Jefferson Lab
Thomas Jefferson National Accelerator Facility
Exploring the Nature of Matter

TITLE: MOLLER Spectrometer – Downstream Torus Magnet Prototype Coil Report on Fabrication and Testing

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SUMMARY OF CHANGES FROM PREVIOUS REVISION:							

REFERENCES

(A) Jefferson Lab Drawing No. A09005-15-03-1002, *SC1 Winding and Potting Coil Assy*, Revision -

(B) Jefferson Lab Drawing No. A09005-15-03-2002, *SC2 Winding and Potting Coil Assy*, Revision -

(C) Jefferson Lab Drawing No. A09005-15-03-3002, *SC3 Winding and Potting Coil Assy*, Revision B

(D) Jefferson Lab Drawing No. A09005-15-03-4002, *SC4 Winding and Potting Coil Assy*, Revision –

(E) Jefferson Lab Drawing No. A09005-15-03-4005, *TM4 Inner Filler Block Assembly*, Revision A

(F) ETI Report, *Manufacturing Process Outline/Traveler, JLab Downstream Torus Magnet*, Report Number 53257-601-SC1

(G) ETI Report, *Manufacturing Process Outline/Traveler, JLab Downstream Torus Magnet*, Report Number 53257-601-SC2

(H) ETI Report, *Manufacturing Process Outline/Traveler, JLab Downstream Torus Magnet*, Report Number 53257-601-SC3

(I) ETI Report, *Manufacturing Process Outline/Traveler, JLab Downstream Torus Magnet*, Report Number 53257-601-SC4

(J) JLab Downstream Torus Magnet Coil Testing Summary (Electronic Document), *MMF_Moller_Prototype_Traveler_20230212*, O:\Magnet_Design_Tools\Magnet Projects\MOLLER - Hall A\8. Testing\Prototype Coil Tests

(K) Engineering Design Estimates for the Downstream Torus Magnet Coils (Electronic Document), *Inductance cal_SegMoll_Sept2022_Config9.xlsx*, O:\Magnet_Design_Tools\Magnet Projects\MOLLER - Hall A\6. Engineering Calculations-Analyses-Simulations\Electromagnetic\OPERA\MathCAD voltage cals

(L) PMAG-0000-0100-R0005, *Use of an Inductive Displacement Sensor to Measure Coil Insulation Thickness*, Revision 0.0

(M) PMAG-0000-0100-R0038, *Measuring the Conductor Location on Prototype Coils*, Revision 1.0

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EXECUTIVE SUMMARY

The purpose of this report is to summarize the testing completed in order to validate the design and operation of the MOLLER Downstream Torus Magnet Coils, in addition to documenting observations and measurements and proposing improvements. Four prototype coils were tested, one from each downstream Torus Magnet; these coils are identified as SC1-01, SC2-01, SC3-01 and SC4-01. These tests included pressure testing, helium mass spectrometer leak testing, resistance testing, inductance testing, hi-pot testing, thermal cycling tests, powering tests, conductor positional alignment and coil exterior flatness inspections. Overall, all four coils passed all of their respective testing (electrical, leak, and pressure tests), both at ETI and JLab; the results are presented in Section 3.0 herein. In addition, alignment and flatness inspections conducted at JLab revealed that each coil has a unique shape and thickness distribution, which can be briefly summarized as follows (further detailed in Section 3.4.8):

- SC1-01 The coil has a raised profile near the upstream end and is very thin throughout much of the coil, often outside of the drawing tolerance.
- SC2-01 The coil has a "pinched" shape, which results is a gradual thinning of the coil near the downstream end and some out-of-tolerance regions.
- SC3-01 The coil has a "cupped" shape, but has fairly consistent thickness throughout, which results in very few out of tolerance regions.
- SC4-01 The coil has a "cupped" shape, but has a fairly consistent thickness throughout, which results in very few out of tolerance regions.

Furthermore, during the testing and inspection of the coils, there were several additional highlights that are important to the coil's overall build integrity:

- Bumps up to 0.5 mm in way of the "push-out regions" are acceptable and can be left on the coils. In order to achieve this, it is better to have these regions located *below* the mold surface rather than above it.

- Fiberglass tape does not impact operation, but it does impact the amount of resin that can flow into a given area. Three layers of tape (i.e. more than the standard ½ lap) can result in over-compression when closing the mold and cause the mold to bulge. This should be avoided, and in the future, being mindful of excessive overlap can improve consistency in the coil thickness. Also, as observed in SC4-01, "pinched" tape may result in damage to the resin surface when the coil is removed from the mold. The coils should be taped with caution in order to ensure minimal overlap and to prevent pinching.

- For SC2-01, a beveled edge was added to the G10 blocks, particularly in way of the conductor-G10 interfaces. This reduced the stress in these regions, resulting in a stronger coil, which did not show breaking of bonds at the conductor-G10 interfaces that were observed at the delivery of the coils to JLab and significantly worsened after thermal cycling.

- In the future, SC4-01 should have threaded inserts permanently installed at the lifting points within the coil's G10 body. This will improve the functionality of the lifting points and improve the long-term integrity of the coil's lifting points.

1.0 INTRODUCTION

The purpose of this report is to summarize the testing completed in order to validate the design and operation of the MOLLER Downstream (DS) Torus Magnet (TM) Coils, in addition to documenting observations and measurements and proposing improvements. The MOLLER DS TM Coils are located inside the DS Enclosure and are installed as part of the four individual TM assemblies, which are identified as TM1, TM2, TM3, and TM4. Each TM has a unique coil design and seven “sub-coils” (SC) positioned circumferentially around the frame, with each coil having a unique naming convention relevant to the respective TM. The SC within a particular TM are identified as follows:

SCX - 0X

Sub-Coil Number (1-4)

Sub-Coil Serial Number

Thus, for example, TM1 SC1 would be identified as SC1-01 and TM1 SC2 would be identified as SC1-02, and so on. This is the naming convention used throughout this report and in the included test reports.

Everson Tesla Inc. (ETI) completed prototyping of four downstream coils for the MOLLER experiment: SC1-01, SC2-01, SC3-01 and SC4-01. After receipt of the coils, Jefferson Lab (JLab) spent a significant amount of time and effort to further understand how well the prototype coils meet the needs of the MOLLER experiment and what can be reasonably done to assure that the MOLLER magnets will provide the necessary magnetic field quality.

The method of fabrication for the prototype coils involved a few extra steps that will *not* be part of the final fabrication. These steps resulted in making the winding more difficult and are not planned for the coil production run. The main difference in the process involved conductor spooling – for each of the prototype coils, a length of conductor was de-spooled from the vendor’s (Luvata) spools and re-spooled on a different spool. Those conductors were sent to a sand blasting vendor where they were once again de-spooled, sand-blasted, re-spooled, and returned to ETI. This extra handling resulted in some work hardening of the conductor and some waviness (also referred to as “local camber”). These factors increased the difficulty in achieving a tightly packed coil.

At key steps in the process, D. Kashy (Magnet Group Principal Engineer and MOLLER lead at JLab), visited ETI, reviewed progress, discussed issues, and provided technical suggestions; ultimately, implementing any changes with JLab’s procurement officer, D. Maddox. SC1-01, SC2-01 and SC3-01 were all wound prior to the first JLab visit. ETI contacted JLab when issues getting the coils into the molds were encountered. This began a series of modifications in process which resulted in being able to complete the prototype coil, SC3-01; this was the first coil produced. SC4-01 was the next coil produced; this coil also required minor changes and allowed some inspection of SC3-01 at JLab to occur in parallel. These initial observations revealed cracking in the bonds at the conductor-G10 interface(s). As a result, additional changes were made to the G10 finish and chamfer for SC2-01 and this proved to eliminate the issue. SC1-01 was produced after SC2-01.

The coil production drawings can be seen in References (A) – (D). As part of production, ETI performed first article inspection and testing for SC1-01, SC2-01, SC3-01, and SC4-01; these four SC are prototypes. This included, but was not limited to, pressure testing, helium mass spectrometer leak testing, resistance testing, inductance testing, and hi-pot testing – most of these tests were also repeated at Jefferson Lab (JLab) upon receipt (with the exception of helium mass spectrometer leak testing). In addition, JLab performed additional inspections and testing, which included visual and physical inspections, thermal cycling tests, powering tests, and coil positional alignment and coil exterior flatness inspections. This report summarizes and explains all testing done by ETI and JLab on SC1-01, SC2-01, SC3-01 and SC4-01.

2.0 COIL SETUP OVERVIEW

In order to prepare the coils for testing, temporary connections were installed that would facilitate electrical and hydro tests. These connections included terminals for powering the coil and inlet / outlet adapters to provide water flow through the internal conductor stacks as shown in Figure 1 and Figure 2. In both figures, one can observe long connections extending away from the coil body, affixed with the necessary fittings for electrical and hydro tests. Note, this report does not provide detailed setups for every test arrangement, unless it is necessary to understand the results.

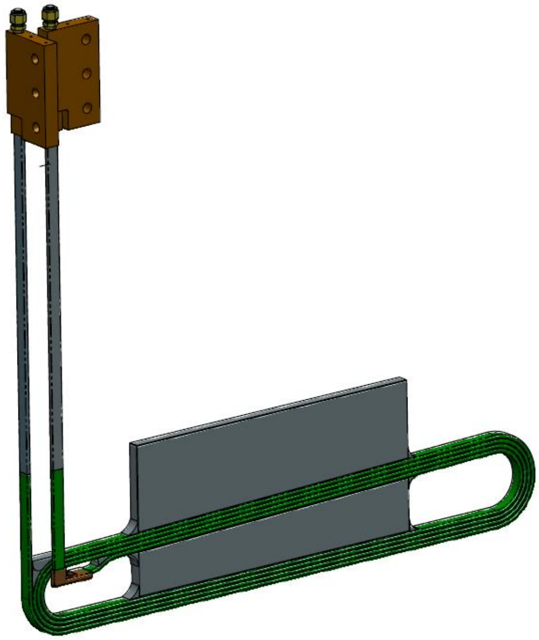


Figure 1 - Typical Baseline Test Configuration for SC1-01, SC2-01, and SC3-01 (SC1-01 CAD shown)

Figure 2 - Baseline Test Configuration for SC4-01

3.0 RESULTS

Figure 3 shows a typical coil and identifies common features. In addition, Figure 3 shows the direction of the beam, which defines the upstream (US) and DS extents of the coil. These features, and the related terminology, are often used when discussing the results presented herein.

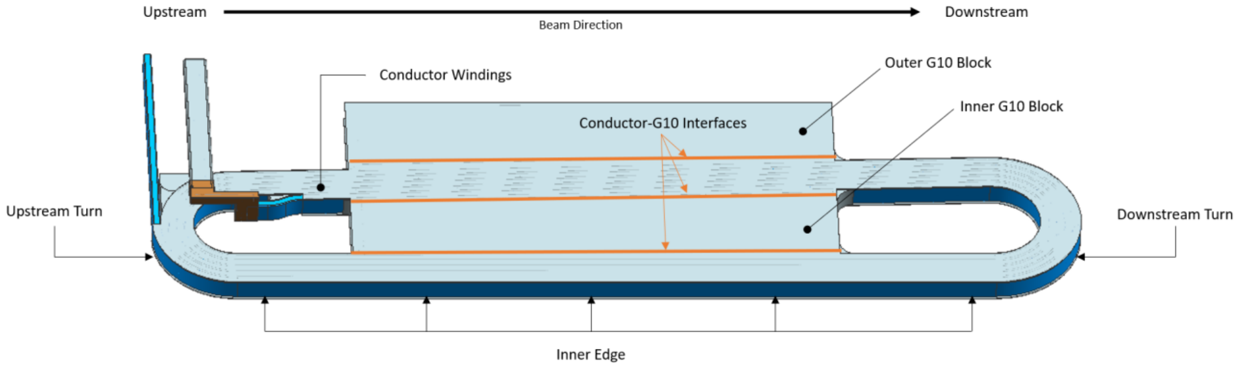


Figure 3 - Typical Coil Features and Terminology

3.1 Visual and Physical Inspections of SC1-01, SC2-01 and SC3-01

The coils were visually and physically inspected (i.e., using measurement devices) prior to testing, during testing, and after testing. A photo of SC1-01, SC2-01 and SC3-01 after testing is shown in Figure 4 and Figure 5. Since these three particular coils are of similar size, it is easier to make side-by-side comparisons about the manufacturing differences, geometry differences, and potential test impacts.

Using Figure 4 and Figure 5 as reference, the following observations can be made of SC1-01, SC2-01 and SC3-01 (Figure 4 and Figure 5 show examples of some of the observations discussed):

General Observations All three coils have observable, but subtle, “waviness” on the resin surface when touched, particularly near the inner and outer longitudinal edges, which appears to have resulted from sanding. The turns tend to be a little rougher than the body of the coils, particularly on SC3-01. Overall, there are very few significant surface blemishes; however, SC1-01 has a large discoloration near the US edge of the coil body (see Figure 5, discoloration appears on the right-most part of the G10 near US turn); this may have resulted from the coil getting caught (i.e., binding) in that region during the mold removal process, causing delamination of the resin.

Press-Out Surfaces All coils have “press-out” marks on the resin surface where the coil was “pressed out” of the mold. After review, it was determined that bumps up to 0.5 mm in way of these “push-out regions” are acceptable and can be left on the coil. Thus, it is better to have these regions located *below* the mold surface rather than above it in order to ensure surface deviations below the 0.5 mm threshold.

Fiberglass Taping In order to bind the coil’s conductors together and bind the conductors stack to the G10 blocks, fiberglass ground wrap tape is wound around the pre-molded assembly. Where the tape overlaps, there are light-colored “tape lines” perpendicular to the conductor’s axis. The more layers of tape in a given area, the more pronounced the tape line becomes (1-3 layers are typical). When comparing the three coils, the tape lines are fairly inconsistent. SC3-01 appears to have the least overlap given there is more light-colored space between tape lines. SC1-01 and SC2-01 seems to be taped with more overlap. Both SC1-02 and SC2-01 have “bright white” tape lines in some very thin regions, likely indicating three or more layers of tape overlapping in that area. Fiberglass tape does not impact operation, but it does impact the amount of resin that can flow into a given area. If there is less tape in a given region of the mold, there is more room for resin and more resin means more localized shrinking. Therefore, fiberglass tape overlap may impact the surface flatness of a given coil. Locations where there are extra layers can result in additional thickness which can cause the molds to bow; if it is the ground wrap, this also causes the turns to be further separated relative to the design value.

Conductor Delamination Upon inspection of the conductor-G10 interface(s) (i.e., where the conductor mates up to the G10 block), there are various levels of delamination amongst the three coils. This particular type of delamination looks like a white line along the conductor edge. SC3-01 has the most obvious delamination along the conductor-G10 interface and extends along nearly the entire length in these regions. SC1-01 is somewhat improved, but still shows some delamination at the conductor-G10 interface. SC2-01 shows little to no delamination at the conductor-G10 interface. The differences between the three coils can be explained by the G10 boundary, which is slightly different on all three coils. Being the first production coil of the three, SC3-01 has an unmodified G10 boundary and the G10 block was essentially mated with the coil “as-is”. Unlike SC3-01, production of SC1-01 required heavy sanding with 60 grit paper on all surfaces of the G10 inserts (this was done to improve bond strength to the G10 and to assure that the surface was cleaned right before wrapping with glass tape). Hence, SC1-01 has a rougher surface and likely a bit more space along the edges of the blocks; thus, more volume for resin, which, during curing and cooldown, gave more material to take up the differences in coefficient of thermal expansion and stiffness of the G10 and copper. SC2-01 is much improved upon SC1-01 by tripling the 1mm chamfer of the G10 blocks to 3.2 mm. This left extra volume to further reduce the stress build-up during curing and cooldown. Of the three coils, this yielded the best overall results and created the least amount of observable delamination at the conductor-G10 interface.

Shims Fiberglass shims were added between the outer G10 blocks and cavity wall face; this was done on both the US and DS ends. The shims were added in order to improve the compaction of the coils in the stack-height direction within the mold. The shim packs appear as solid-white patches near the US and DS ends of the upper resin boundary. SC1-01 and SC2-01 have shims of near constant thickness at the US and DS ends, creating a fairly even resin boundary on the upper edge throughout the coil length. In SC3-01, the shim packs are fairly different in size (the US end has more shim), which creates a taper along the upper resin edge. Several factors may have contributed to this including the tightness of the initial conductor windings, coil stiffness, and cold working. By being the first coil made, SC3-01 did not benefit from the “lessons learned” from previous builds; thus, the coils were not wound as tight, resulting in the need to “post wind bend” the coil. Clamps were used to “squeeze” the coil into a shape that would allow fitting the coil into the mold. This may have impacted the amount of shim necessary to fit the mold.

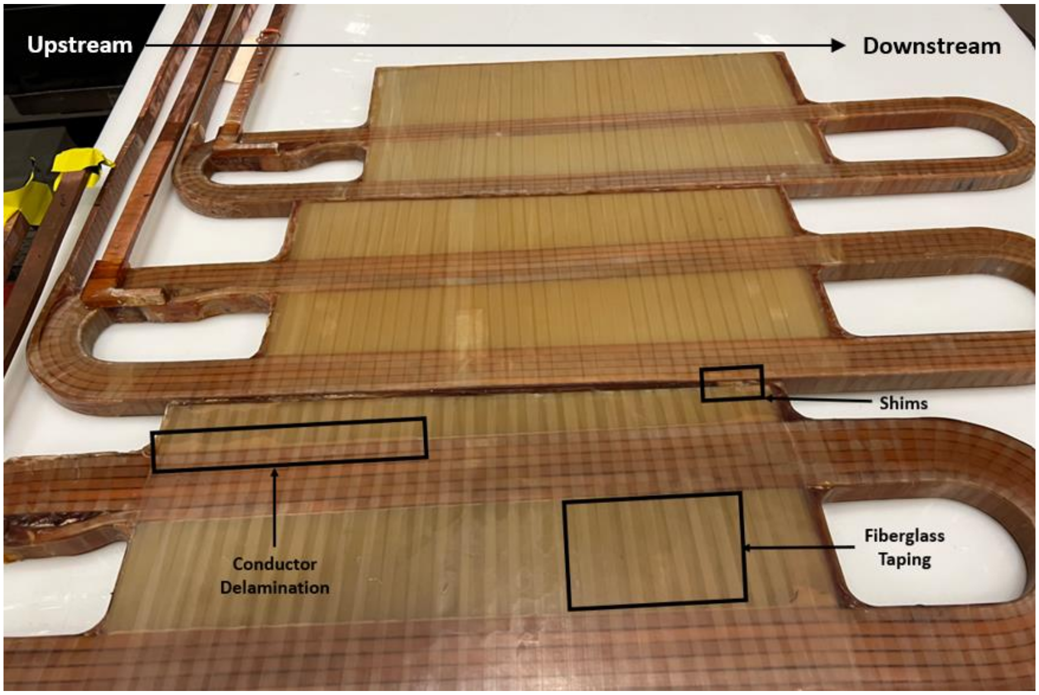


Figure 4 - Left Side of SC1-01 (Top), SC2-01 (Middle) and SC3-01 (Bottom); Taken on March 8th, 2023

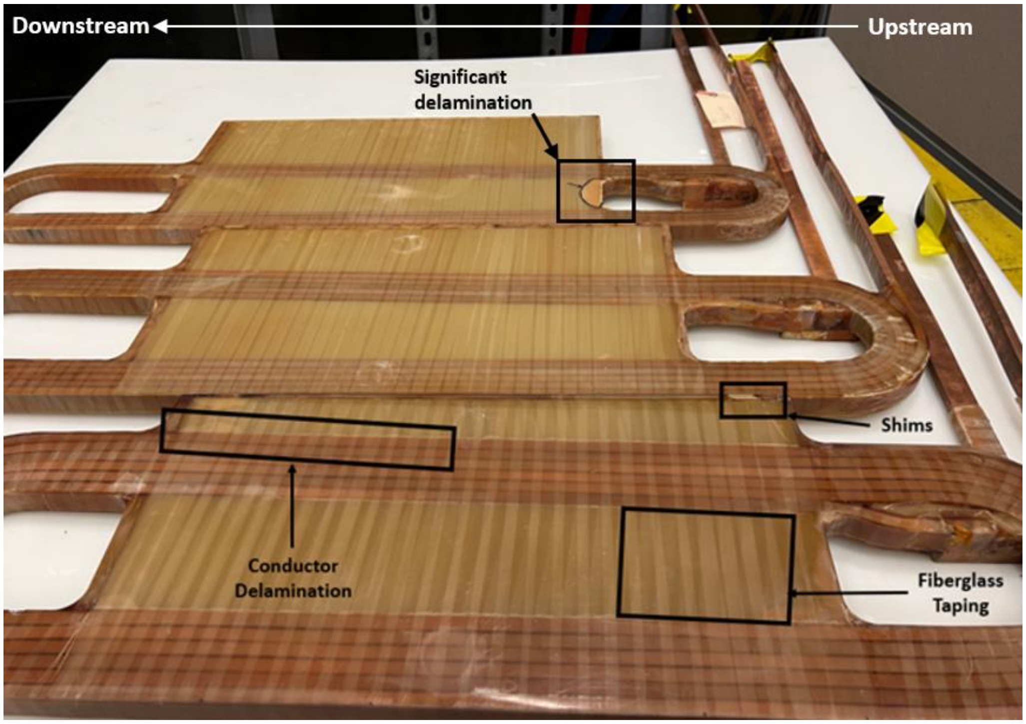


Figure 5 – Right Side of SC1-01 (Top), SC2-01 (Middle), and SC3-01 (Bottom); Taken on March 8th, 2023

3.2 Visual and Physical Inspections of SC4-01

SC4-01 was also visually and physically inspected. Using Figure 6 as reference, the following observations can be made about SC4-01:

General Observations SC4-01 is fairly smooth to the touch over the surface. Overall, there are very few significant surface blemishes. There are some patches of discoloration near the center of the G10 at various locations; this probably is the result of using Sharpie pens to mark fiberglass for cutting of the pancake-to-pancake layers of glass cloth. Further, there are regions of delamination-related discoloration occur near “push-out” regions, near threaded lift points, and where there is a bend in the coil (e.g., there is fairly significant discoloration near the middle of the coil where the coil tightens and narrows). There are three observations requiring more detail:

1) There was a machining error on the inner G10 filler block, see Figure 7. As shown in Figure 8, and in Reference (E) Section A-A, the inner G10 block has a stepped taper on the US end. As shown in Figure 7, this feature was machined on the wrong side of the coil.
2) On the inside of the DS turn, there is damage to the resin surface as shown in Figure 9. The damages are at the surface where the center piece of the 3-piece block, the system which fills the space between the inner and outer legs of the coil, meets up. Although difficult to determine the exact source, it appears that some fiberglass tape may have been “pinched” between the mold parts and conductor, possibly causing the fiberglass tape to “rip off” with the resin when the coil was removed from the mold.
3) There are black marks observed at several locations on the coil’s outer face. As shown in Figure 10, these marks are of various size, pattern, and hue. It is difficult to determine the exact cause, but it is most likely permanent marker that was put on the glass cloth layers which separate the two pancakes and this was dissolved by the resin.

Press-Out Surfaces SC4-01 has “press-out” marks on the resin surface where the coil was “pressed out” of the mold. As was mentioned in Section 3.1.1, it was determined that bumps up to 0.5 mm in way of these “push-out regions” are acceptable and can be left on the coil. Thus, it is better to have these regions located *below* the mold surface rather than above it in order to ensure surface deviations below the 0.5 mm threshold.

Fiberglass Taping Overall, the taping is fairly consistent. There are very few regions of “brighter white” color, which indicates there are few regions with significant tape overlap. As previously stated, it appears that some tape may have been “pinched” near the DS turn, causing damage to the resin.

Conductor Delamination There is limited delamination throughout the coil at the conductor-G10 interface. Similar to the delamination observed in the center of the G10 blocks, much of the observable delamination at the conductor-G10 interface occurs near the middle of the coil, where the coil tightens and narrows in size. There is also some delamination near the DS end, near where the coil has a slight bend. In flat areas, delamination at the conductor-G10 interface is almost non-existent.

Threaded Lifting Points The threaded lifting points have significant discoloration and delamination around the feature. The internal threads themselves do not appear to be significantly damaged, but there does appear to be signs of very light debris, potentially indicating that the threads are wearing out during continued use and continued removal of lifting hardware. In the future, a threaded silicon bronze insert should be used and permanently installed within the coil G10. In doing so, the G10 will not experience continued removal of lifting hardware, ultimately improving the integrity of the threads.

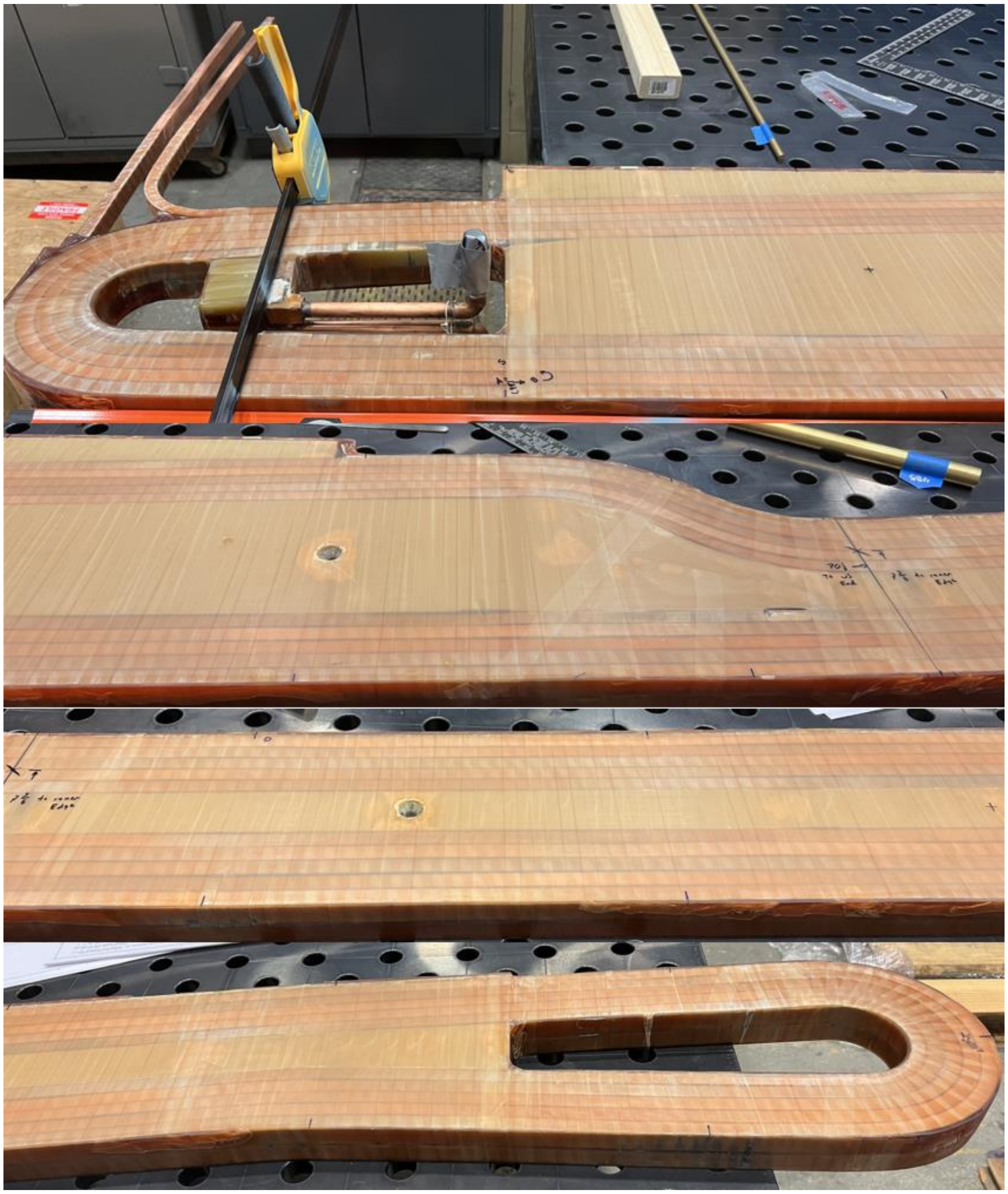


Figure 6 - SC4-01, Upstream End (Top of Figure) Moving Towards the Downstream End (Bottom of Figure), Taken March 13th, 2023

Figure 7 - Machining Error on the Inner G10 block of SC4-01, Upstream End, Right Side

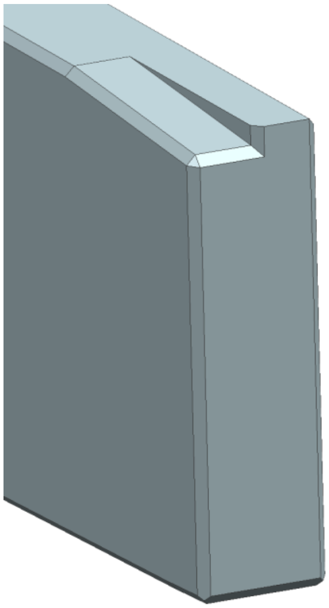


Figure 8 - Stepped Taper on SC4-01 (from CAD Model, Upstream End)

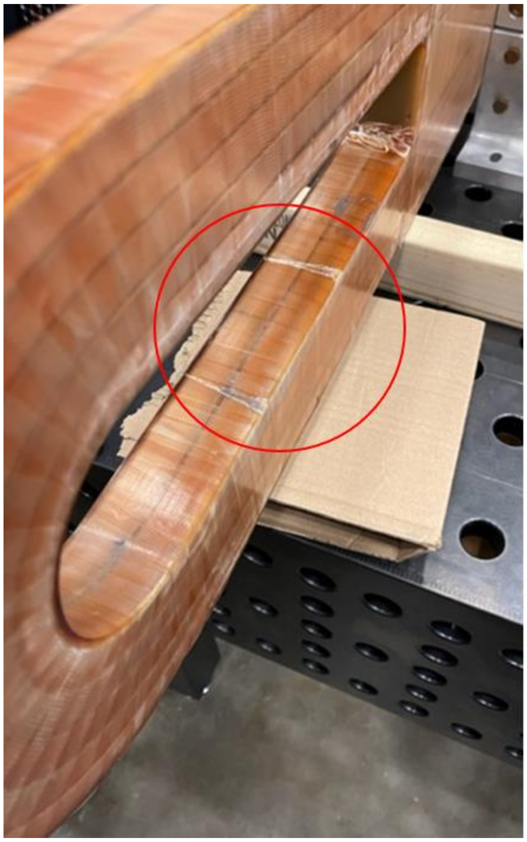


Figure 9 - Damage to Resin on the Inside Edge of the Upstream Turn, SC4-01

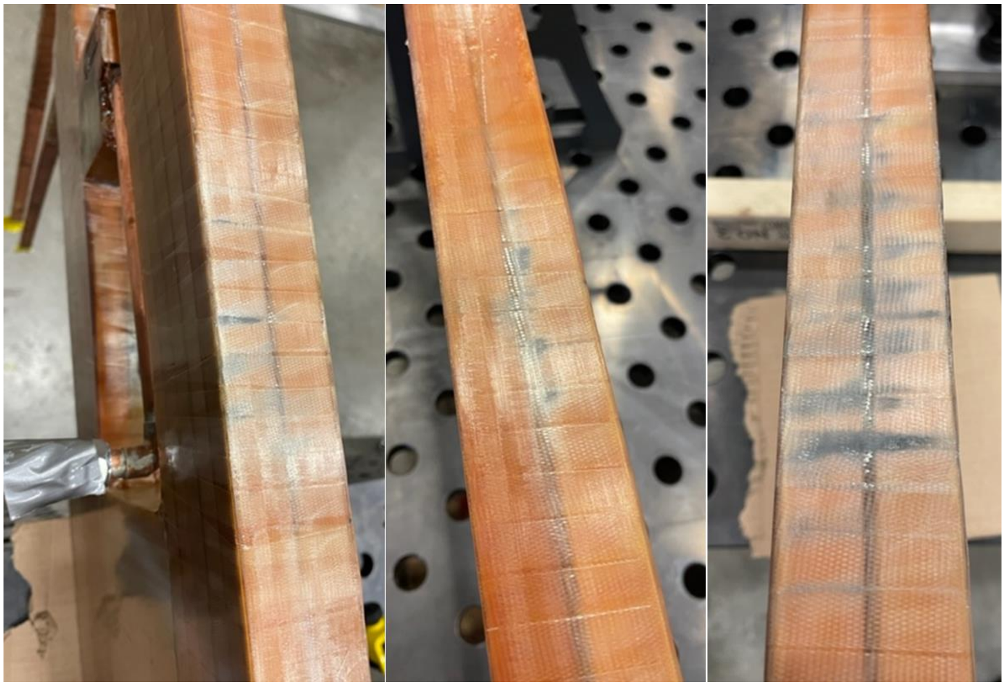


Figure 10 - Black Marks on Outside Face of SC4-01 near the Upstream End (left), Middle (center), and Downstream End (right)

3.3 Conductor Measurements

An inductive displacement sensor from Baumer was employed in order to locate the conductors within the coils; the sensor's capabilities and performance are characterized in Reference (L). The location of the conductors within SC1-01, SC2-01, SC3-01 and SC4-01 are documented in Reference (M). When placed near an electrically conductive surface, the sensor can be used to measure the distance to that surface. When the sensor is touching the surface (0 mm), the sensor output is 0 VDC and when the sensor is 8 mm away from the surface, the sensor output is 10 VDC. The sensor is quite linear with a maximum error of 0.1 mm. The sensor can be used to measure the thickness of the glass/resin layer on the prototype coils. A graphic of how this works is shown in Figure 11. The inner edge of the coil(s) was selected for measurement because of its overall importance to the MOLLER experiment. For the production coils, this sensor will likely be used (along with other techniques) in order to provide the best possible understanding of the conductor locations within each coil.

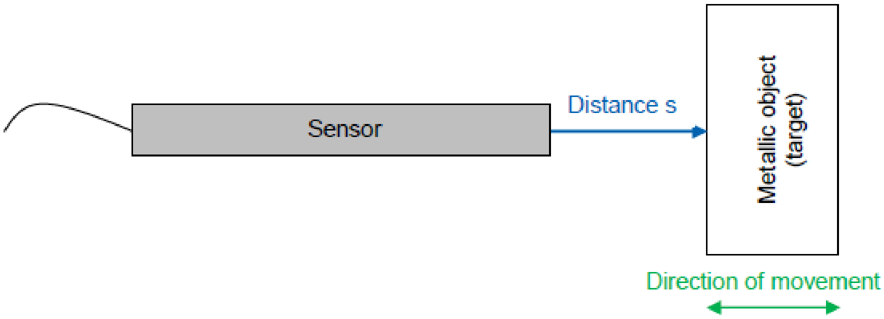


Figure 11 - Inductive Displacement Sensor Operating Diagram

Starting at the on the US end, the “zero” position was defined at the approximate US tangent point along the inside edge of the coil. Additional positions were marked every two inches DS, up to the 32-inch position; this resulted in 17 total measurement positions along the inner edge of SC1-01, SC2-01 and SC3-01 as shown in Figure 12. All coils were measured in the molded condition, meaning there was no prior modification to the inner coil edge before measuring the conductor location using the inductive displacement sensor. Table 1 contains the measurements for SC1-01, SC2-01 and SC3-01 along the inner edge of each respective coil; this data is also plotted in Figure 13.

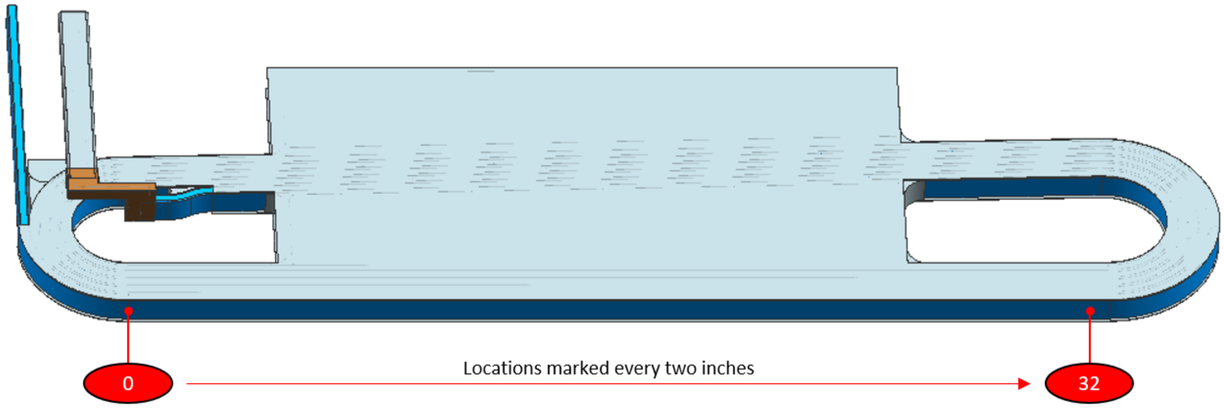


Figure 12 - Conductor Measurement Locations along the Inner Coil Edge, Typical for SC1-01, SC2-01 and SC3-01

Table 1 - Conductor Measurements for SC1-01, SC2-01 and SC3-01

Measurement Location (in)	Distance (mm)		
	SC1-01	SC2-01	SC3-01
0	3.3584	1.7072	2.9920
2	1.3624	0.8592	0.9240
4	1.1592	0.9696	0.5880
6	0.7760	0.8264	1.1240
8	1.0024	1.2552	1.2320
10	0.8920	1.0600	1.4968
12	0.7344	2.3056	1.7352
14	0.7824	2.3072	2.2912
16	0.8152	2.1784	2.1200
18	1.3152	2.1176	2.3616
20	1.2000	1.0256	2.1919
22	1.5096	0.9680	2.1920
24	1.1648	1.3304	2.0008
26	0.6304	0.9720	1.8512
28	1.3192	1.1440	0.9456
30	1.092	1.0968	0.5992
32	0.5824	0.7232	n/a

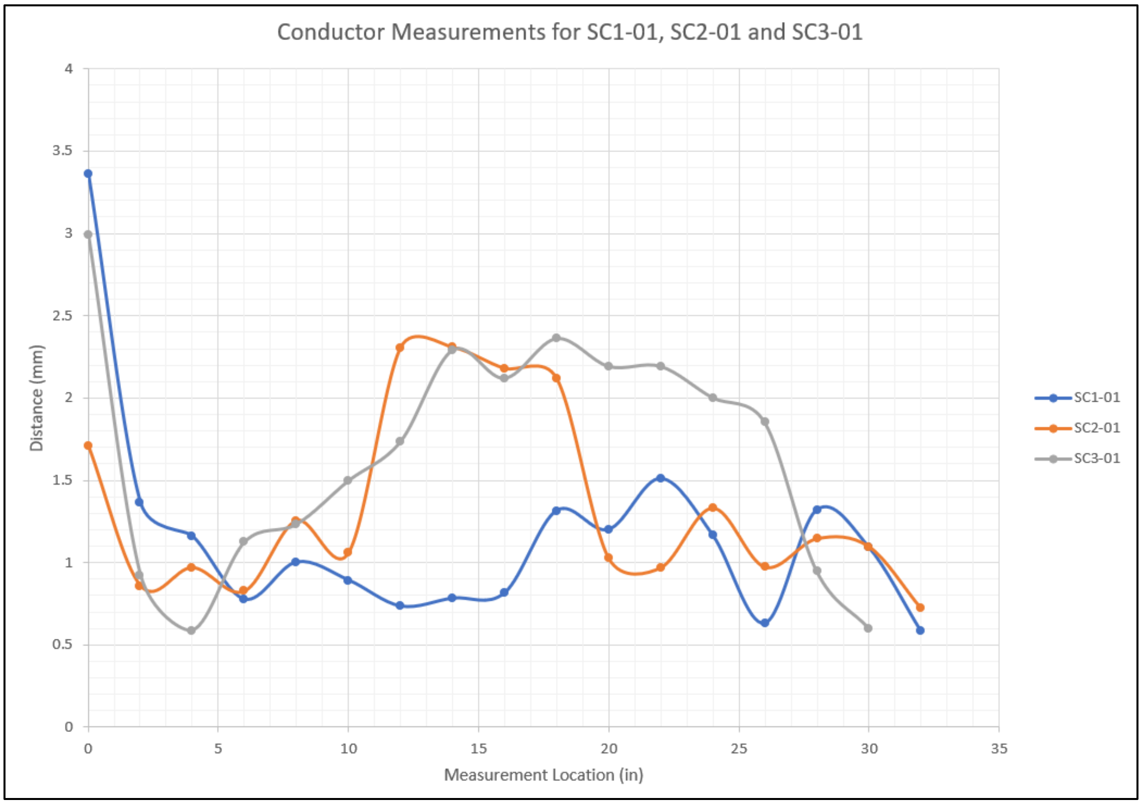


Figure 13 - Conductor Measurements Plot for SC1-01, SC2-01 and SC3-01

From the data shown in Figure 13, it appears that SC2-01 and SC3-01 likely had too much “post-wind bending”, which resulted in the central areas of the coil not being pressed against the mold wall along its full length (SC1-01 likely has less post-wind bending due to the lower stack height and reduced stiffness, relative to SC2-01 and SC3-01). The result for SC1-01 is quite good and it would be ideal to replicate those results for all production coils.

SC4-01 was measured a little differently than the other three coils. SC4-01 was secured such that the inner edge of the coil faced upwards. The “zero” position was defined as the tangent point on the US turn. The measurement points were located at relevant features along the coil’s inner edge, such as near turns, bends, etc. Additional measurement points were spaced uniformly (every 5 inches) along straight portions of SC4-01’s inner edge. In total, there were 42 measurement locations. The total distance of the measurement location from the zero position correlates to the total length along the coil’s inner path. Figure 14 shows some of the locations along SC4-01’s inner edge in order to highlight the overall scale and distribution of measurement locations. Both of the conductor stacks were measured on SC4-01, designated the “near side” and “far side” conductor, based on the orientation shown in Figure 15. Table 2 reports the measurements for SC4-01, which are plotted in Figure 16.

