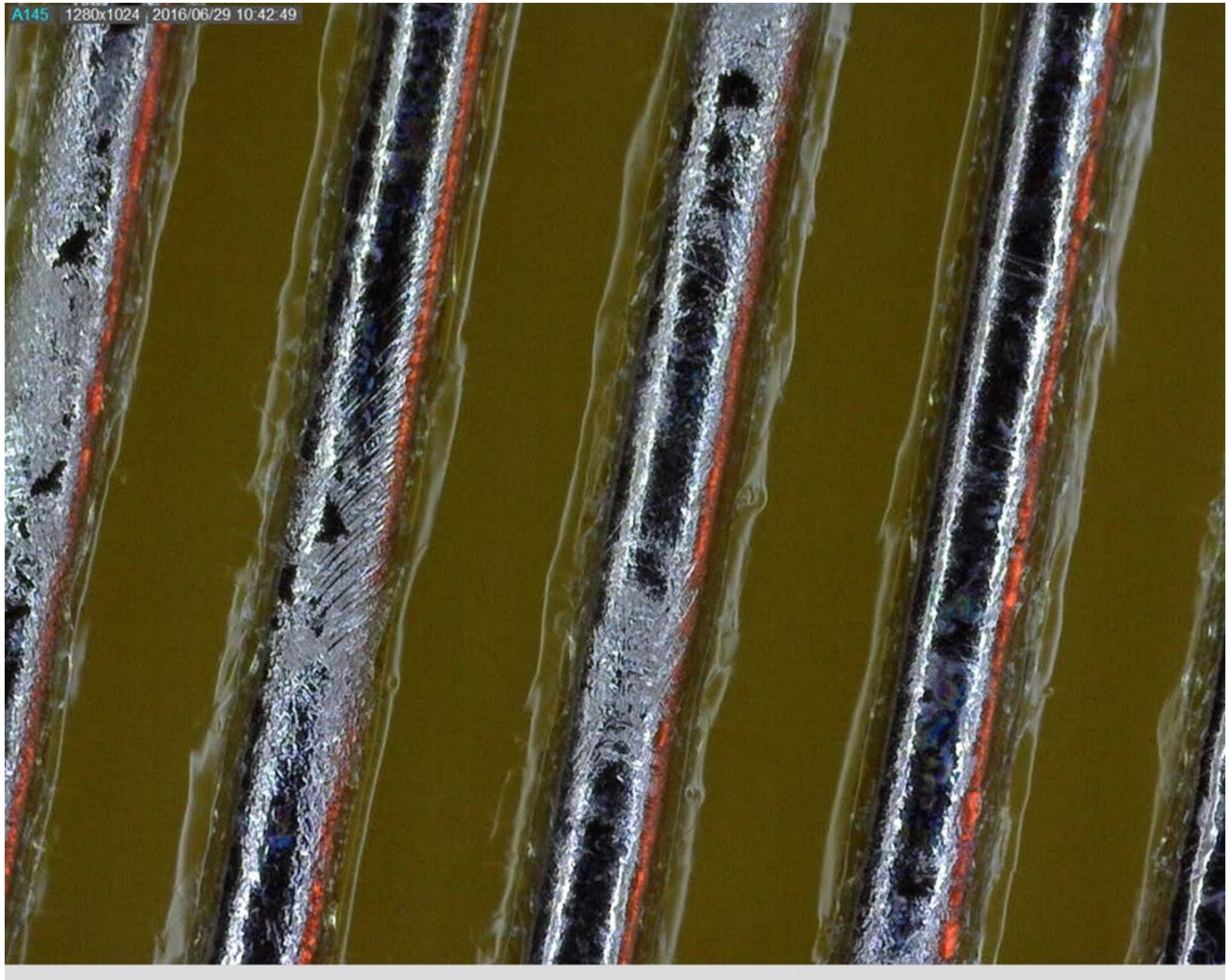
Halogen Free – No Thermal Cycling



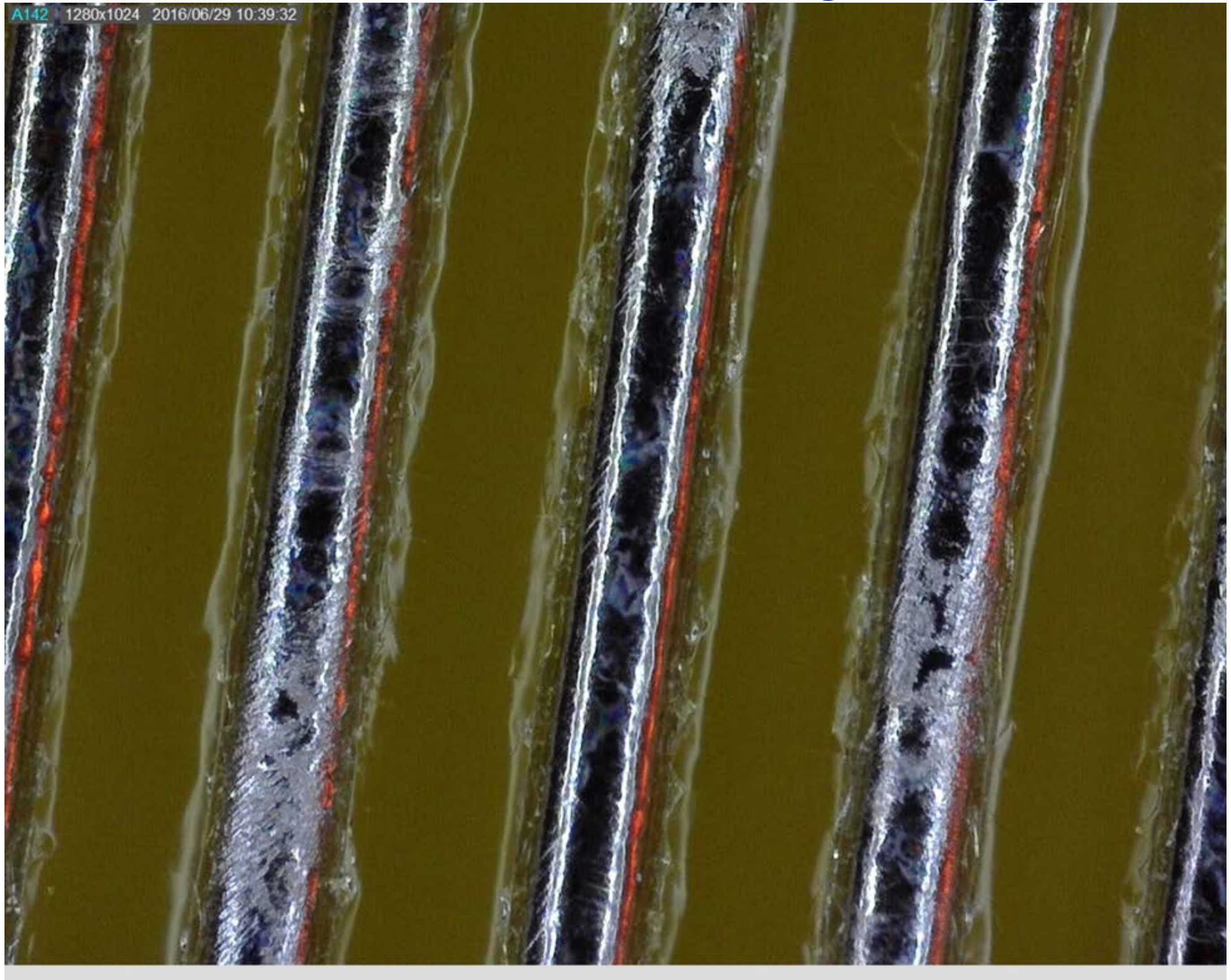
Halogen Containing – No Thermal Cycling



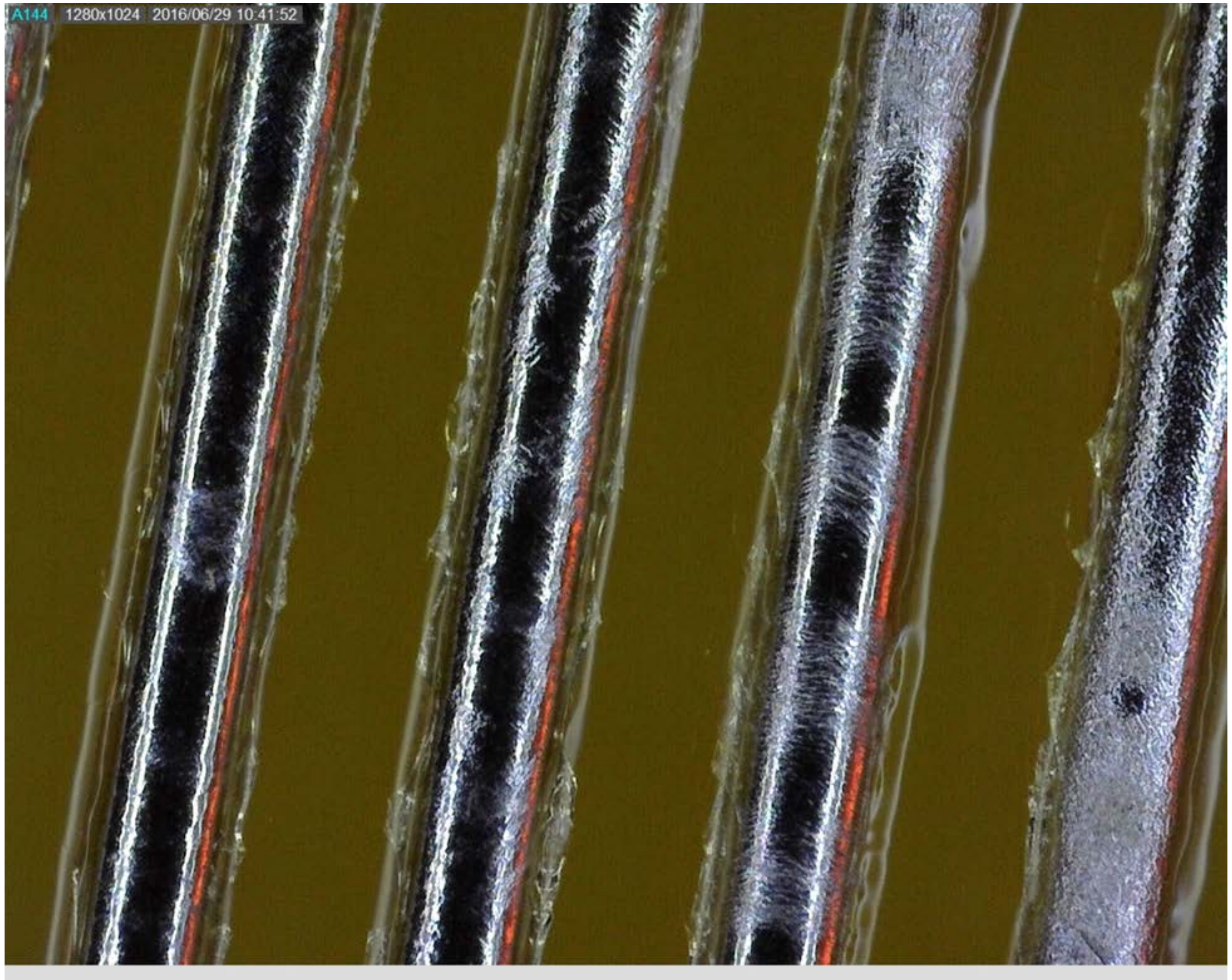
Halogen Free - -40C to +125C Thermal Cycling – Horizontal Orientation