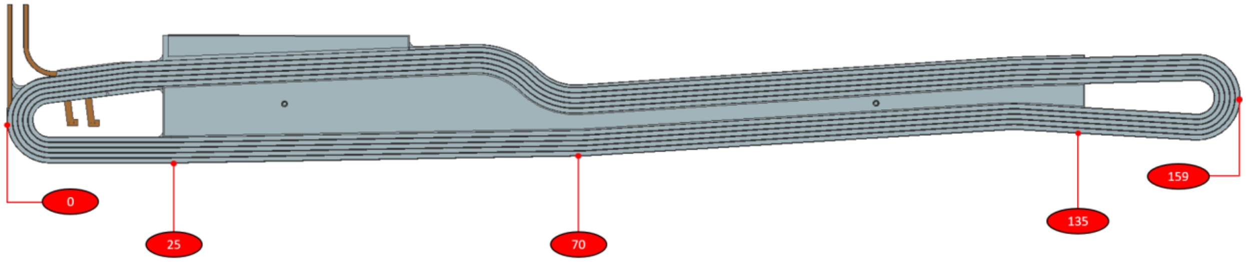


Figure 14 - Conductor Measurements Along the Inner Coil Edge, SC4-01

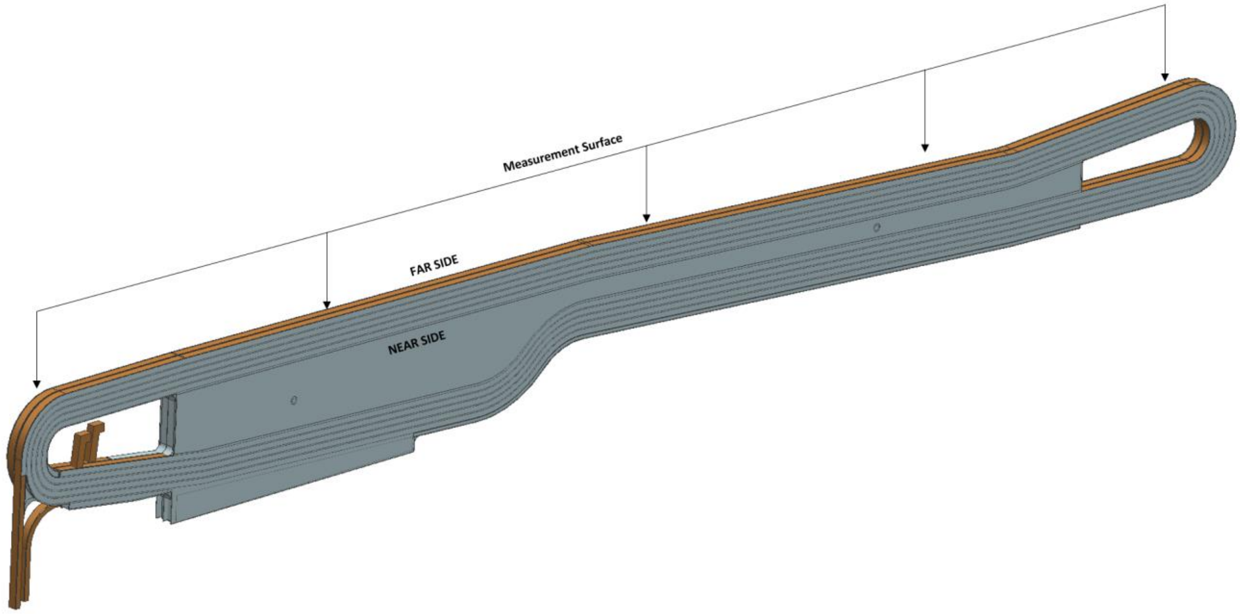


Figure 15 - SC4-01 Conductor Stack Nomenclature

Table 2 - Conductor Measurements for SC4-01

Measurement Location (in)	Distance (mm)	
	SC4-01 Near Side Conductor	SC4-01 Far Side Conductor
0	1.36	>8
1.75	3.1472	4.696
4*	6.728	5.696
6*	>8	6.04
8*	>8	6.904
10	7.92	3.8448
3.12	4.832	1.9416
14	3.3432	1.6392
16	2.0152	1.4576
18	1.16	1.4888
20	0.7808	1.2464
25	2.1736	2.3488
30	2.408	2.9728
35	2.4736	1.4344
40	2.46	2.2816
45	2.44	2.7848
50	2.6736	2.5928
55	2.3536	2.1592
60	2.7296	0.936
65	1.5832	2.404
66	1.6616	2.5104
68	2.0032	2.5976
70	2.4672	2.7328
75	4.1976	4.768
80	2.7656	2.8032
85	2.0296	1.1744
90	3.0688	1.6248
95	2.7696	1.4688
100	2.9928	2.7296
105	2.6144	3.272
110	2.3808	2.0592
115	2.0216	1.38
120	1.4336	2.0952
125	1.4936	3.6776
130	1.6768	2.3664
135	1.3504	2.4528
140	0.7848	1.0424
145	0.7288	1.0656
150	1.6384	3.6696
155*	1.9728	3.644
157*	1.6264	2.8952
159*	2.4568	3.7592

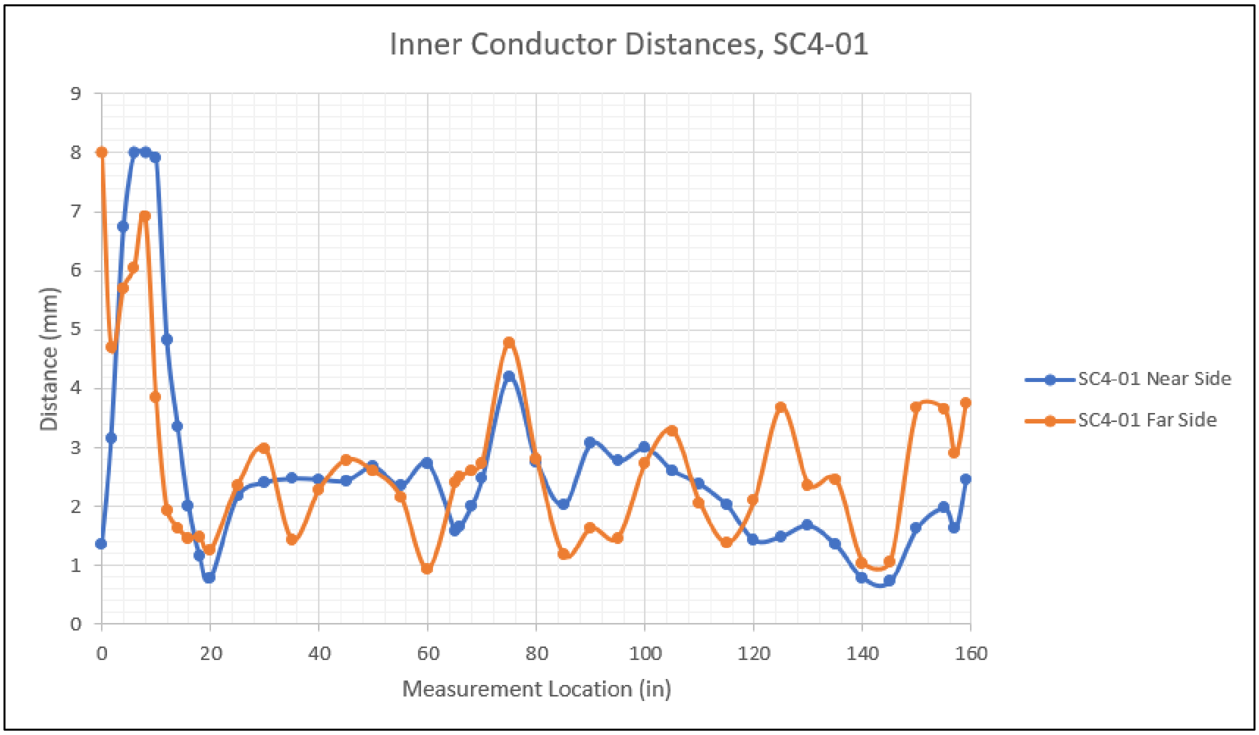


Figure 16 – Conductor Measurements Plot for SC4-01

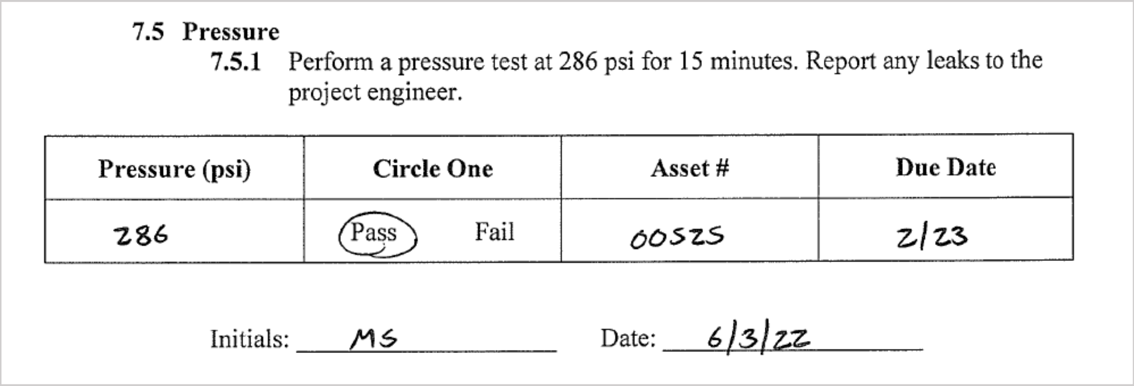
3.4 Test Results

ETI performed first article inspection and testing for SC1-01, SC2-01, SC3-01, and SC4-01; see Reference (F) – (I). These tests included, but were not limited to, pressure testing, resistance testing, inductance testing, and hi-pot testing (refer to ETI test reports for additional data / tests), which are critical to understanding the coil's functionality – these tests were also repeated at JLab upon receipt. In addition, JLab performed additional testing, which includes thermal cycling tests, powering tests, and alignment and flatness inspections. The test results for the coils are summarized in the following sections:

3.4.1 Pressure Test

As shown in Figure 17 through Figure 23, ETI performed a hydrostatic pressure test on all four coils and reported the results in each coil's respective test report, References (F) – (I). The test was performed at 286 psi for 15 minutes prior to potting the coil and after potting the coil (with the exception of SC4-01, which does not have pre-potting pressure test results reported in Reference (I)). All coils passed ETI's pressure testing.

3.4.1.1 ETI Pressure Test Results Prior to Potting the Coil



7.5 Pressure

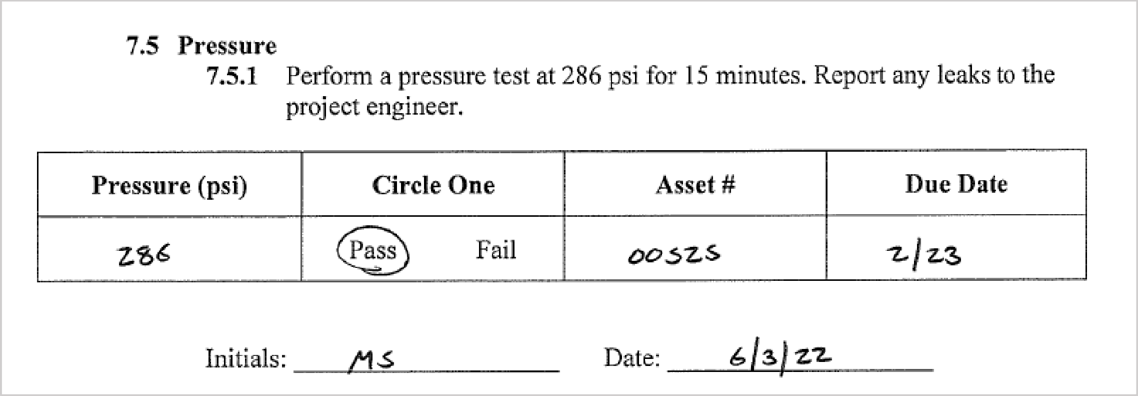
7.5.1 Perform a pressure test at 286 psi for 15 minutes. Report any leaks to the project engineer.

Pressure (psi)	Circle One	Asset #	Due Date
286	[✓ Pass] Fail	00525	2/23

Initials: MS

Date: 6/3/22

Figure 17 - ETI Hydrostatic Pressure Test Results, Before Potting, SC1-01



7.5 Pressure

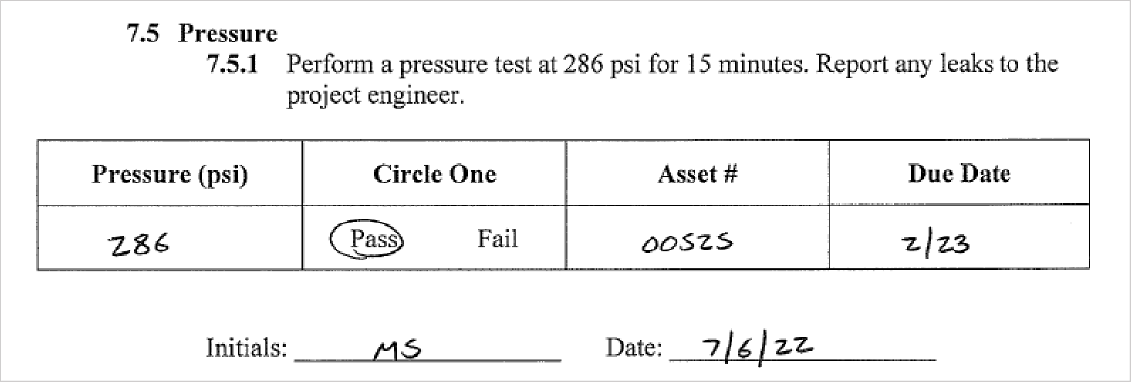
7.5.1 Perform a pressure test at 286 psi for 15 minutes. Report any leaks to the project engineer.

Pressure (psi)	Circle One	Asset #	Due Date
286	[✓ Pass] Fail	00525	2/23

Initials: MS

Date: 6/3/22

Figure 18 - ETI Hydrostatic Pressure Test Results, Before Potting, SC2-01



7.5 Pressure

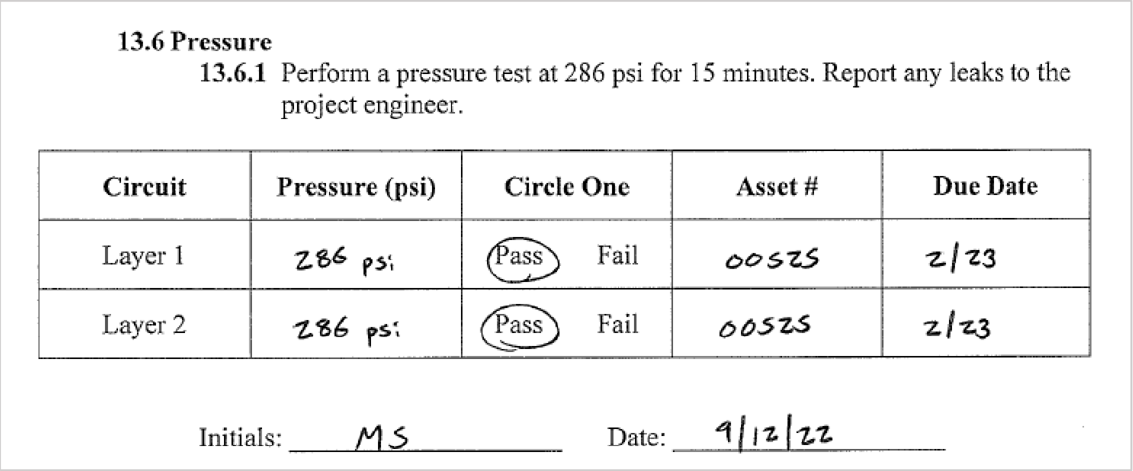
7.5.1 Perform a pressure test at 286 psi for 15 minutes. Report any leaks to the project engineer.

Pressure (psi)	Circle One	Asset #	Due Date
286	[✓ Pass] Fail	00525	2/23

Initials: MS

Date: 7/6/22

Figure 19 - ETI Hydrostatic Pressure Test Results, Before Potting, SC3-01



13.6 Pressure

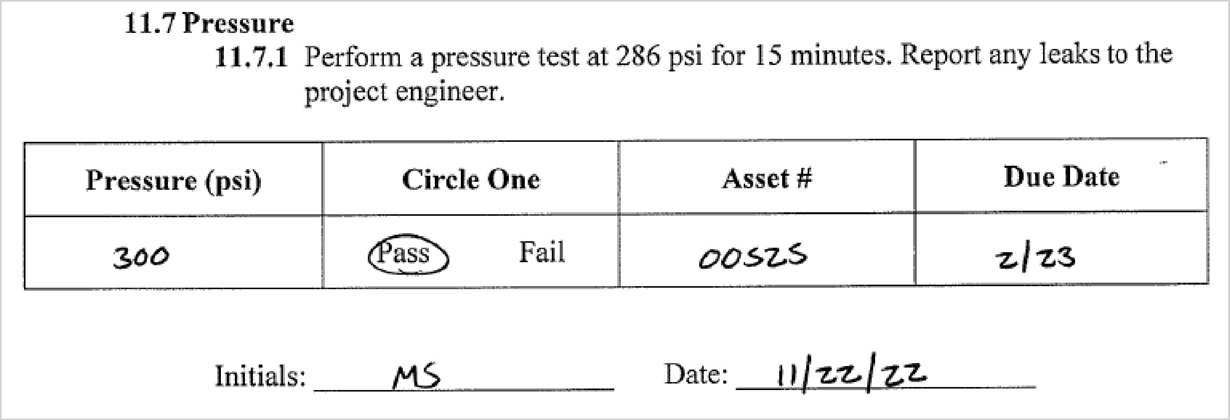
13.6.1 Perform a pressure test at 286 psi for 15 minutes. Report any leaks to the project engineer.

Circuit	Pressure (psi)	Circle One	Asset #	Due Date
Layer 1	286 psi	[✓ Pass] Fail	00525	2/23
Layer 2	286 psi	[✓ Pass] Fail	00525	2/23

Initials: MS Date: 9/12/22

Figure 20 - ETI Hydrostatic Pressure Test Results, Before Potting, SC4-01

3.4.1.2 ETI Pressure Test Results After Potting the Coil



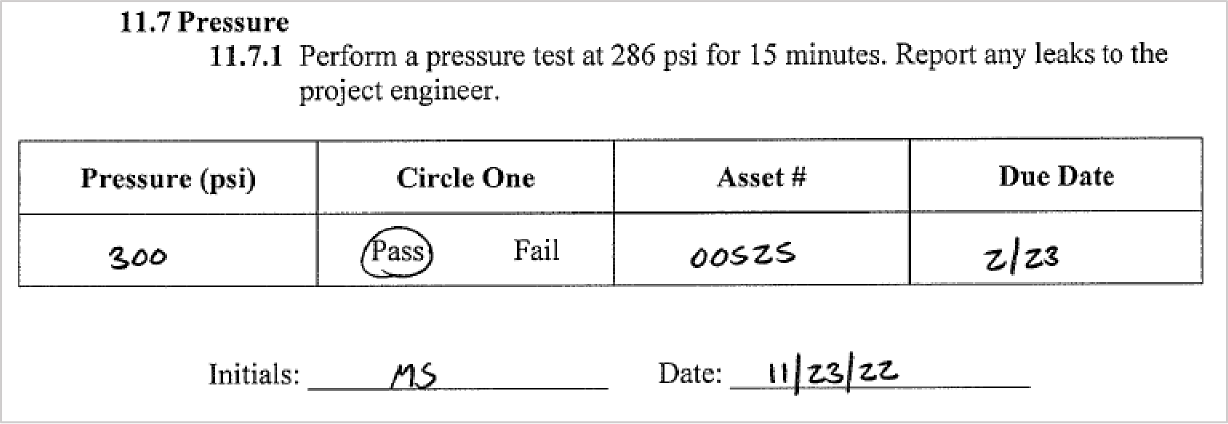
11.7 Pressure

11.7.1 Perform a pressure test at 286 psi for 15 minutes. Report any leaks to the project engineer.

Pressure (psi)	Circle One	Asset #	Due Date
300	[✓ Pass] Fail	00525	2/23

Initials: MS Date: 11/22/22

Figure 21 - ETI Hydrostatic Pressure Test Results, After Potting, SC1-01



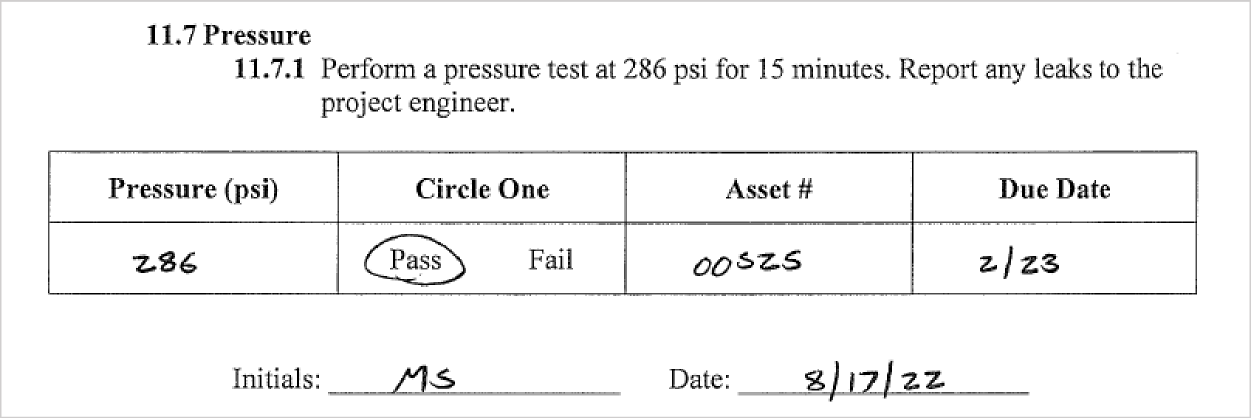
11.7 Pressure

11.7.1 Perform a pressure test at 286 psi for 15 minutes. Report any leaks to the project engineer.

Pressure (psi)	Circle One	Asset #	Due Date
300	[✓ Pass] Fail	00525	2/23

Initials: MS Date: 11/23/22

Figure 22 - ETI Hydrostatic Pressure Test Results, After Potting, SC2-01



11.7 Pressure

11.7.1 Perform a pressure test at 286 psi for 15 minutes. Report any leaks to the project engineer.

Pressure (psi)	Circle One	Asset #	Due Date
286	[✓ Pass] Fail	00525	2/23

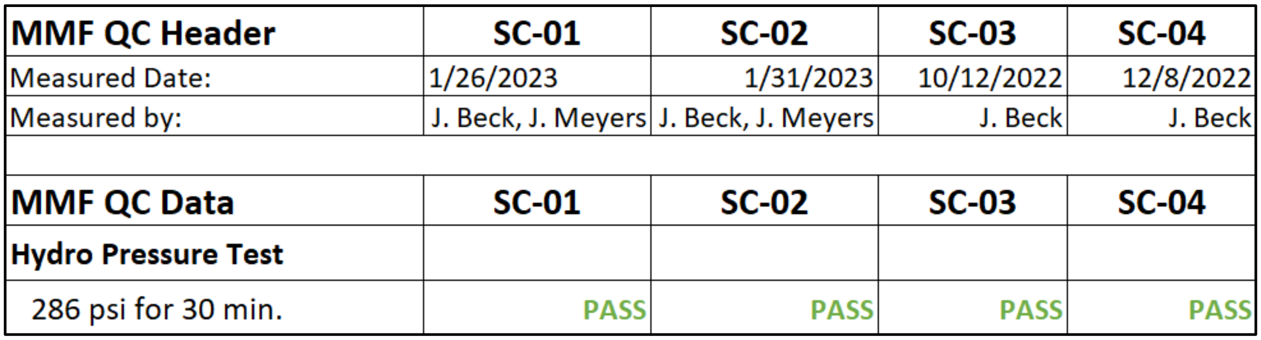
Initials: MS

Date: 8/17/22

Figure 23 - ETI Hydrostatic Pressure Test Results, After Potting, SC3-01

3.4.1.3 JLab Pressure Test Results After Potting the Coil

Similarly, as shown in Figure 24, JLab also performed a hydrostatic pressure test on all four coils and reported the results in Reference (J). The test was performed at 286 psi for 30 minutes. Note that for SC4-01, both layers were pressure tested. All coils passed JLab's pressure testing.



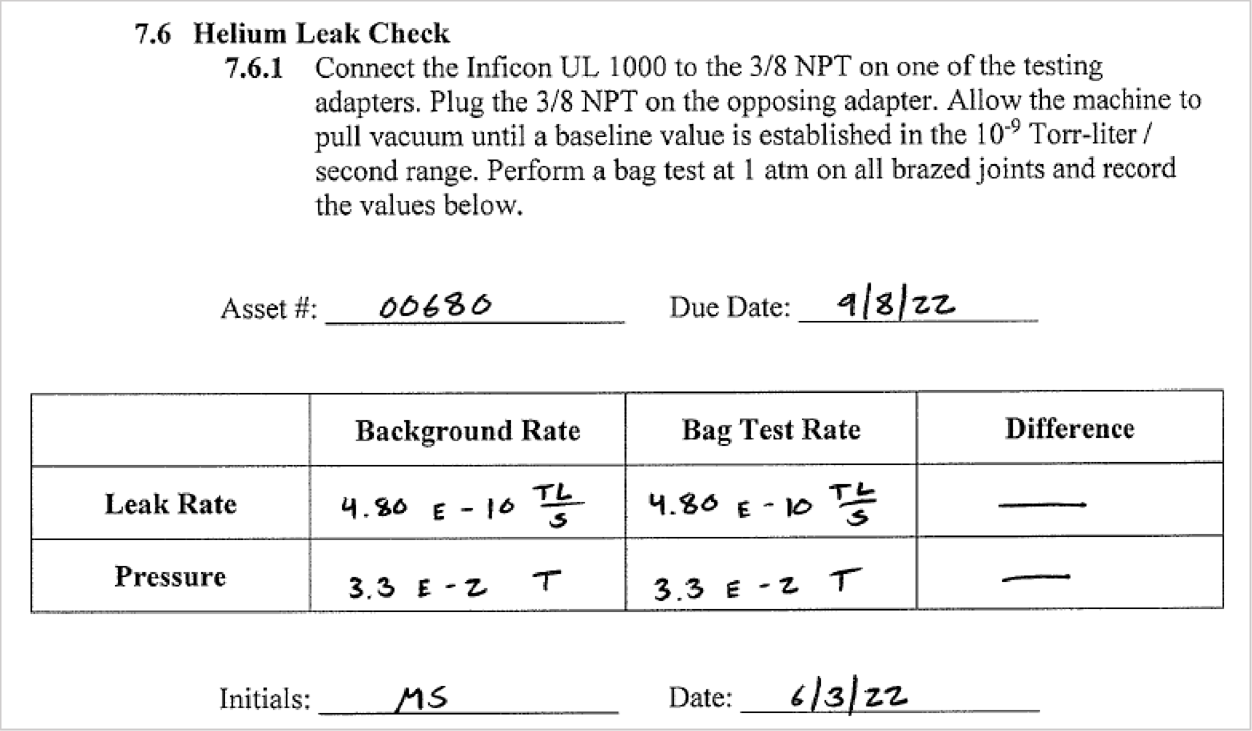
MMF QC Header	**SC-01**	**SC-02**	**SC-03**	**SC-04**
Measured Date:	1/26/2023	1/31/2023	10/12/2022	12/8/2022
Measured by:	J. Beck, J. Meyers	J. Beck, J. Meyers	J. Beck	J. Beck
MMF QC Data	**SC-01**	**SC-02**	**SC-03**	**SC-04**
Hydro Pressure Test				
286 psi for 30 min.	PASS	PASS	PASS	PASS

Figure 24 - JLAB Hydrostatic Pressure Test Results for SC1-01, SC2-01, SC3-01 and SC4-01

3.4.2 Helium Mass Spectrometer Leak Test

As shown in Figure 25 through Figure 32, ETI performed a helium mass spectrometer leak test on all four coils and reported the results in each coil's respective test report, References (F) – (I). This was done prior to potting the coils and after potting the coils. No leaks were detected on any of the four coils. JLab did not conduct a similar test.

3.4.2.1 ETI Helium Mass Spectrometer Leak Test Prior to Potting



7.6 Helium Leak Check

7.6.1 Connect the Inficon UL 1000 to the 3/8 NPT on one of the testing adapters. Plug the 3/8 NPT on the opposing adapter. Allow the machine to pull vacuum until a baseline value is established in the 10^{-9} Torr-liter / second range. Perform a bag test at 1 atm on all brazed joints and record the values below.

Asset #: 00680

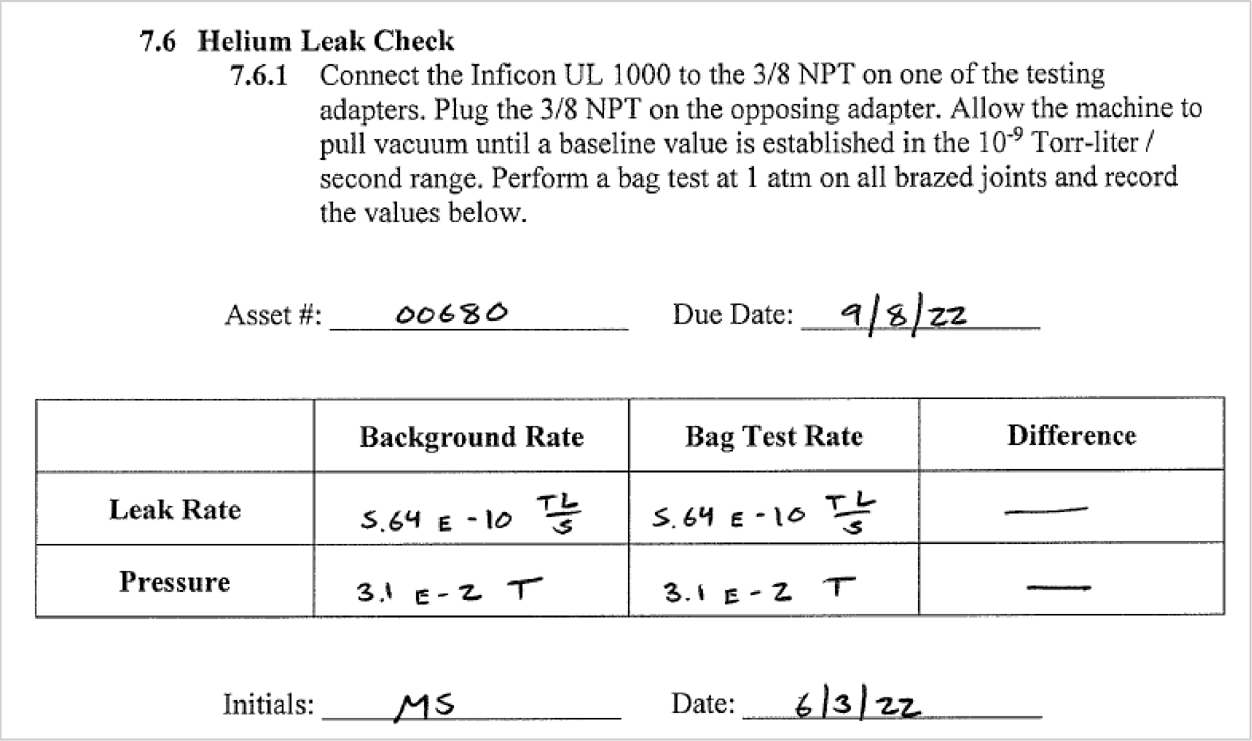
Due Date: 9/8/22

	Background Rate	Bag Test Rate	Difference
Leak Rate	4.80 E-10 $\frac{TL}{S}$	4.80 E-10 $\frac{TL}{S}$	—
Pressure	3.3 E-2 T	3.3 E-2 T	—

Initials: MS

Date: 6/3/22

Figure 25 – ETI Helium Mass Spectrometer Leak Test Results, Before Potting, SC1-01



7.6 Helium Leak Check

7.6.1 Connect the Inficon UL 1000 to the 3/8 NPT on one of the testing adapters. Plug the 3/8 NPT on the opposing adapter. Allow the machine to pull vacuum until a baseline value is established in the 10^{-9} Torr-liter / second range. Perform a bag test at 1 atm on all brazed joints and record the values below.

Asset #: 00680

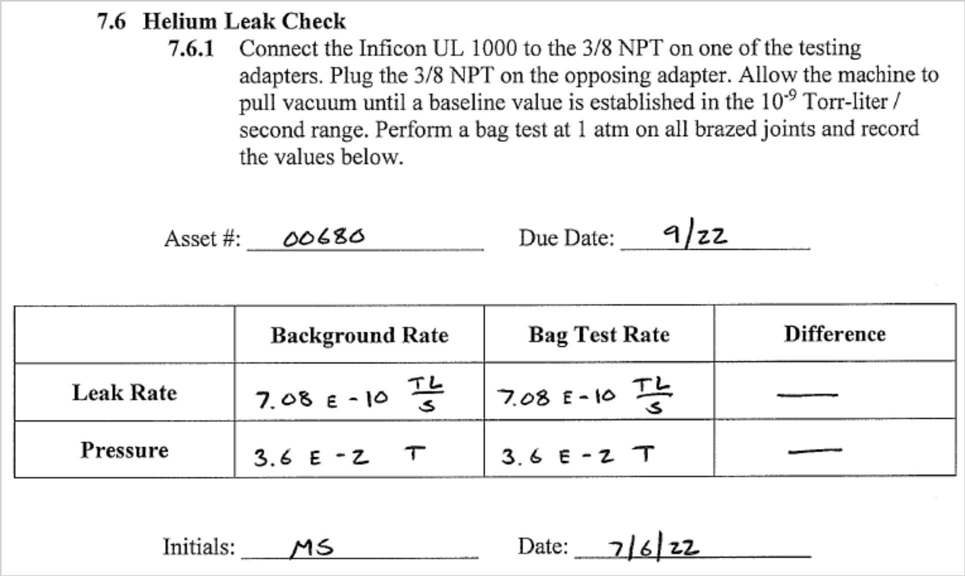
Due Date: 9/8/22

	Background Rate	Bag Test Rate	Difference
Leak Rate	5.64 E-10 $\frac{TL}{S}$	5.64 E-10 $\frac{TL}{S}$	—
Pressure	3.1 E-2 T	3.1 E-2 T	—

Initials: MS

Date: 6/3/22

Figure 26 - ETI Helium Mass Spectrometer Leak Test Results, Before Potting, SC2-01



7.6 Helium Leak Check

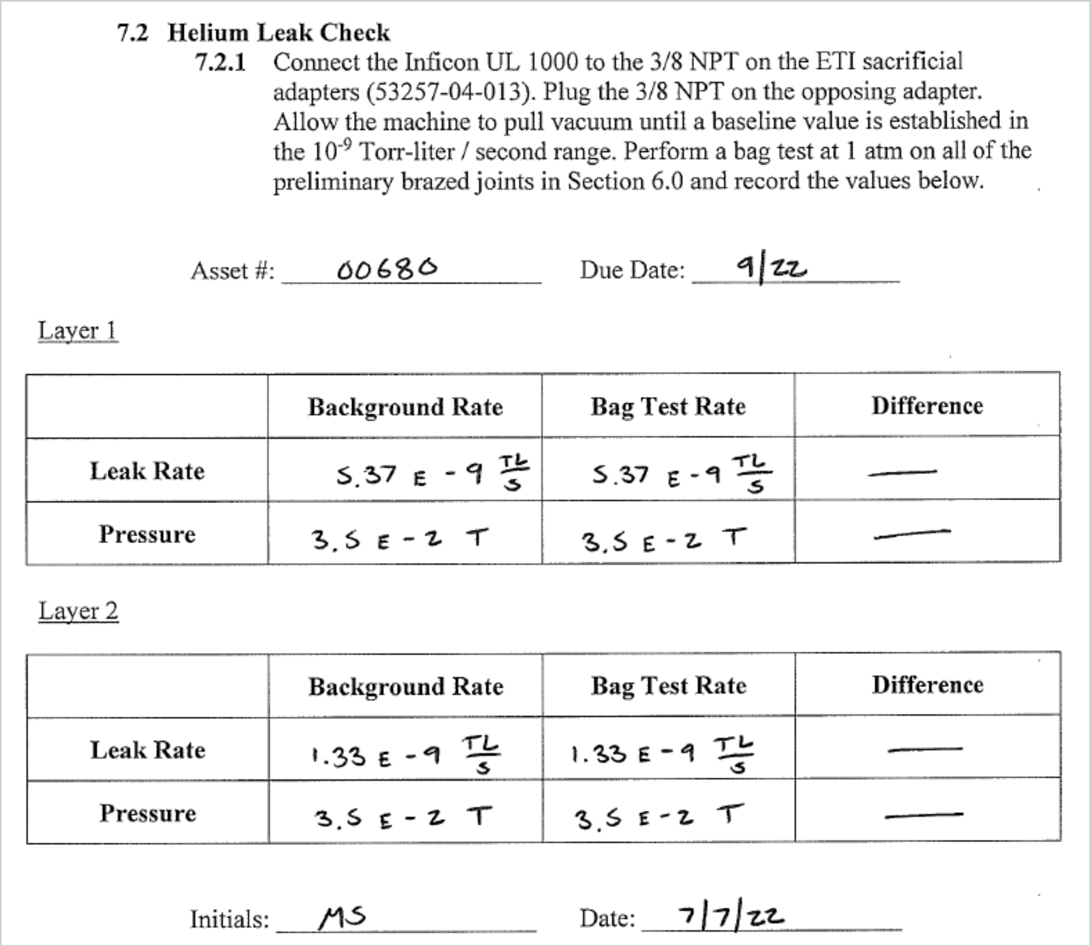
7.6.1 Connect the Inficon UL 1000 to the 3/8 NPT on one of the testing adapters. Plug the 3/8 NPT on the opposing adapter. Allow the machine to pull vacuum until a baseline value is established in the 10^{-9} Torr-liter / second range. Perform a bag test at 1 atm on all brazed joints and record the values below.

Asset #: 00680 Due Date: 9/22

	Background Rate	Bag Test Rate	Difference
Leak Rate	7.08 E-10 $\frac{TL}{S}$	7.08 E-10 $\frac{TL}{S}$	—
Pressure	3.6 E-2 T	3.6 E-2 T	—

Initials: MS Date: 7/6/22

Figure 27 - ETI Helium Mass Spectrometer Leak Test Results, Before Potting, SC3-01



7.2 Helium Leak Check

7.2.1 Connect the Inficon UL 1000 to the 3/8 NPT on the ETI sacrificial adapters (53257-04-013). Plug the 3/8 NPT on the opposing adapter. Allow the machine to pull vacuum until a baseline value is established in the 10^{-9} Torr-liter / second range. Perform a bag test at 1 atm on all of the preliminary brazed joints in Section 6.0 and record the values below.

Asset #: 00680 Due Date: 9/22

Layer 1

	Background Rate	Bag Test Rate	Difference
Leak Rate	5.37 E-9 $\frac{TL}{S}$	5.37 E-9 $\frac{TL}{S}$	—
Pressure	3.5 E-2 T	3.5 E-2 T	—

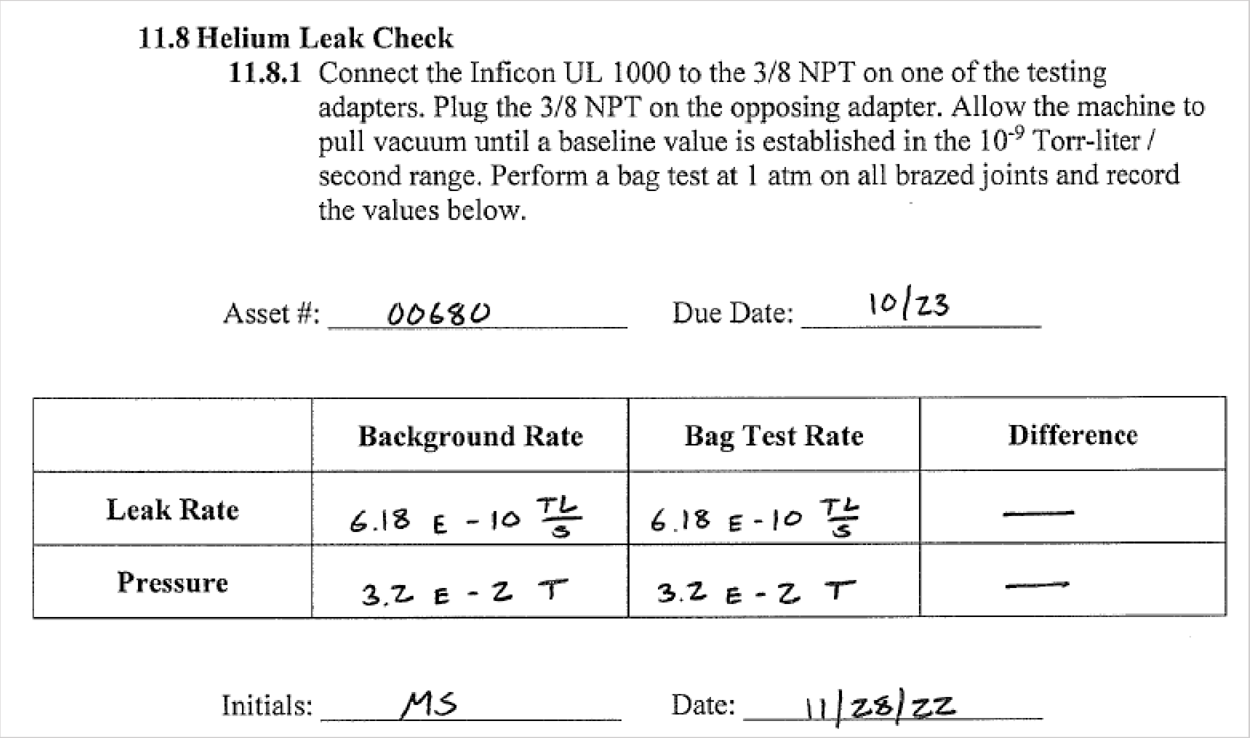
Layer 2

	Background Rate	Bag Test Rate	Difference
Leak Rate	1.33 E-9 $\frac{TL}{S}$	1.33 E-9 $\frac{TL}{S}$	—
Pressure	3.5 E-2 T	3.5 E-2 T	—

Initials: MS Date: 7/7/22

Figure 28 - ETI Helium Mass Spectrometer Leak Test Results, Before Potting, SC4-01

3.4.2.2 ETI Helium Mass Spectrometer Leak Test After Potting



11.8 Helium Leak Check

11.8.1 Connect the Inficon UL 1000 to the 3/8 NPT on one of the testing adapters. Plug the 3/8 NPT on the opposing adapter. Allow the machine to pull vacuum until a baseline value is established in the 10^{-9} Torr-liter / second range. Perform a bag test at 1 atm on all brazed joints and record the values below.

Asset #: 00680

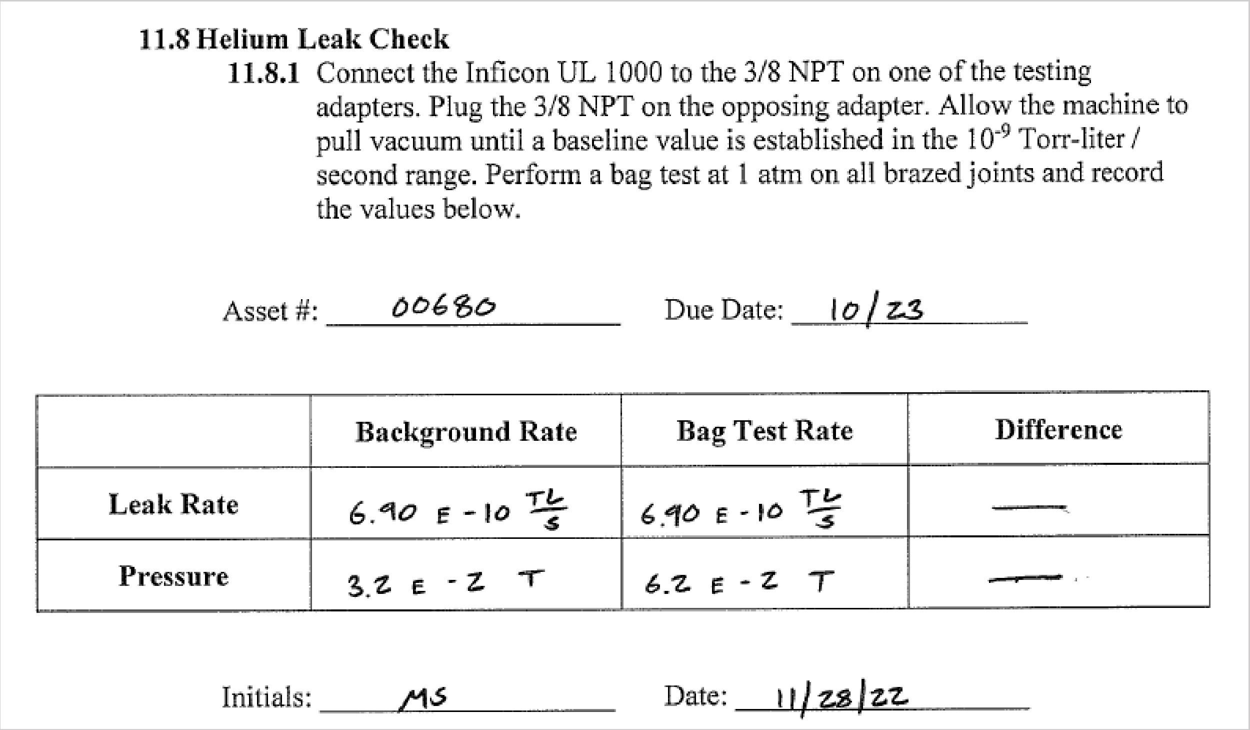
Due Date: 10/23

	Background Rate	Bag Test Rate	Difference
Leak Rate	6.18 E-10 TL/s	6.18 E-10 TL/s	—
Pressure	3.2 E-2 T	3.2 E-2 T	—

Initials: MS

Date: 11/28/22

Figure 29 - ETI Helium Mass Spectrometer Leak Test Results, After Potting, SC1-01



11.8 Helium Leak Check

11.8.1 Connect the Inficon UL 1000 to the 3/8 NPT on one of the testing adapters. Plug the 3/8 NPT on the opposing adapter. Allow the machine to pull vacuum until a baseline value is established in the 10^{-9} Torr-liter / second range. Perform a bag test at 1 atm on all brazed joints and record the values below.

Asset #: 00680

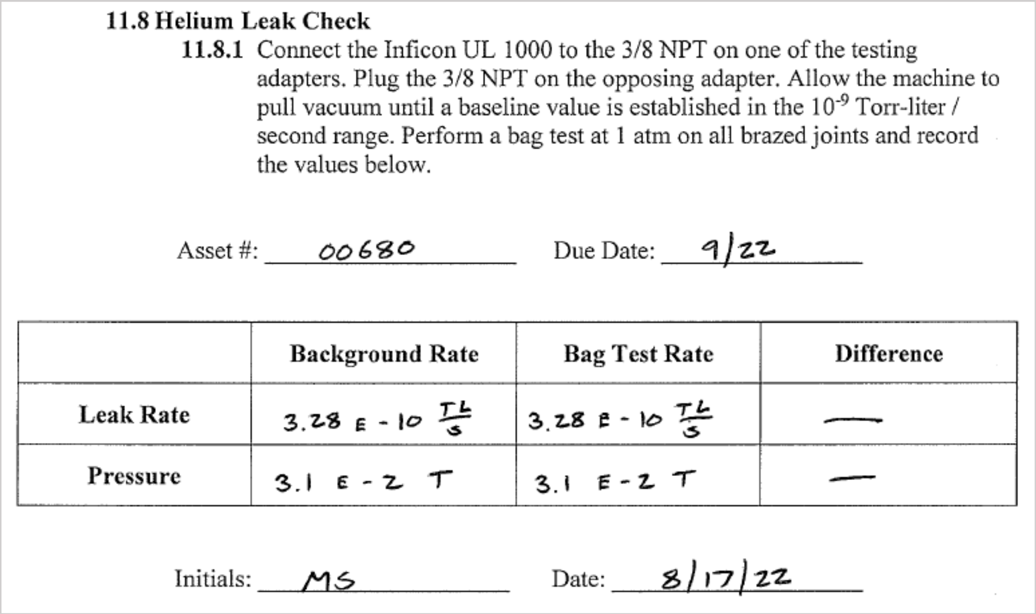
Due Date: 10/23

	Background Rate	Bag Test Rate	Difference
Leak Rate	6.90 E-10 TL/s	6.90 E-10 TL/s	—
Pressure	3.2 E-2 T	6.2 E-2 T	—

Initials: MS

Date: 11/28/22

Figure 30 - ETI Helium Mass Spectrometer Leak Test Results, After Potting, SC01



11.8 Helium Leak Check

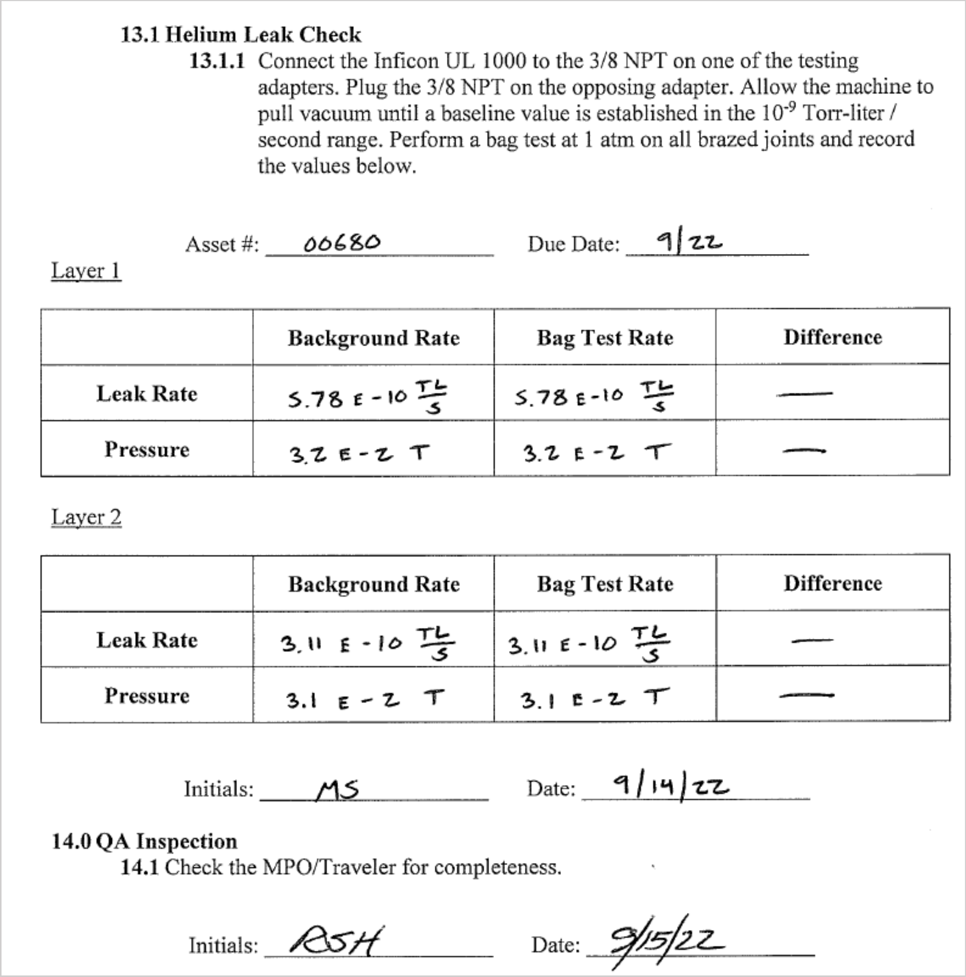
11.8.1 Connect the Inficon UL 1000 to the 3/8 NPT on one of the testing adapters. Plug the 3/8 NPT on the opposing adapter. Allow the machine to pull vacuum until a baseline value is established in the 10^{-9} Torr-liter / second range. Perform a bag test at 1 atm on all brazed joints and record the values below.

Asset #: 00680 Due Date: 9/22

	Background Rate	Bag Test Rate	Difference
Leak Rate	3.28 E-10 TL/S	3.28 E-10 TL/S	—
Pressure	3.1 E-2 T	3.1 E-2 T	—

Initials: MS Date: 8/17/22

Figure 31 - ETI Helium Mass Spectrometer Leak Test Results, After Potting, SC3-01



13.1 Helium Leak Check

13.1.1 Connect the Inficon UL 1000 to the 3/8 NPT on one of the testing adapters. Plug the 3/8 NPT on the opposing adapter. Allow the machine to pull vacuum until a baseline value is established in the 10^{-9} Torr-liter / second range. Perform a bag test at 1 atm on all brazed joints and record the values below.

Asset #: 00680 Due Date: 9/22

Layer 1

	Background Rate	Bag Test Rate	Difference
Leak Rate	5.78 E-10 TL/S	5.78 E-10 TL/S	—
Pressure	3.2 E-2 T	3.2 E-2 T	—

Layer 2

	Background Rate	Bag Test Rate	Difference
Leak Rate	3.11 E-10 TL/S	3.11 E-10 TL/S	—
Pressure	3.1 E-2 T	3.1 E-2 T	—

Initials: MS Date: 9/14/22

14.0 QA Inspection

14.1 Check the MPO/Traveler for completeness.

Initials: RSH Date: 9/15/22

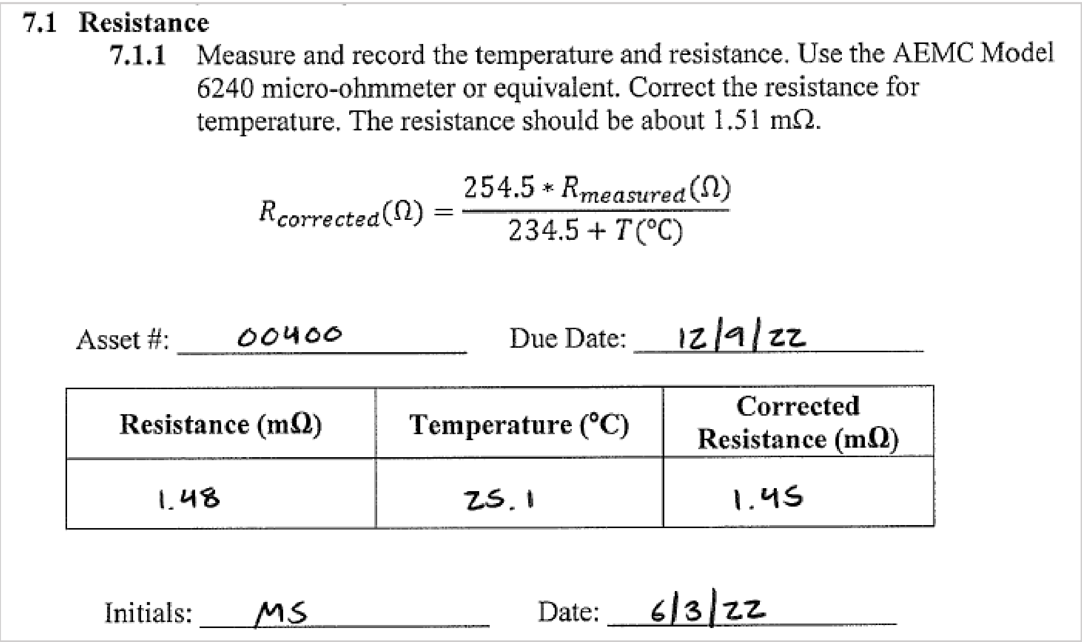
Figure 32 - ETI Helium Mass Spectrometer Leak Test Results, After Potting, SC4-01

3.4.3 Resistance Test

As shown in Figure 33 through Figure 36, ETI performed a resistance test on all four coils and reported the results in each coil's respective test report, References (F) – (I). Reference (K) contains the resistance design estimate for all four coils; these values are summarized in Table 3. All four coils were measured to be very close to expected values and the results were deemed satisfactory.

Table 3 - Resistance Design Estimates

Coil	Design Estimate, Resistance (mΩ)
SC1-01	1.460
SC2-01	1.387
SC3-01	1.403
SC4-01	7.040



7.1 Resistance

7.1.1 Measure and record the temperature and resistance. Use the AEMC Model 6240 micro-ohmmeter or equivalent. Correct the resistance for temperature. The resistance should be about 1.51 mΩ.

$$R_{corrected}(\Omega) = \frac{254.5 * R_{measured}(\Omega)}{234.5 + T(°C)}$$

Asset #: 00400

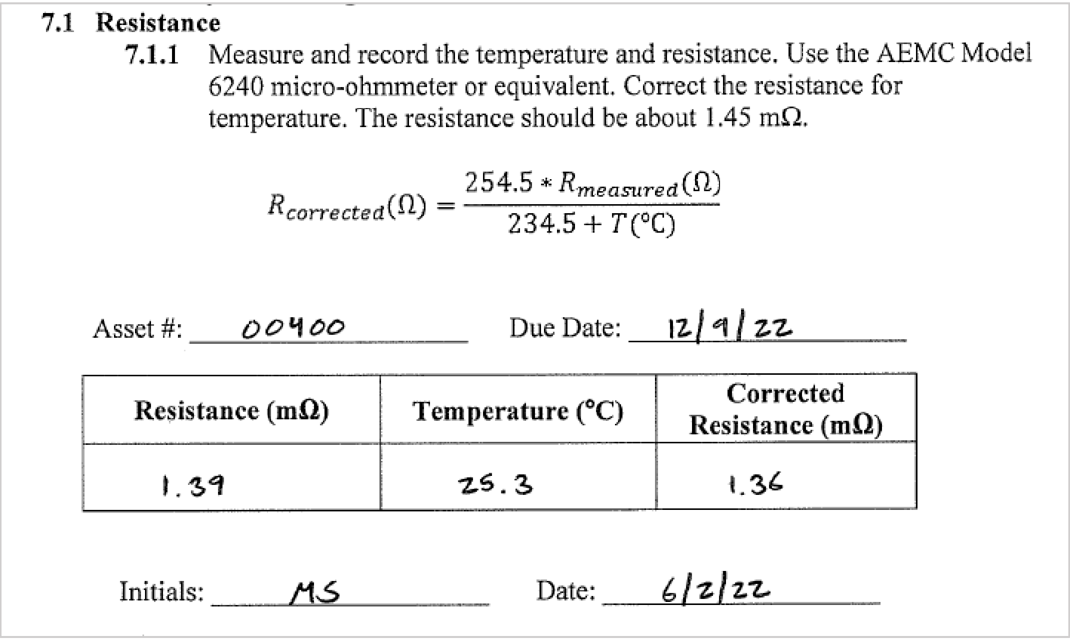
Due Date: 12/9/22

Resistance (mΩ)	Temperature (°C)	Corrected Resistance (mΩ)
1.48	25.1	1.45

Initials: MS

Date: 6/3/22

Figure 33 - ETI Resistance Test Results, SC1-01



7.1 Resistance

7.1.1 Measure and record the temperature and resistance. Use the AEMC Model 6240 micro-ohmmeter or equivalent. Correct the resistance for temperature. The resistance should be about 1.45 mΩ.

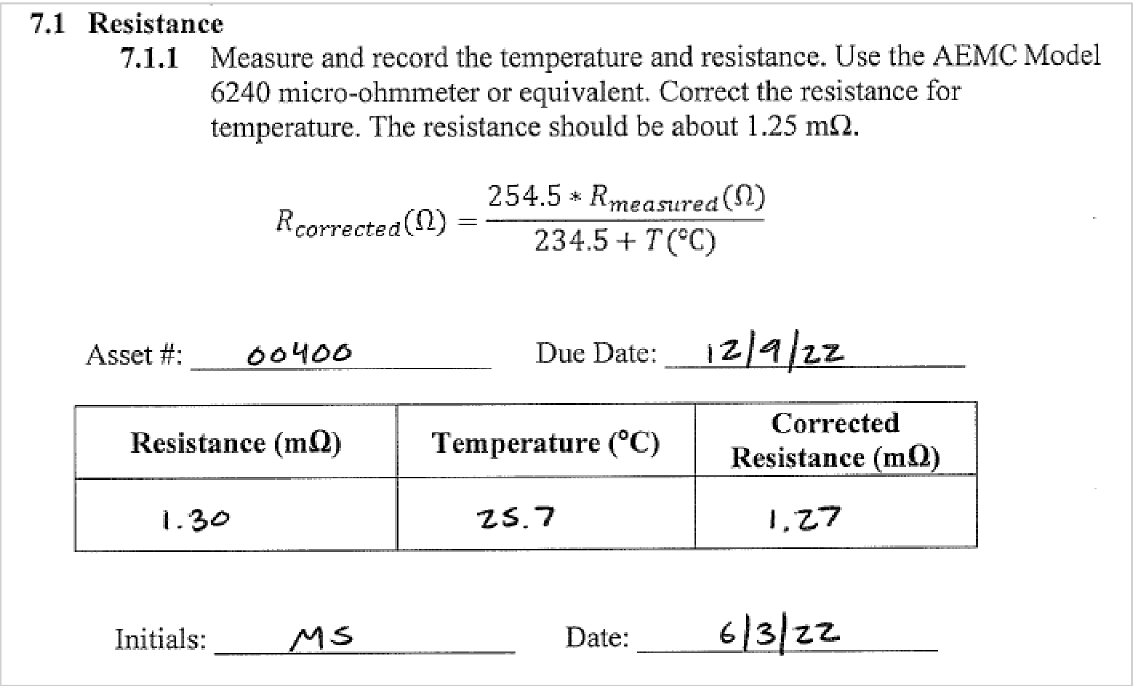
$$R_{corrected}(\Omega) = \frac{254.5 * R_{measured}(\Omega)}{234.5 + T(°C)}$$

Asset #: 00400 Due Date: 12/9/22

Resistance (mΩ)	Temperature (°C)	Corrected Resistance (mΩ)
1.39	25.3	1.36

Initials: MS Date: 6/2/22

Figure 34 - ETI Resistance Test Results, SC2-01



7.1 Resistance

7.1.1 Measure and record the temperature and resistance. Use the AEMC Model 6240 micro-ohmmeter or equivalent. Correct the resistance for temperature. The resistance should be about 1.25 mΩ.

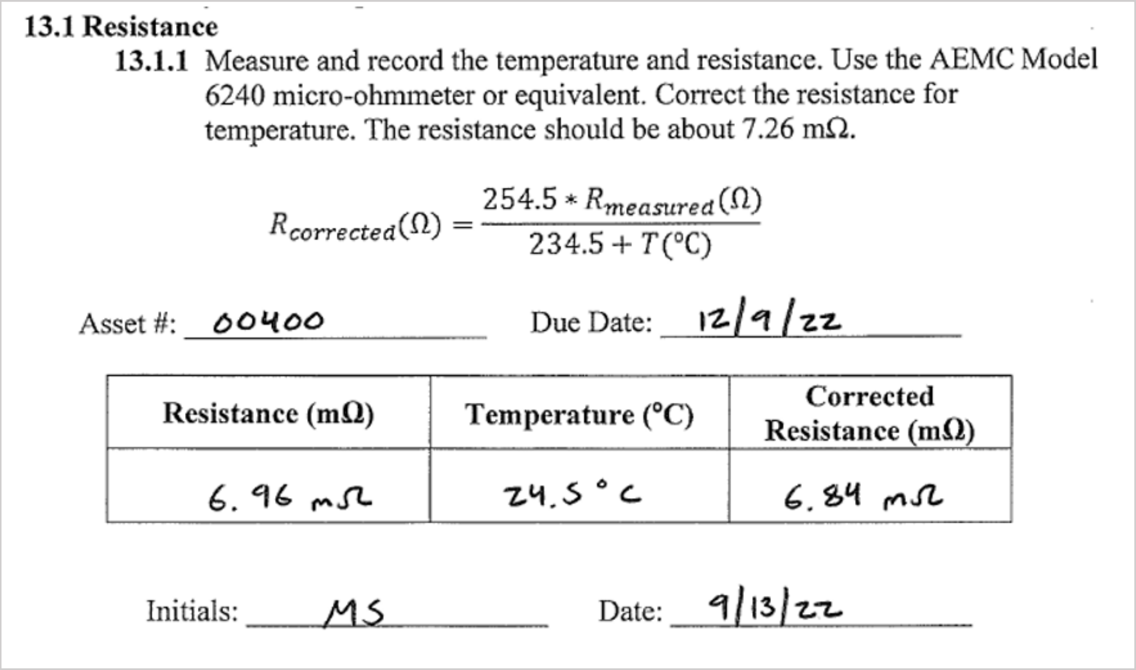
$$R_{corrected}(\Omega) = \frac{254.5 * R_{measured}(\Omega)}{234.5 + T(°C)}$$

Asset #: 00400 Due Date: 12/9/22

Resistance (mΩ)	Temperature (°C)	Corrected Resistance (mΩ)
1.30	25.7	1.27

Initials: MS Date: 6/3/22

Figure 35 - ETI Resistance Test Results, SC3-01



13.1 Resistance

13.1.1 Measure and record the temperature and resistance. Use the AEMC Model 6240 micro-ohmmeter or equivalent. Correct the resistance for temperature. The resistance should be about 7.26 mΩ.

$$R_{corrected}(\Omega) = \frac{254.5 * R_{measured}(\Omega)}{234.5 + T(°C)}$$

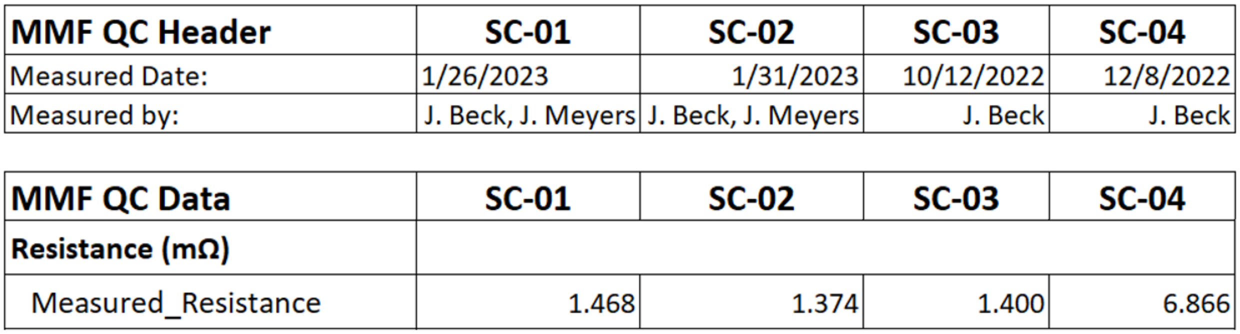
Asset #: 00400 Due Date: 12/9/22

Resistance (mΩ)	Temperature (°C)	Corrected Resistance (mΩ)
6.96 mΩ	24.5 °C	6.84 mΩ

Initials: MS Date: 9/13/22

Figure 36 - ETI Resistance Test Results, SC4-01

Similarly, as shown in Figure 37, JLab also performed a resistance test on all four coils and reported the results in Reference (J). For this test, JLab used a BK Precision 891 LCR meter. The resistance required a 4-wire measurement using the BK Precision 891 LCR meter since the coils had very little resistance (milliohms). This was done by subtracting the resistance of the shorted meter cables from the measured LCR reading. ETI and JLab have very similar results, which increases confidence in the results. The difference in values between ETI and JLab's data sets is considered negligible and the results are considered satisfactory.



MMF QC Header	SC-01	SC-02	SC-03	SC-04
Measured Date:	1/26/2023	1/31/2023	10/12/2022	12/8/2022
Measured by:	J. Beck, J. Meyers	J. Beck, J. Meyers	J. Beck	J. Beck

MMF QC Data	SC-01	SC-02	SC-03	SC-04
Resistance (mΩ)				
Measured_Resistance	1.468	1.374	1.400	6.866

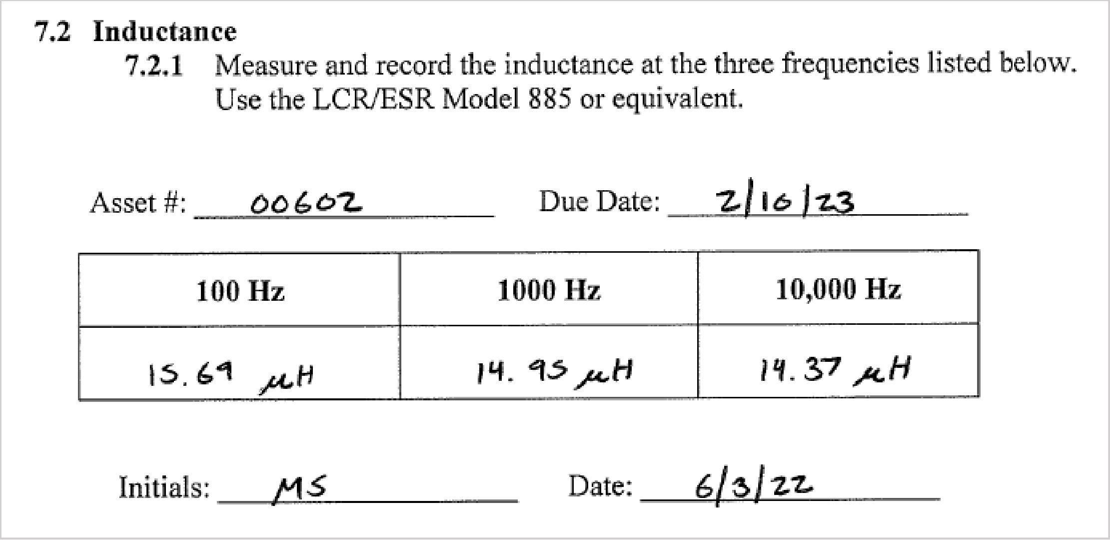
Figure 37 - JLab Resistance Test Results for SC1-01, SC2-01, SC3-01 and SC4-01

3.4.4 Inductance Test

As shown in Figure 38 through Figure 41, ETI performed an inductance test on all four coils and reported the results in each coil's respective test report, References (F) – (I). Reference (K) documents the inductance design estimate for all four coils; these values are summarized in Table 4. Inductance was measured at 100, 1000, and 10000 Hz for all four coils.

Table 4 - Inductance Design Estimates

Coil	Design Estimate, Inductance (µH)
SC1-01	11.92
SC2-01	19.15
SC3-01	27.15
SC4-01	238.02



7.2 Inductance

7.2.1 Measure and record the inductance at the three frequencies listed below. Use the LCR/ESR Model 885 or equivalent.

Asset #: 00602

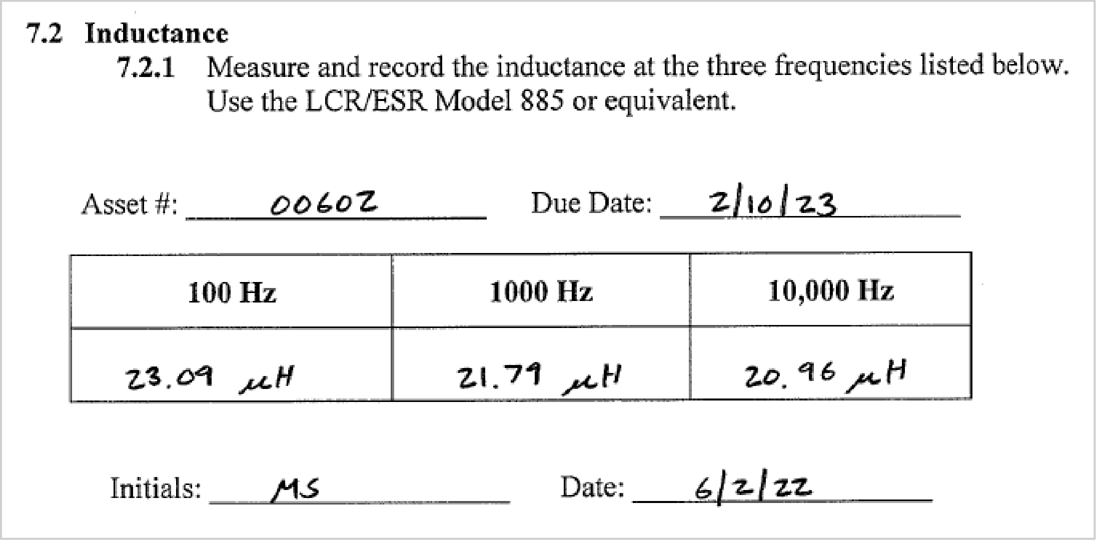
Due Date: 2/16/23

100 Hz	1000 Hz	10,000 Hz
15.69 µH	14.95 µH	14.37 µH

Initials: MS

Date: 6/3/22

Figure 38 - ETI Inductance Test Results, SC1-01



7.2 Inductance

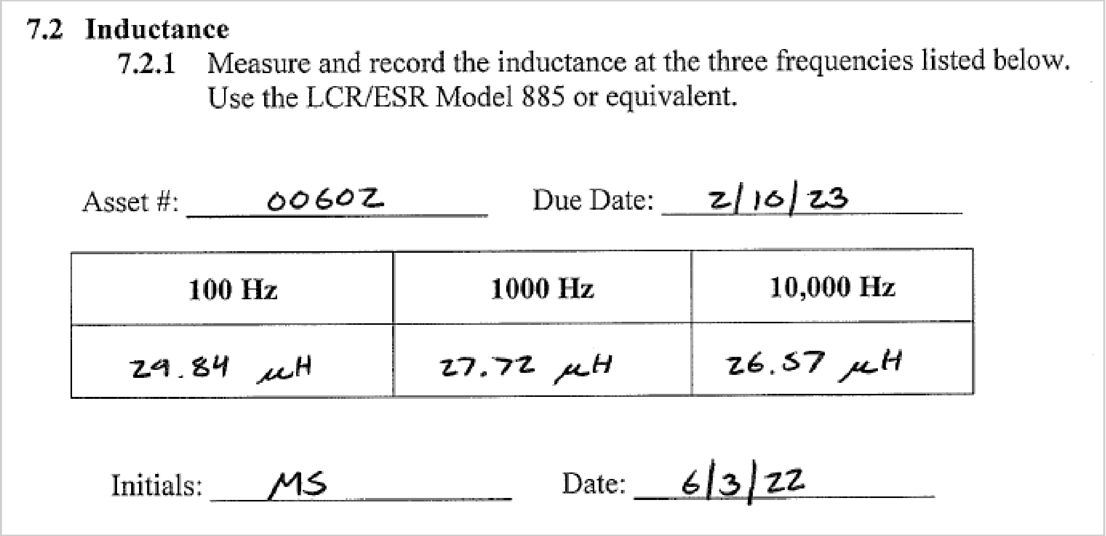
7.2.1 Measure and record the inductance at the three frequencies listed below. Use the LCR/ESR Model 885 or equivalent.

Asset #: 00602 Due Date: 2/10/23

100 Hz	1000 Hz	10,000 Hz
23.09 μH	21.79 μH	20.96 μH

Initials: MS Date: 6/2/22

Figure 39 - ETI Inductance Test Results, SC2-01



7.2 Inductance

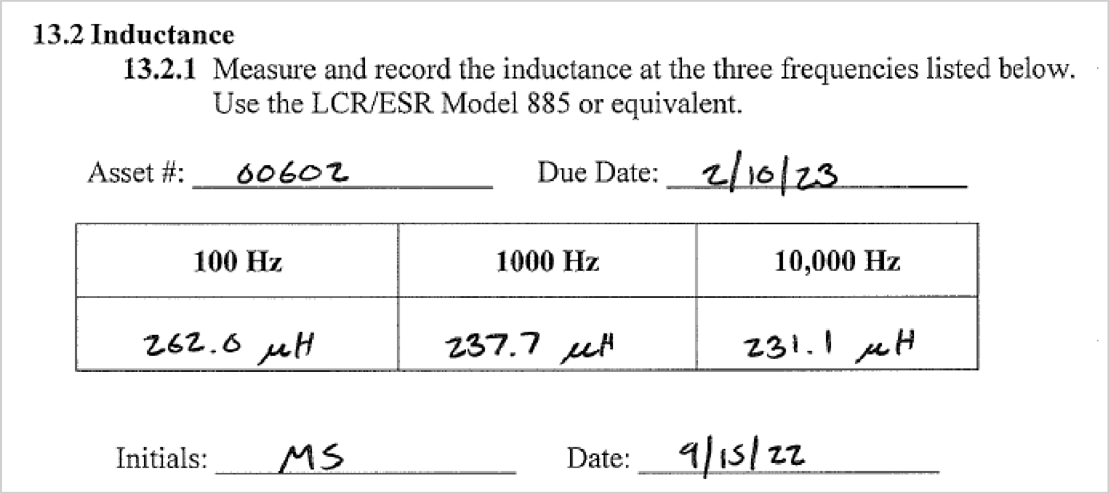
7.2.1 Measure and record the inductance at the three frequencies listed below. Use the LCR/ESR Model 885 or equivalent.

Asset #: 00602 Due Date: 2/10/23

100 Hz	1000 Hz	10,000 Hz
29.84 μH	27.72 μH	26.57 μH

Initials: MS Date: 6/3/22

Figure 40 - ETI Inductance Test Results, SC3-01



13.2 Inductance

13.2.1 Measure and record the inductance at the three frequencies listed below. Use the LCR/ESR Model 885 or equivalent.

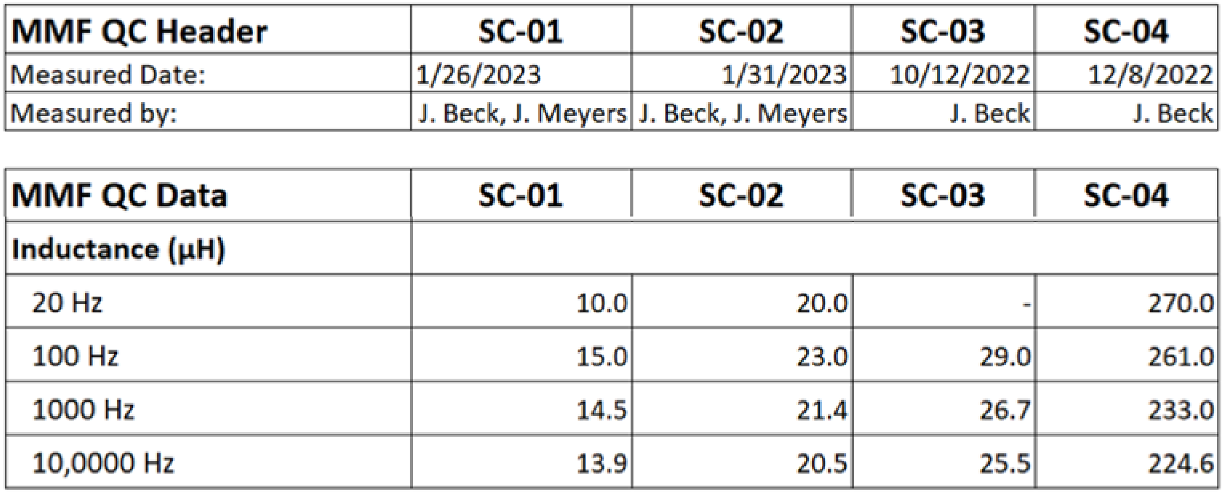
Asset #: 60602 Due Date: 2/10/23

100 Hz	1000 Hz	10,000 Hz
262.0 μH	237.7 μH	231.1 μH

Initials: MS Date: 9/15/22

Figure 41 - ETI Inductance Test Results, SC4-01

Similarly, as shown in Figure 42, JLab also performed an inductance test on all four coils and reported the results in Reference (J). JLab measured inductance at 20, 100, 1000, and 10000 Hz for all four coils using an HP 4192A (values were re-checked with BK 878B handheld). ETI and JLab have very similar results, which increases confidence in the results. The difference in values between ETI and JLab's data sets is considered negligible and the results are considered satisfactory.



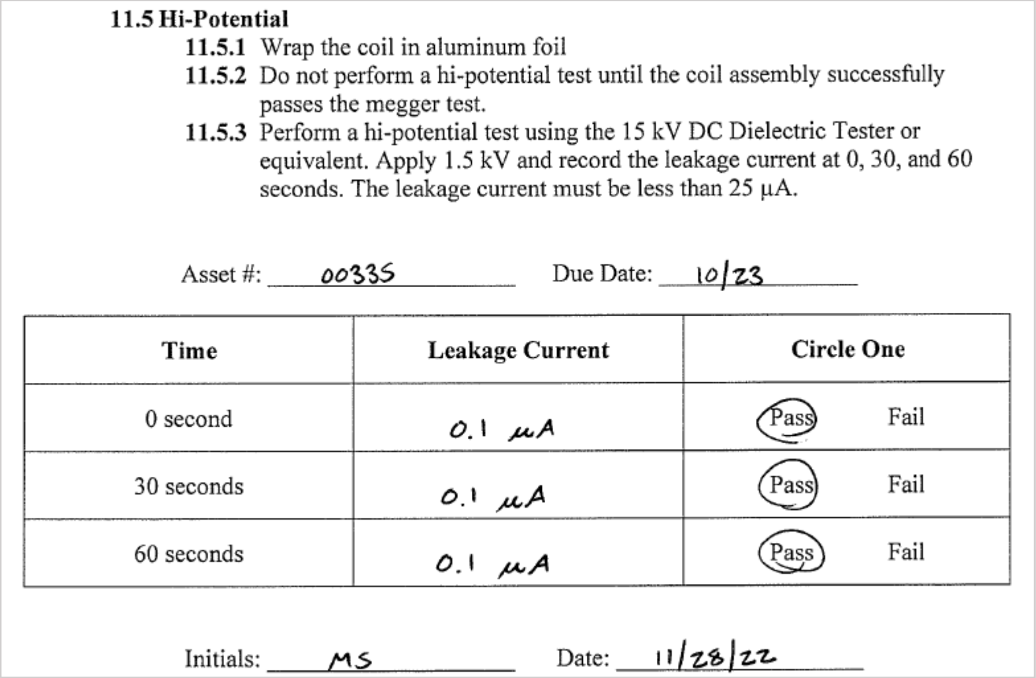
MMF QC Header	SC-01	SC-02	SC-03	SC-04
Measured Date:	1/26/2023	1/31/2023	10/12/2022	12/8/2022
Measured by:	J. Beck, J. Meyers	J. Beck, J. Meyers	J. Beck	J. Beck

MMF QC Data	SC-01	SC-02	SC-03	SC-04
Inductance (μH)				
20 Hz	10.0	20.0	-	270.0
100 Hz	15.0	23.0	29.0	261.0
1000 Hz	14.5	21.4	26.7	233.0
10,0000 Hz	13.9	20.5	25.5	224.6

Figure 42 - JLab Inductance Test Results for SC1-01, SC2-01, SC3-01 and SC4-01

3.4.5 Hi-Pot Test

As shown in Figure 43 through Figure 46, ETI performed a hi-pot test on all four coils and reported the results in each coil's respective test report, References (F) – (I). The test measured leakage current at 0, 30, and 60 second time intervals. ETI recorded leakage current well below the allowable limit, 25 μA, for all four coils.



11.5 Hi-Potential

11.5.1 Wrap the coil in aluminum foil

11.5.2 Do not perform a hi-potential test until the coil assembly successfully passes the megger test.

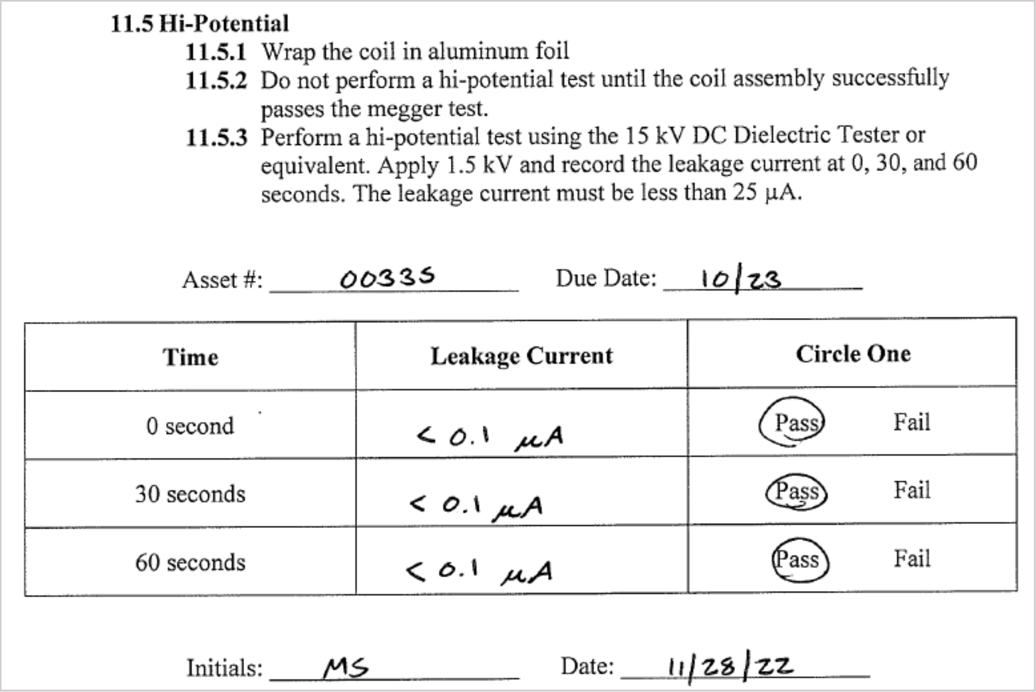
11.5.3 Perform a hi-potential test using the 15 kV DC Dielectric Tester or equivalent. Apply 1.5 kV and record the leakage current at 0, 30, and 60 seconds. The leakage current must be less than 25 µA.