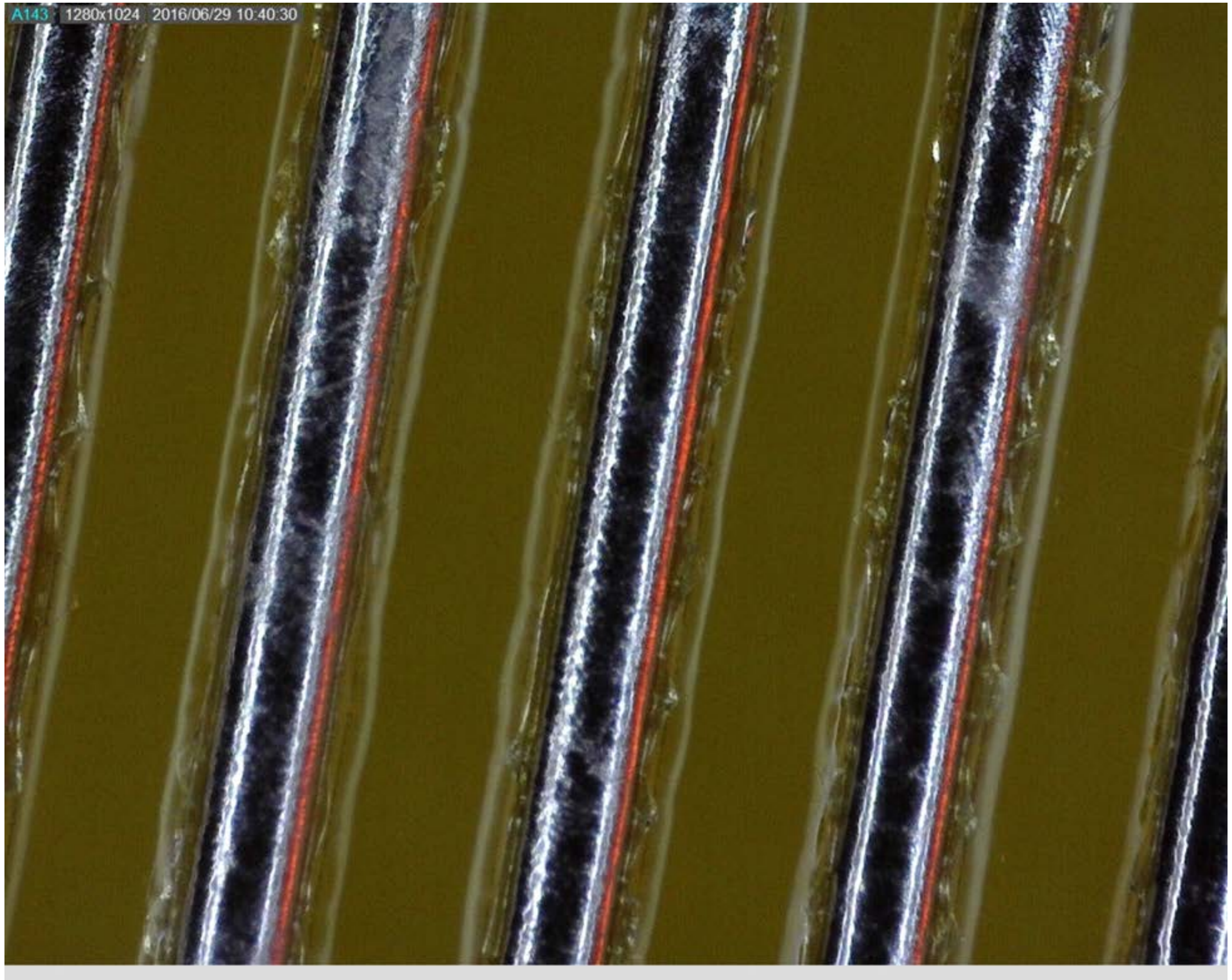
Halogen Free - -40C to +125C Thermal Cycling – Vertical Orientation



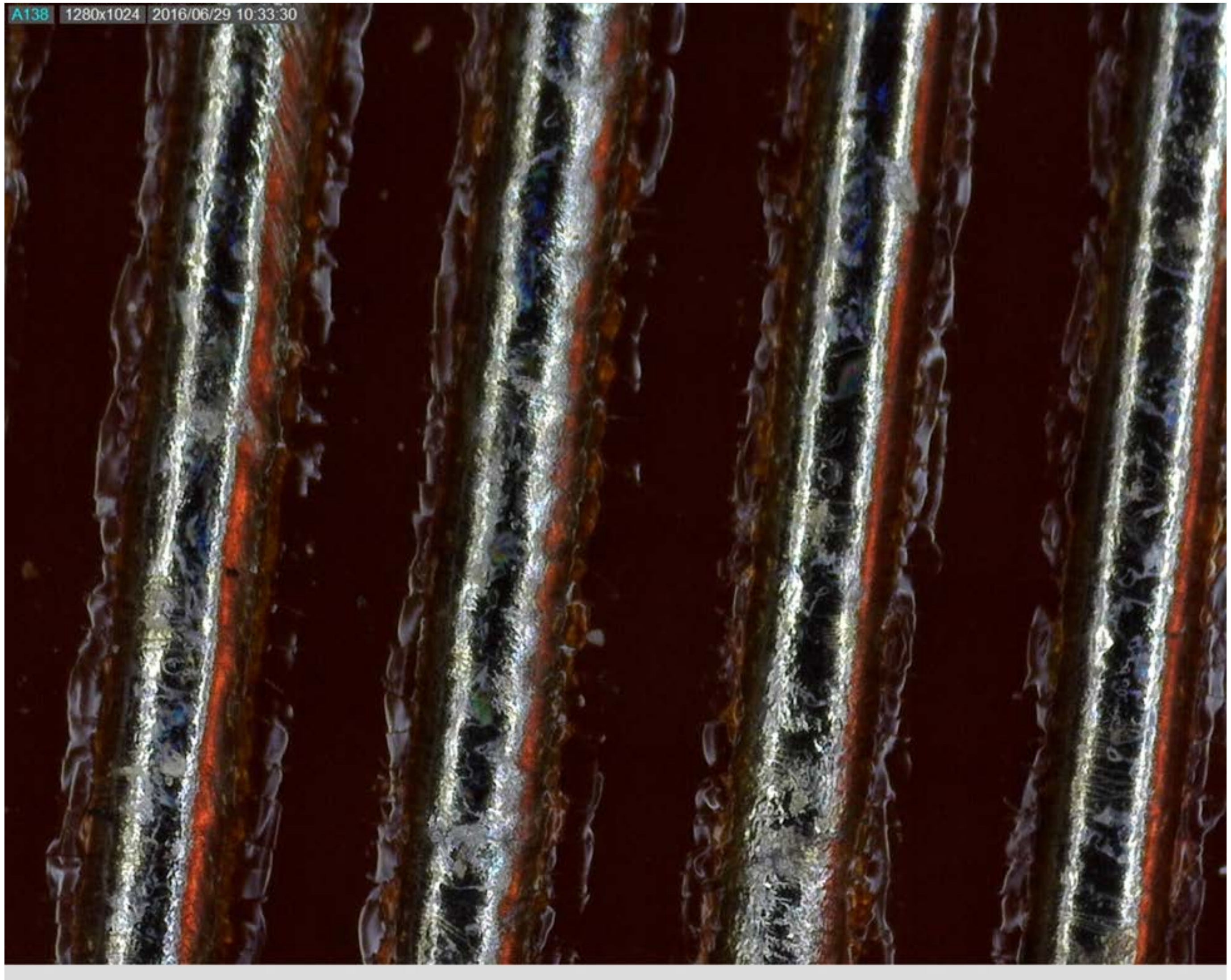
Halogen Containing - -40C to +125C Thermal Cycling – Horizontal Orientation



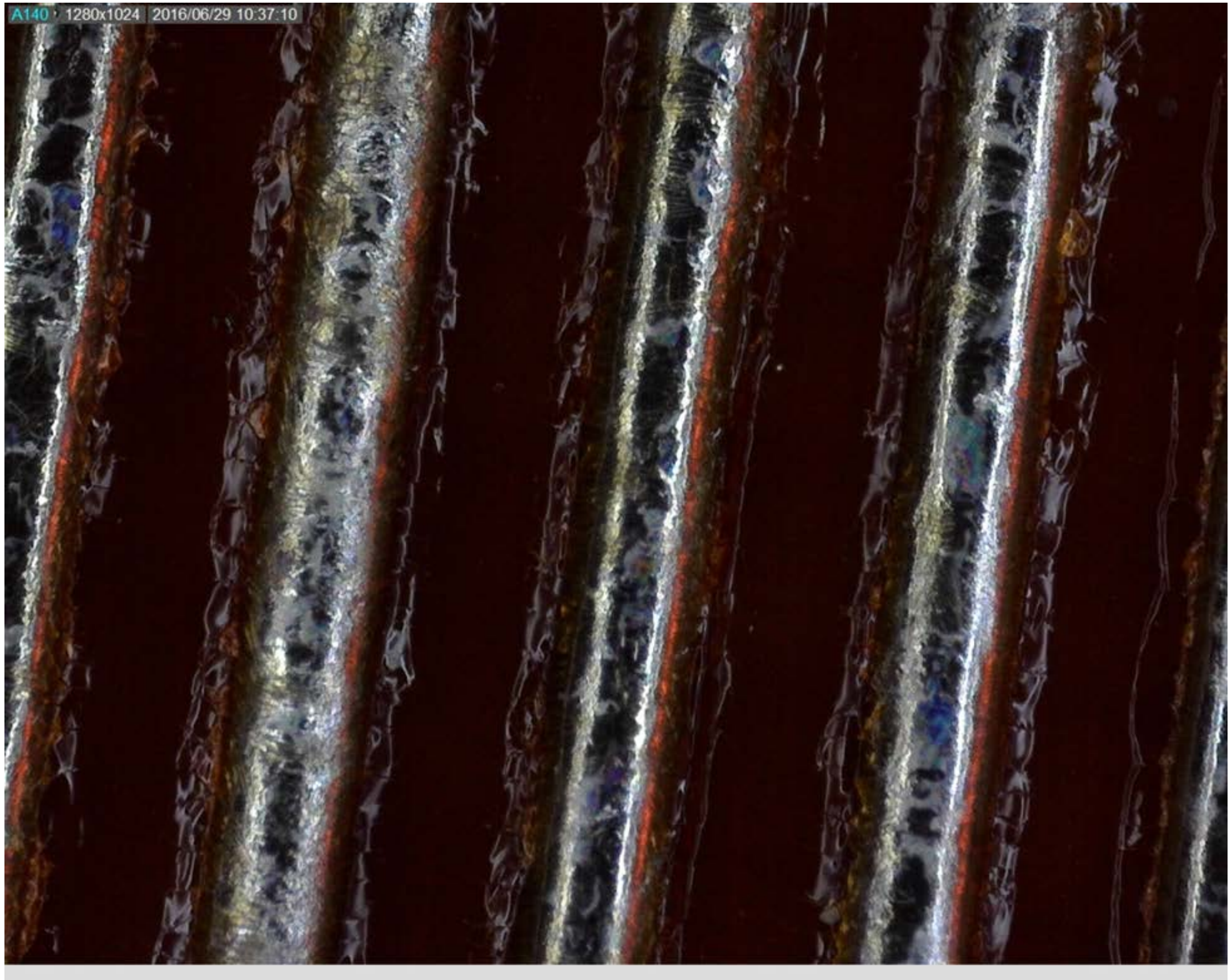
Halogen Containing - -40C to +125C Thermal Cycling – Vertical Orientation