Asset #: 00335 Due Date: 10/23

Time	Leakage Current	Circle One
0 second	0.1 µA	[✓ Pass] Fail
30 seconds	0.1 µA	[✓ Pass] Fail
60 seconds	0.1 µA	[✓ Pass] Fail

Initials: MS Date: 11/28/22

Figure 43 - ETI Hi-Pot Test Results, SC1-01



11.5 Hi-Potential

11.5.1 Wrap the coil in aluminum foil

11.5.2 Do not perform a hi-potential test until the coil assembly successfully passes the megger test.

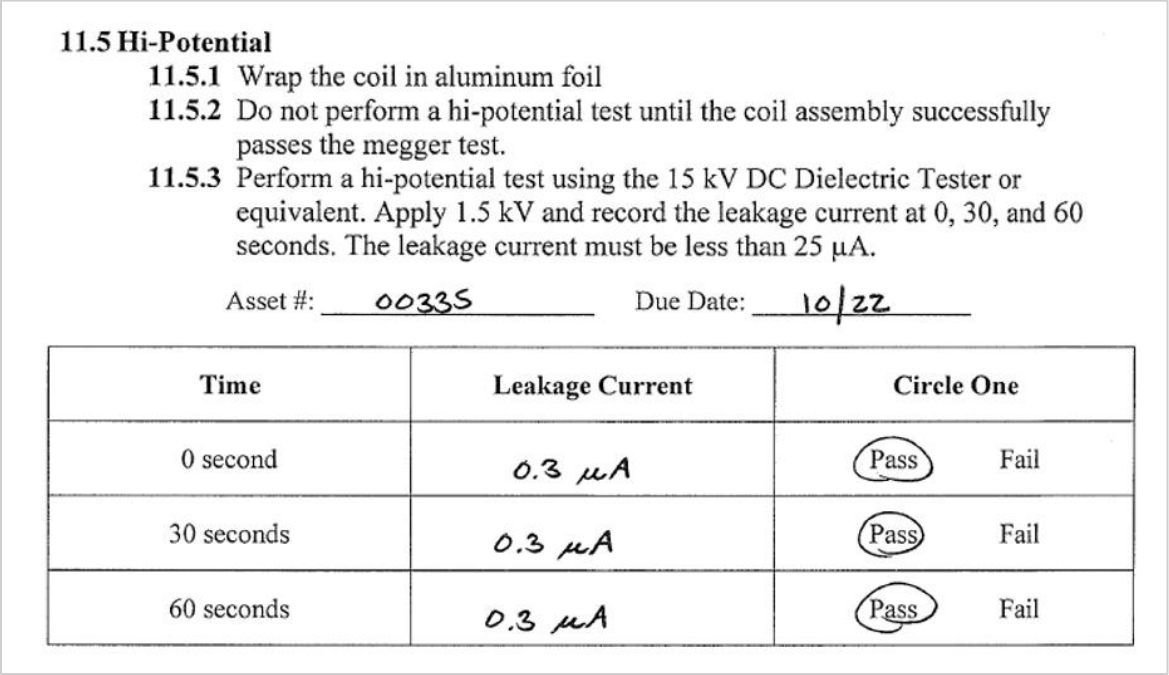
11.5.3 Perform a hi-potential test using the 15 kV DC Dielectric Tester or equivalent. Apply 1.5 kV and record the leakage current at 0, 30, and 60 seconds. The leakage current must be less than 25 µA.

Asset #: 00335 Due Date: 10/23

Time	Leakage Current	Circle One
0 second	< 0.1 µA	[✓ Pass] Fail
30 seconds	< 0.1 µA	[✓ Pass] Fail
60 seconds	< 0.1 µA	[✓ Pass] Fail

Initials: MS Date: 11/28/22

Figure 44 - ETI Hi-Pot Test Results, SC2-01



11.5 Hi-Potential

11.5.1 Wrap the coil in aluminum foil

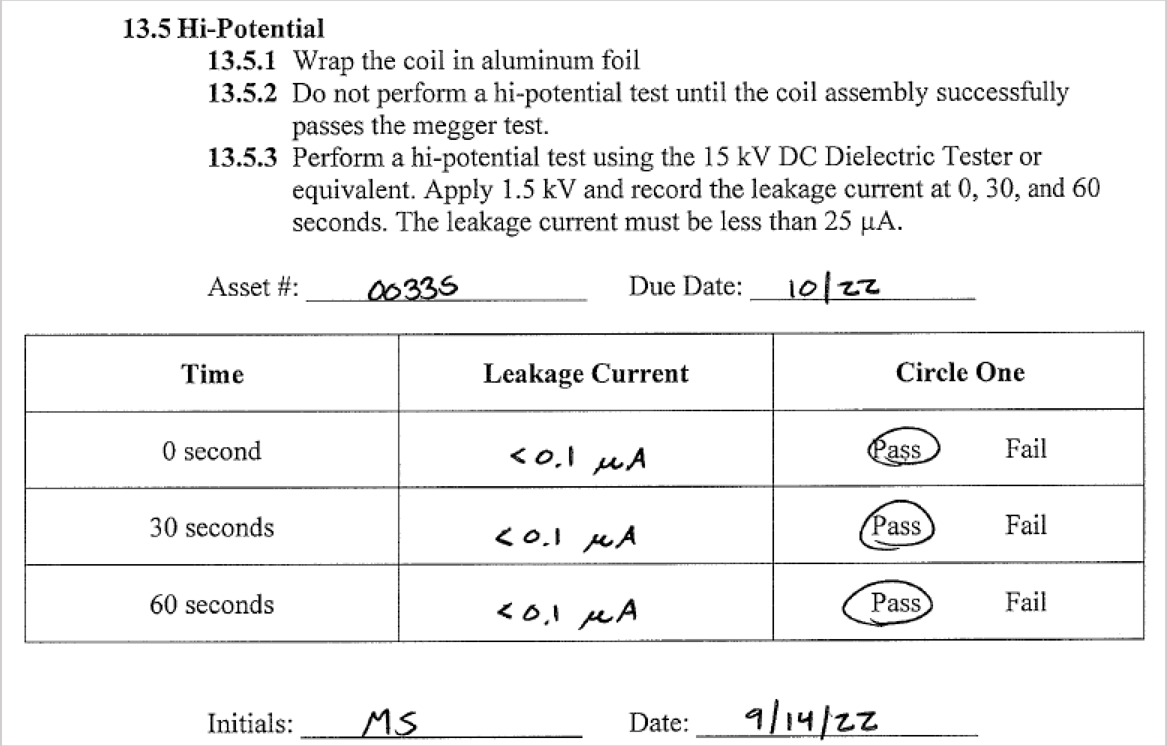
11.5.2 Do not perform a hi-potential test until the coil assembly successfully passes the megger test.

11.5.3 Perform a hi-potential test using the 15 kV DC Dielectric Tester or equivalent. Apply 1.5 kV and record the leakage current at 0, 30, and 60 seconds. The leakage current must be less than 25 µA.

Asset #: 00335 Due Date: 10/22

Time	Leakage Current	Circle One
0 second	0.3 µA	[✓ Pass] Fail
30 seconds	0.3 µA	[✓ Pass] Fail
60 seconds	0.3 µA	[✓ Pass] Fail

Figure 45 - ETI Hi-Pot Test Results, SC3-01



13.5 Hi-Potential

13.5.1 Wrap the coil in aluminum foil

13.5.2 Do not perform a hi-potential test until the coil assembly successfully passes the megger test.

13.5.3 Perform a hi-potential test using the 15 kV DC Dielectric Tester or equivalent. Apply 1.5 kV and record the leakage current at 0, 30, and 60 seconds. The leakage current must be less than 25 µA.

Asset #: 00335 Due Date: 10/22

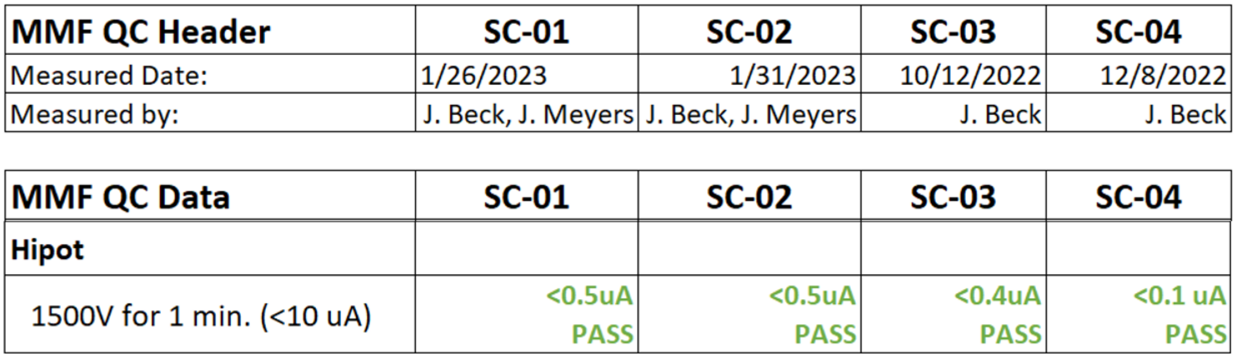
Time	Leakage Current	Circle One
0 second	< 0.1 µA	[✓ Pass] Fail
30 seconds	< 0.1 µA	[✓ Pass] Fail
60 seconds	< 0.1 µA	[✓ Pass] Fail

Initials: MS Date: 9/14/22

Figure 46 - ETI Hi-Pot Test Results, SC4-01

Similarly, as shown in Figure 47, JLab also performed a hi-pot test on all four coils and reported the results in Reference (J). For this test, JLab used a Baker ST112E.

JLab reported similar results and like ETI, all values were well below the 25 µA requirement. All four coils passed the inductance test.



MMF QC Header	SC-01	SC-02	SC-03	SC-04
Measured Date:	1/26/2023	1/31/2023	10/12/2022	12/8/2022
Measured by:	J. Beck, J. Meyers	J. Beck, J. Meyers	J. Beck	J. Beck

MMF QC Data	SC-01	SC-02	SC-03	SC-04
Hipot				
1500V for 1 min. (<10 uA)	<0.5uA PASS	<0.5uA PASS	<0.4uA PASS	<0.1 uA PASS

Figure 47 - JLab Hi-Pot Test Results for SC1-01, SC2-01, SC3-01 and SC4-01

3.4.6 Thermal Cycling Test

Thermal cycling tests were only conducted on SC2-01 and SC3-01 (SC1-01 and SC4-01 were not tested). After receiving sub-coils SC2-01 and SC3-01, JLab performed thermal cycling tests in order to investigate if what appeared to be debonding within the coil at the G10-conductor interfaces on SC3-01 would continue to grow and to investigate if SC2-01, which showed none of this, would have some develop.

The coils were set on table and connected through a series of valves to a water heater and to city water. This allowed sending cold water and warm water through the coil; the system piping and instrumentation diagram is presented in Appendix A. City water was used as a cold-water supply and two chiller units were used to heat a volume of water, which was pumped through the coil as a warm water supply. Resistance temperature sensors (RTDs) were also attached at several locations on the coil body.

SC2-01 and SC3-01 were tested individually and the results are presented in Appendix A and Appendix B, respectively. As shown in Appendix A, a total of 80 thermal cycles were completed on SC2-01. As shown in the data, the chillers were typically in the range of 72°C - 78°C (~162°F - 172°F) at the time of the cycle; this indicates the temperature of the hot water supply pumped into the coil. The coil was studied for any signs of damage during testing. Appendix A contains images of the coil at the start of testing (cycle 0) and the end of testing (cycle 80). The lead side of the coil and the non-lead side of the coil were photographed and before / after images can be compared. As seen in the figures, little to no visible damage is observed as a result of the thermal cycling.

SC3-01 was tested in a similar way as described in Appendix A. When testing SC3-01, RTD data was recorded and plotted; these sensors measure temperature at various locations on the coil body. The RTD data is presented in Appendix B. As observed in Appendix B, many of the RTD sensors follow the same general pattern over time, with various highs and lows depending on their position on the coil. Throughout the testing, the highest temperatures recorded consistently approach ~55°C and the lowest temperatures recorded approach ~22°C (with some exceptions). As observed in the data, RTD5 (which is placed on the center of the coil body) appears to "spike" in the left and right data sets, but is more stable in the middle data set. This spike can be attributed to the time the test took place – the middle data set was taken in the morning when ambient temperatures were cooler and sunlight was not penetrating the lab. Thus, the middle data set appears more stable over time.

SC2-01, which had the 3.2 mm chamfer, did not have any observable delamination at the G10-conductor interface. Unlike SC2-01, SC3-01 did have observable delamination at those boundaries and it increased significantly as a result of thermal cycling. A photograph record of SC3-01 over time is included in Appendix B. The photographs document the observed delamination before and after testing, including during manufacture. The delamination appears as a light discoloration relative to surrounding material and seen in the photographs, it appears more pronounced and continues further down the length of the coil after thermal cycling.

3.4.7 Powering Test

JLab conducting powering tests on all four coils. The coils were powered from 0 – 700 A at increasing 100-amp intervals. At each 100-amp interval, several minutes (2-3 typical) were allowed to elapsed before amperage was increased. During this time, cooling water was flowing through the coil. Once the coil was powered using 700 A, the cooling water supply was cut-off, and the coil was exposed to a constant 700 A load until the coil body reached approximately 65°C (this was the safe working limit *for the lab* as determined by lab staff). Once the temperature reached 65°C on the coil, the current supply was turned off and cooling water was pumped back through the coil.

Appendix C contains powering data for SC1-01, SC2-01, SC3-01 and SC4-01. When testing SC1-01 and SC2-01, data was recorded in a notebook and lab staff monitored conditions. However, while testing SC3-01 and SC4-01, in addition to lab staff monitoring conditions, RTD data, amperage data, and flow data were electronically monitored, recorded, and plotted. These plots help paint a clear picture of test operations and conditions over time.

Regardless of how the data was recorded, all four coils were tested successfully and no damage or operational failure was observed. JLab concluded that the powering tests had no impact to any of the coil's physical integrity and was unlikely to impact operating or performance characteristics of the coil(s).

3.4.8 Alignment and Flatness Test

The JLab metrology department, in coordination with engineering, conducted an alignment / flatness survey of each coil. The surveys were done using a laser tracker and the SMR (spherically mounted retroflector) was positioned by the surveyor at approximate locations along the coil body. The "left" side of the coils were surveyed and the "right" side of the coils were surveyed. The "left" and "right" designations are based on the X-axis orientation established in the JLab survey; this was done by fitting a best-fit plane on either side of the coil and then located the YZ plane in between them. Once the YZ plane was located, the origin was established at the center of the coil's upstream turn. With the origin located, the positive X-axis was defined as left (when looking downstream), the Y-axis was defined positive up, and the Z-axis was defined as positive downstream. It is important to note that the resulting "right" side of the coil is the cover side of the respective coil mold. Figure 48 shows an example of some surveyed points along the right of SC3-01 and the coordinate system axes.

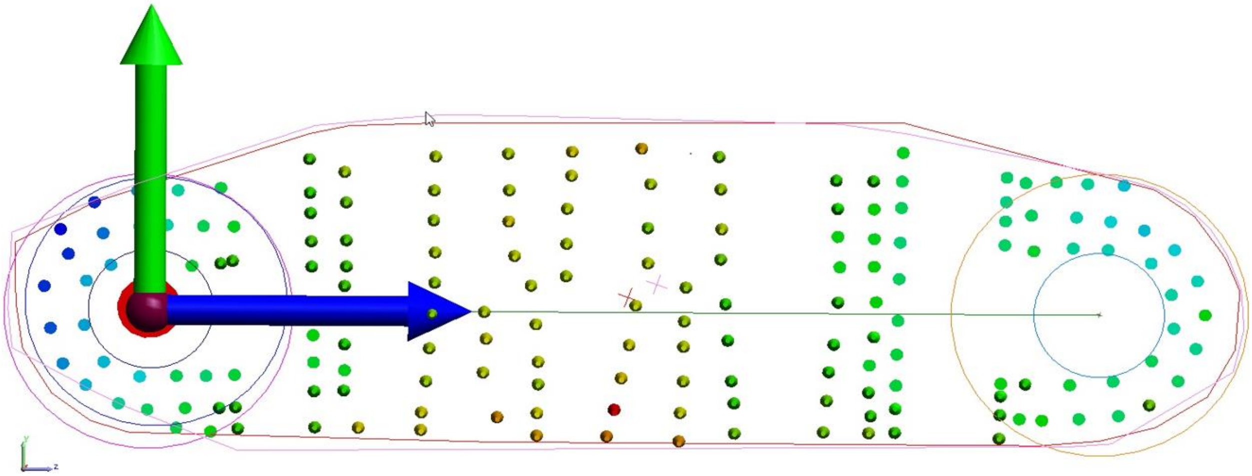


Figure 48 – Surveyed Points Example, Right Side of SC3-01, X-Axis (red), Y-Axis (green), Z-axis (blue)

Table 5 summarizes the coil thickness (and tolerance) as seen on the coil production drawings, References (A) – (D). The "thickness" values in Table 5 reflect the *total* coil thickness and tolerance values. Half of the "thickness" value in Table 5 represents the left and right thickness of the coil, which is also listed in Table 5 for convenience (tolerances are removed since they are only applied to the total thickness). Table 6 summarizes the maximum and minimum thickness values from the JLab survey data for each coil – i.e., the X-coordinate from the left and right halves of the coils reported in the surveys.

Table 5 - Coil Thickness on Production Drawings

	SC1-01	SC2-01	SC3-01	SC4-01
Thickness (mm)	$22.7^{+0.8}_{-0.3}$	$25.9^{+0.8}_{-0.3}$	$26.9^{+0.8}_{-0.3}$	$49.4^{+0.8}_{-0.3}$
Left and Right Nominal Thickness (mm)	11.35	12.95	13.45	24.7

Table 6 - Summary of Coil Thickness Data from JLab Surveys

	SC1-01		SC2-01		SC3-01		SC4-01	
	Left	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
Minimum (mm)*	10.75	-11.65	12.57	-13.05	13.03	-13.90	24.19	-25.06
Maximum (mm)*	11.67	-10.77	13.10	-12.16	13.72	-12.91	24.93	-24.31

*NOTE: All values are based on the X-coordinates reported in the survey data.

In order to better understand coil size and geometry, it was necessary to use existing survey data in such a way as to understand the coil's geometry at non-surveyed points. For each coil, the respective survey data was imported in MATLAB and outlier data points (those outside 3 standard deviations) were removed in order to eliminate potential points that may have measured high/low spots caused by surface blemishes, etc. A surface was fit to the remaining left-side data and another surface was fit to the remaining right-side data. Each surface passes through the survey points and interpolates the surface *between* survey points based on a user specified grid size. As a result, the left-side and the right-side data can be surface-fit using the same exact grid in 3D-space (i.e., the grid points are at the same location in the YZ plane); this makes it possible to have discrete points that are "mirrored" between the left and right side of the coil, i.e., these points are exactly 180° apart. The total distance between corresponding grid points represents the coil's thickness in way of that specific pair of mirrored grid points. By calculating the difference in the grid points X-location (i.e. the left/right thickness at that grid point), the thickness can be calculated at every grid point and the coil's thickness can *also* be surface-fit. By have a left-side surface plot, right-side surface plot, and thickness plot, once can better understand the geometry of the coil, even in way of locations not explicitly surveyed.

SC1-01, SC2-01, SC3-01, and SC4-01 were all surface-fit on a 100 × 200-point grid, resulting in 20,000 unique grid points. However, the grid is automatically trimmed to the rough-coil shape, ultimately reducing the effective grid size. This reduces the amount of empty space accounted for in the surfaces, ultimately refining the results and making the data easier to understand.

Appendix D presents all the surface plots for the left-side and right-side of SC1-01, SC2-01, SC3-01, and SC4-01. Appendix D also presents the thickness plots for the coils. Each plot is presented as an isometric view and in a “flattened” view (note – when looking at the plots in Appendix D, pay attention to the X-coordinate, which can be either positive or negative as a result of the survey coordinate system). Table 7 summarizes the maximum and minimum left and right thickness values on from the respective grid points of the surface plots; this could be compared to the design values shown in Table 5. Similarly, Table 8 summarizes the maximum and minimum *total* thickness values from the respective surface plots; these values can be compared to the total thickness design values presented in Table 5. It is important to note that the total thickness can be greatly affected by how much the coils were sanded during coil clean-up.

Table 7 - Minimum and Maximum Left/Right Thickness Values from Surface Plots

	SC1-01		**SC2-01**		**SC3-01**		**SC4-01**	
	Left	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
Minimum (mm)*	10.7576	-11.6393	12.5703	-13.0492	13.0344	-13.9000	24.2016	-25.0472
Maximum (mm)*	11.4600	-10.7792	13.0699	-12.5701	13.7187	-12.9238	24.9280	-24.3116

Table 8 - Minimum and Maximum Thickness Values from Surface Plots

	SC1-01	**SC2-01**	**SC3-01**	**SC4-01**
Maximum Thickness (mm)	22.6166	25.9020	27.1808	49.4949
Minimum Thickness (mm)	22.0333	25.3162	26.3554	48.7427

Additional plots were made in order to highlight in-tolerance regions and any potential out-of-tolerance regions. If any grid points were less than the minimum allowable thickness, they were plotted to highlight “thin” regions. Similarly, if any grid points were greater than the maximum allowable thickness, they were plotted; however, no such condition existed in any of the four coils. The out-of-tolerance plots are also presented in Appendix D and are only shown in a flattened view in order to improve overall clarity.

In order to validate the results output by the MATLAB code, the coils were laid on a flat table and probed with feeler gages; the feeler gages help locate and quantify the highs and lows of the coil's shape. As a general rule, the MATLAB data closely mimicked the actual coil condition in location and amplitude. Thus, with reasonably high confidence, the MATLAB data can be trusted to give a good overall geometric map for any given coil.

When observing the data presented in Appendix D, it is clear that each coil has its own unique shape and thickness distribution. Some general observations for each coil are summarized herein:

- SC1-01 There is a noticeable rise near the US end of the coil. This rising action creates a low-spot on the right side of the coil and a high-spot on the left side of the coil. The coil is fairly thin overall, with very few regions within tolerance.
- SC2-01 The coil's shape is somewhat pinched. The DS end is thinner and the upper end is thicker; this is clearly shown in the thickness plot. The surface profiles also mimic this phenomenon, as shown by the gradual sloping of the surface itself. In addition, this "pinching" causes much of the DS region to be out of tolerance.
- SC3-01 The coil has a somewhat "cupped" shape, which is fairly clear in the surface plots. This causes there to be a low-spot on the right side of the coil near the center. Similarly, there are high-spots on the left side of the coil near the US and DS ends. The thickness is fairly consistent throughout and much of the coil is within tolerance, with very few thin regions near the US end.
- SC4-01 Similar to SC3-01, there is a "cupped" shape to the coil, resulting in a high-spot on the left side of the coil near the center and low spots on the right side of the coil near the US and DS ends. The coil also has a very consistent thickness, with only a few scattered thin regions.

4.0 CONCLUSION

All four coils underwent various degrees of testing at ETI and JLab. A summary of the tests each coil underwent and the respective conclusions are summarized herein; this summary reflects only the testing completed at the time of this report.

- SC1-01
  - *Pressure Test* – Successfully passed the pressure test at both ETI and JLab.
  - *Helium Mass Spectrometer Leak Test* – Successfully passed the helium mass spectrometer leak test before and after testing at ETI.
  - *Resistance Test* – Successfully passed the resistance test at both ETI and JLab.
  - *Inductance Test* – Successfully passed the inductance test at both ETI and JLab.
  - *Hi-Pot Test* – Successfully passed the hi-pot test at both ETI and JLab.
  - *Powering Test* – Successfully passed the powering test at JLab without damage.

  - *Alignment and Flatness Test* – The coil has a raised profile near the US end and is very thin throughout much of the coil, often outside the drawing tolerance.
- SC2-01
  - *Pressure Test* – Successfully passed the pressure test at both ETI and JLab.
  - *Helium Mass Spectrometer Leak Test* – Successfully passed the helium mass spectrometer leak test before and after testing at ETI.
  - *Resistance Test* – Successfully passed the resistance test at both ETI and JLab.
  - *Inductance Test* – Successfully passed the inductance test at both ETI and JLab.
  - *Hi-Pot Test* – Successfully passed the hi-pot test at both ETI and JLab.
  - *Thermal Cycling Test* – There was no physical damage observed after testing at JLAB.
  - *Powering Test* – Successfully underwent the powering test at JLab without damage.
  - *Alignment and Flatness Test* – The coil has a “pinched” shape, which results in a gradual thinning of the coil near the DS end and some out-of-tolerance regions.
- SC3-01
  - *Pressure Test* – Successfully passed the pressure test at both ETI and JLab.
  - *Helium Mass Spectrometer Leak Test* – Successfully passed the helium mass spectrometer leak test before and after testing at ETI.
  - *Resistance Test* – Successfully passed the resistance test at both ETI and JLab.
  - *Inductance Test* – Successfully passed the inductance test at both ETI and JLab.
  - *Hi-Pot Test* – Successfully passed the hi-pot test at both ETI and JLab.
  - *Thermal Cycling Test* – Delamination appeared to have worsened as a result of the thermal cycling test at JLAB.
  - *Powering Test* – Successfully underwent the powering test at JLab without damage.
  - *Alignment and Flatness Test* – The coil has a “cupped” shape, but has fairly consistent thickness throughout, which results in very few out of tolerance regions.
- SC4-01
  - *Pressure Test* – Successfully passed the pressure test at both ETI and JLab.
  - *Helium Mass Spectrometer Leak Test* – Successfully passed the helium mass spectrometer leak test before and after testing at ETI.
  - *Resistance Test* – Successfully passed the resistance test at both ETI and JLab.
  - *Inductance Test* – Successfully passed the inductance test at both ETI and JLab.
  - *Hi-Pot Test* – Successfully passed the hi-pot test at both ETI and JLab.
  - *Powering Test* – Successfully passed the powering test at JLab without damage.

  - *Alignment and Flatness Test* – The coil has a "cupped" shape, but has a fairly consistent thickness throughout, which results in very few out of tolerance regions.

In addition, during the testing and inspection of the coils, there were several additional highlights that are important to the coil's overall build integrity:

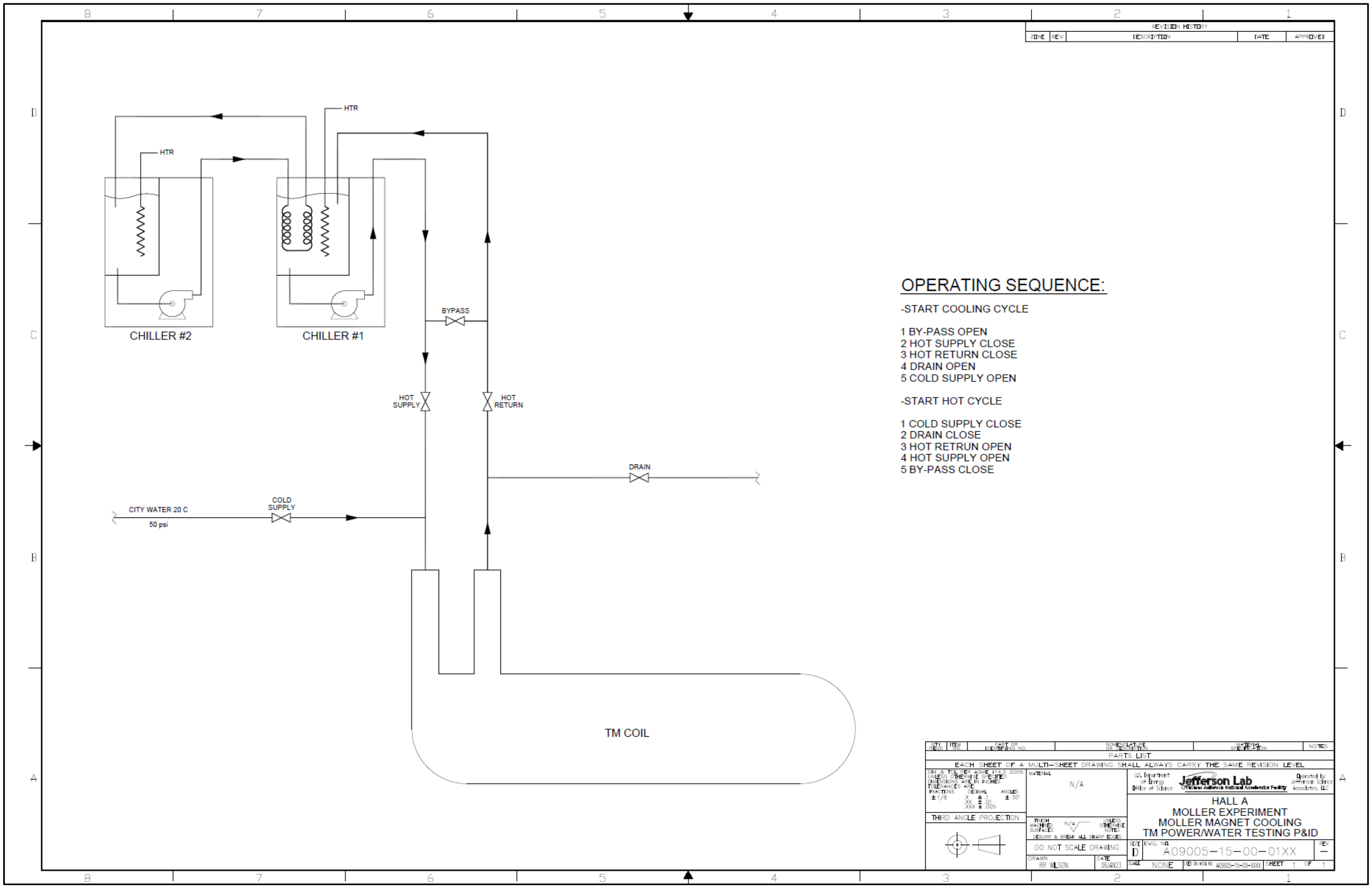
- Bumps up to 0.5 mm in way of the "push-out regions" are acceptable and can be left on the coil. In order to achieve this, it is better to have these regions located *flush or below* the mold surface rather than above it.
- Fiberglass tape does not impact operation, but it does impact the amount of resin that can flow into a given area. When taping, being mindful of overlap can improve consistency and improve the flow and setting-in of resin, potentially improving the consistency of the coil's thickness. Also, as observed in SC4-01, "pinched" tape may result in damage to the resin surface when the coil is removed from the mold. The coils should be taped with caution in order to ensure minimal overlap and to prevent pinching.
- Adding a beveled edge to G10 blocks, particularly in way of the conductor-G10 interfaces, can improve the flow and setting-in of resin in these regions. Ultimately, such a feature reduces sharp resin transitions and greatly reduces the amount of delamination observed along the conductor-G10 interface. All of these drawings have been updated for the production run to include the SC2-01 level of bevel.
- In the future, SC4-01 should have threaded insert permanently installed within the coil's G10 body. This will improve the functionality of the lifting points and improve the long-term integrity of the internal G10 threads.

CONTRIBUTORS

The following individuals contributed towards the completion of this report: Calvin Barnes, Mike Beck, Kris Cleveland, Brian Eng, Probir Ghoshal, Sandesh Gopinath, Chris Gould, Kaiyi Hall, Dave Kashy, Joe Lamont, Joe Meyers, Rachel Reese, Eric Sun, Randall Wilson and Daniel Young.

APPENDIX A

SC2-01 Thermal Cycling Test Results



OPERATING SEQUENCE:

-START COOLING CYCLE

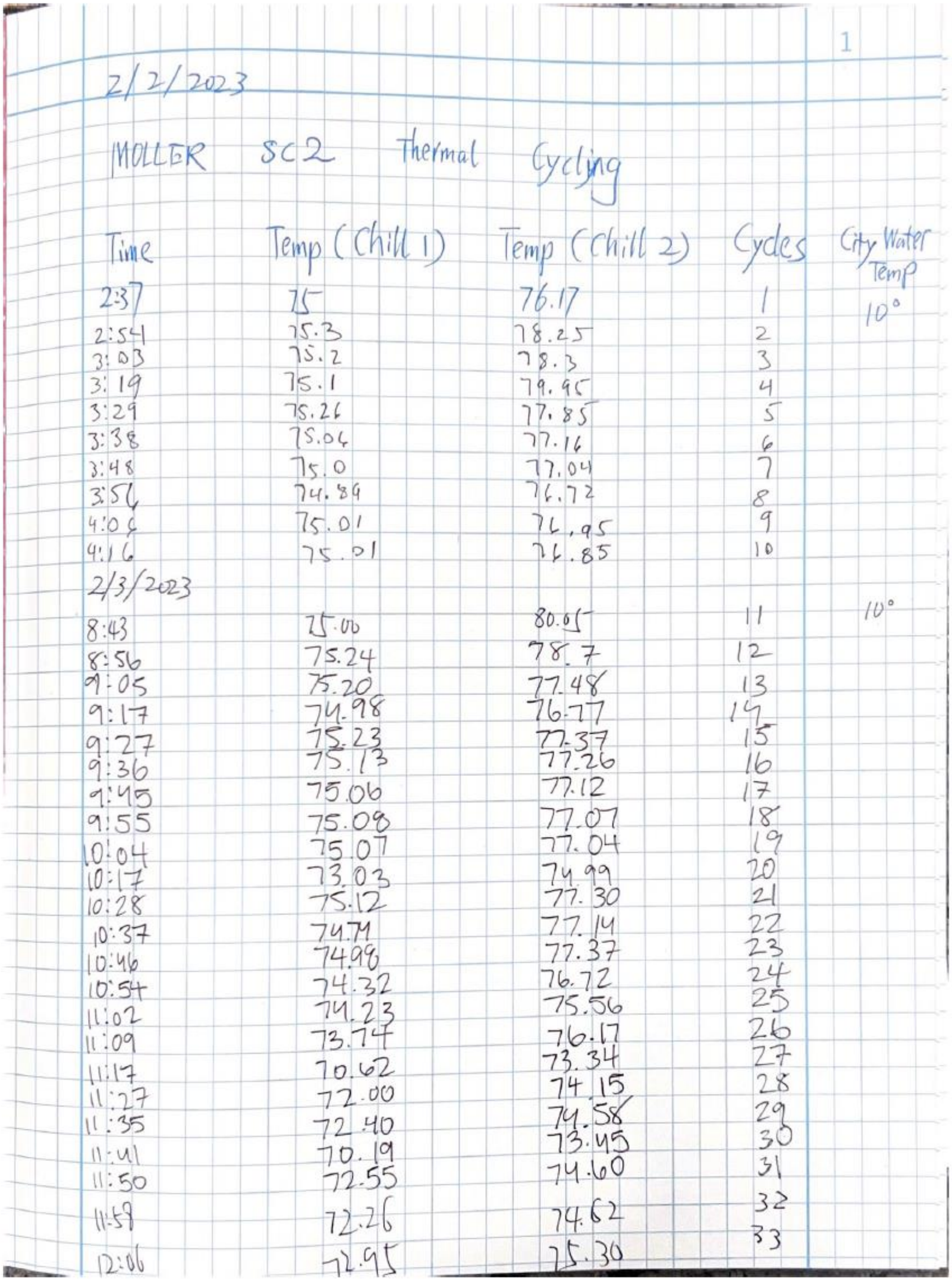
1 BY-PASS OPEN
2 HOT SUPPLY CLOSE
3 HOT RETURN CLOSE
4 DRAIN OPEN
5 COLD SUPPLY OPEN

-START HOT CYCLE

1 COLD SUPPLY CLOSE
2 DRAIN CLOSE
3 HOT RETRUN OPEN
4 HOT SUPPLY OPEN
5 BY-PASS CLOSE

Figure 49 - Test Setup for Thermal Cycle Testing of SC2-01 and SC3-01 and Test Operating Sequence (Informal Sketch)

RAW DATA

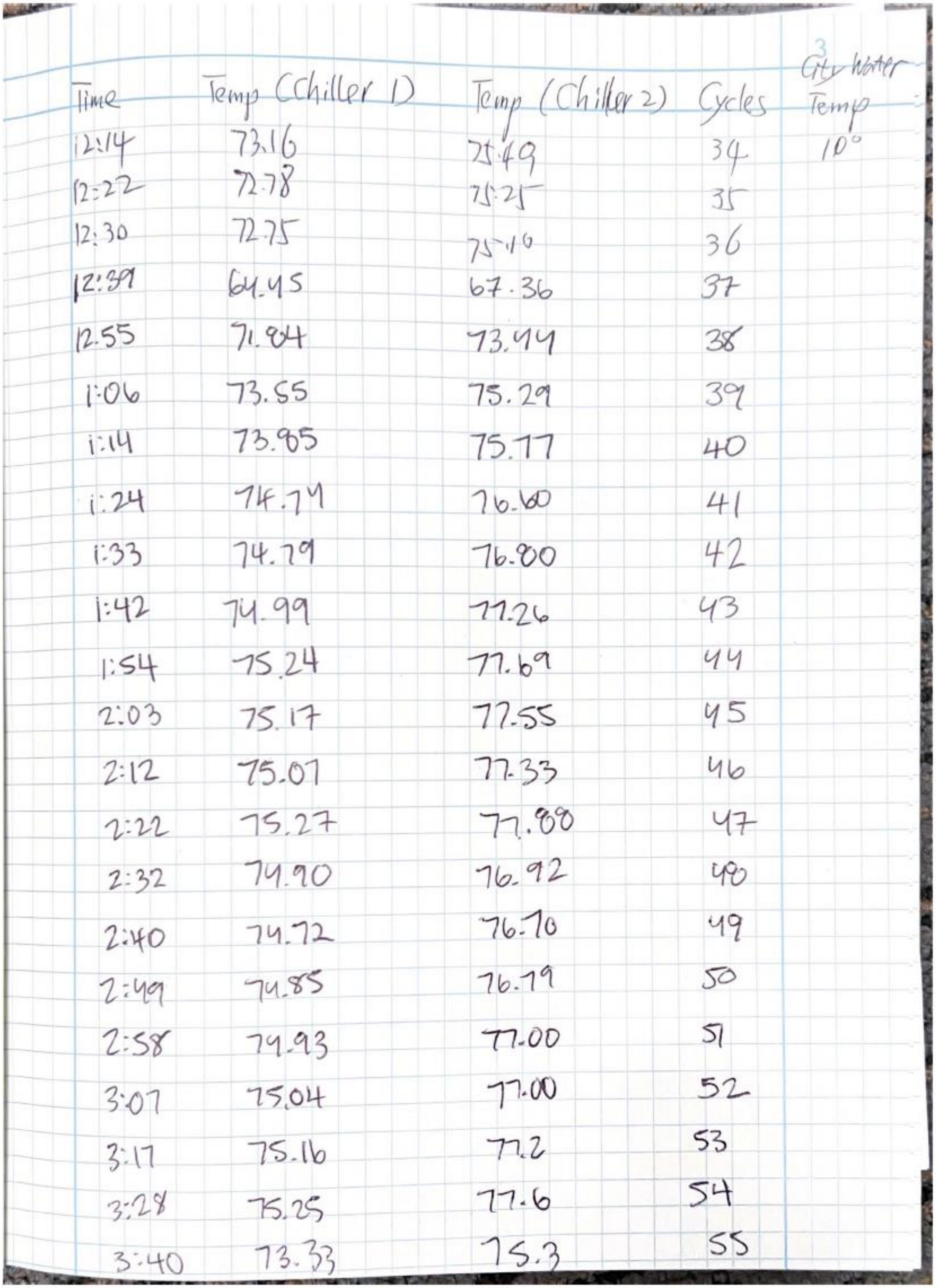


1

2/2/2023

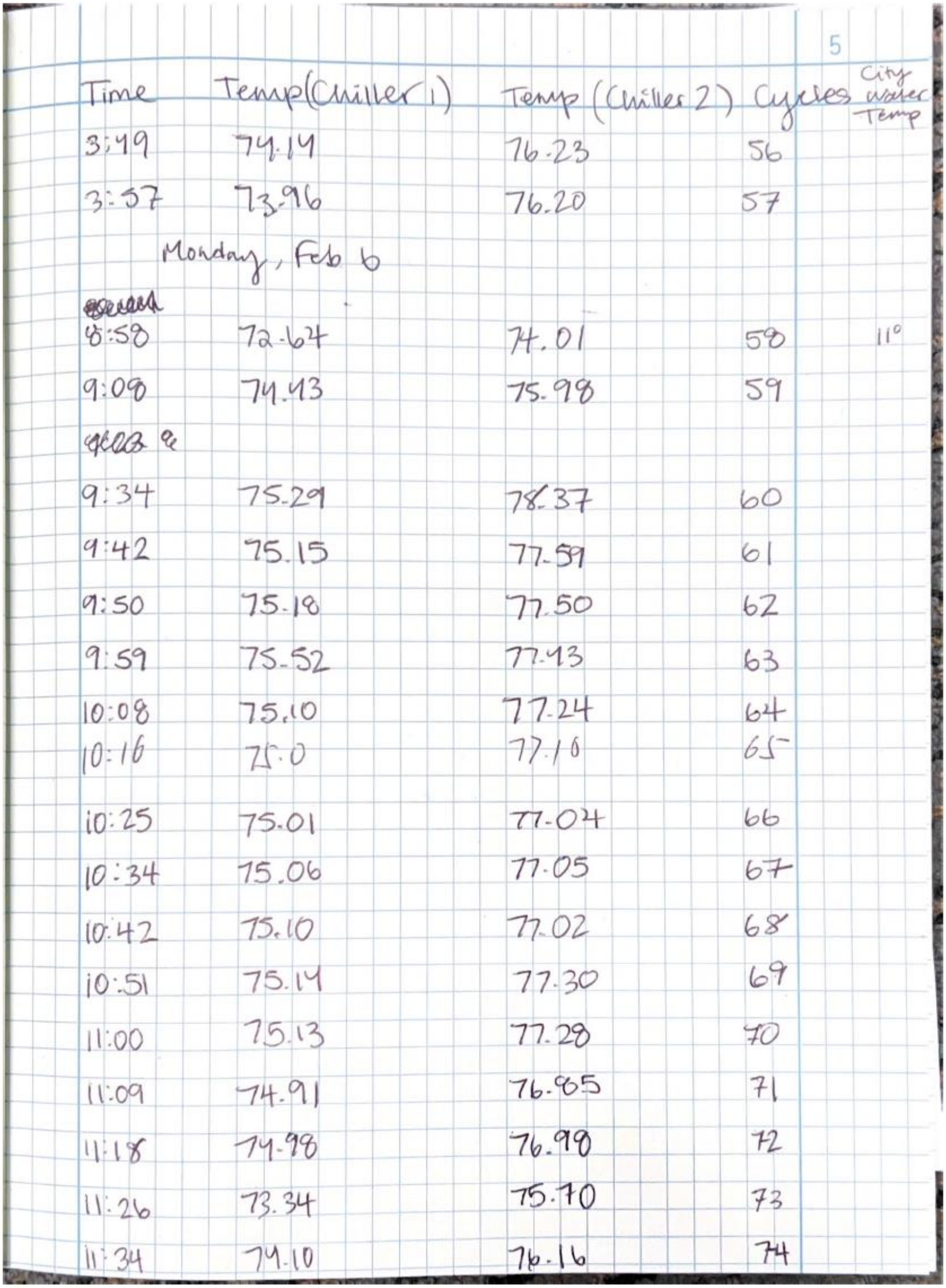
MOLLER SC2 Thermal Cycling

Time	Temp (Chill 1)	Temp (Chill 2)	Cycles	City Water Temp
2:37	75	76.17	1	10°
2:54	75.3	78.25	2	
3:03	75.2	78.3	3	
3:19	75.1	79.95	4	
3:29	75.26	77.85	5	
3:38	75.06	77.16	6	
3:48	75.0	77.04	7	
3:56	74.89	76.72	8	
4:06	75.01	76.95	9	
4:16	75.01	76.85	10	
2/3/2023				
8:43	75.00	80.05	11	10°
8:56	75.24	78.7	12	
9:05	75.20	77.48	13	
9:17	74.98	76.77	14	
9:27	75.23	77.37	15	
9:36	75.13	77.26	16	
9:45	75.06	77.12	17	
9:55	75.08	77.07	18	
10:04	75.07	77.04	19	
10:17	73.03	74.99	20	
10:28	75.12	77.30	21	
10:37	74.74	77.14	22	
10:46	74.98	77.37	23	
10:54	74.32	76.72	24	
11:02	74.23	75.56	25	
11:09	73.74	76.17	26	
11:17	70.62	73.34	27	
11:27	72.00	74.15	28	
11:35	72.40	74.58	29	
11:41	70.19	73.45	30	
11:50	72.55	74.60	31	
11:59	72.26	74.62	32	
12:06	72.95	75.30	33	



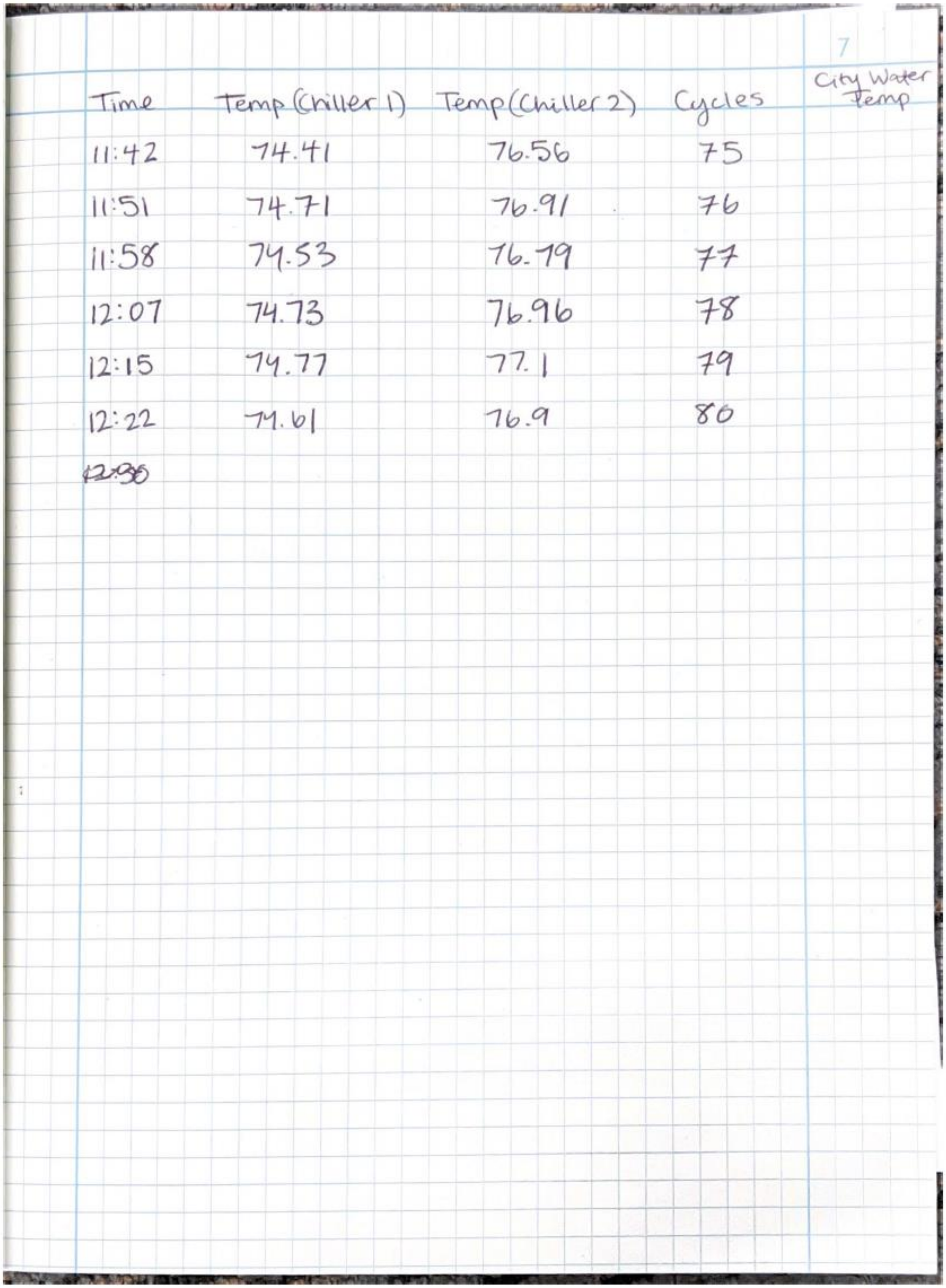
3

Time	Temp (Chiller 1)	Temp (Chiller 2)	Cycles	City Water Temp
12:14	73.16	75.49	34	10°
12:22	72.78	75.25	35	
12:30	72.75	75.16	36	
12:39	64.45	67.36	37	
12.55	71.84	73.44	38	
1:06	73.55	75.29	39	
1:14	73.85	75.77	40	
1:24	74.74	76.60	41	
1:33	74.79	76.80	42	
1:42	74.99	77.26	43	
1:54	75.24	77.69	44	
2:03	75.17	77.55	45	
2:12	75.07	77.33	46	
2:22	75.27	77.88	47	
2:32	74.90	76.92	48	
2:40	74.72	76.70	49	
2:49	74.85	76.79	50	
2:58	74.93	77.00	51	
3:07	75.04	77.00	52	
3:17	75.16	77.2	53	
3:28	75.25	77.6	54	
3:40	73.33	75.3	55	



5

Time	Temp(Chiller 1)	Temp (Chiller 2)	Cycles	City water Temp
3:49	74.14	76.23	56	
3:57	73.96	76.20	57	
Monday, Feb 6				
8:58	72.64	74.01	58	11°
9:09	74.43	75.98	59	
9:34	75.29	78.37	60	
9:42	75.15	77.59	61	
9:50	75.18	77.50	62	
9:59	75.52	77.43	63	
10:08	75.10	77.24	64	
10:16	75.0	77.10	65	
10:25	75.01	77.04	66	
10:34	75.06	77.05	67	
10:42	75.10	77.02	68	
10:51	75.14	77.30	69	
11:00	75.13	77.28	70	
11:09	74.91	76.85	71	
11:18	74.98	76.98	72	
11:26	73.34	75.70	73	
11:34	74.10	76.16	74	



7

Time	Temp (Chiller 1)	Temp (Chiller 2)	Cycles	City Water Temp
11:42	74.41	76.56	75	
11:51	74.71	76.91	76	
11:58	74.53	76.79	77	
12:07	74.73	76.96	78	
12:15	74.77	77.1	79	
12:22	74.61	76.9	80	
12:30				

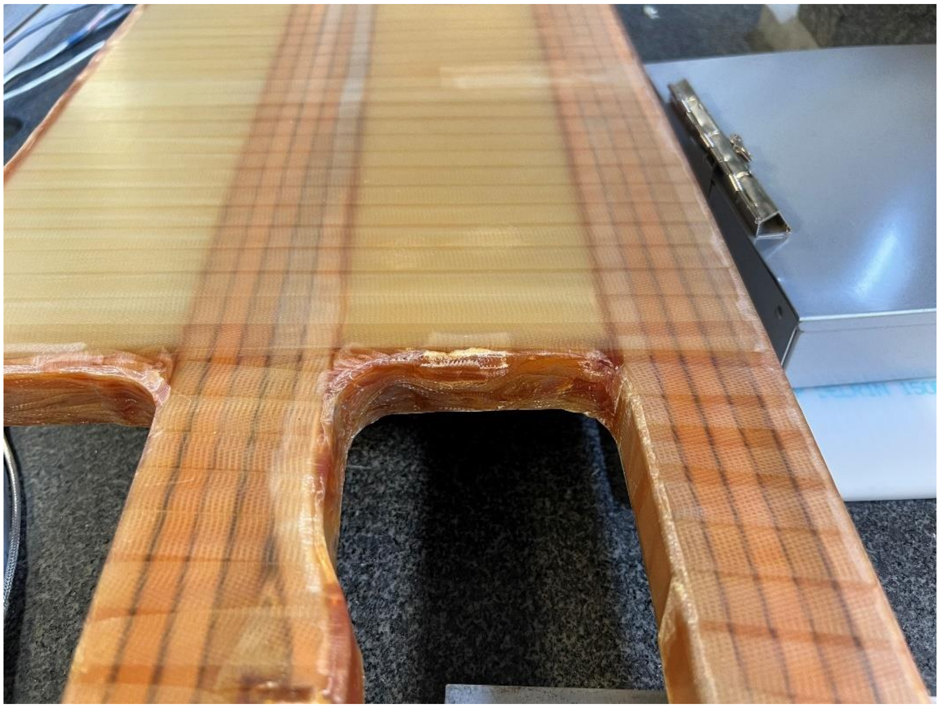


Figure 50 – Lead Side of SC2-01 at Cycle 0 (Start of Testing)

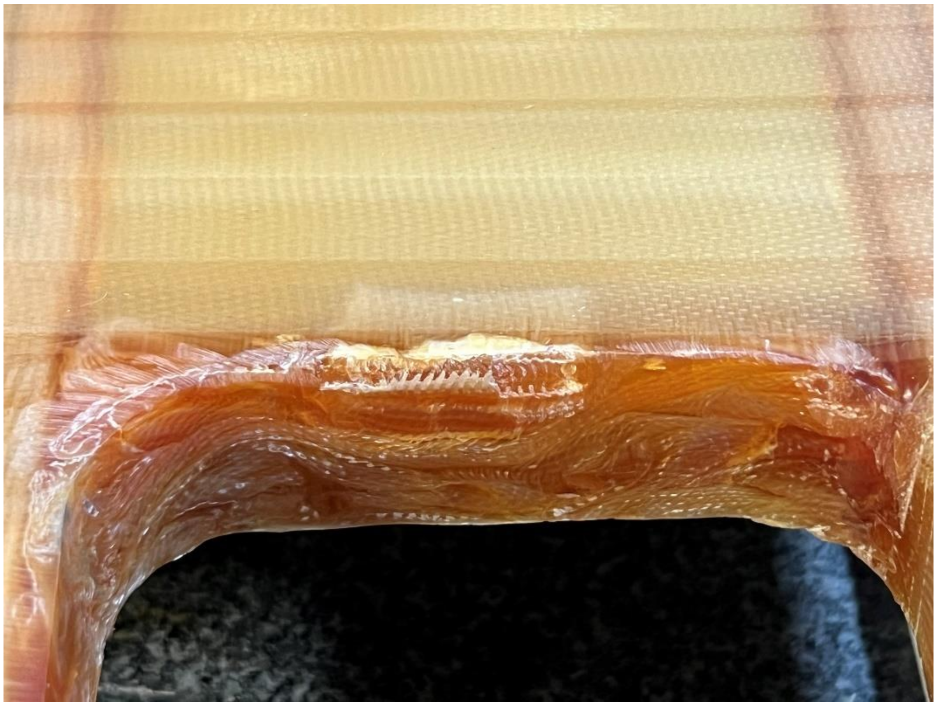


Figure 51 - Enhanced View of the Lead Side SC2-01 at Cycle 0 (Start of Testing)

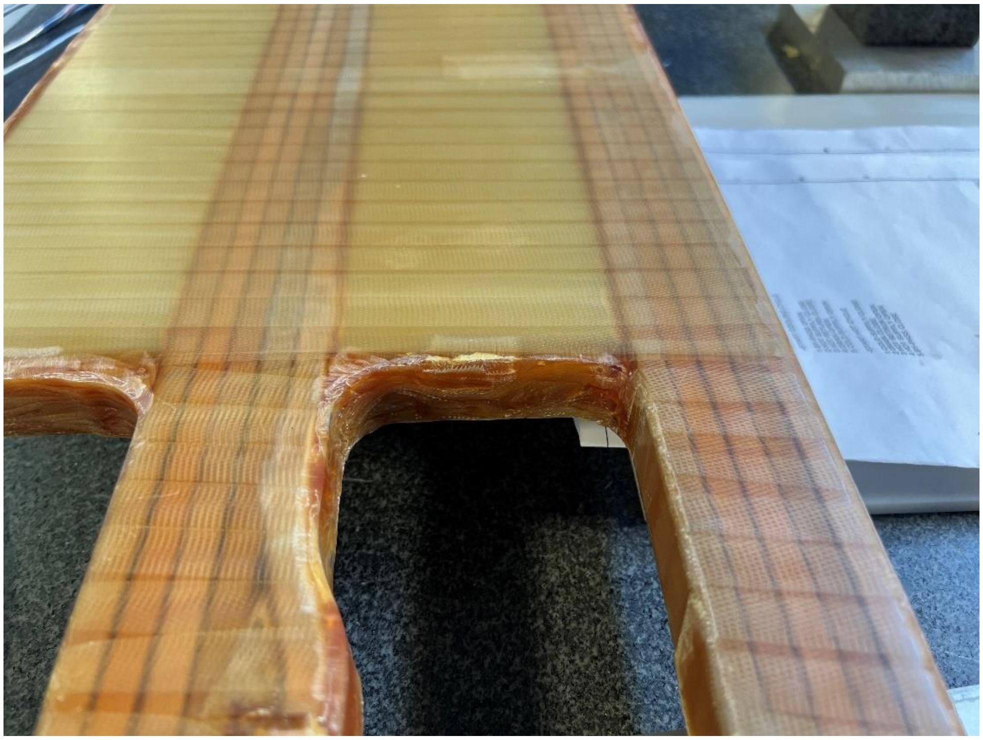


Figure 52 - Lead Side of SC2-01 at Cycle 80 (End of Testing)

Figure 53 - Enhanced View of the Lead Side SC2-01 at Cycle 80 (End of Testing)

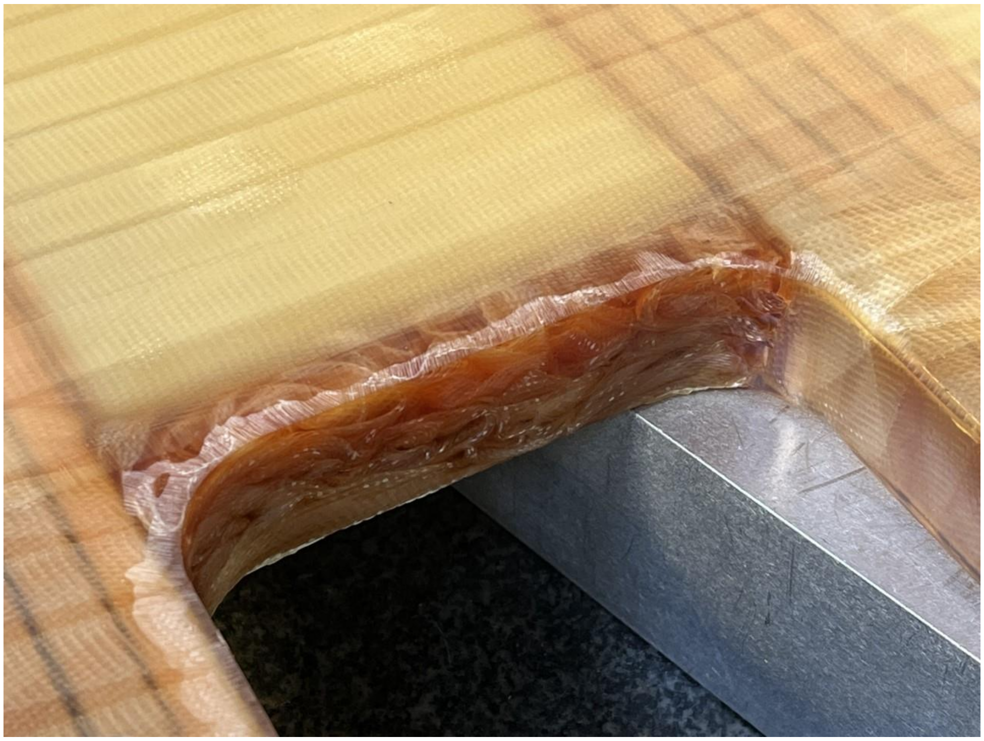


Figure 54 - Non-Lead Side of SC2-01 at Cycle 0 (Start of Testing)

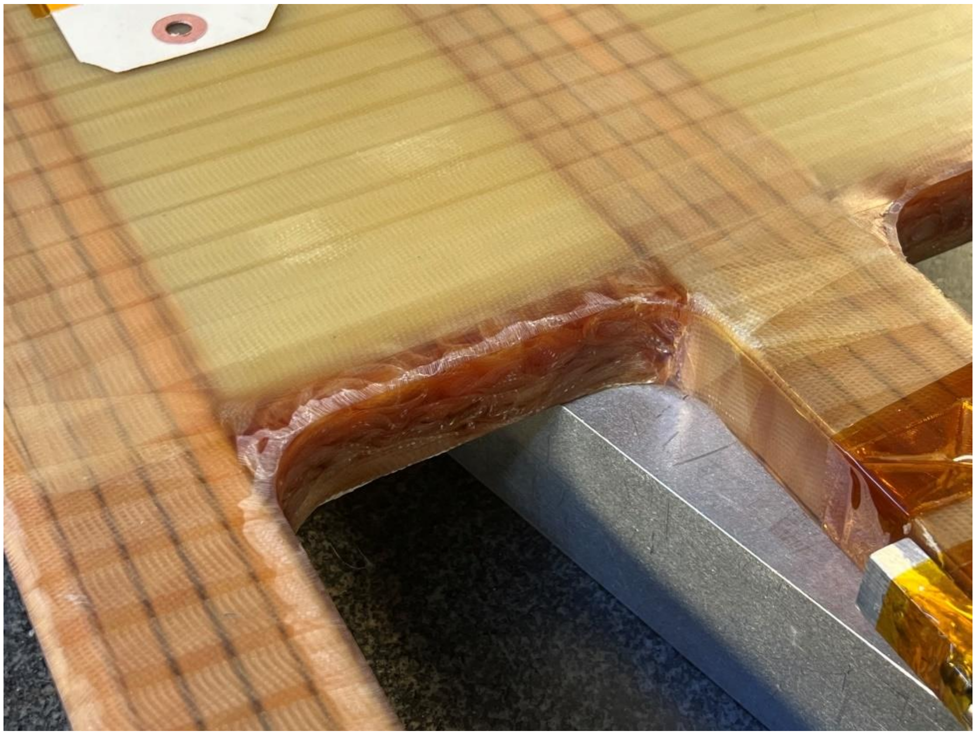


Figure 55 - Non-Lead Side of SC2-01 at Cycle 80 (End of Testing)

Figure 56 - SC2-01 After Thermal Cycling Testing on February 20, 2022

APPENDIX B

SC3-01 Thermal Cycling Test Results

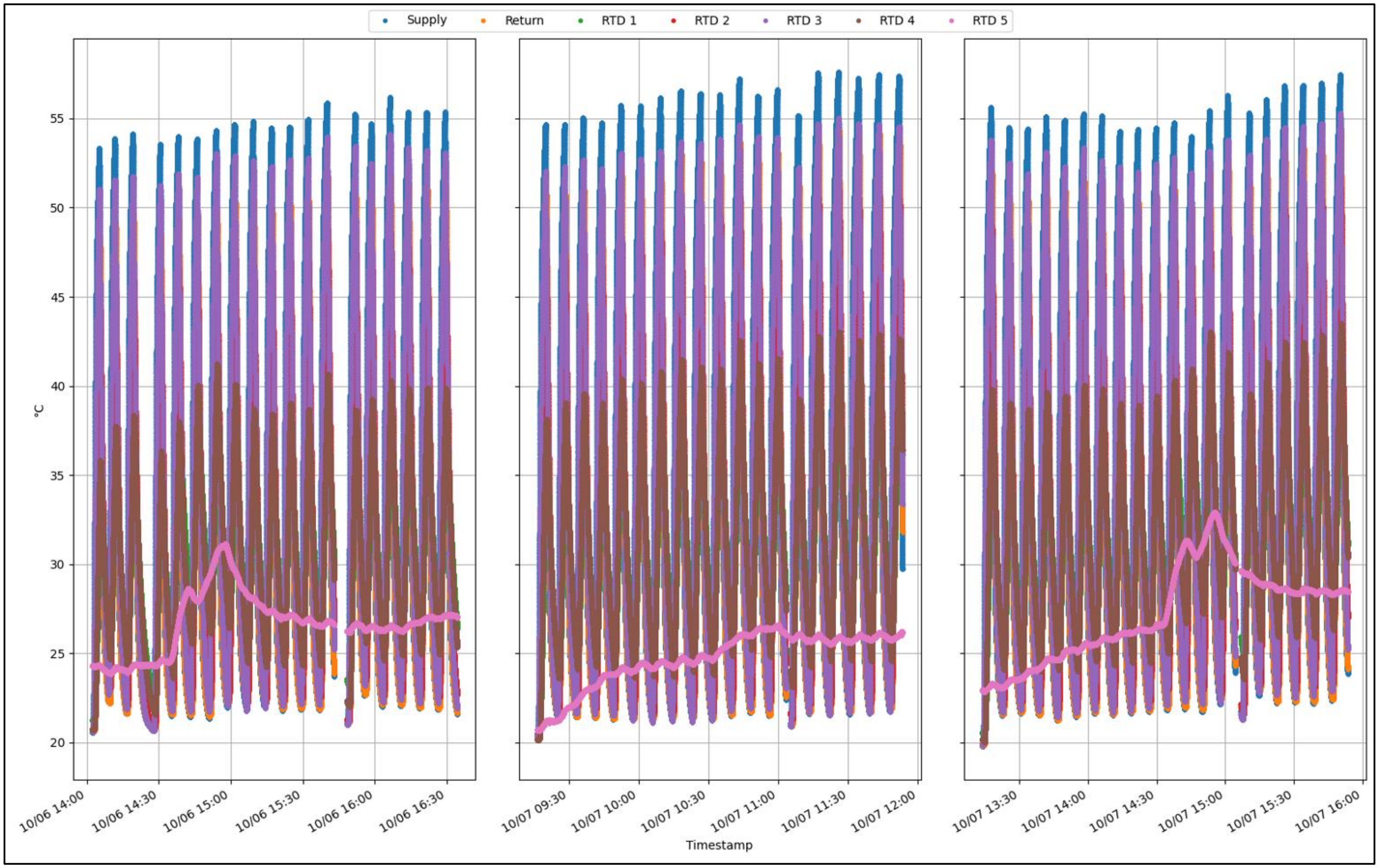


Figure 57 - RTD Data Plot, Temperature (°C) vs. Time

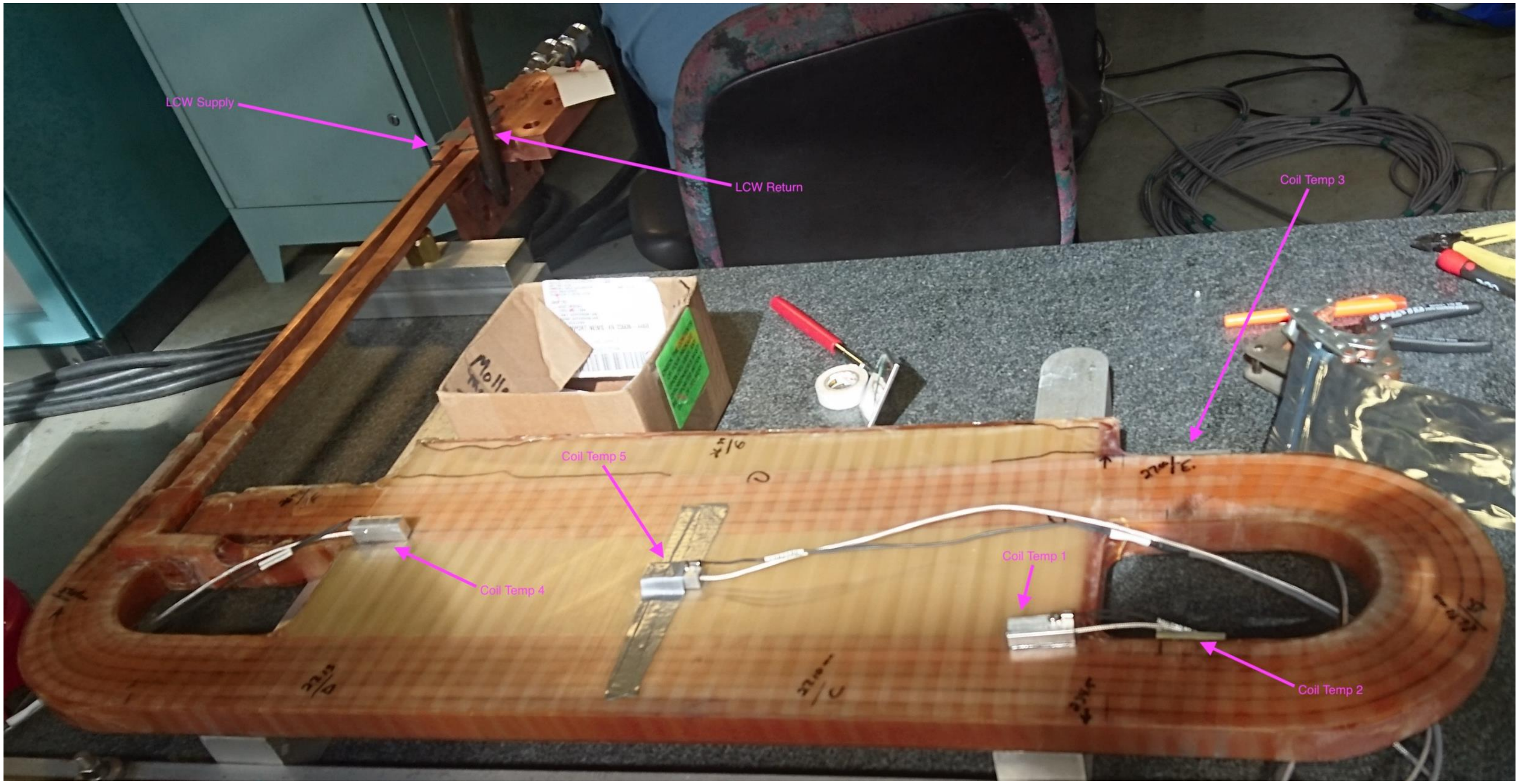


Figure 58 - RTD Sensor Locations on SC3-01

Figure 59 - SC3-01 Out of the Model on August 9, 2022

Figure 60 - SC3-01 Out of the Mold on August 17, 2022

Figure 61 - SC3-01 Before Thermal Cycling on September 5, 2022

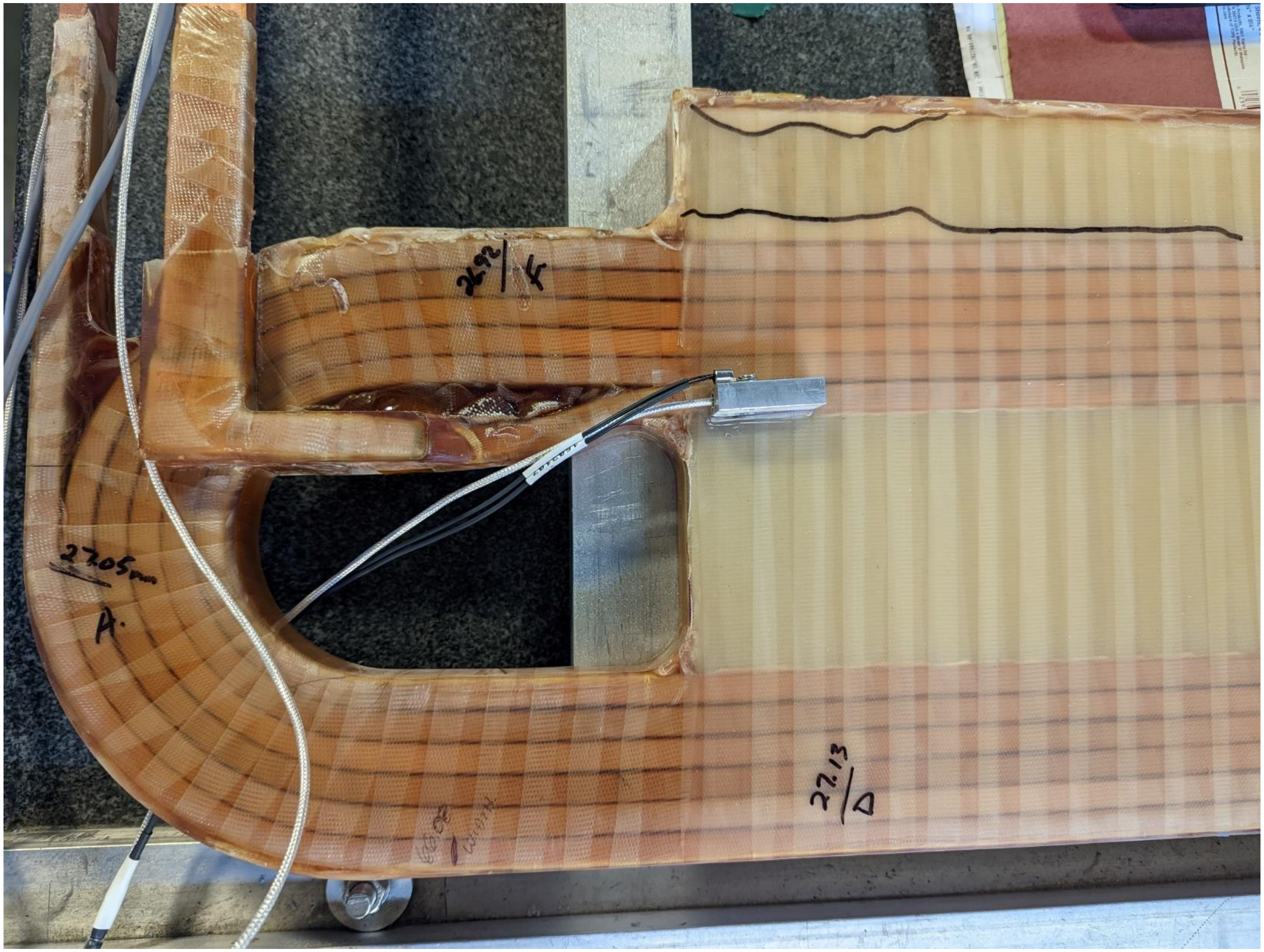


Figure 62 - SC3-01 Before Thermal Cycling on September 13, 2022

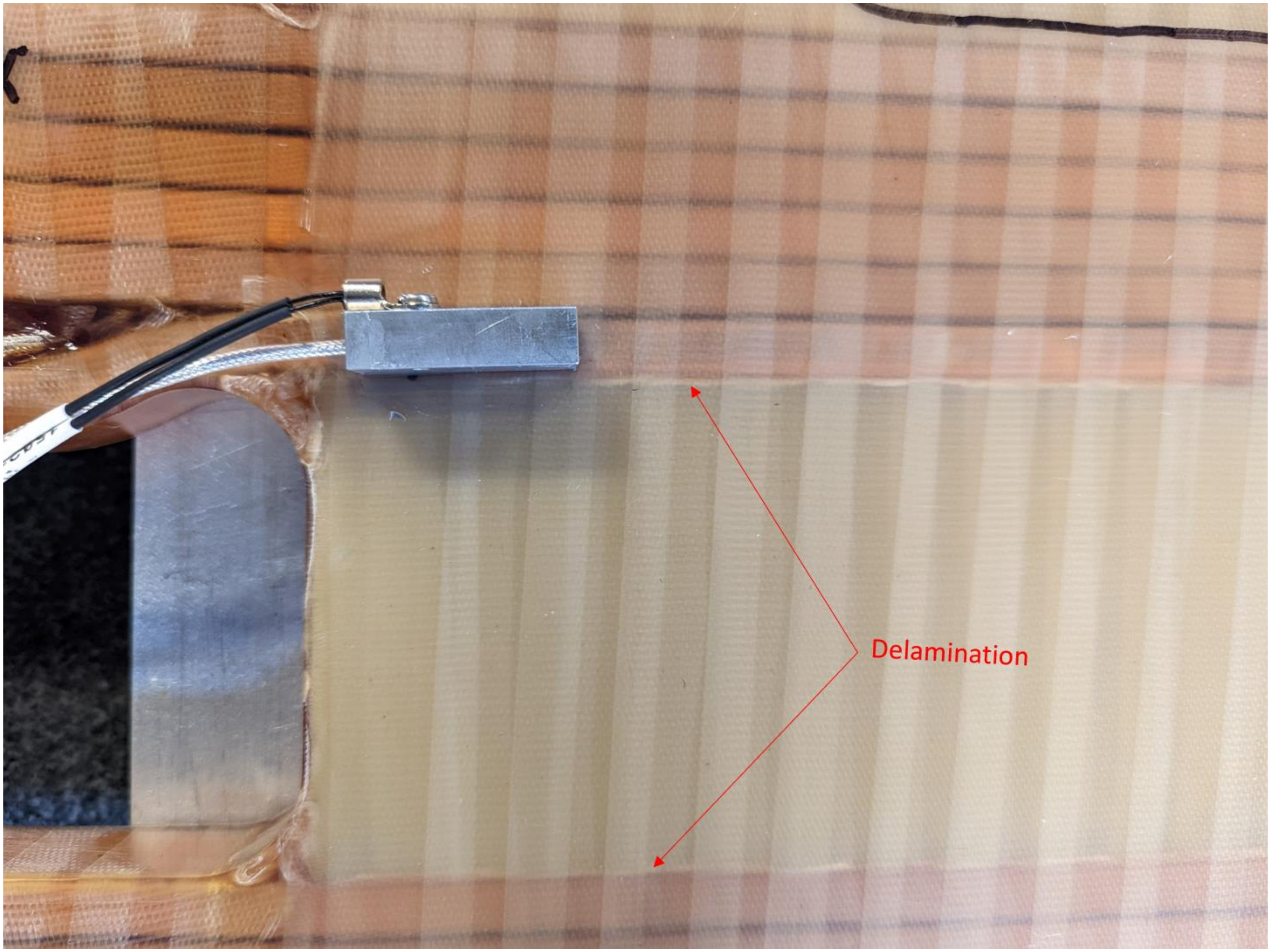


Figure 63 - SC3-01 Before Thermal Cycling on September 13, 2022

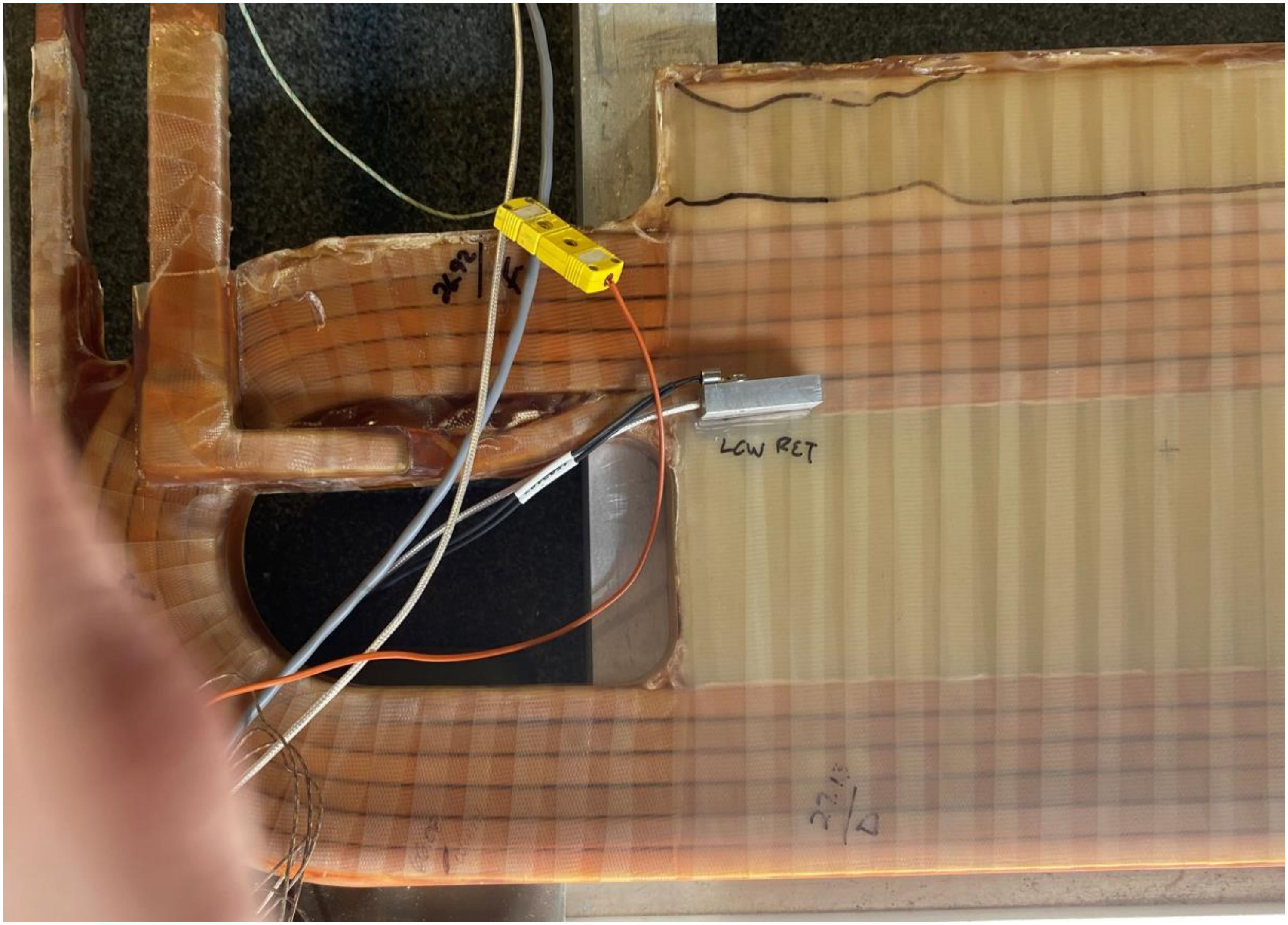
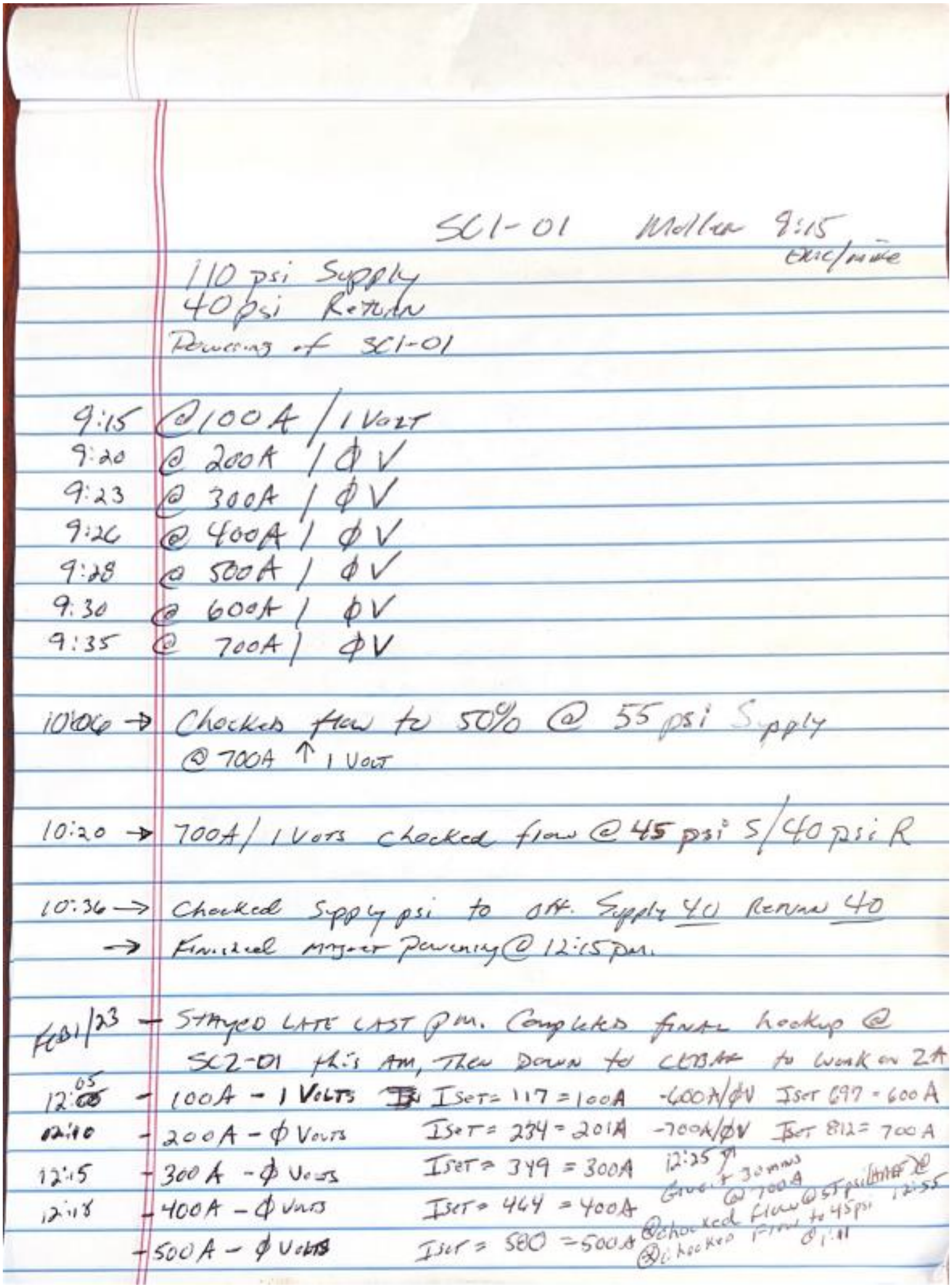


Figure 64 - SC3-01 After Thermal Cycling on October 14, 2022

Figure 65 - SC3-01 on February 20, 2023

APPENDIX C

Powering Test Data for SC1-01, SC2-01, SC3-01 and SC4-01



SC1-01 Moller 9:15
Eric/Mike

110 psi Supply
40 psi Return
Powering of SC1-01

9:15 @100A / 1 Volt
9:20 @ 200A / Φ V
9:23 @ 300A / Φ V
9:26 @ 400A / Φ V
9:28 @ 500A / Φ V
9:30 @ 600A / Φ V
9:35 @ 700A / Φ V

10:06 → Chocked flow to 50% @ 55 psi Supply
@ 700A ↑ 1 Volt

10:20 → 700A / 1 Volts chocked flow @ 45 psi S / 40 psi R

10:36 → Chocked Supply psi to off. Supply 40 Return 40
→ Finished magnet powering @ 12:15 pm.