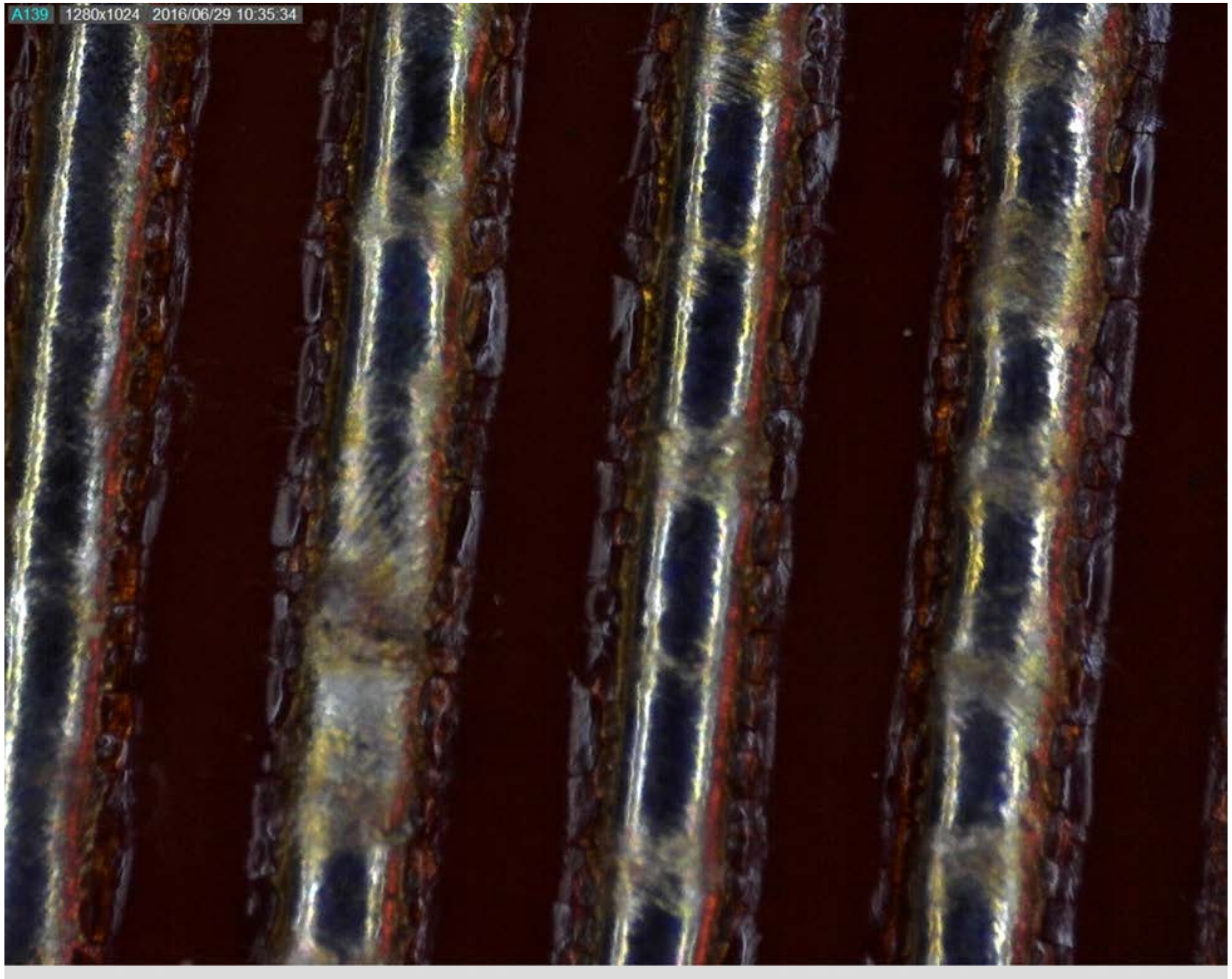
Halogen Free - -55C to +175C Thermal Cycling – Horizontal Orientation



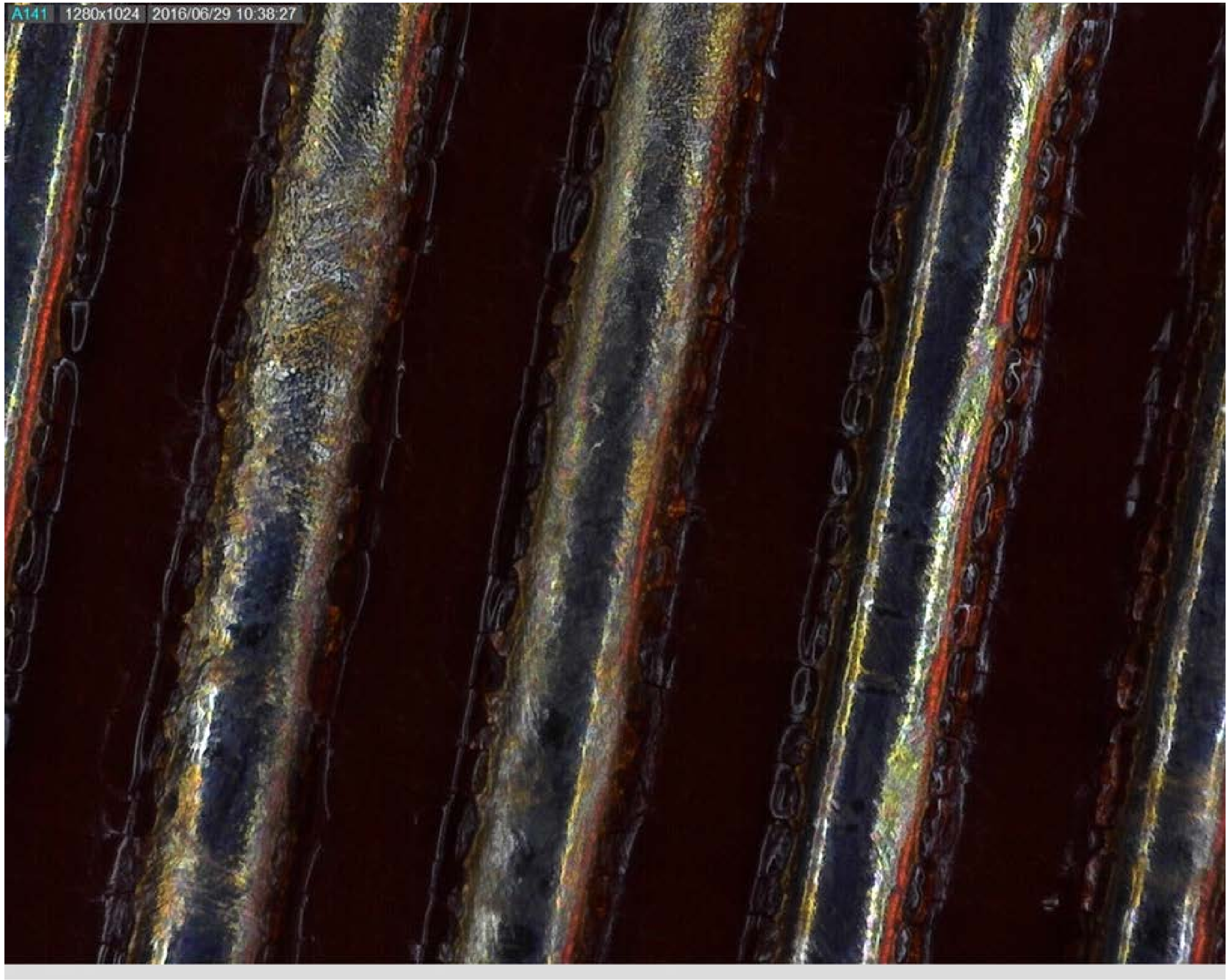
Halogen Free - -55C to +175C Thermal Cycling – Vertical Orientation



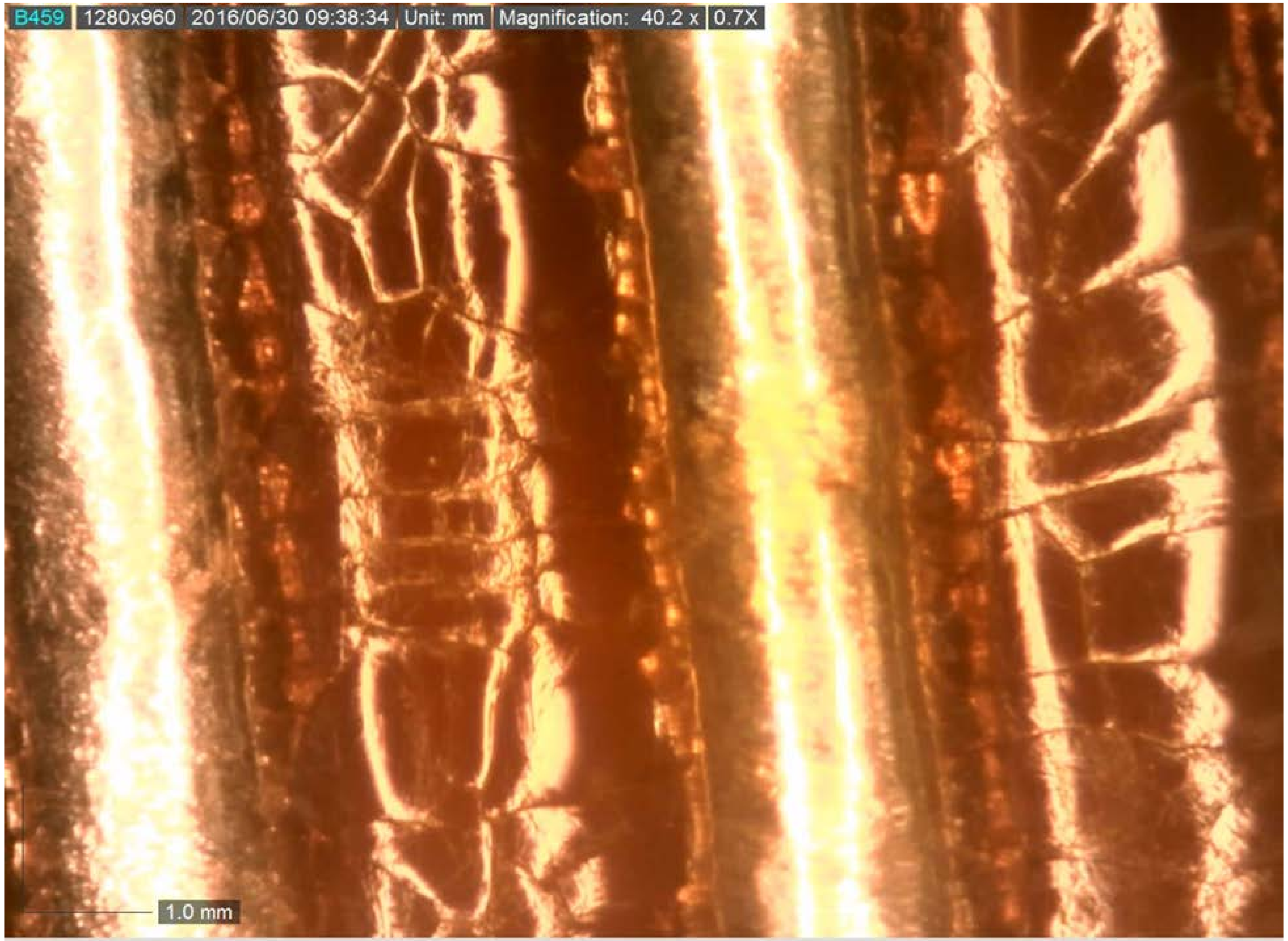
Halogen Containing - -55C to +175C Thermal Cycling – Horizontal Orientation