FEB1/23 – STAYED LATE LAST pm. Completed final hookup @ SC2-01 this AM, Then Down to CEBAF to work on 2A

12:05 – 100A – 1 VOLTS ISET = 117 = 100A –600A/ΦV ISET 697 = 600 A
12:10 – 200A – Φ Volts ISET = 234 = 201A –700A/ΦV ISET 812 = 700 A
12:15 – 300 A – Φ Volts ISET = 349 = 300A 12:25 pm
12:18 – 400A – Φ Volts ISET = 464 = 400A
– 500A – Φ Volts ISET = 580 = 500A

Good for 30 mins @ 700A
① chocked flow @ 55 psi 12:55
② chocked flow to 45 psi @ 1:11

Figure 66 - Powering Test Data for SC1-01 and SC2-01

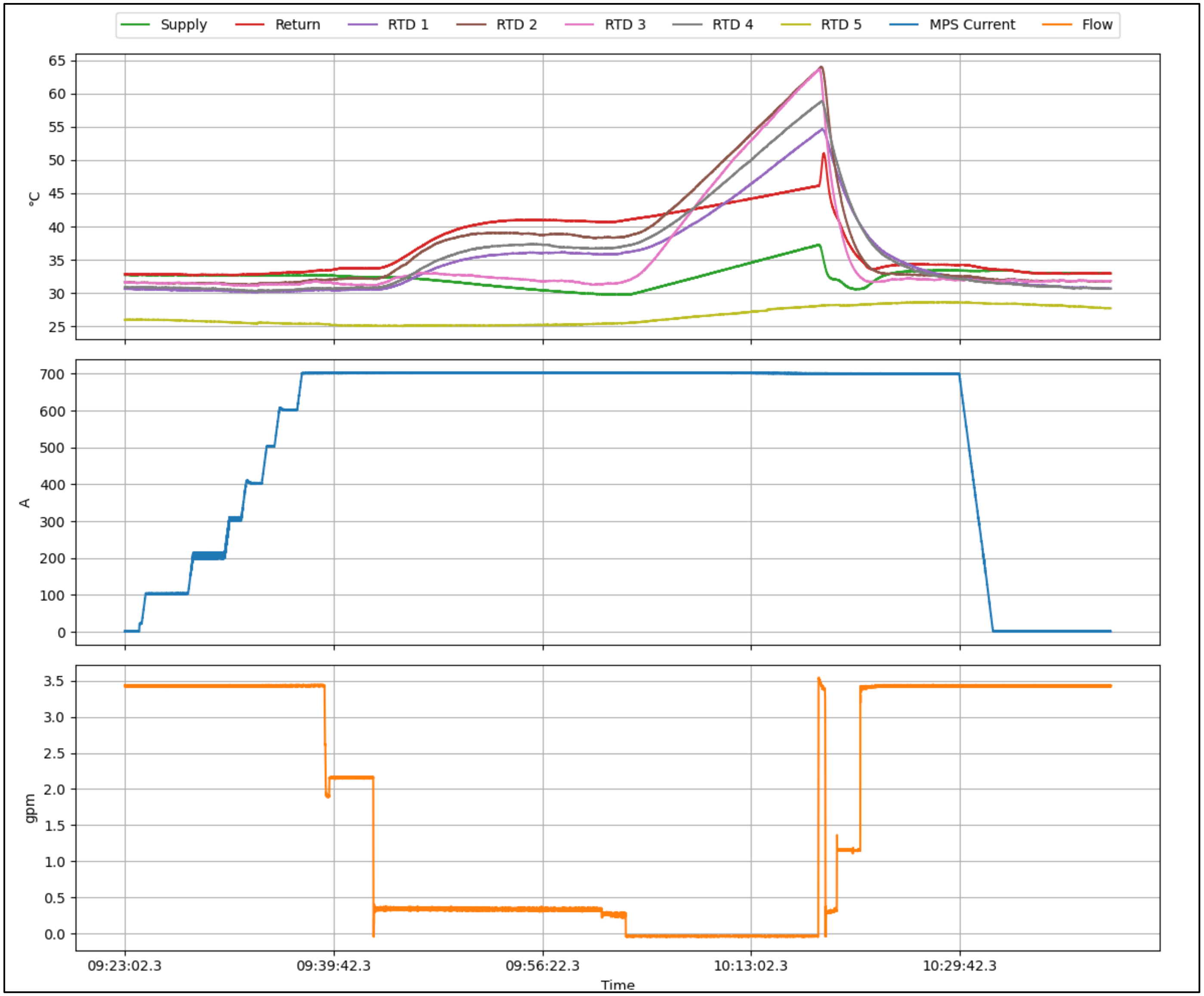


Figure 67 - Powering Test Data for SC3-01

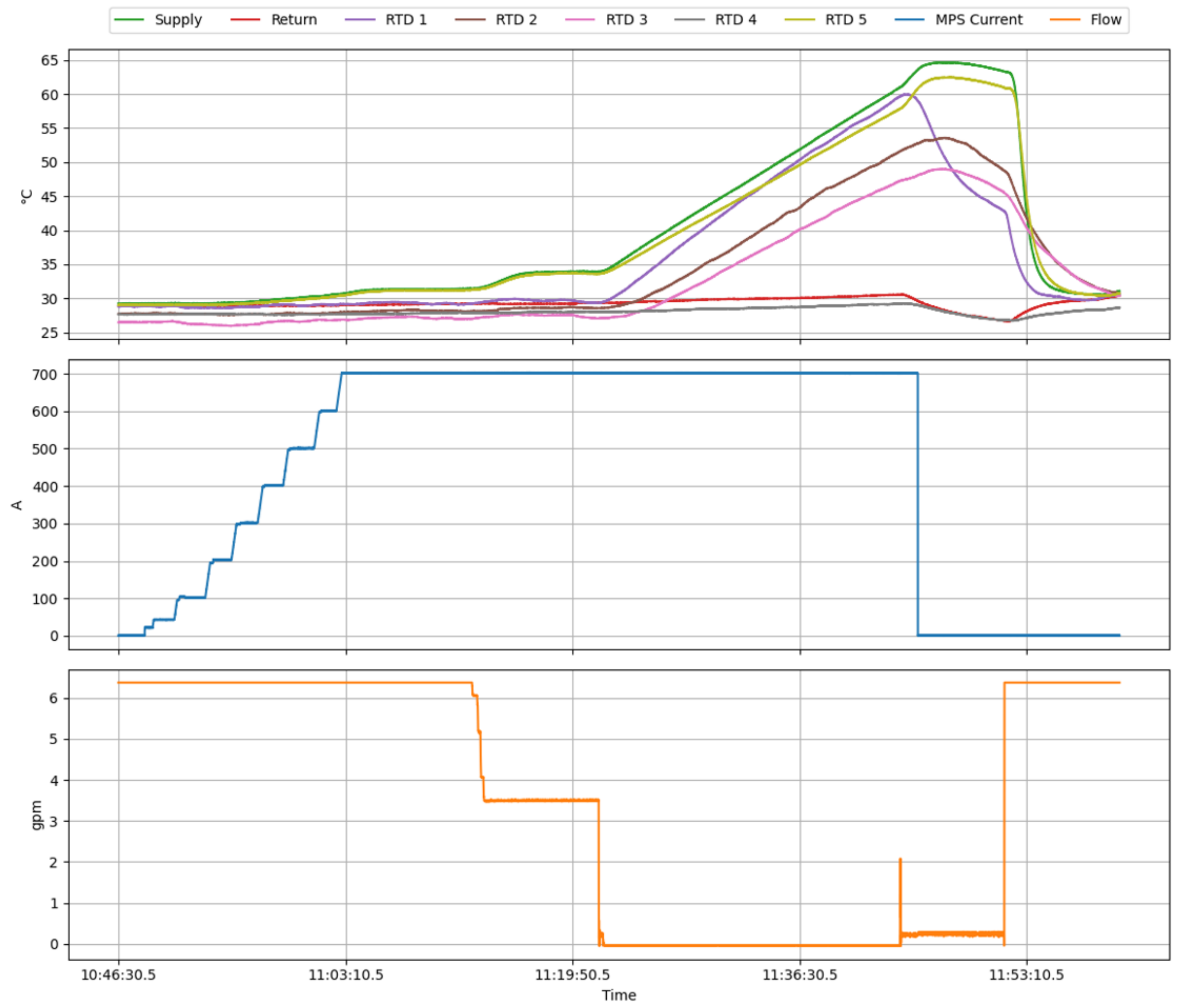


Figure 68 - Powering Test Data for SC4-01

APPENDIX D

Alignment and Flatness Test Data for SC1-01, SC2-01, SC3-01 and SC4-01

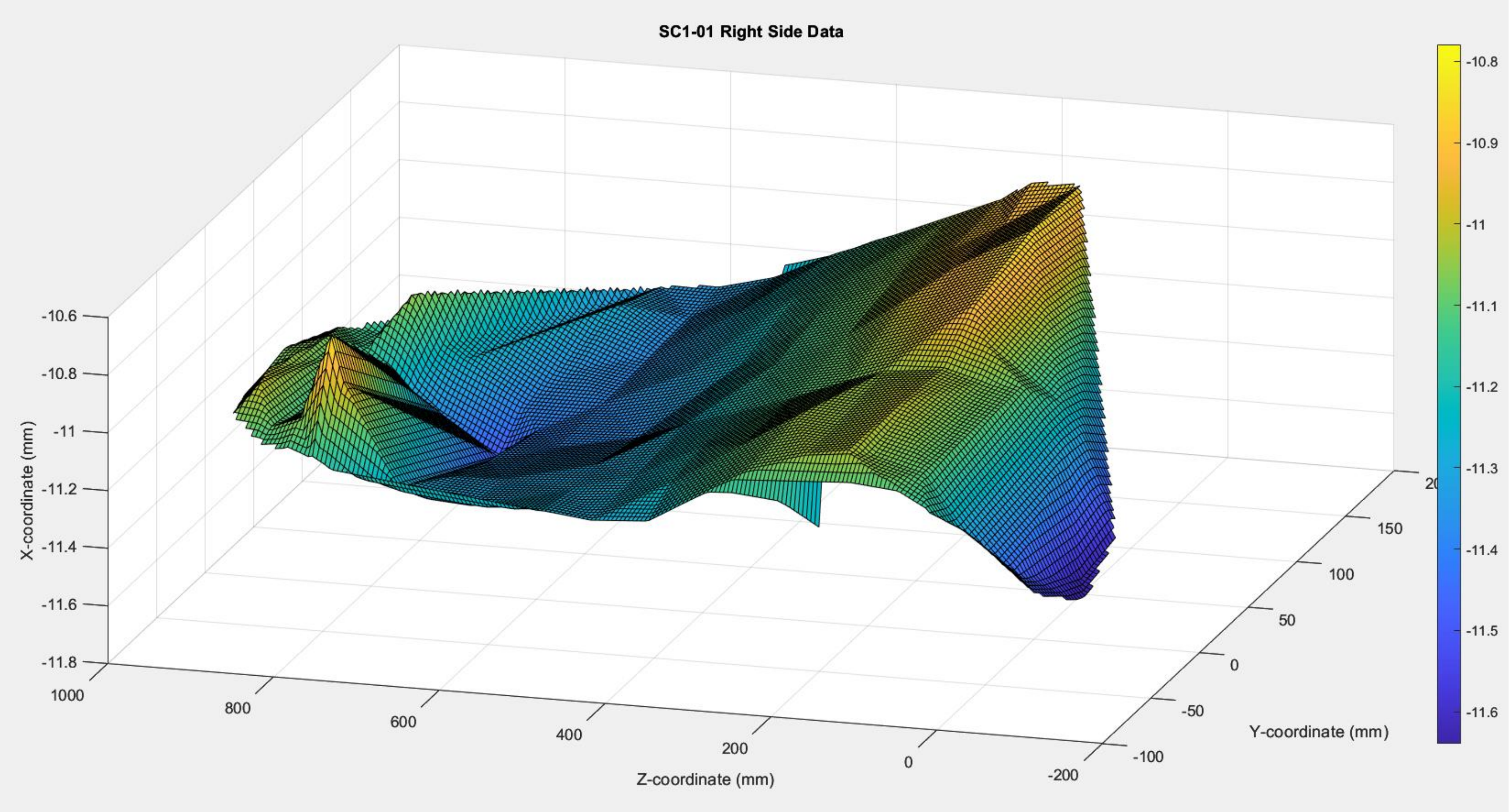


Figure 69 - SC1-01 Right Side Plot, Isometric

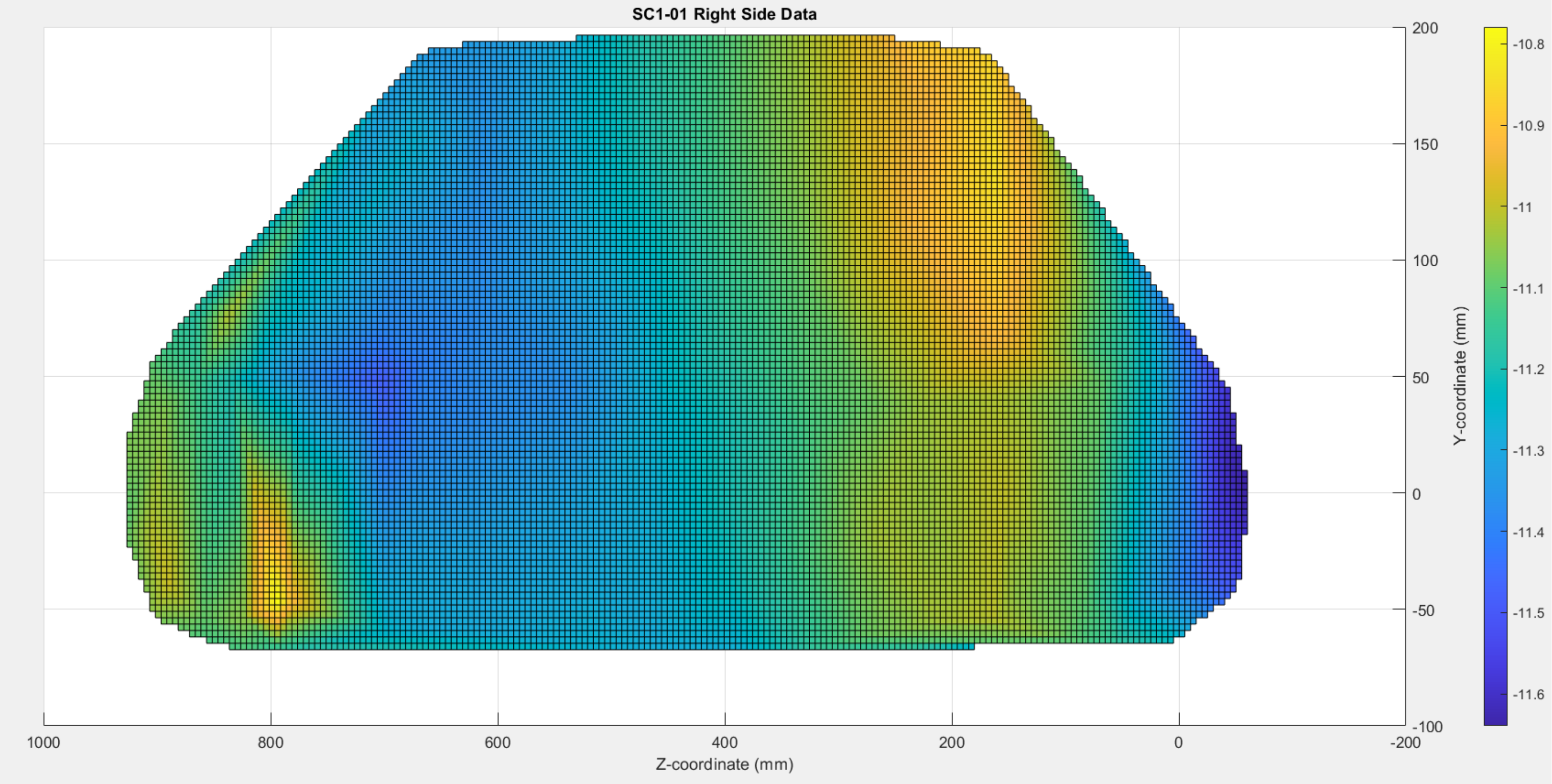


Figure 70 - SC1-01 Right Side Plot, Flattened

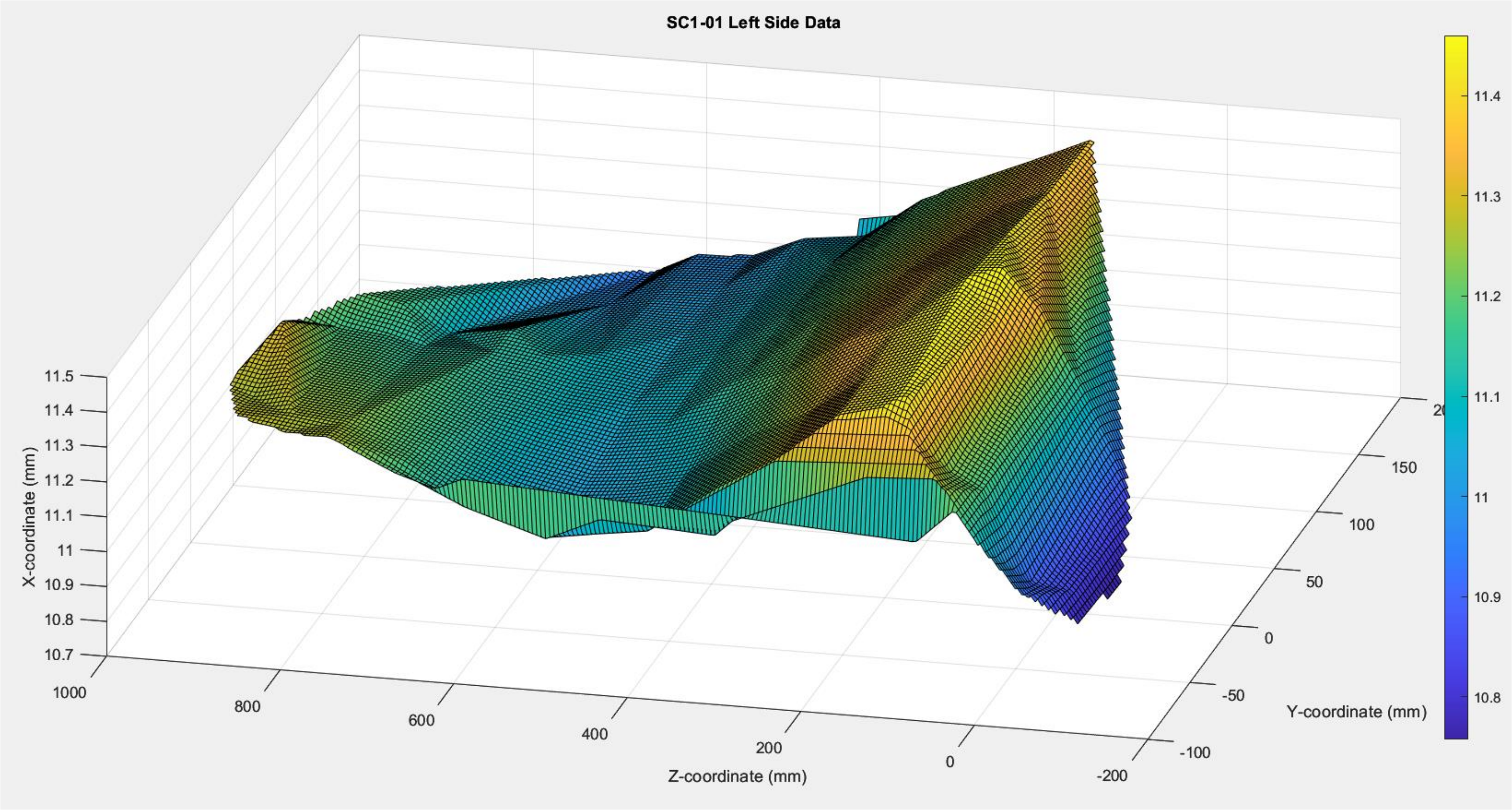


Figure 71 - SC1-01 Left Side Plot, Isometric

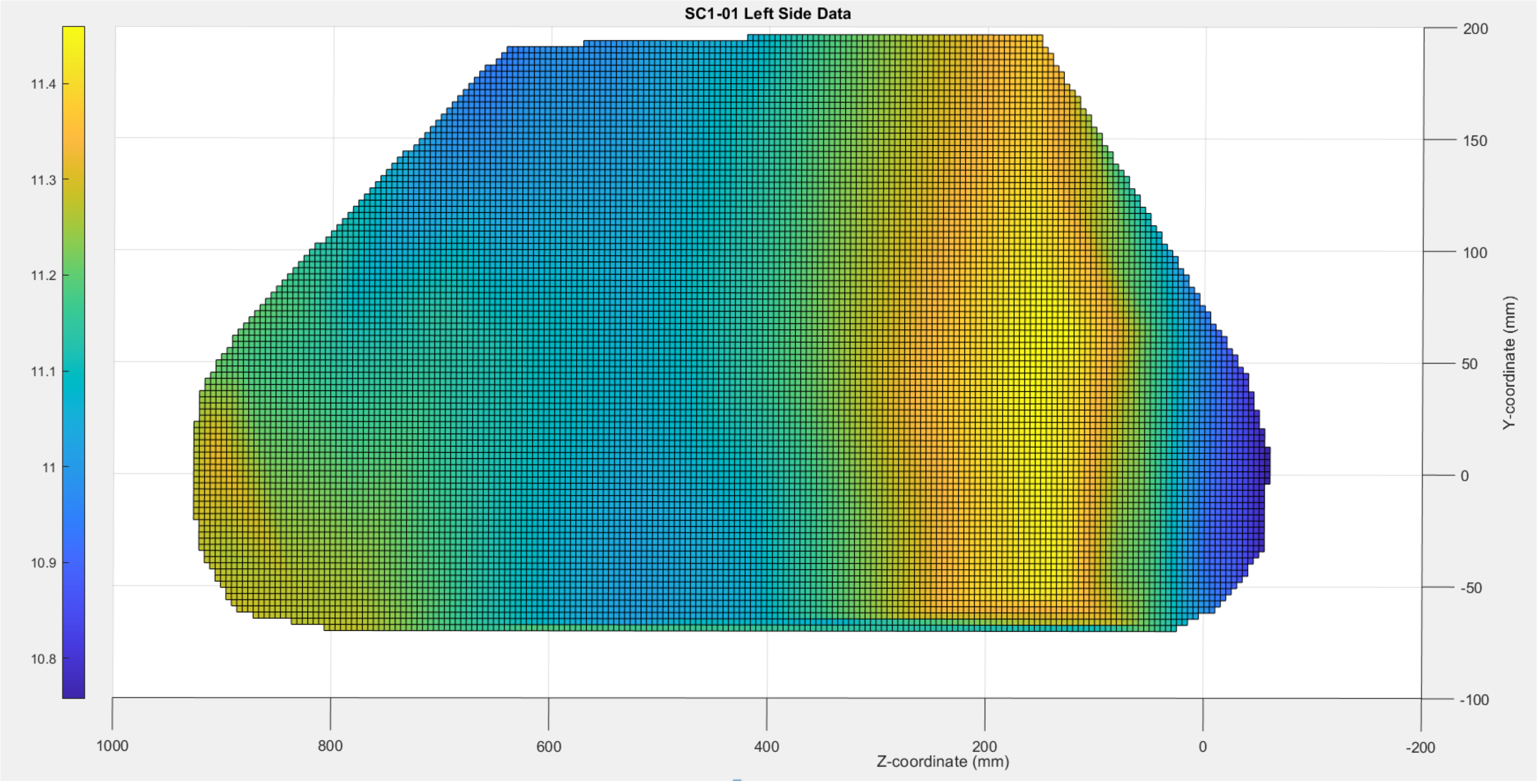


Figure 72 - SC1-01 Left Side Plot, Flattened

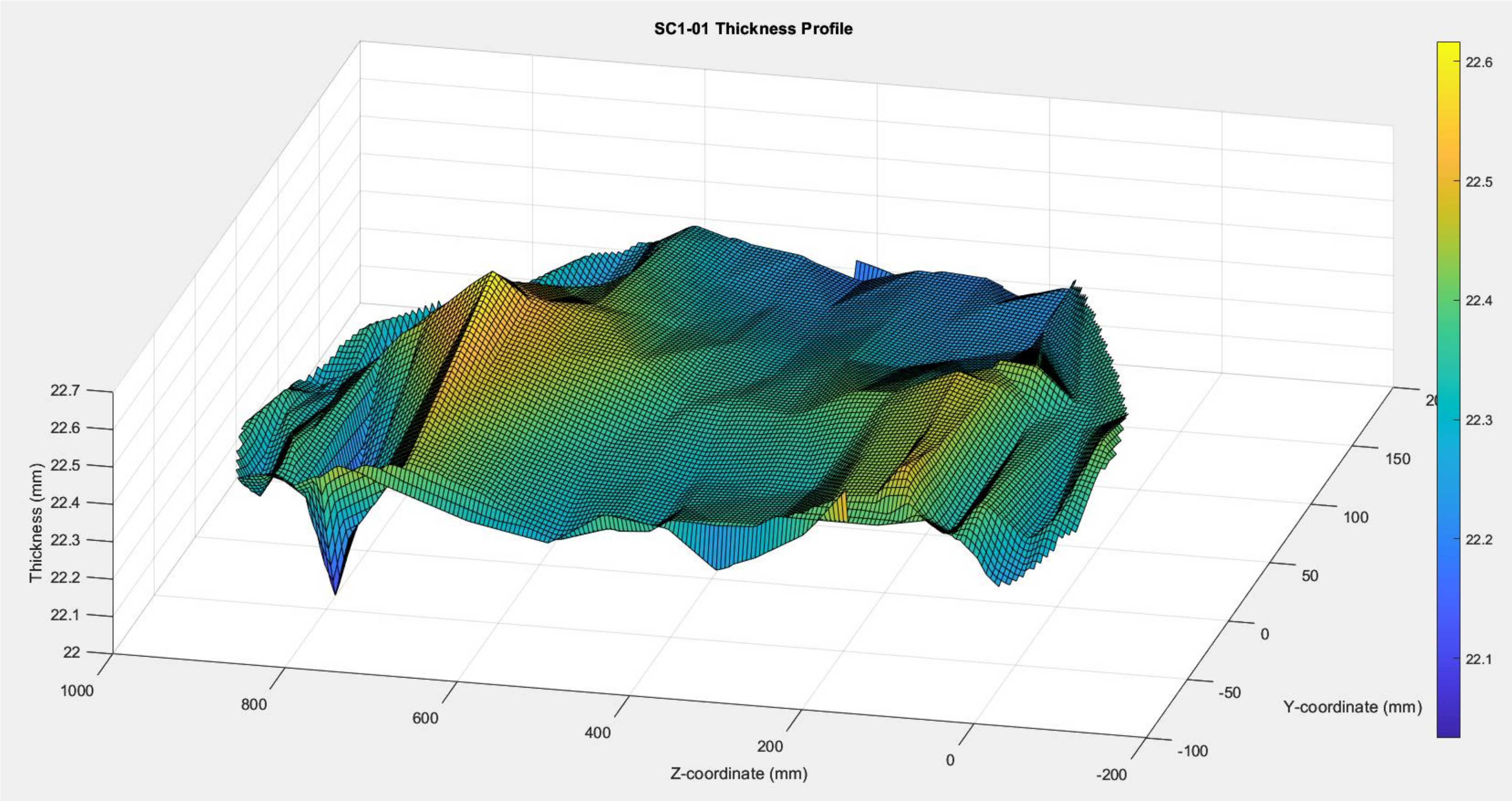


Figure 73 - SC1-01 Thickness Plot, Isometric