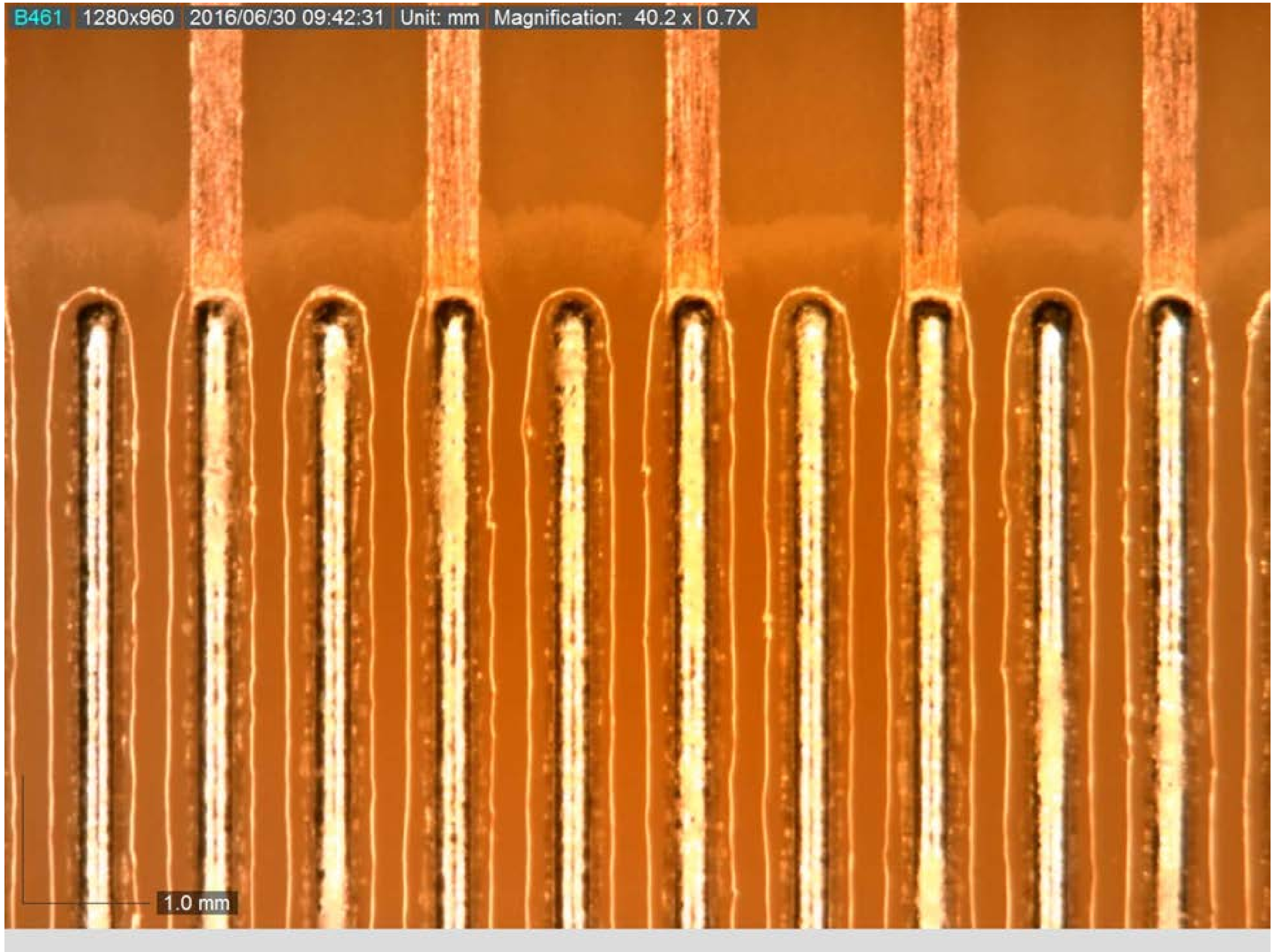
Halogen Containing - -55C to +175C Thermal Cycling – Vertical Orientation



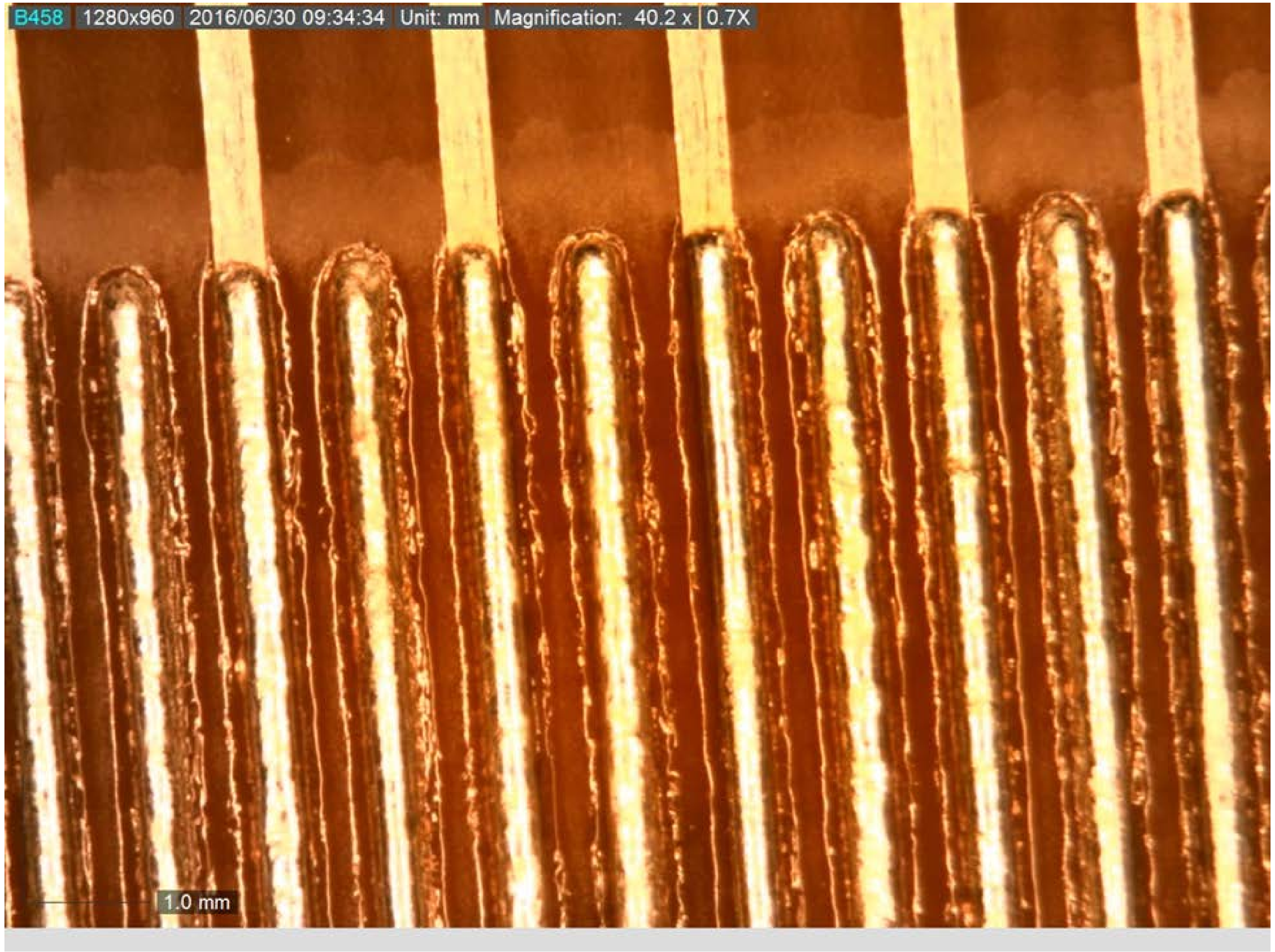
Flux Cracking - -55C to 175C Thermal Cycling