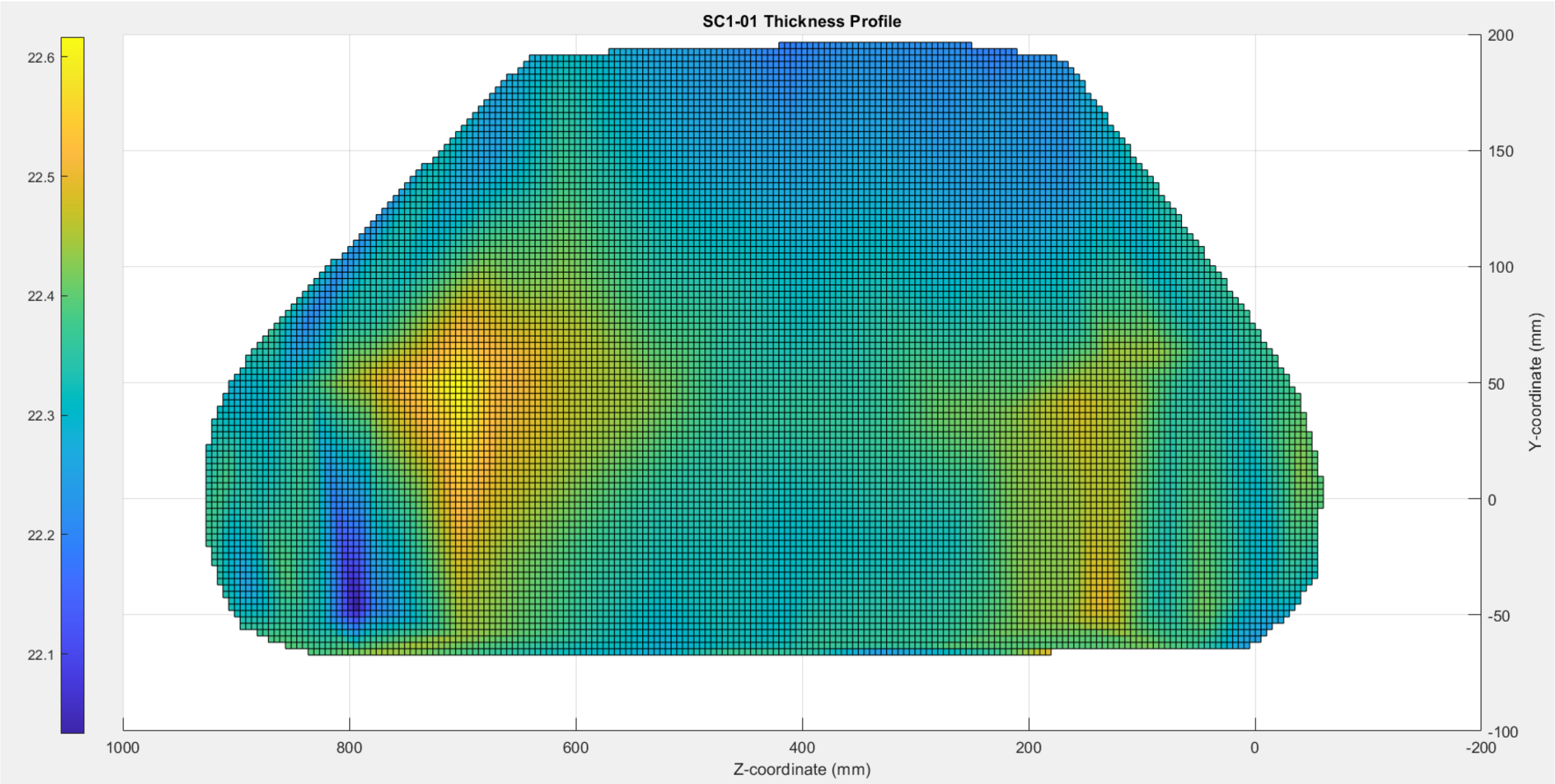


Figure 74 - SC1-01 Thickness Plot, Flattened

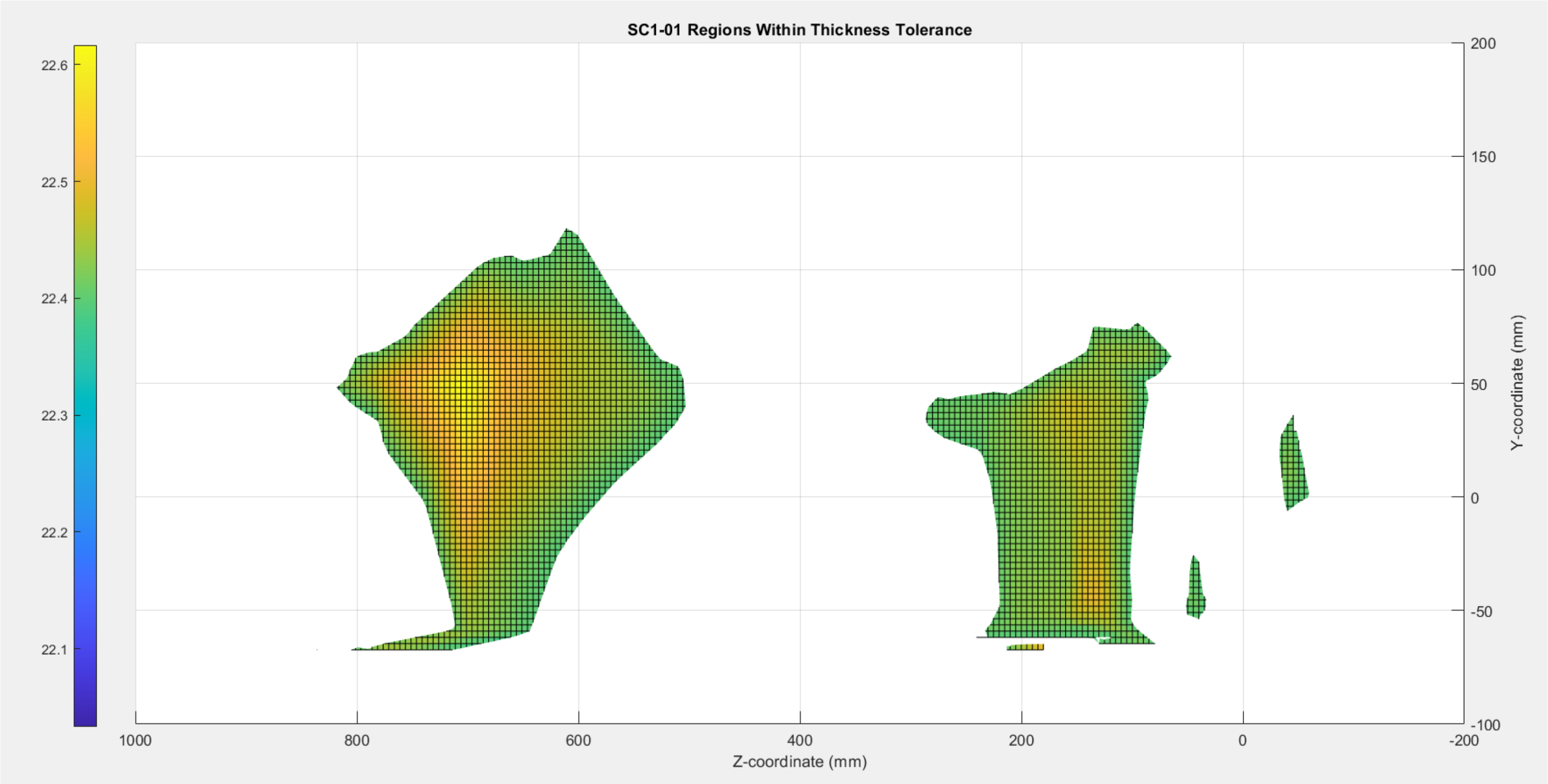


Figure 75 - SC1-01 Regions Within Tolerance

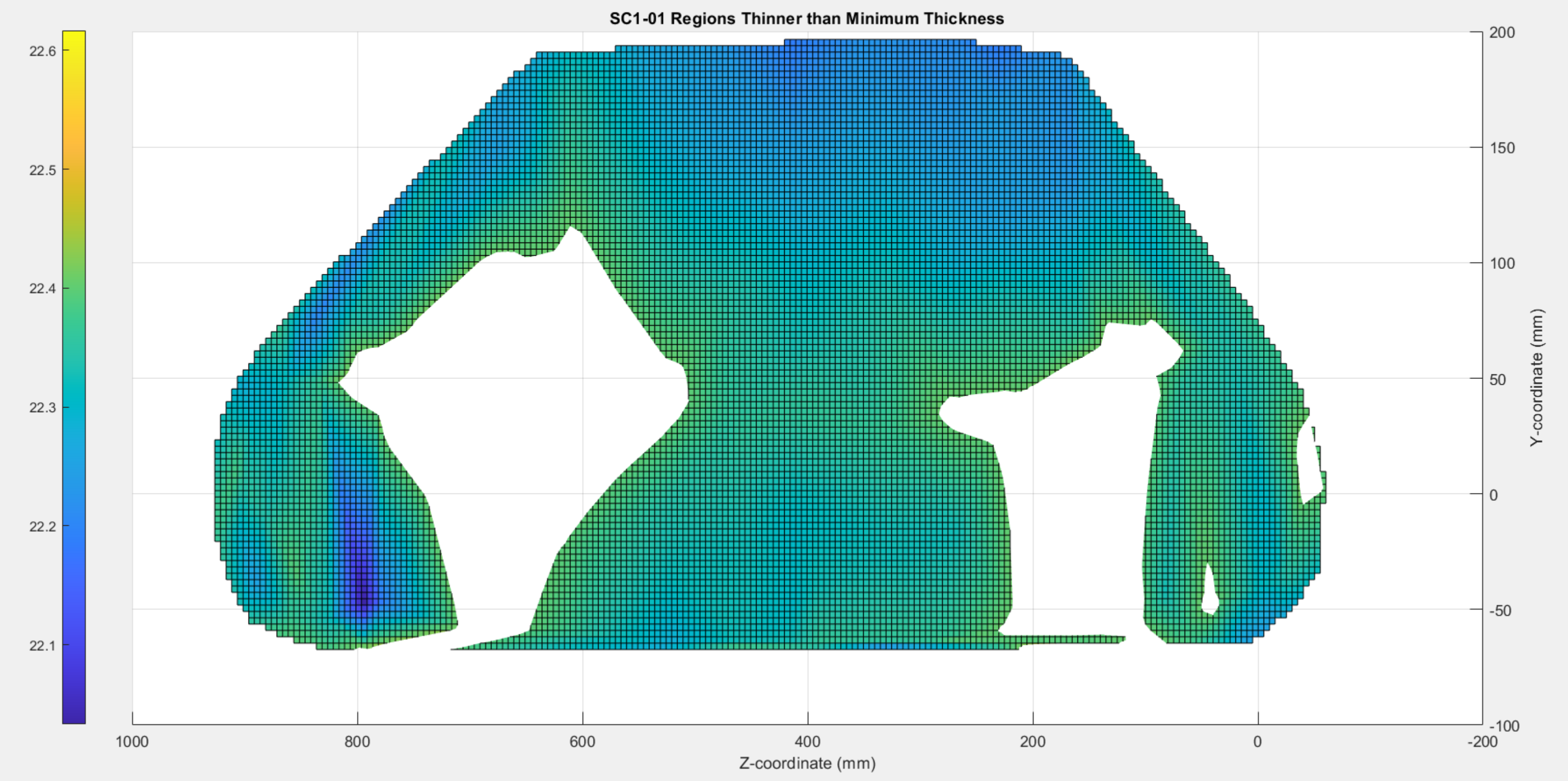


Figure 76 - SC1-01 Out of Tolerance Regions, Thin

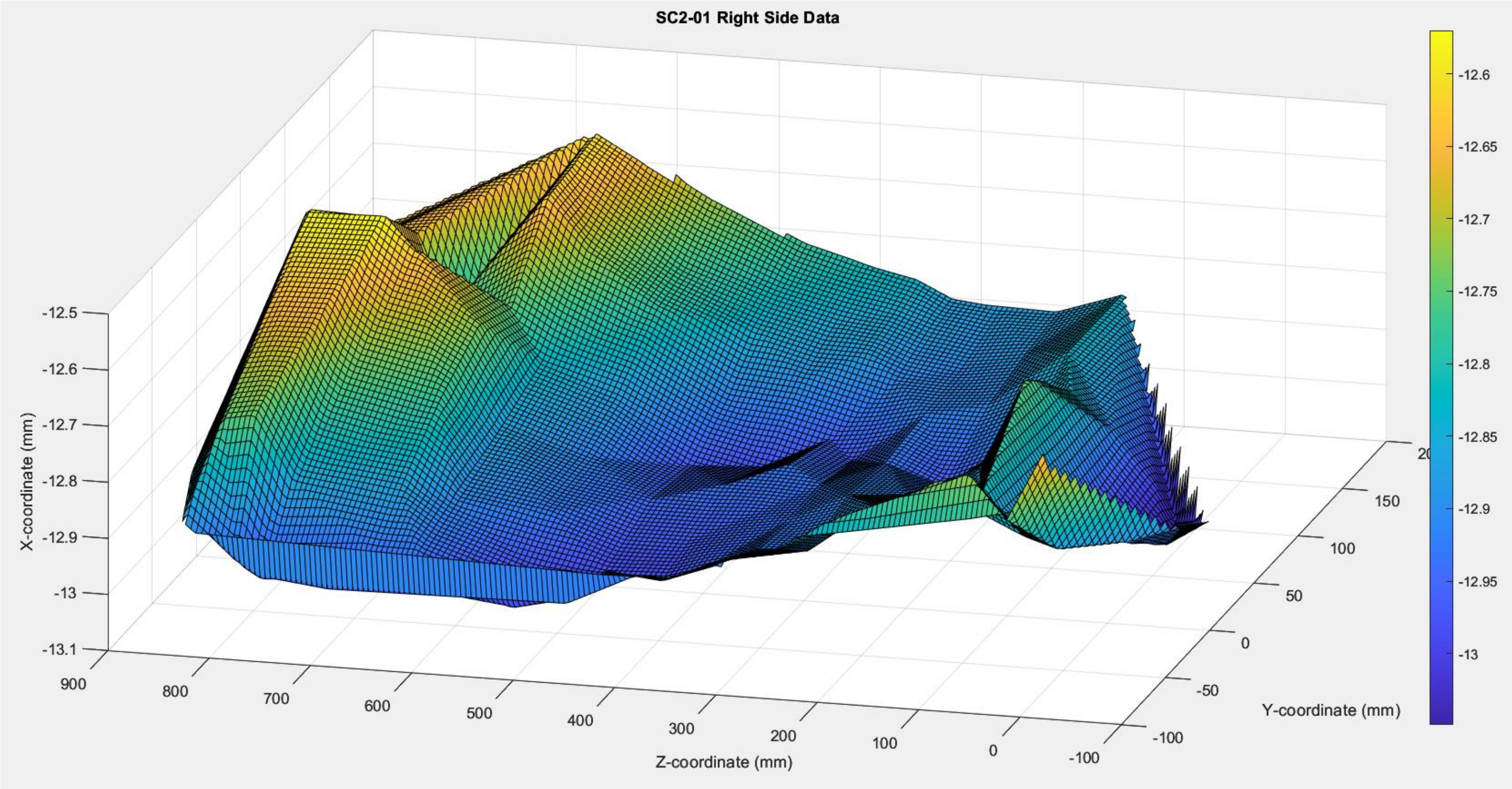


Figure 77 - SC2-01 Right Side Plot, Isometric

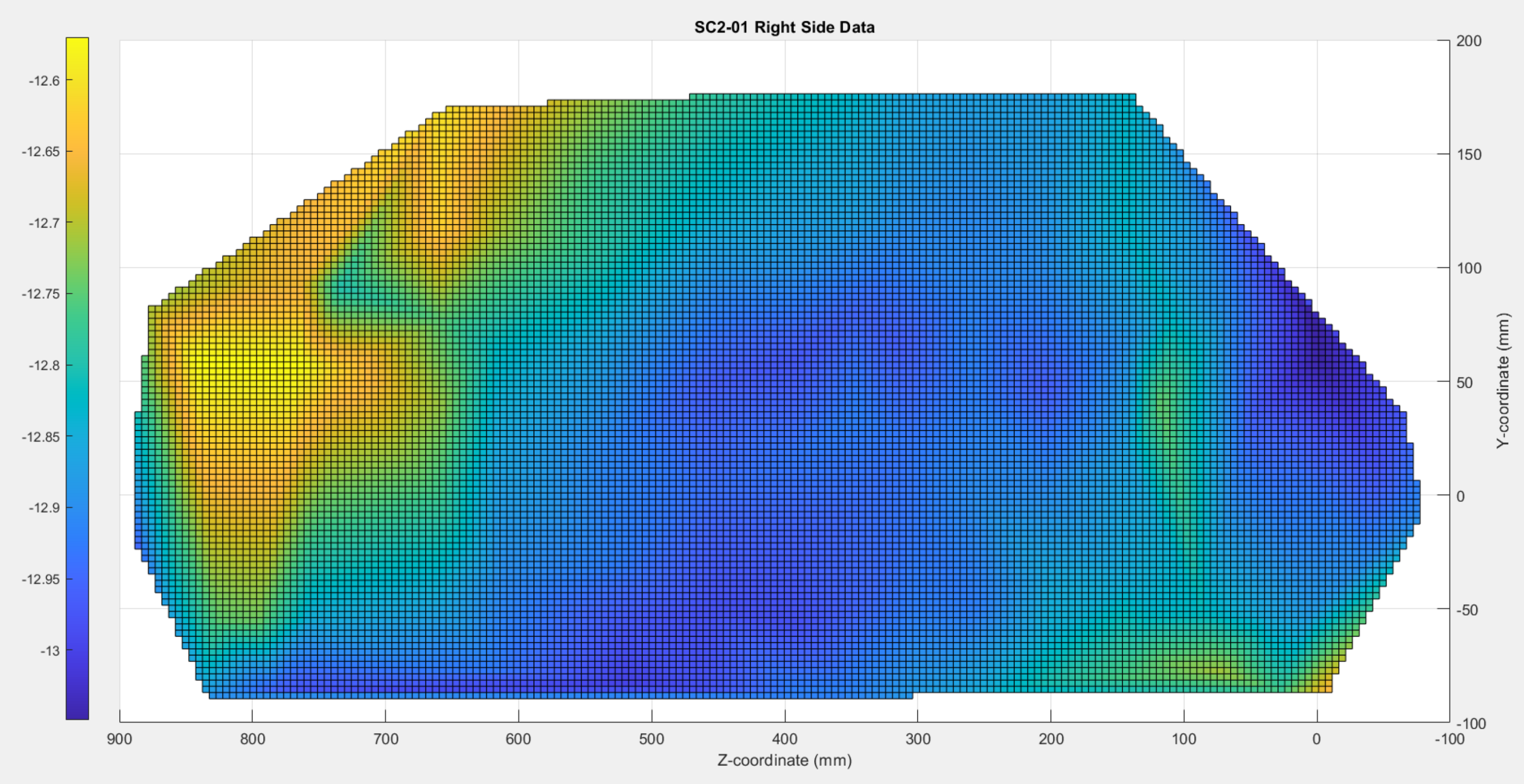


Figure 78 - SC2-01 Right Side Plot, Flattened

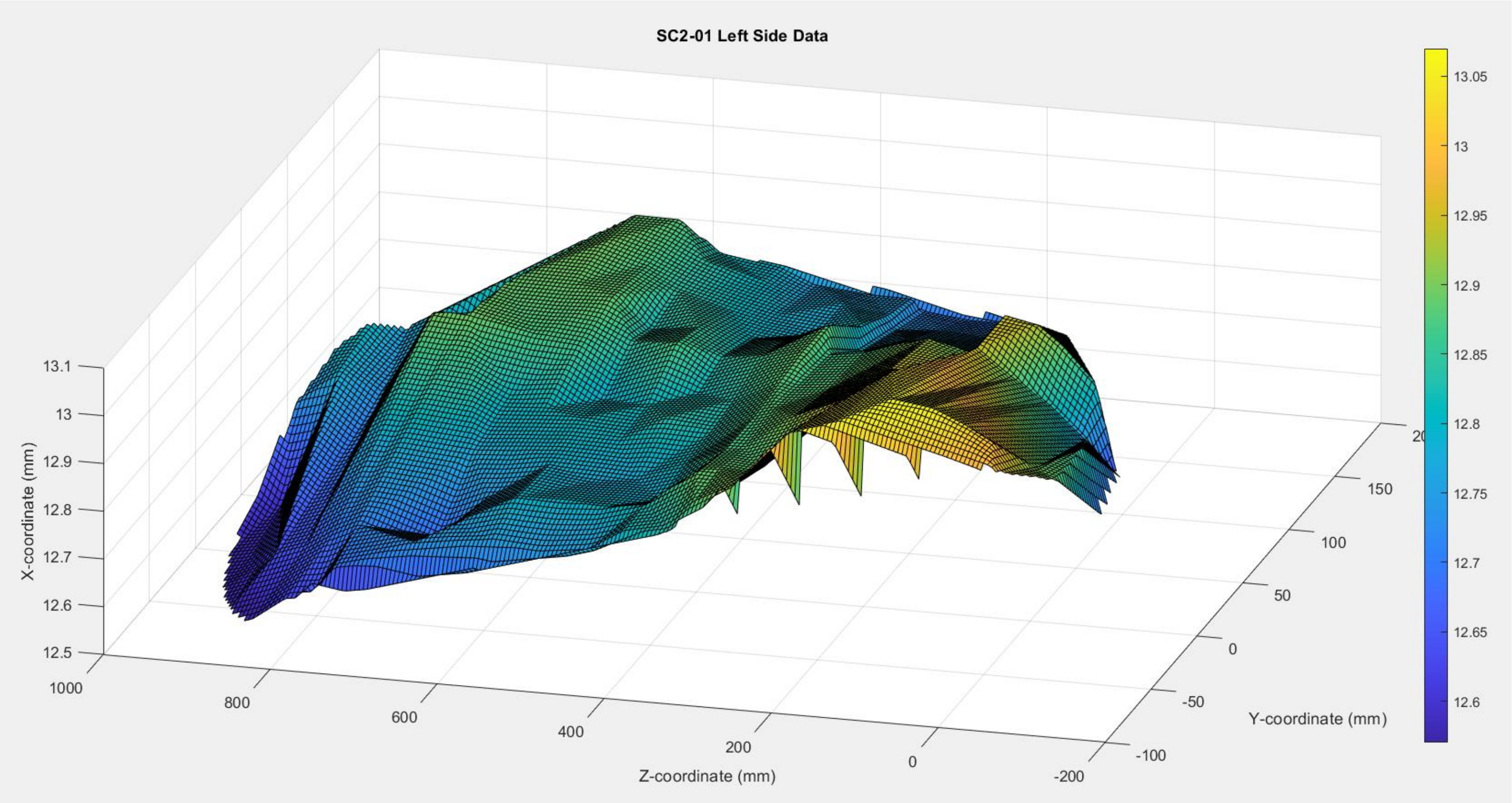


Figure 79 - SC2-01 Left Side Plot, Isometric

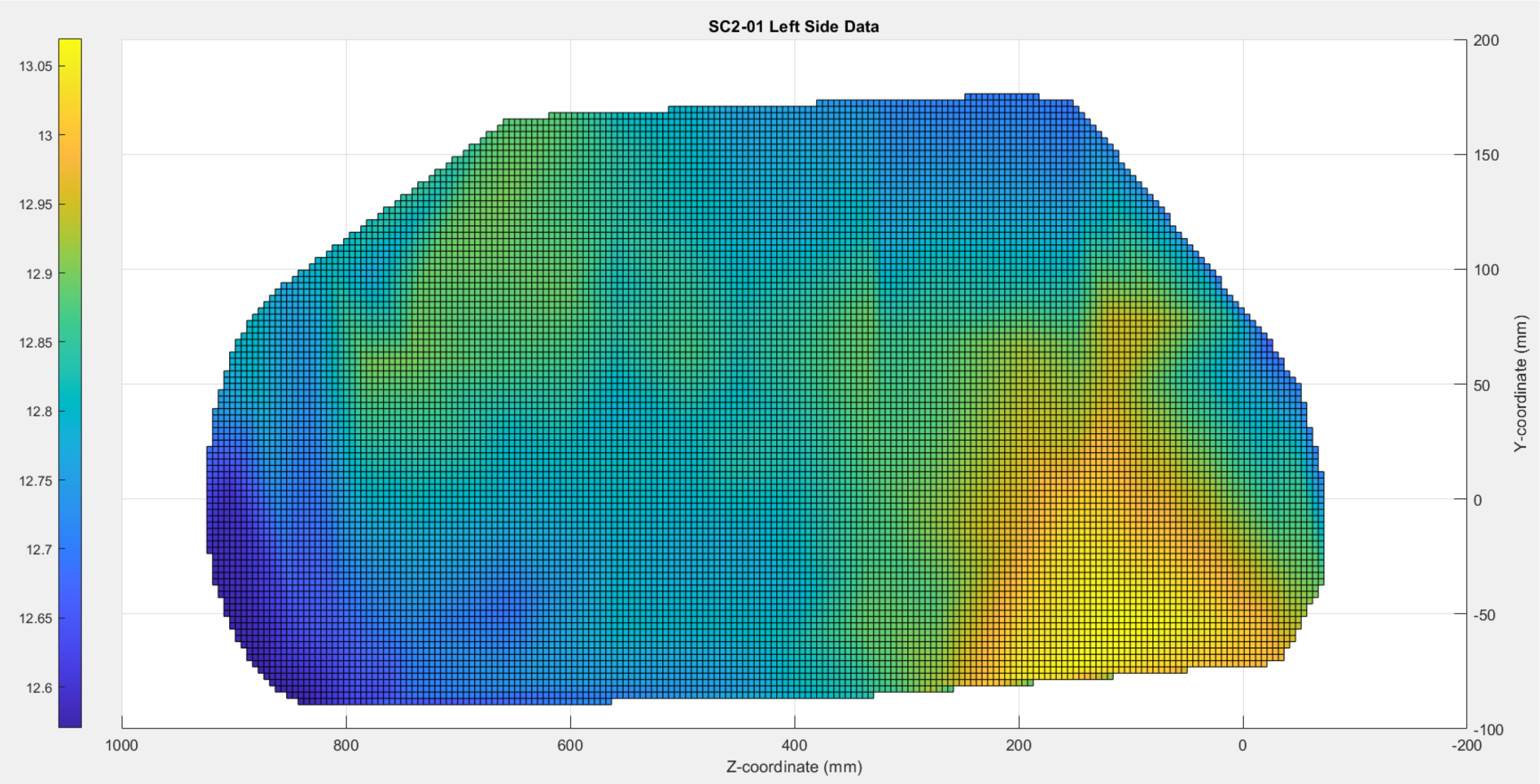


Figure 80 - SC2-01 Left Side Plot, Flattened

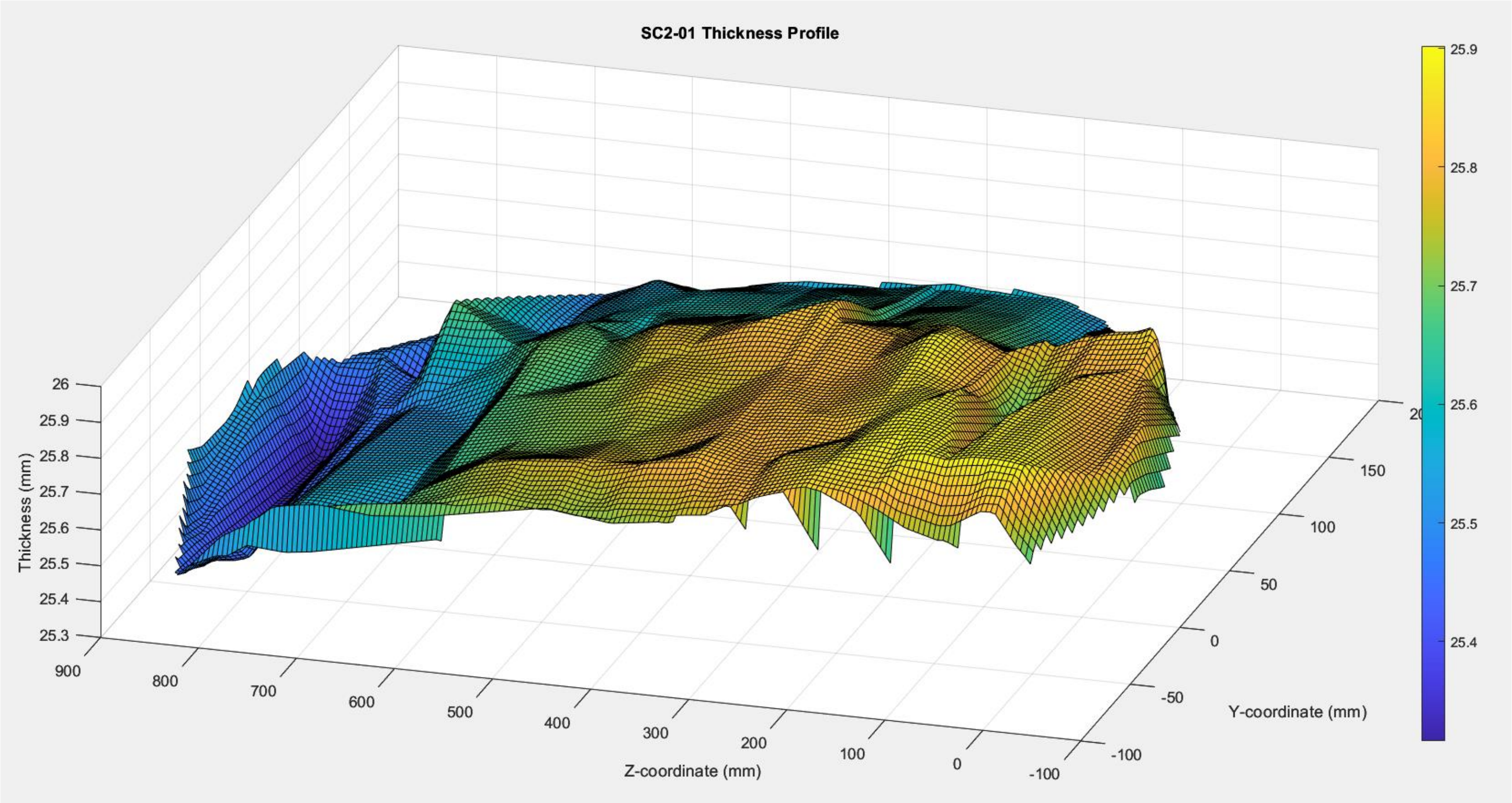


Figure 81 - SC2-01 Thickness Plot, Isometric

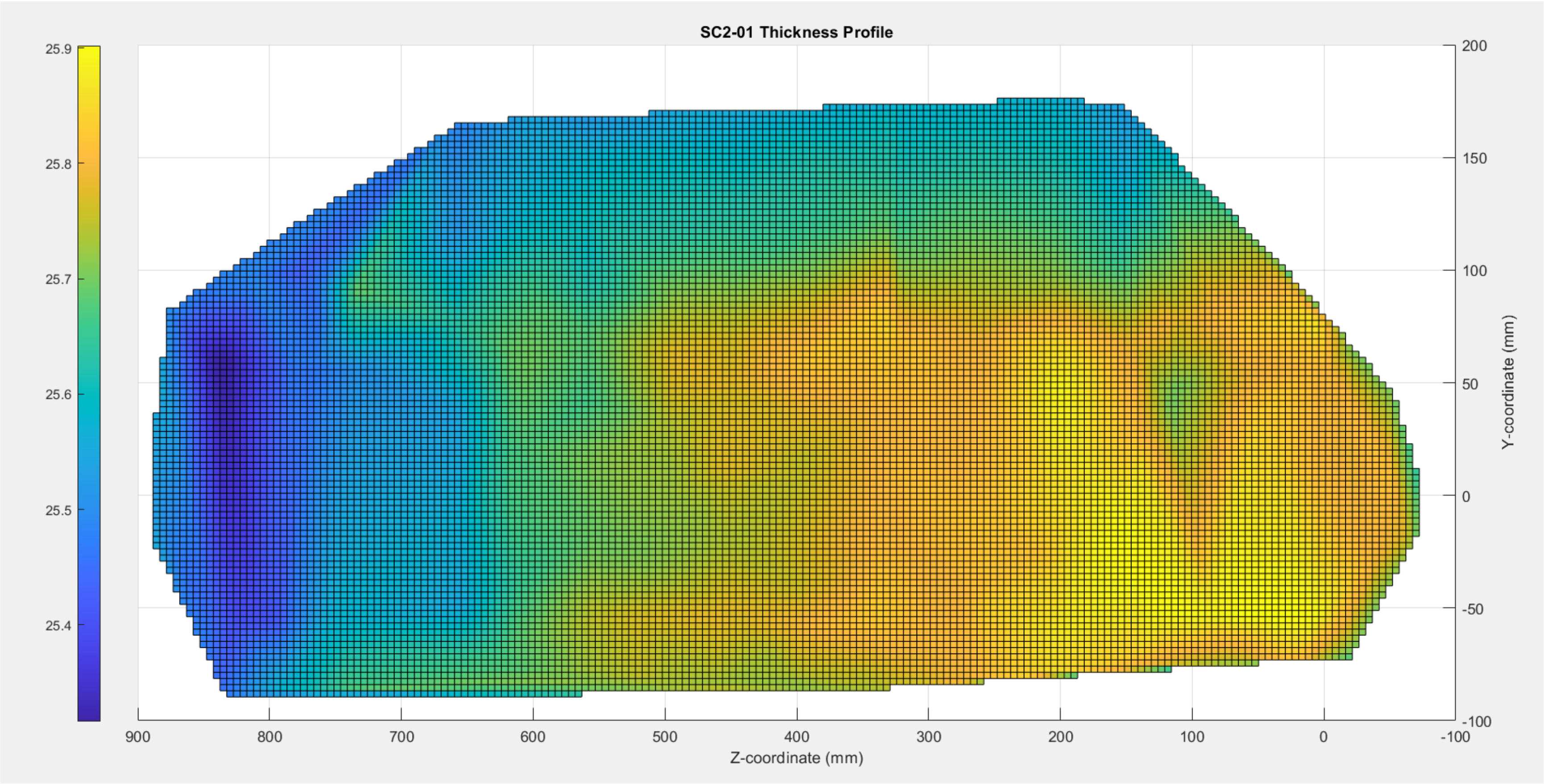


Figure 82 - SC2-01 Thickness Plot, Flattened

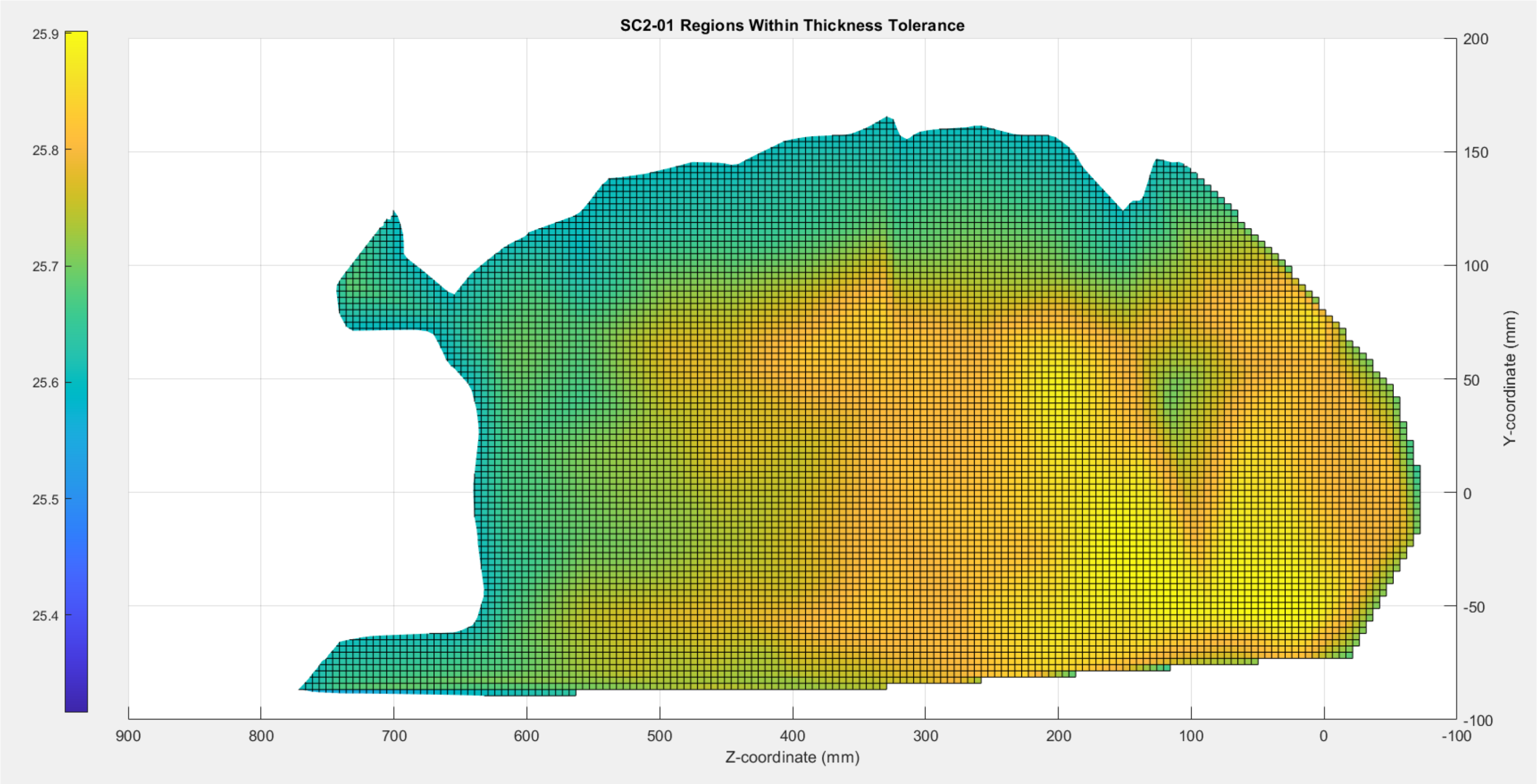


Figure 83 - SC2-01 Regions Within Tolerance

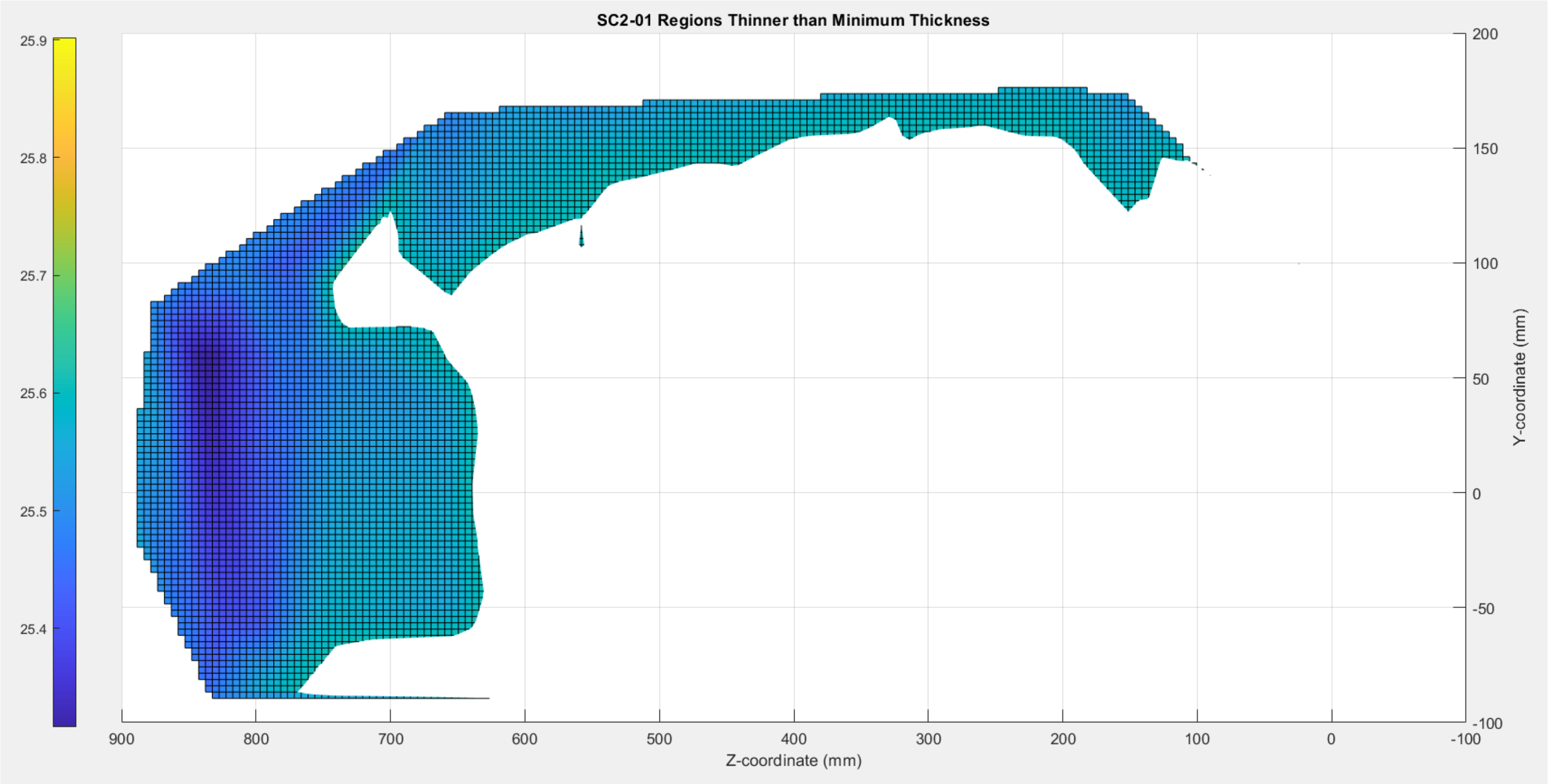


Figure 84 - SC2-01 Out of Tolerance Regions, Thin

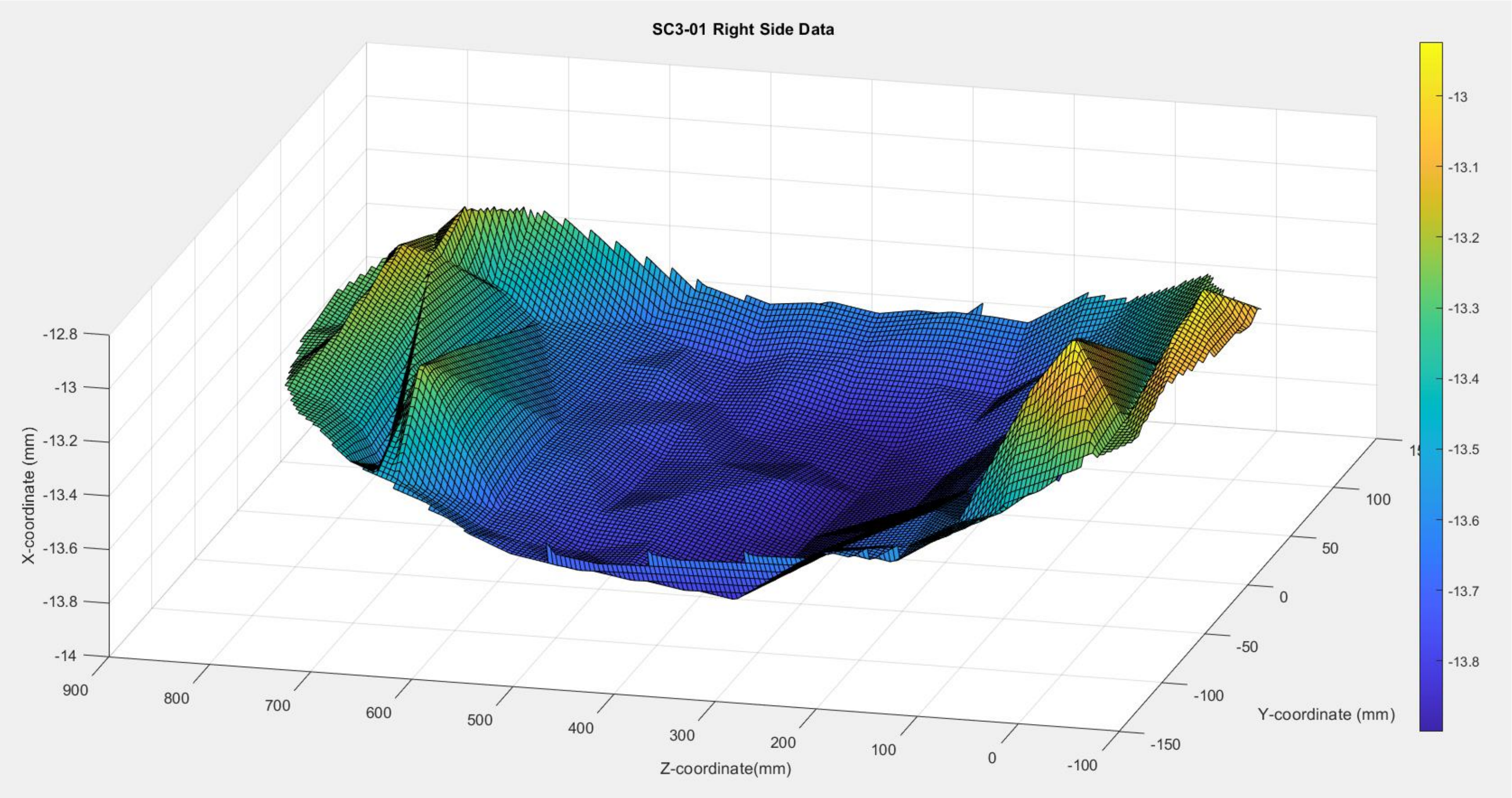


Figure 85 - SC3-01 Right Side Plot, Isometric

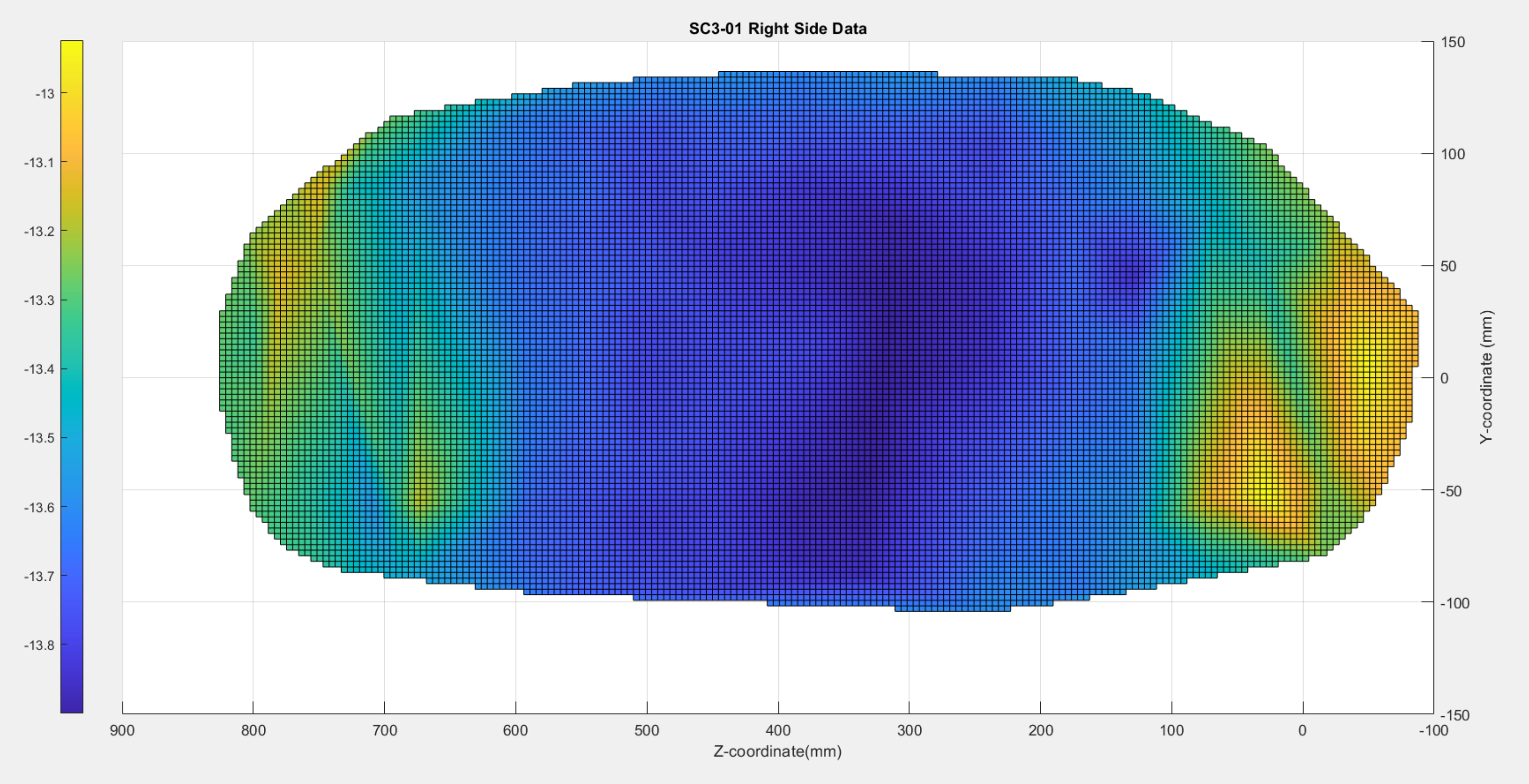


Figure 86 - SC3-01 Right Side Plot, Flattened

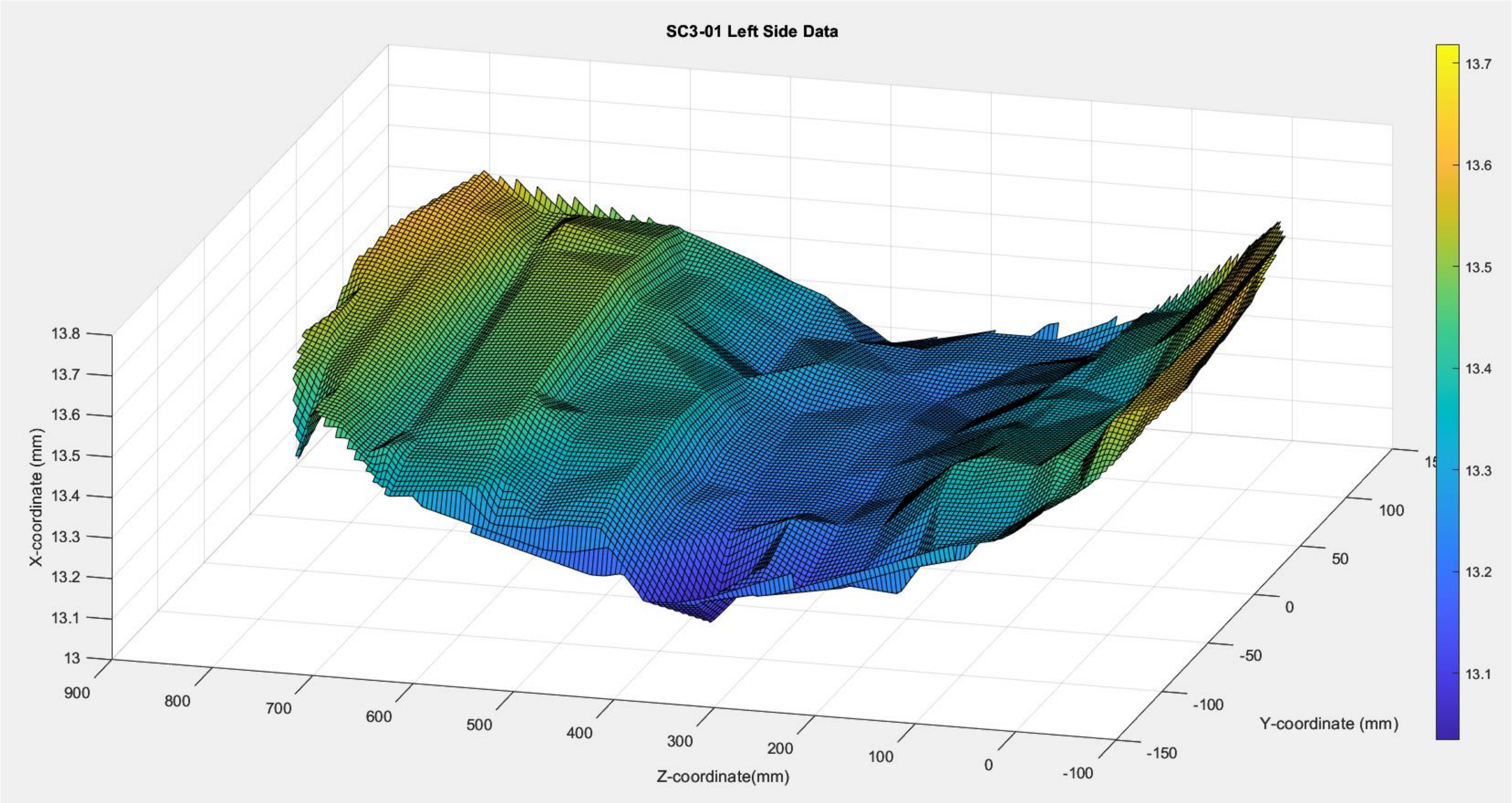