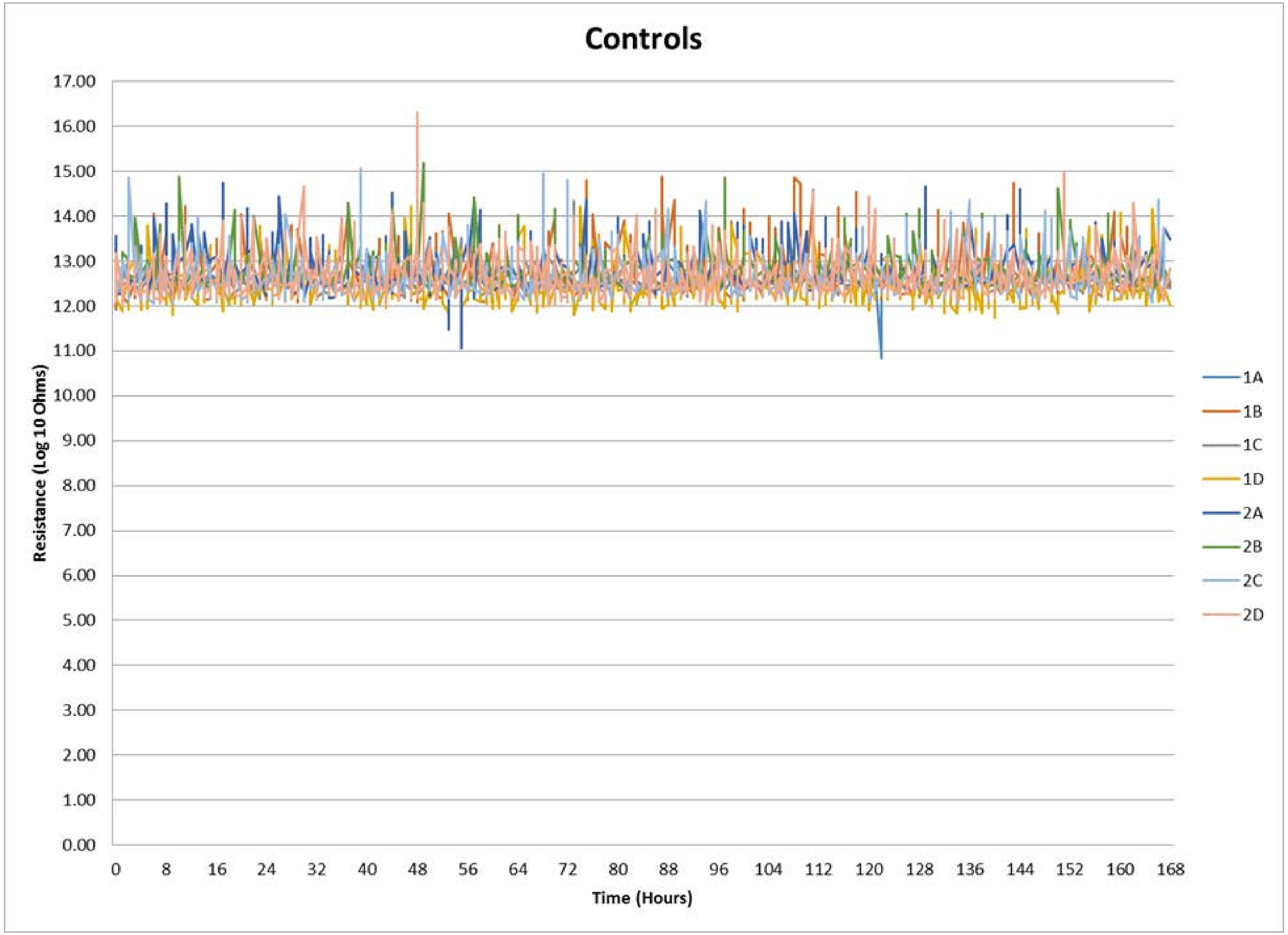


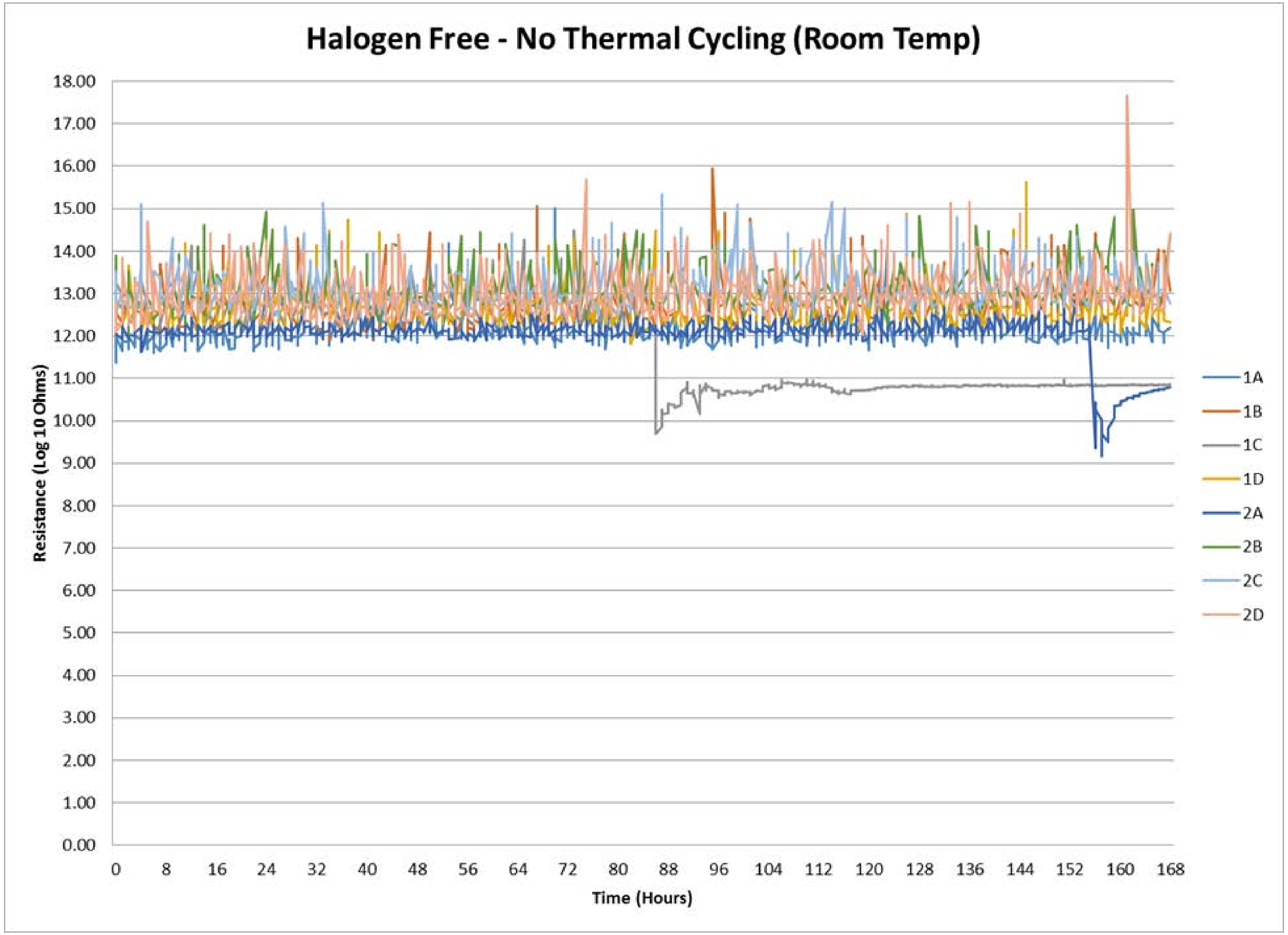
Flux Migration - -40C to +125C

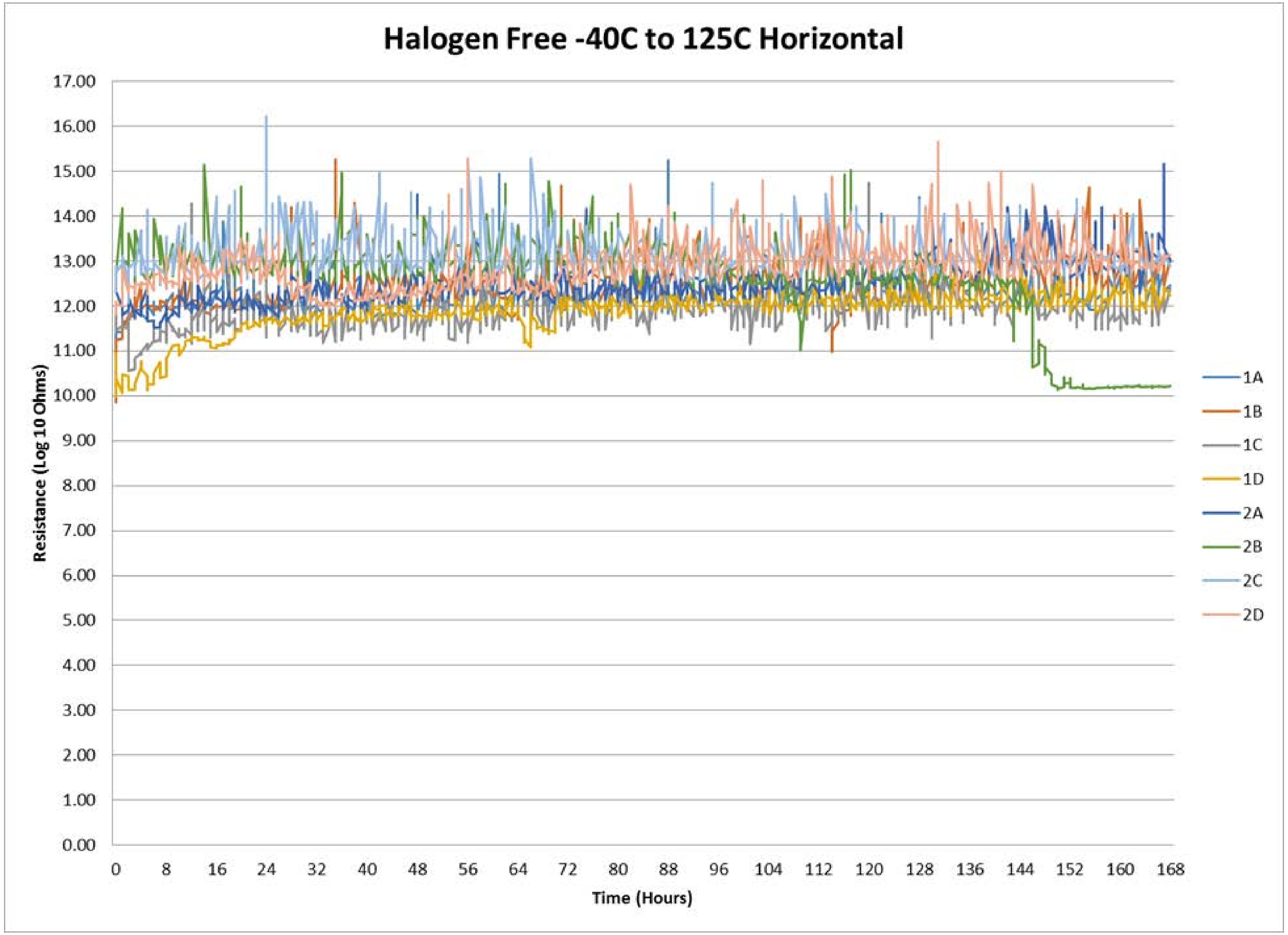


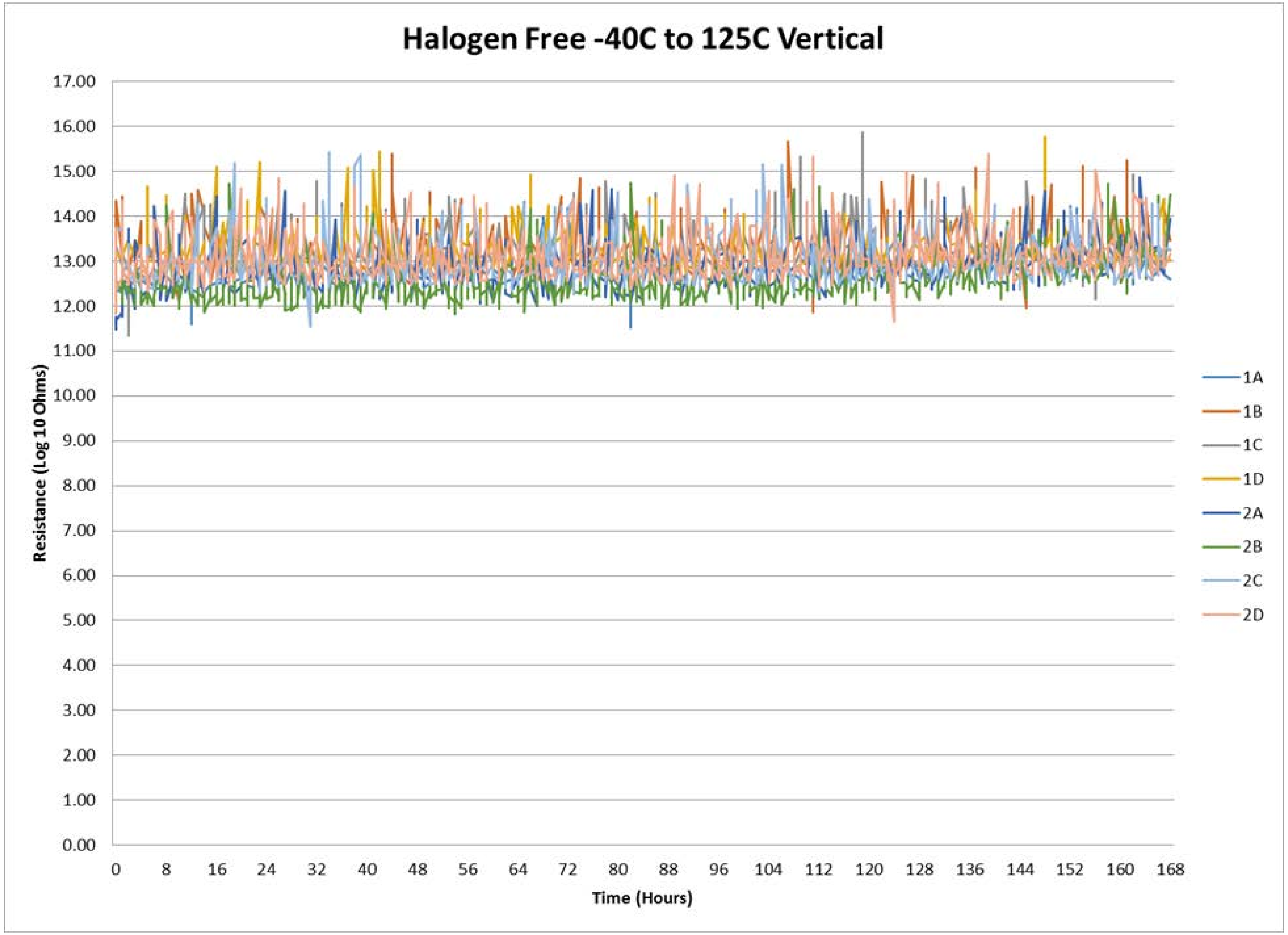
Flux Migration - -55C to +175C

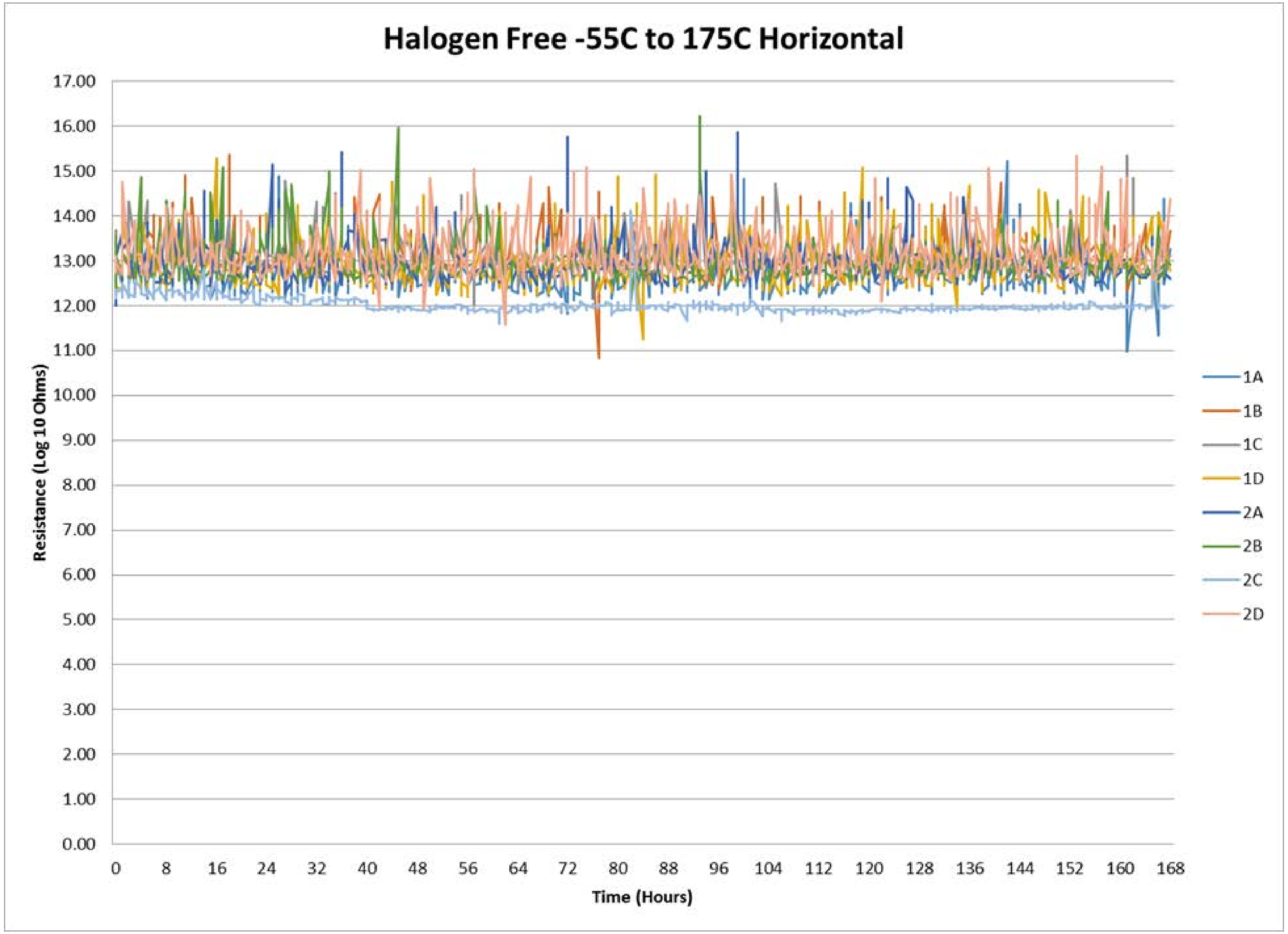


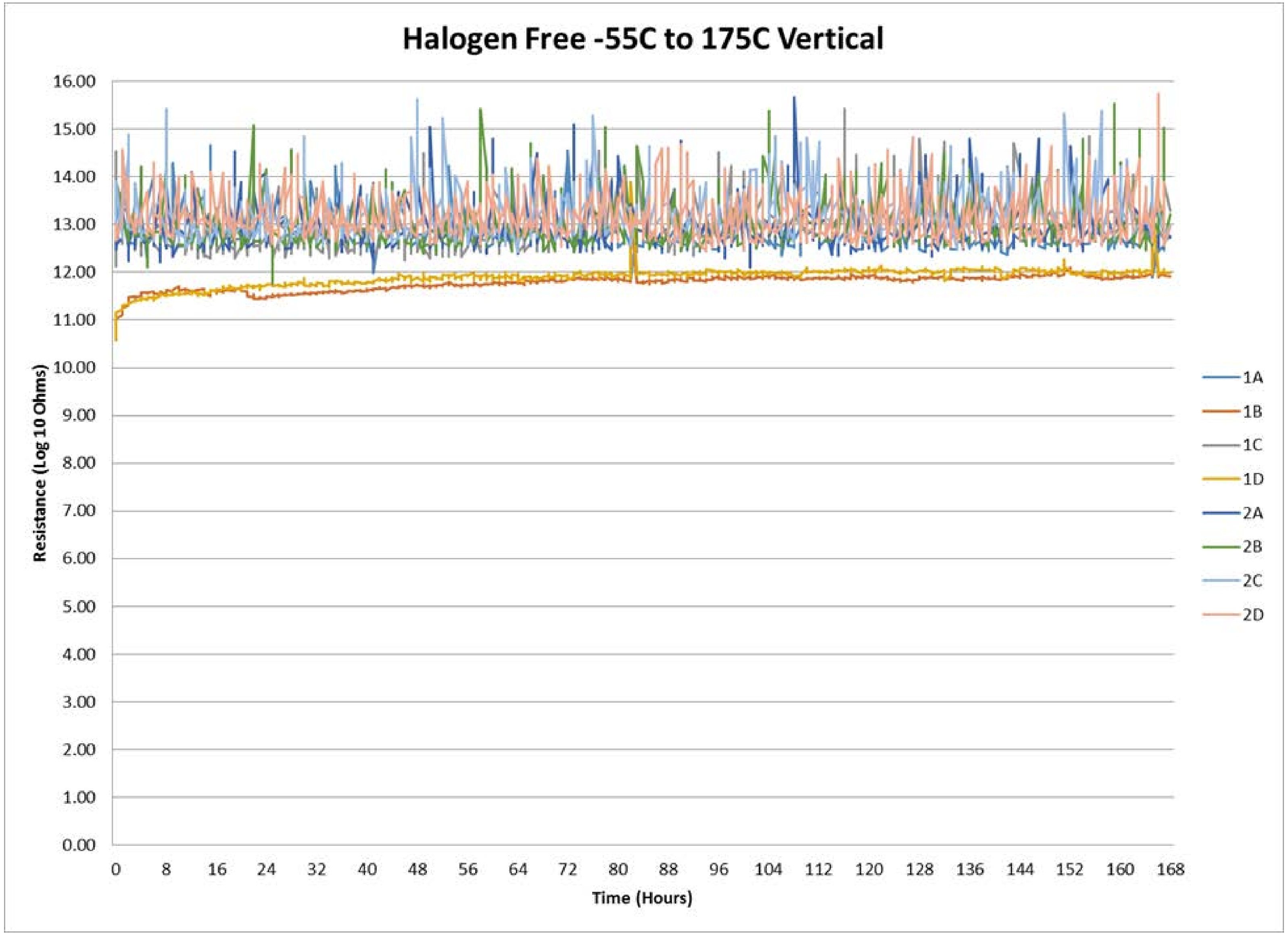

Controls
Resistance (Log 10 Ohms)
17.00
16.00
15.00
14.00
13.00
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
8
16
24
32
40
48
56
64
72
80
88
96
104
112
120
128
136
144
152
160
168
Time (Hours)
1A
1B
1C
1D
2A
2B
2C
2D

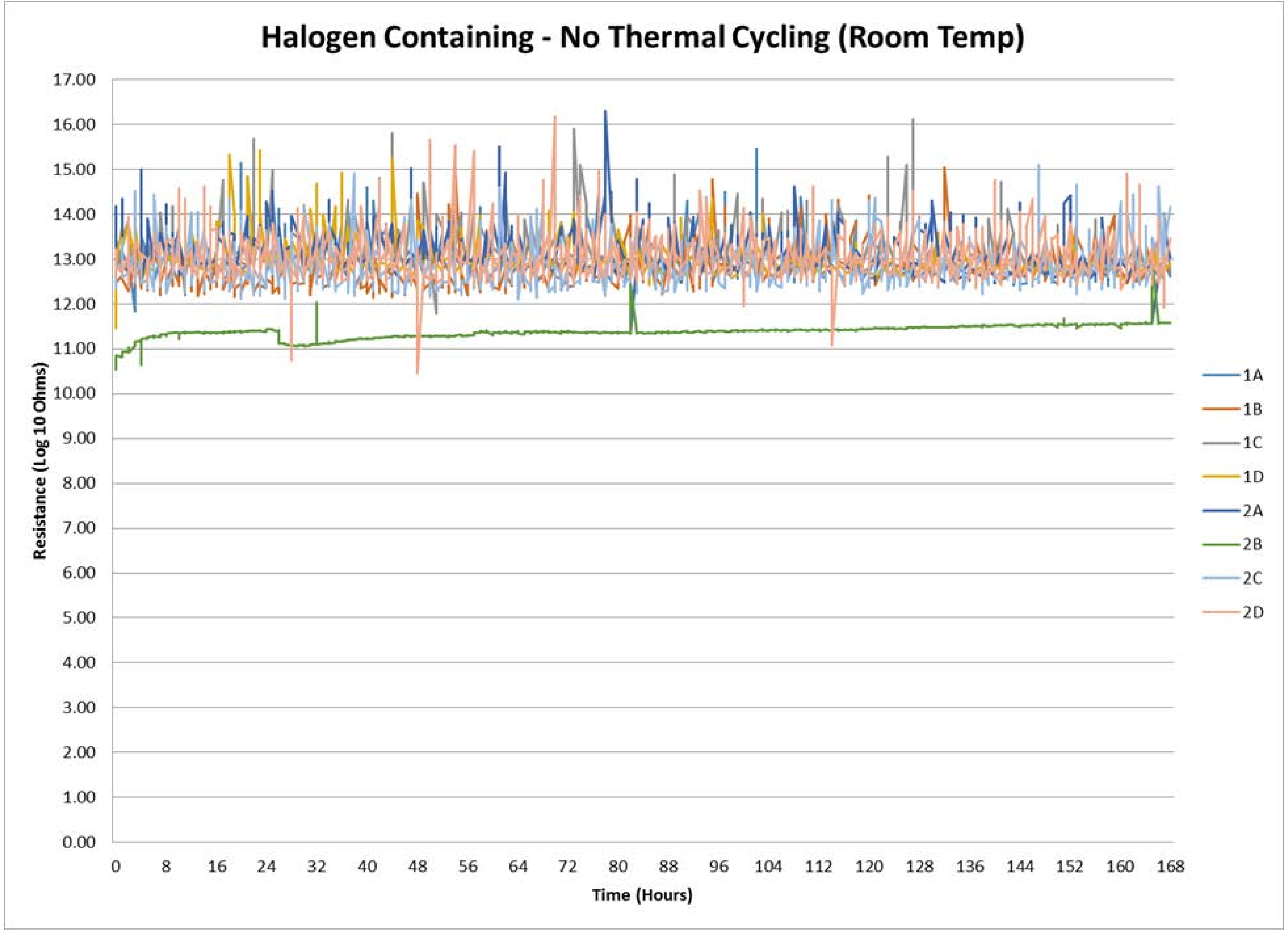

Halogen Free - No Thermal Cycling (Room Temp)
Resistance (Log 10 Ohms)
18.00
17.00
16.00
15.00
14.00
13.00
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
8
16
24
32
40
48
56
64
72
80
88
96
104
112
120
128
136
144
152
160
168
Time (Hours)
1A
1B
1C
1D
2A
2B
2C
2D

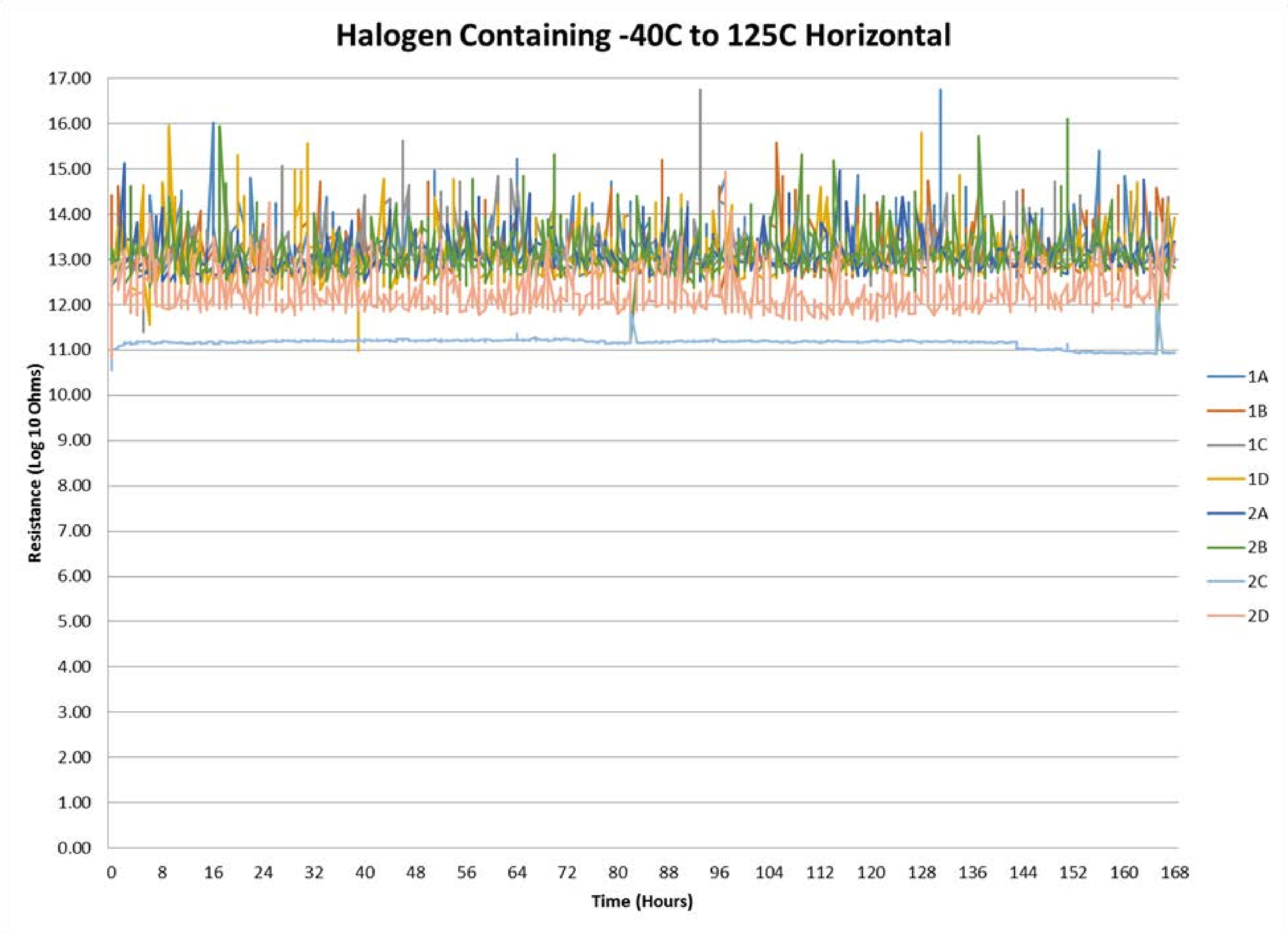

Halogen Free -40C to 125C Horizontal
Resistance (Log 10 Ohms)
17.00
16.00
15.00
14.00
13.00
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
8
16
24
32
40
48
56
64
72
80
88
96
104
112
120
128
136
144
152
160
168
Time (Hours)
1A
1B
1C
1D
2A
2B
2C
2D

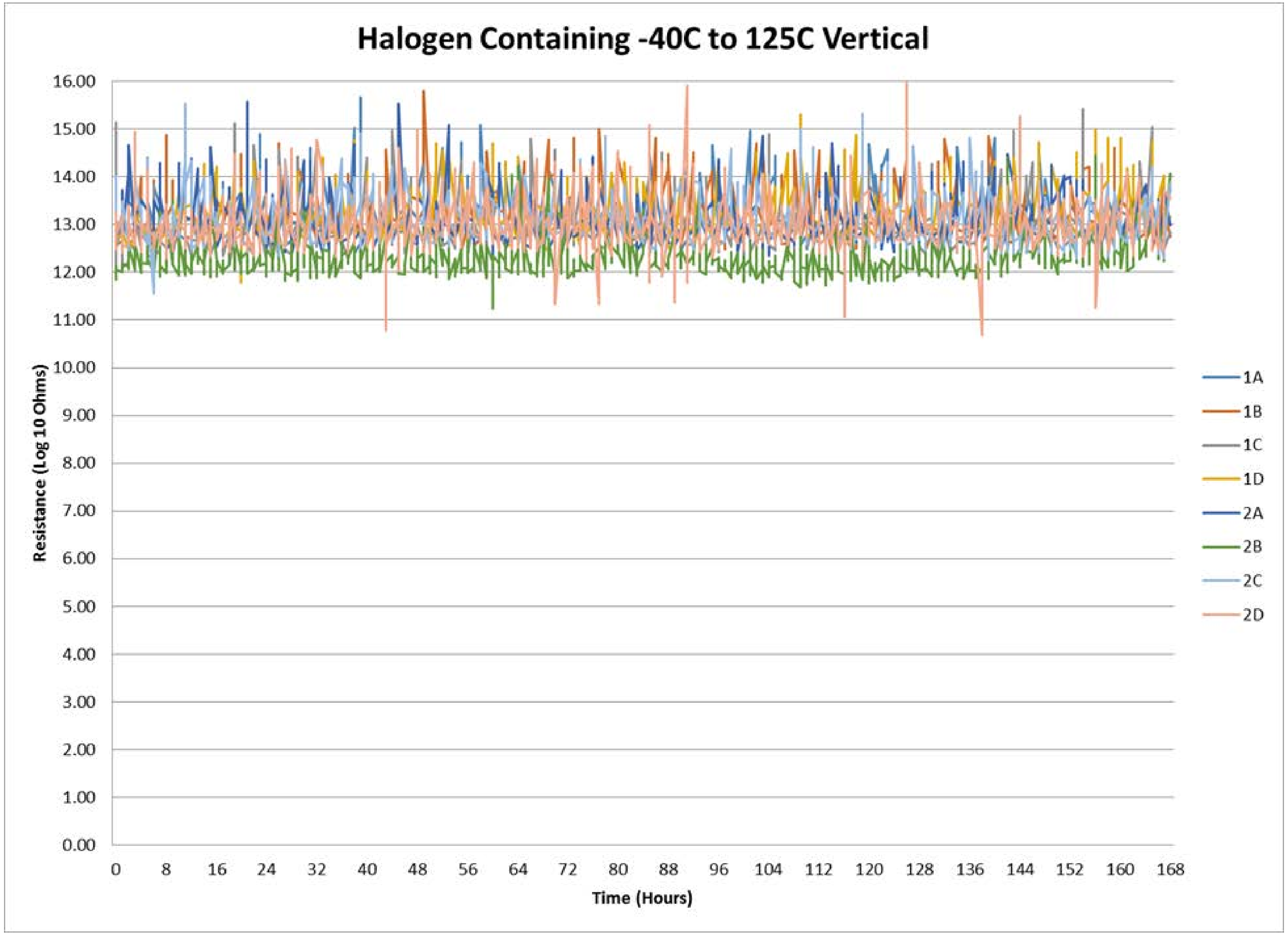

Halogen Free -40C to 125C Vertical
Resistance (Log 10 Ohms)
17.00
16.00
15.00
14.00
13.00
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
8
16
24
32
40
48
56
64
72
80
88
96
104
112
120
128
136
144
152
160
168
Time (Hours)
1A
1B
1C
1D
2A
2B
2C
2D

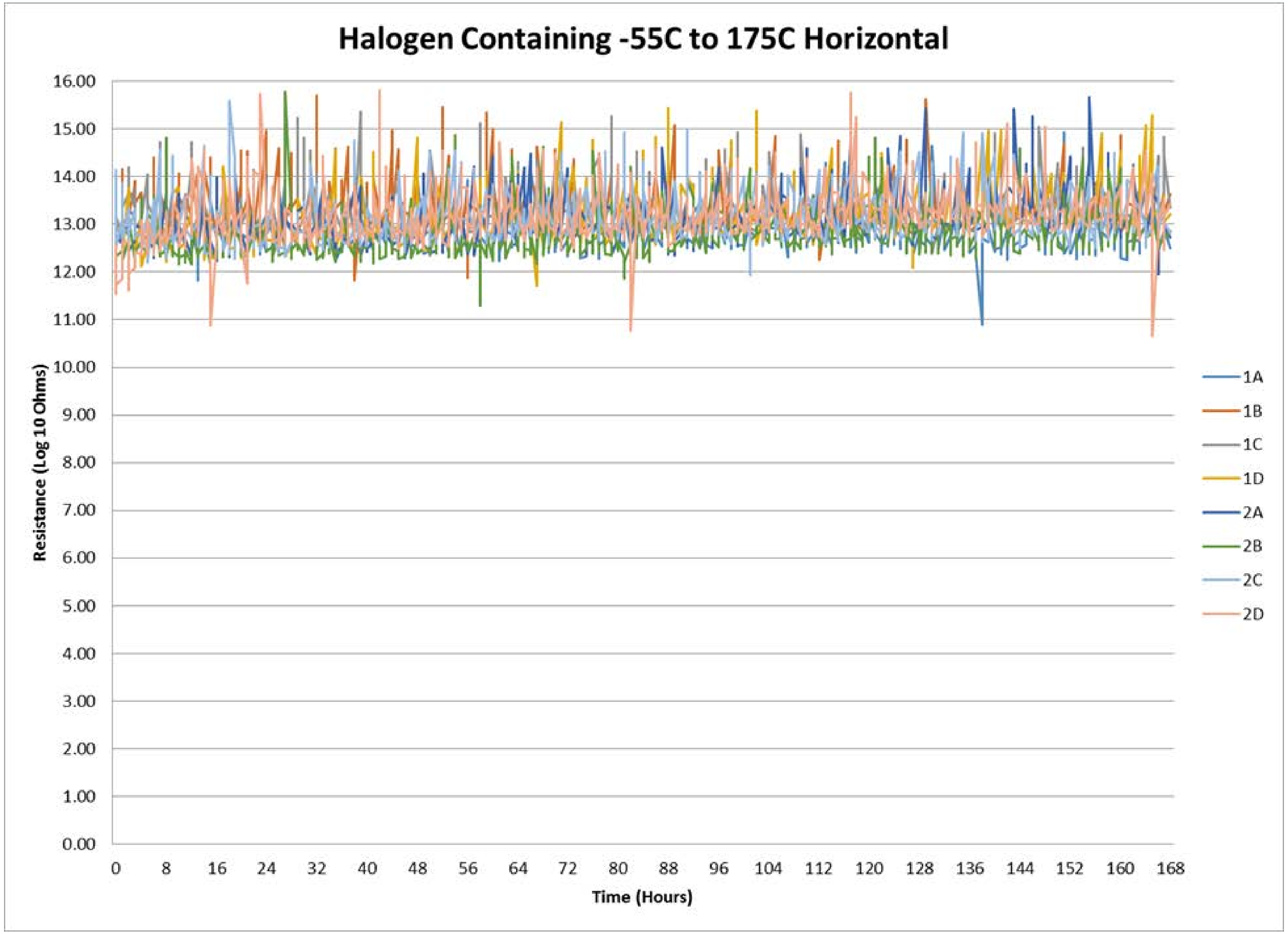

Halogen Free -55C to 175C Horizontal
17.00
16.00
15.00
14.00
13.00
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Resistance (Log 10 Ohms)
0
8
16
24
32
40
48
56
64
72
80
88
96
104
112
120
128
136
144
152
160
168
Time (Hours)
1A
1B
1C
1D
2A
2B
2C
2D

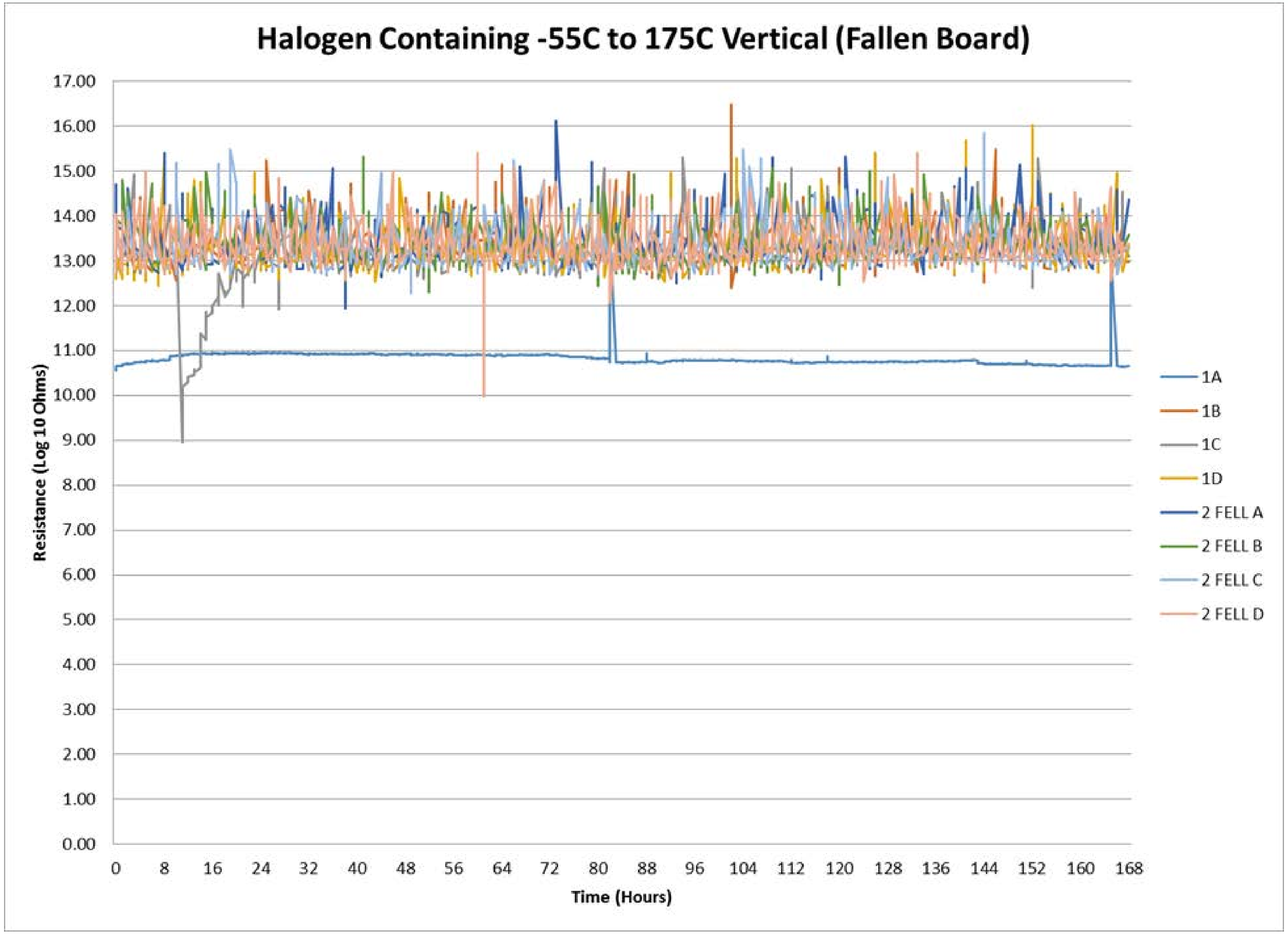

Halogen Free -55C to 175C Vertical
Resistance (Log 10 Ohms)
16.00
15.00
14.00
13.00
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
8
16
24
32
40
48
56
64
72
80
88
96
104
112
120
128
136
144
152
160
168
Time (Hours)
1A
1B
1C
1D
2A
2B
2C
2D

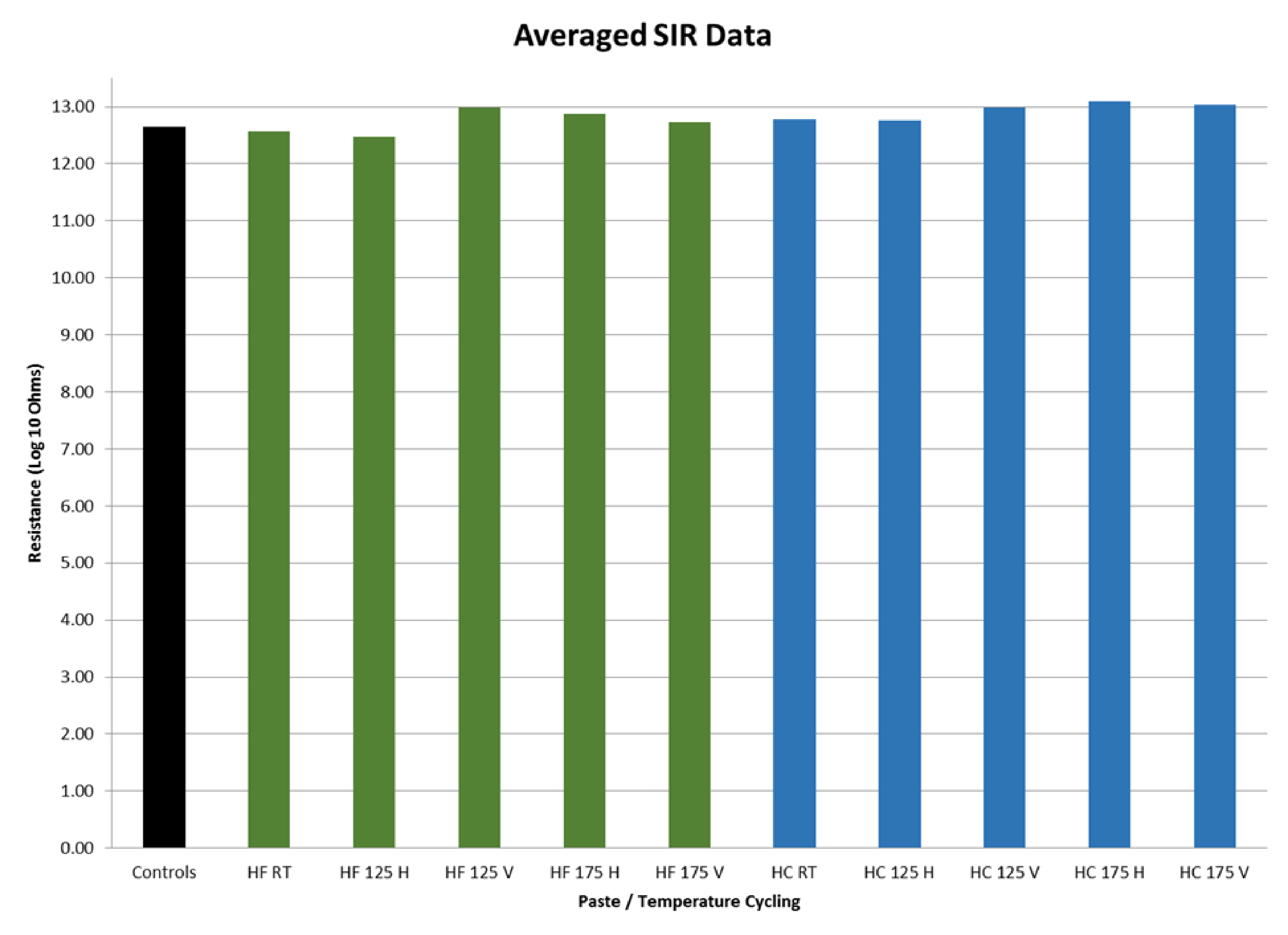

Halogen Containing - No Thermal Cycling (Room Temp)
Resistance (Log 10 Ohms)
17.00
16.00
15.00
14.00
13.00
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0 8 16 24 32 40 48 56 64 72 80 88 96 104 112 120 128 136 144 152 160 168
Time (Hours)
1A
1B
1C
1D
2A
2B
2C
2D


Halogen Containing -40C to 125C Horizontal
Resistance (Log 10 Ohms)
17.00
16.00
15.00
14.00
13.00
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
8
16
24
32
40
48
56
64
72
80
88
96
104
112
120
128
136
144
152
160
168
Time (Hours)
1A
1B
1C
1D
2A
2B
2C
2D


Halogen Containing -40C to 125C Vertical
Resistance (Log 10 Ohms)
16.00
15.00
14.00
13.00
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
8
16
24
32
40
48
56
64
72
80
88
96
104
112
120
128
136
144
152
160
168
Time (Hours)
1A
1B
1C
1D
2A
2B
2C
2D


Halogen Containing -55C to 175C Horizontal
Resistance (Log 10 Ohms)
16.00
15.00
14.00
13.00
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
8
16
24
32
40
48
56
64
72
80
88
96
104
112
120
128
136
144
152
160
168
Time (Hours)
1A
1B
1C
1D
2A
2B
2C
2D


Halogen Containing -55C to 175C Vertical (Fallen Board)
Resistance (Log 10 Ohms)
17.00
16.00
15.00
14.00
13.00
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
8
16
24
32
40
48
56
64
72
80
88
96
104
112
120
128
136
144
152
160
168
Time (Hours)
1A
1B
1C
1D
2 FELL A
2 FELL B
2 FELL C
2 FELL D


Averaged SIR Data
Resistance (Log 10 Ohms)
13.00
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Controls
HF RT
HF 125 H
HF 125 V
HF 175 H
HF 175 V
HC RT
HC 125 H
HC 125 V
HC 175 H
HC 175 V
Paste / Temperature Cycling

1) The averaged SIR values of all scenarios are virtually identical.

2) The averaged SIR values of the temperature cycled pastes are virtually identical to their respective room temperature scenarios.

3) All of the scenarios produced average SIR values that are comparable to or higher than the controls.

4) All of the averaged SIR values are at least 4 orders or magnitude higher than the minimum J-STD-004B requirement of 1 x 10^8 Ohms.

5) There is no meaningful difference between how the Halogen Free and Halogen Containing solder paste formulations respond to temperature cycling.

6) The orientation of the boards, horizontal and vertical, did not have any impact on the SIR values.

7) The number of cycles and range of the temperature cycling has no meaningful impact on the averaged SIR values.

8) Even with the inclusion of (a) pattern(s) that exhibited noticeably lower values than the rest of the patterns for a given scenario, the impact to the average was minimal. See pattern 1A in Figure 29 for an example.

- Cause(s) of Cracking?
  - *CTE Mismatch – Flux Residue/Solder*
  - *Flux Residue – Dry Out/Burn Off*
- Cracks "Heal" or Re-encapsulate?
  - *Above Softening/Liquefying Point of Rosin*
- Activators/ Metal Oxide By-Products Exposed?
- No Significant Flux Residue Flow
  - *Wicking/ Wetting*
  - *FR4 – No Mask*
- Thermal Cycling and Cracking – No Deleterious Effect to Electrical Reliability

Thank you!

Questions??