Figure 87 - SC3-01 Left Side Plot, Isometric

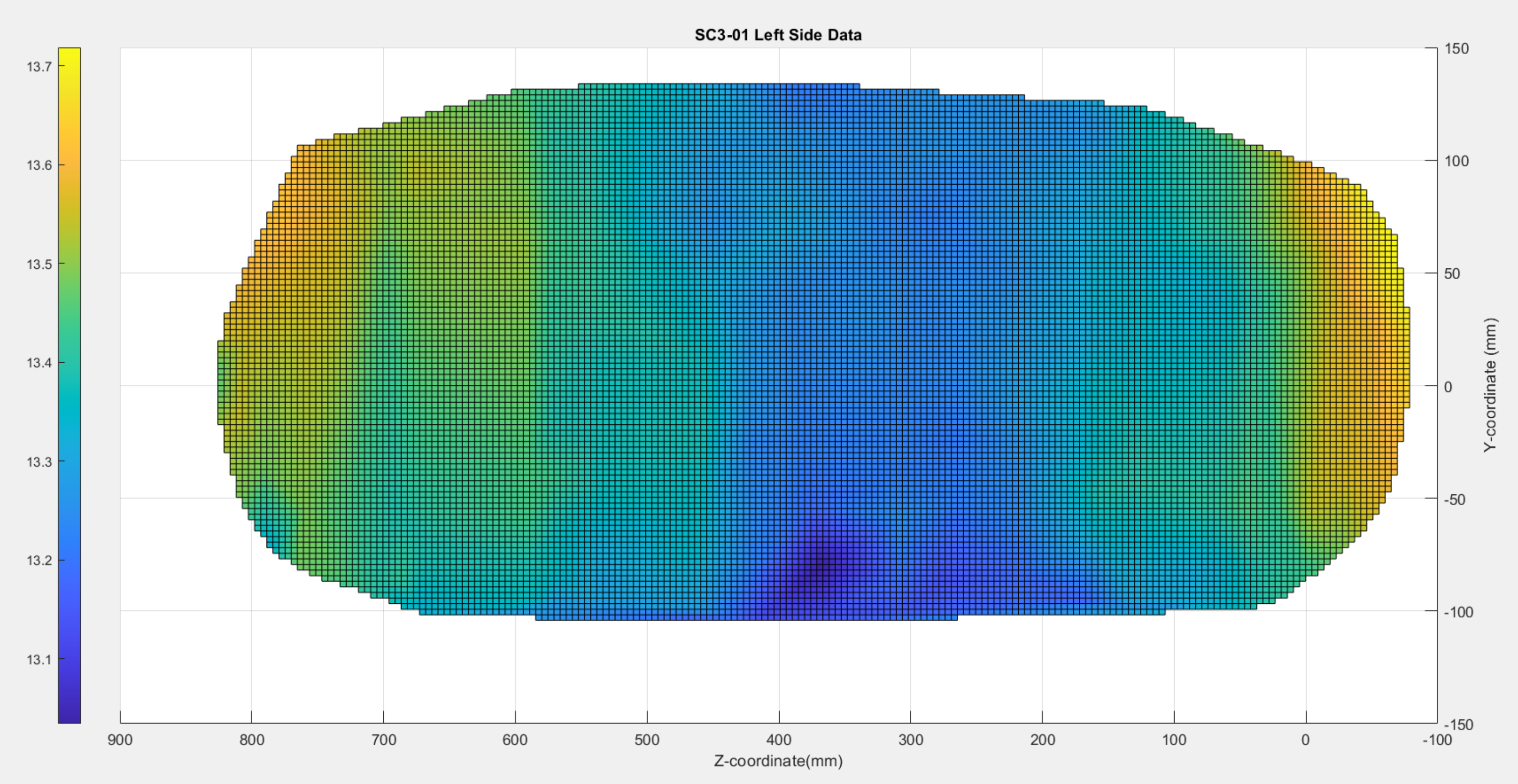


Figure 88 - SC3-01 Left Side Plot, Flattened

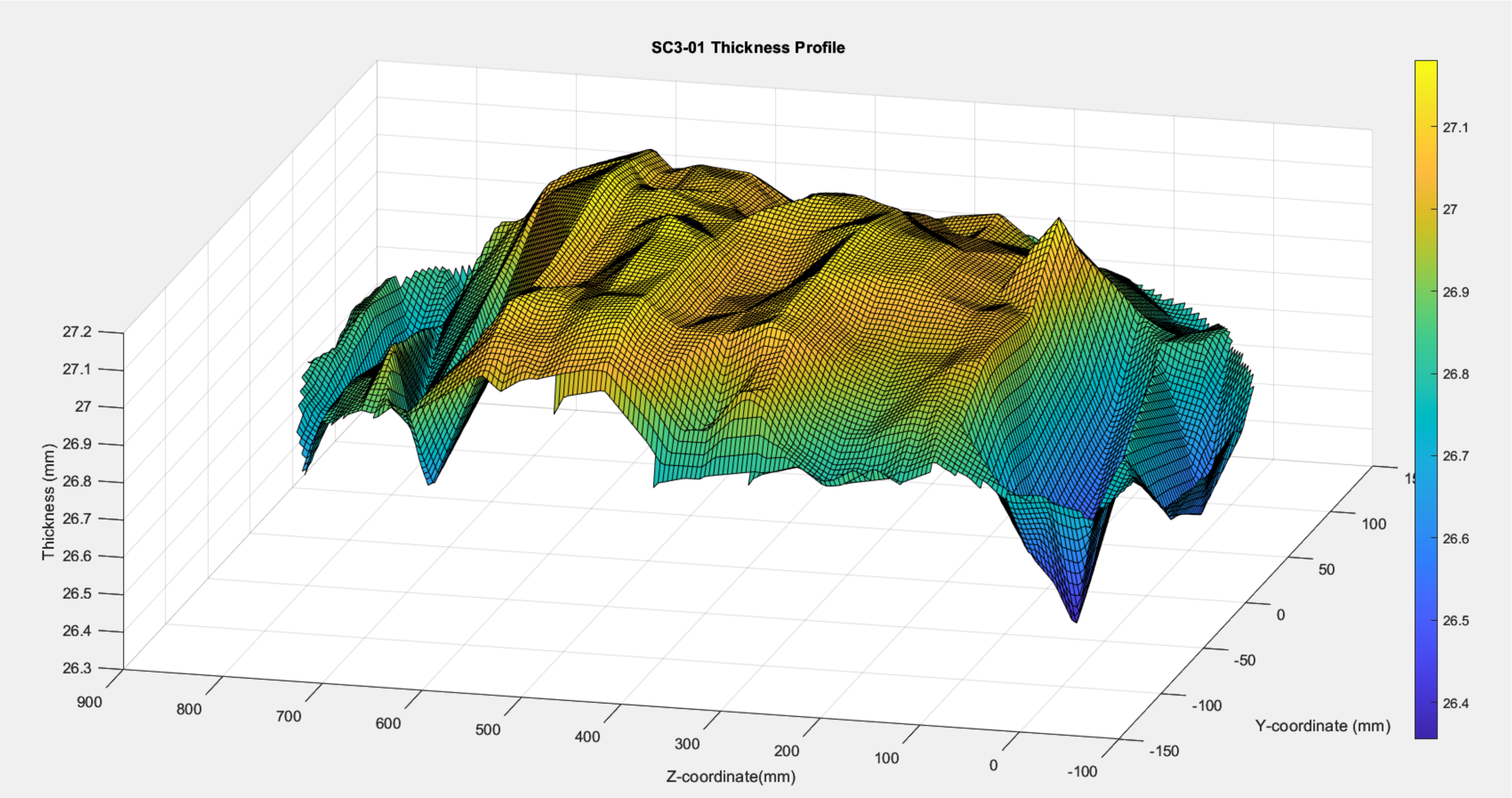


Figure 89 - SC3-01 Thickness Plot, Isometric

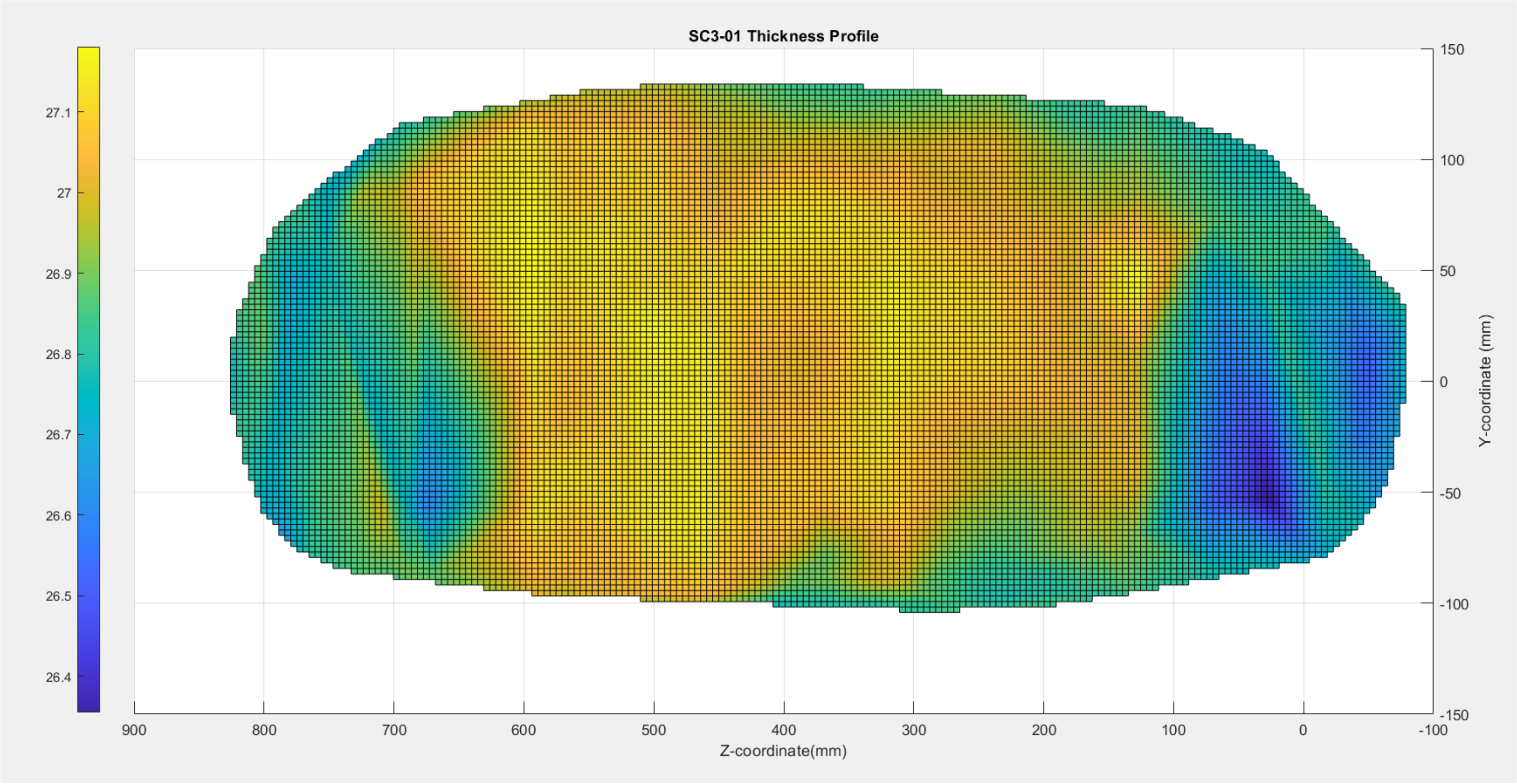


Figure 90 - SC3-01 Thickness Plot, Flattened

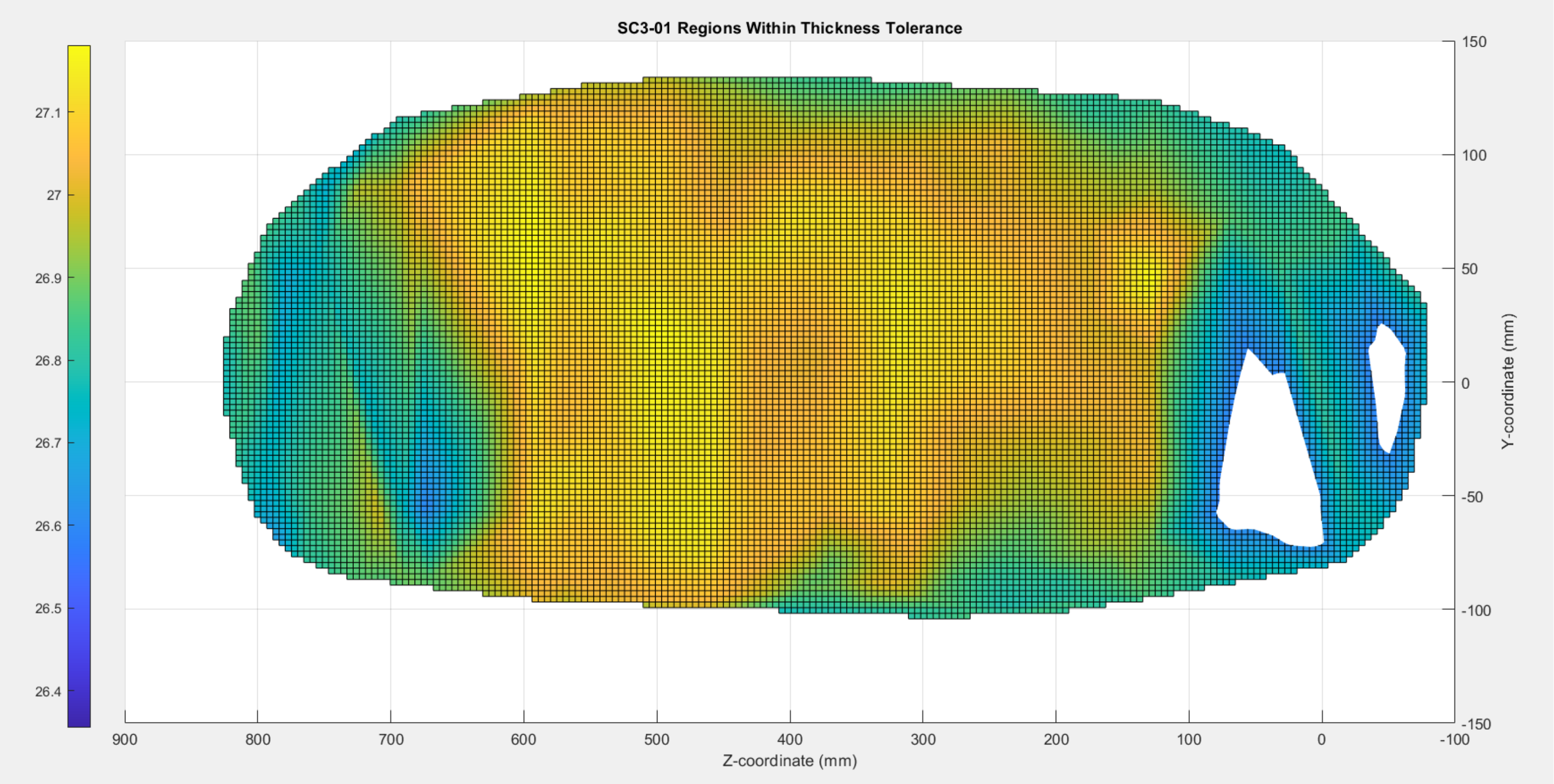


Figure 91 - SC3-01 Regions Within Tolerance

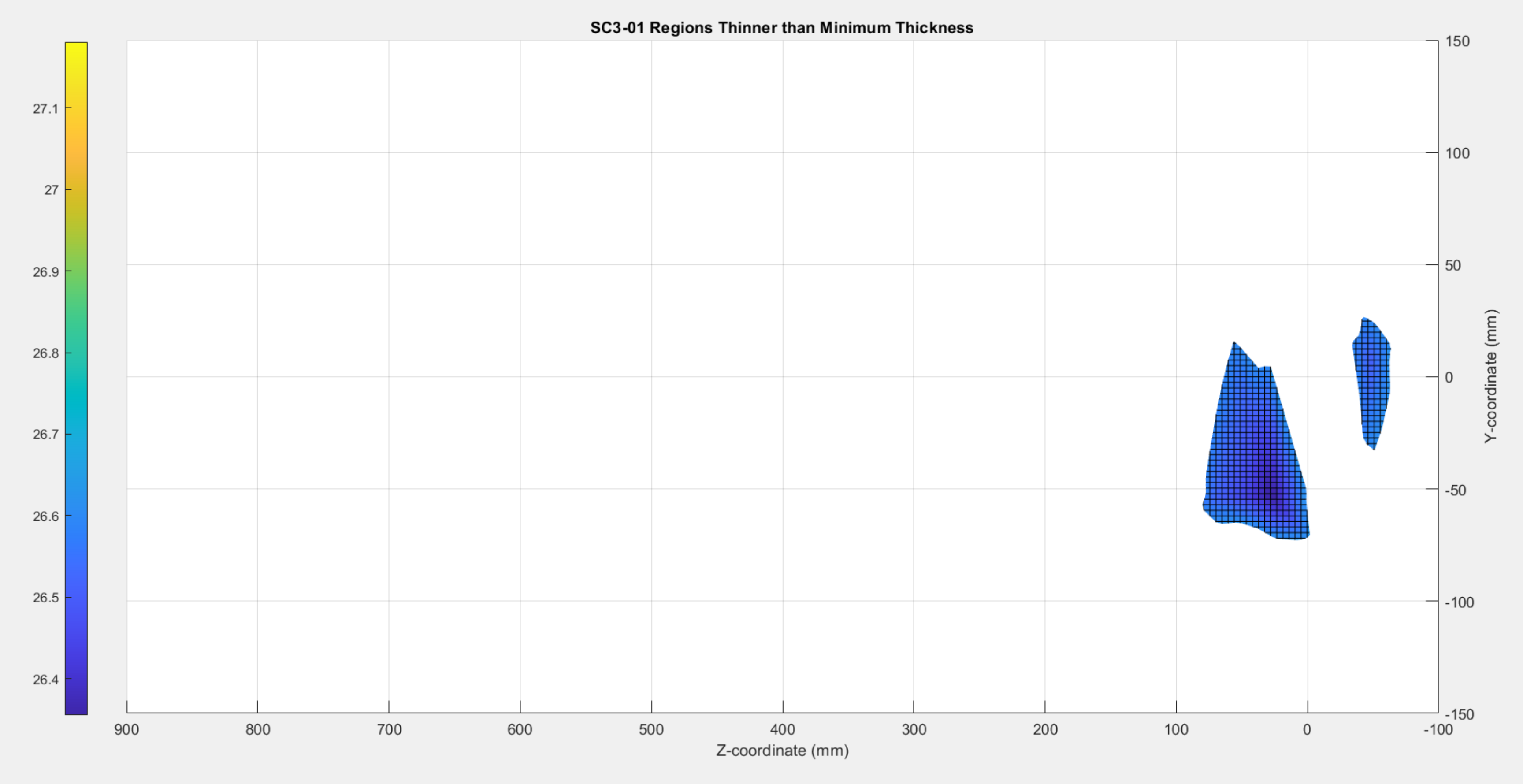


Figure 92 - SC3-01 Out of Tolerance Regions, Thin

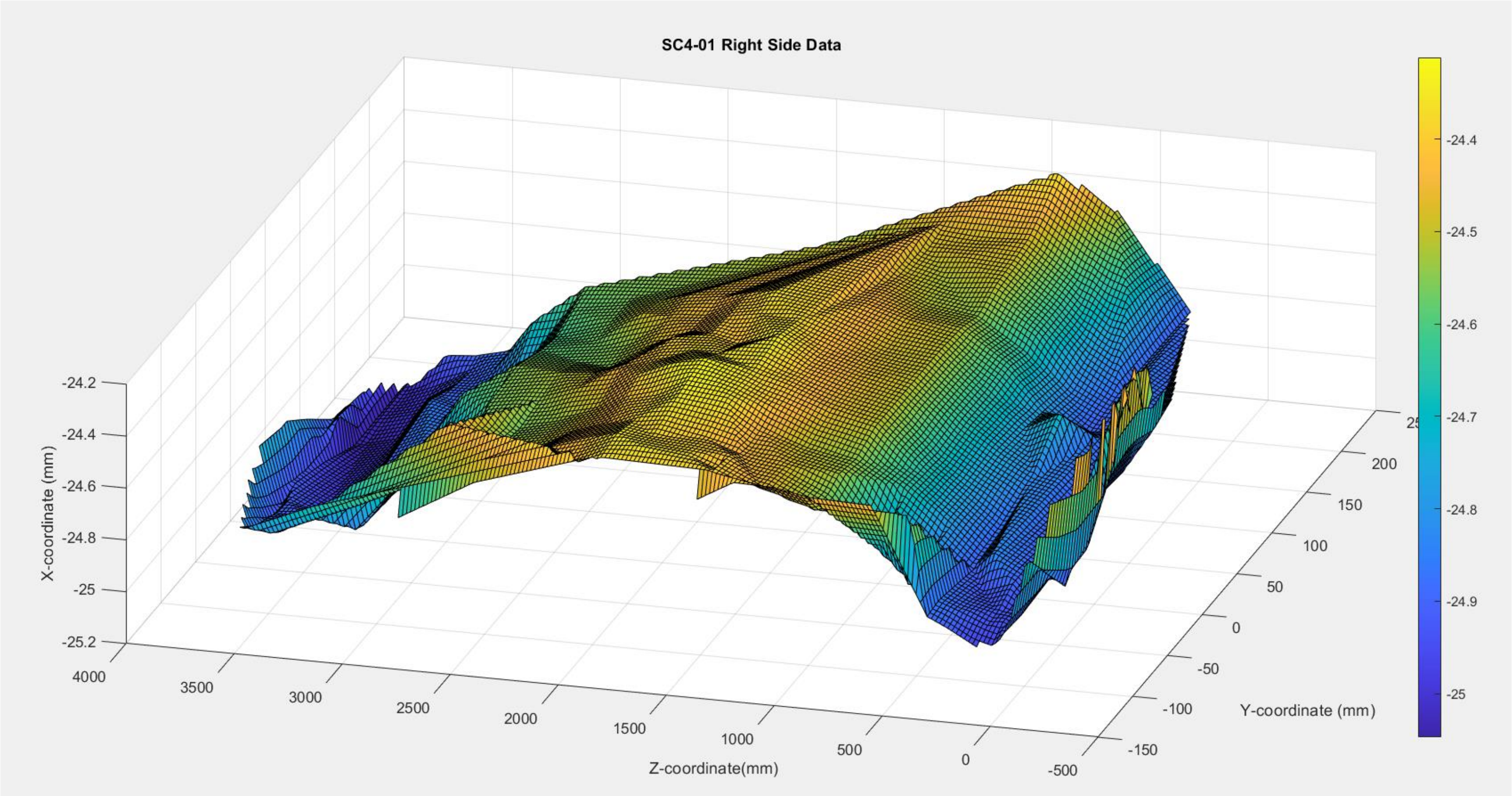


Figure 93 - SC4-01 Right Side Plot, Isometric

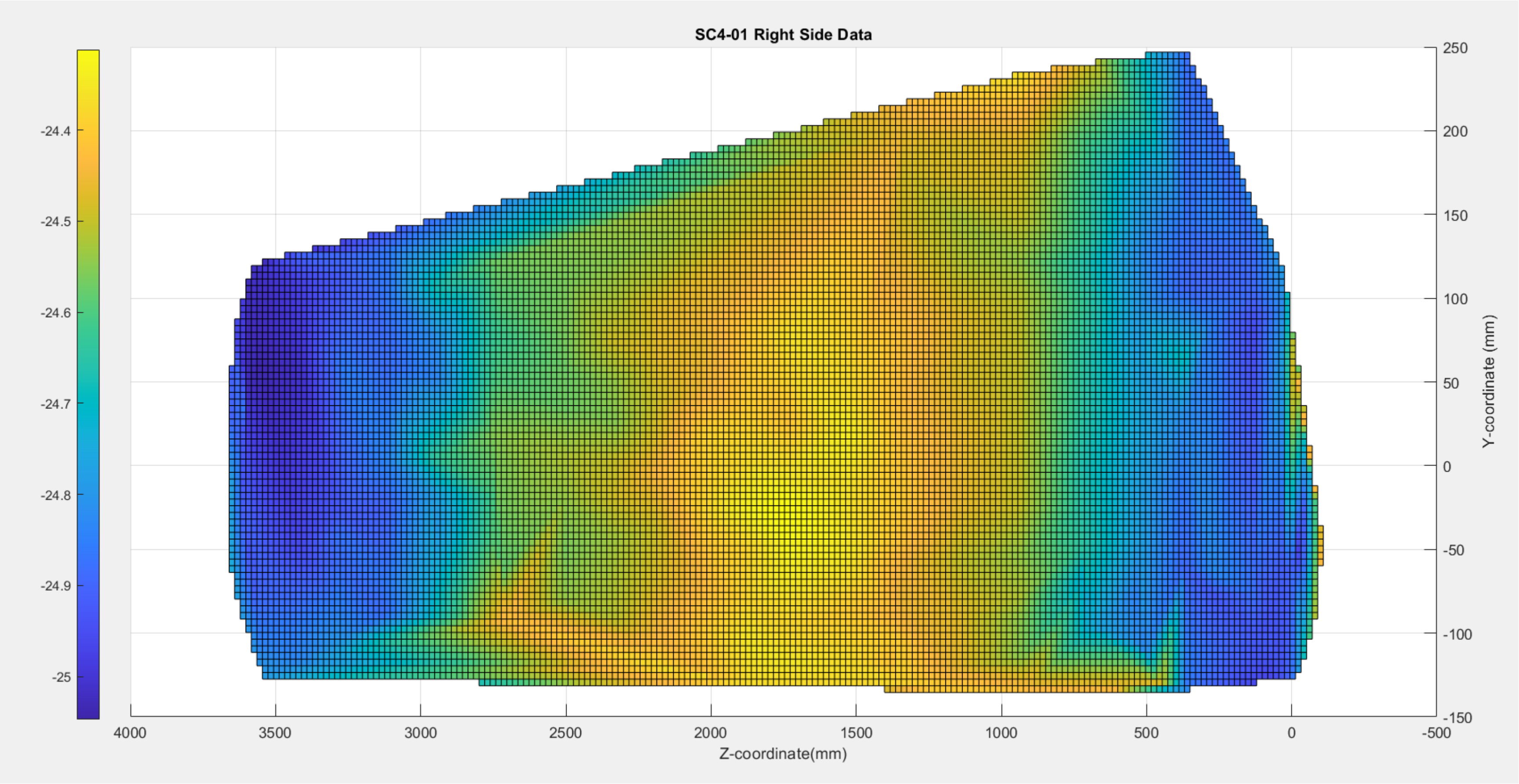


Figure 94 - SC4-01 Right Side Plot, Flattened

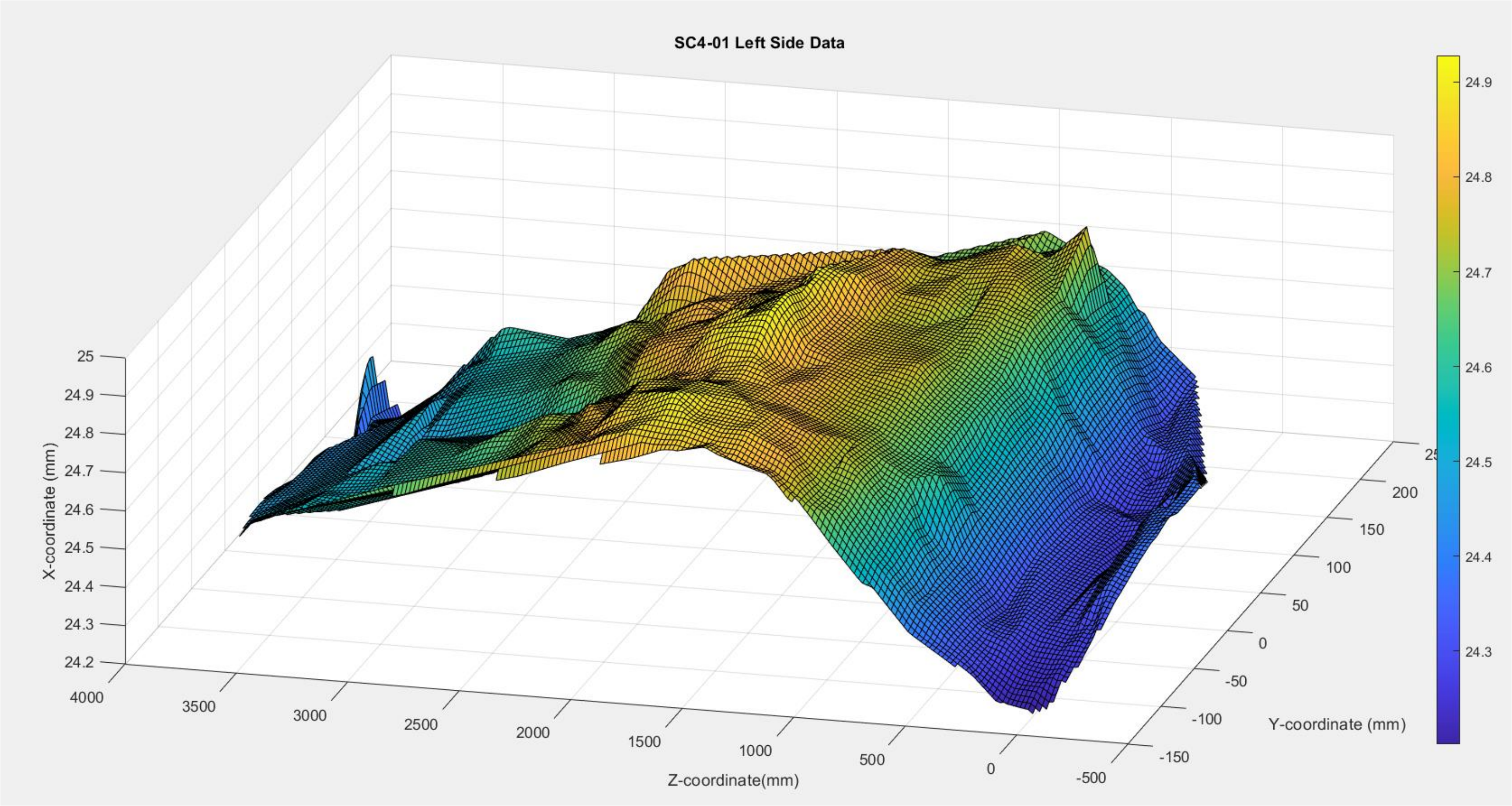


Figure 95 - SC4-01 Left Side Plot, Isometric

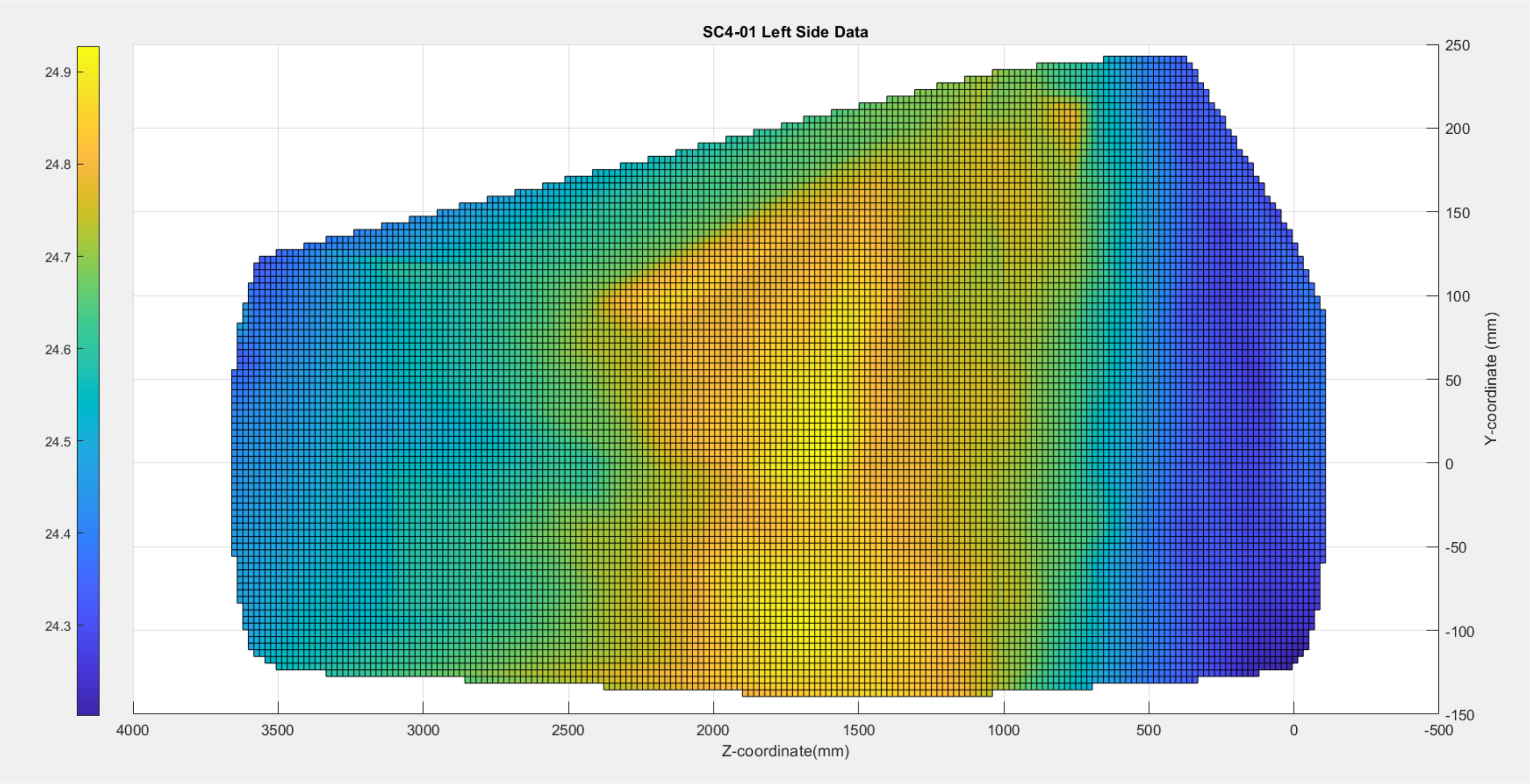


Figure 96 - SC4-01 Left Side Plot, Flattened

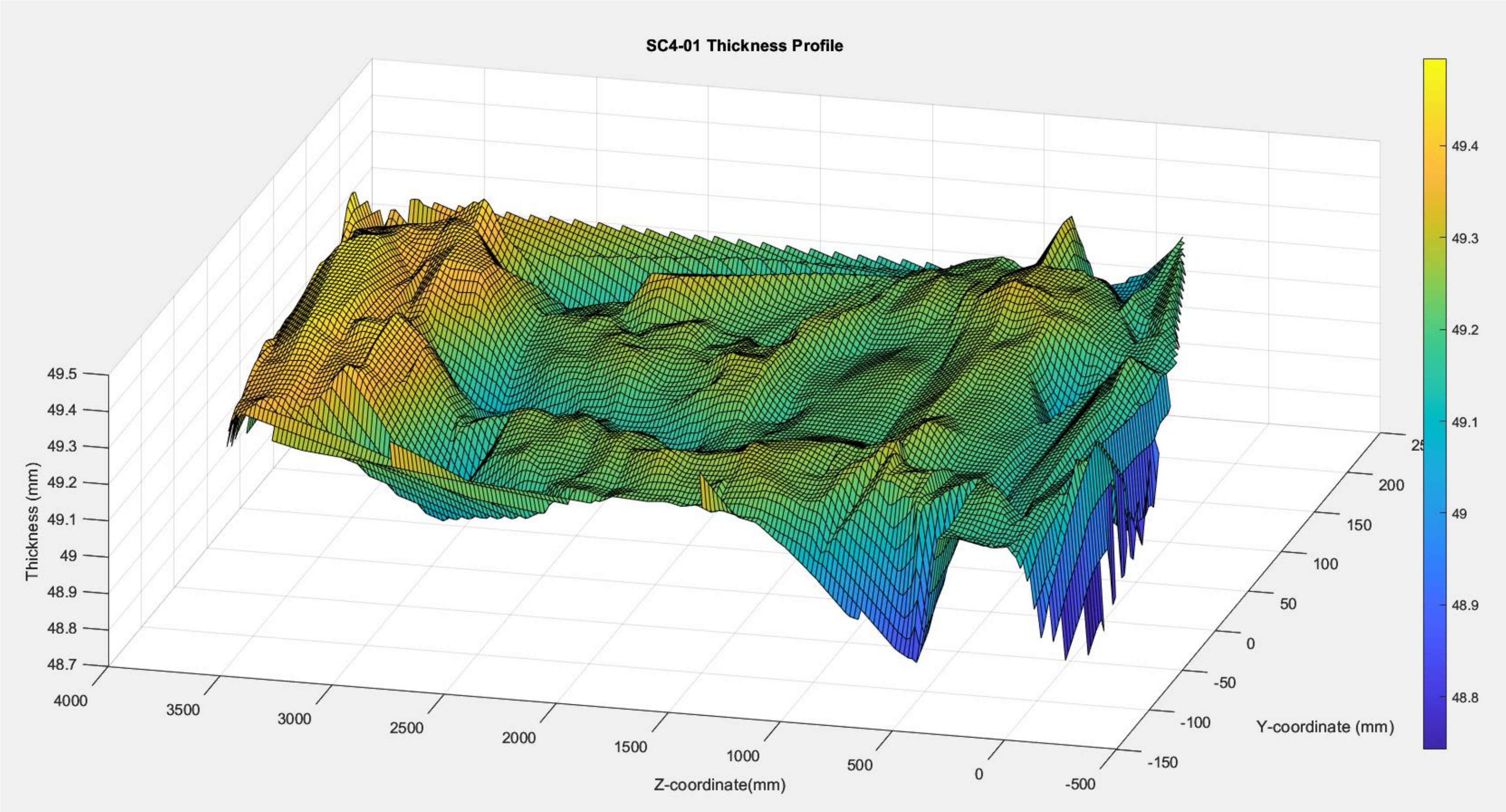


Figure 97 - SC4-01 Thickness Plot, Isometric

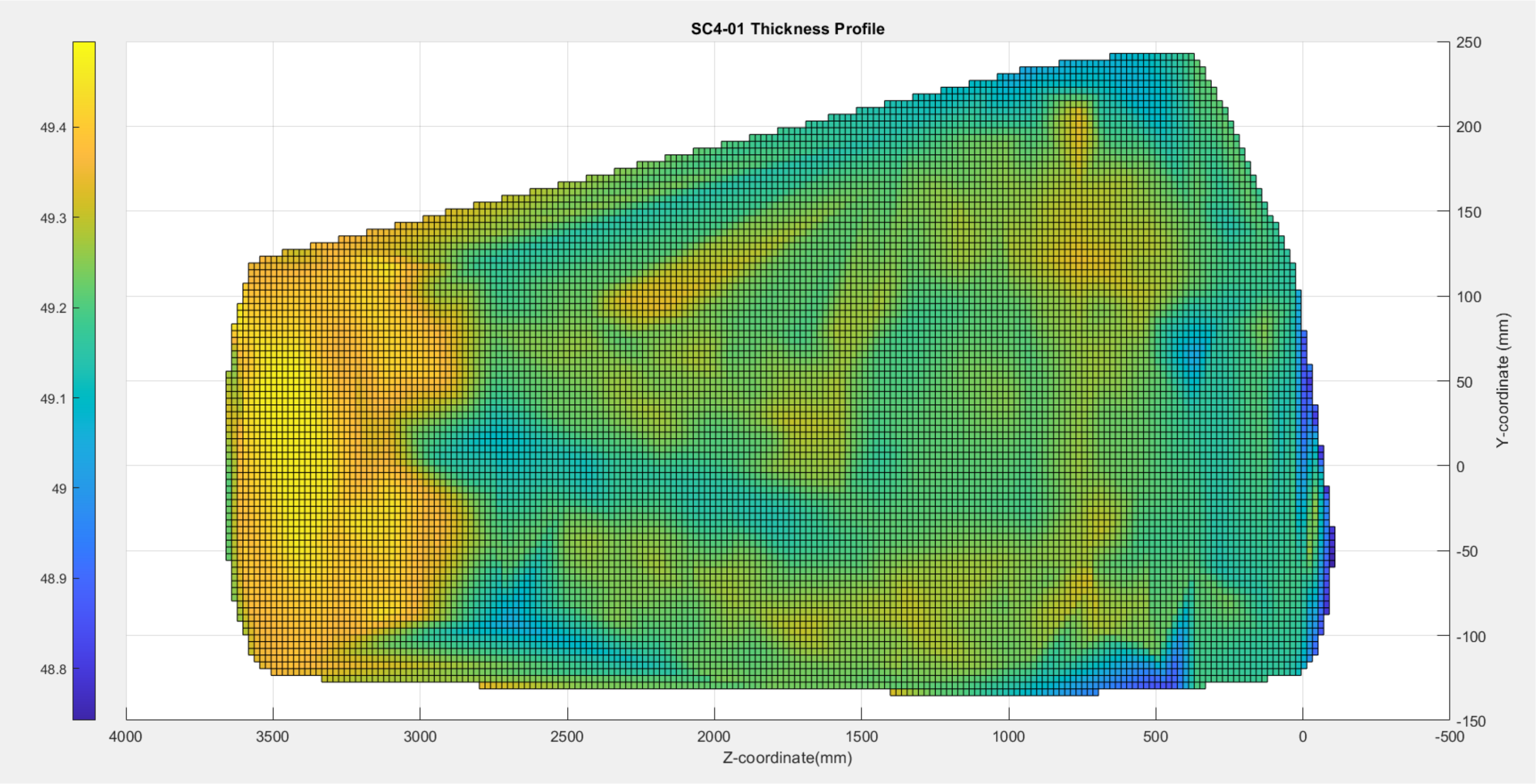


Figure 98 - SC4-01 Thickness Plot, Flattened

Approved: 05/01/2023; E-Sign ID: 495968; Signed By: Reviewer 1: S. Gopinath; Reviewer 2: E. Sun; Approver 1: D. Kashy; Approver 2: M. Dion; DCG Quality Check: T. Fuell

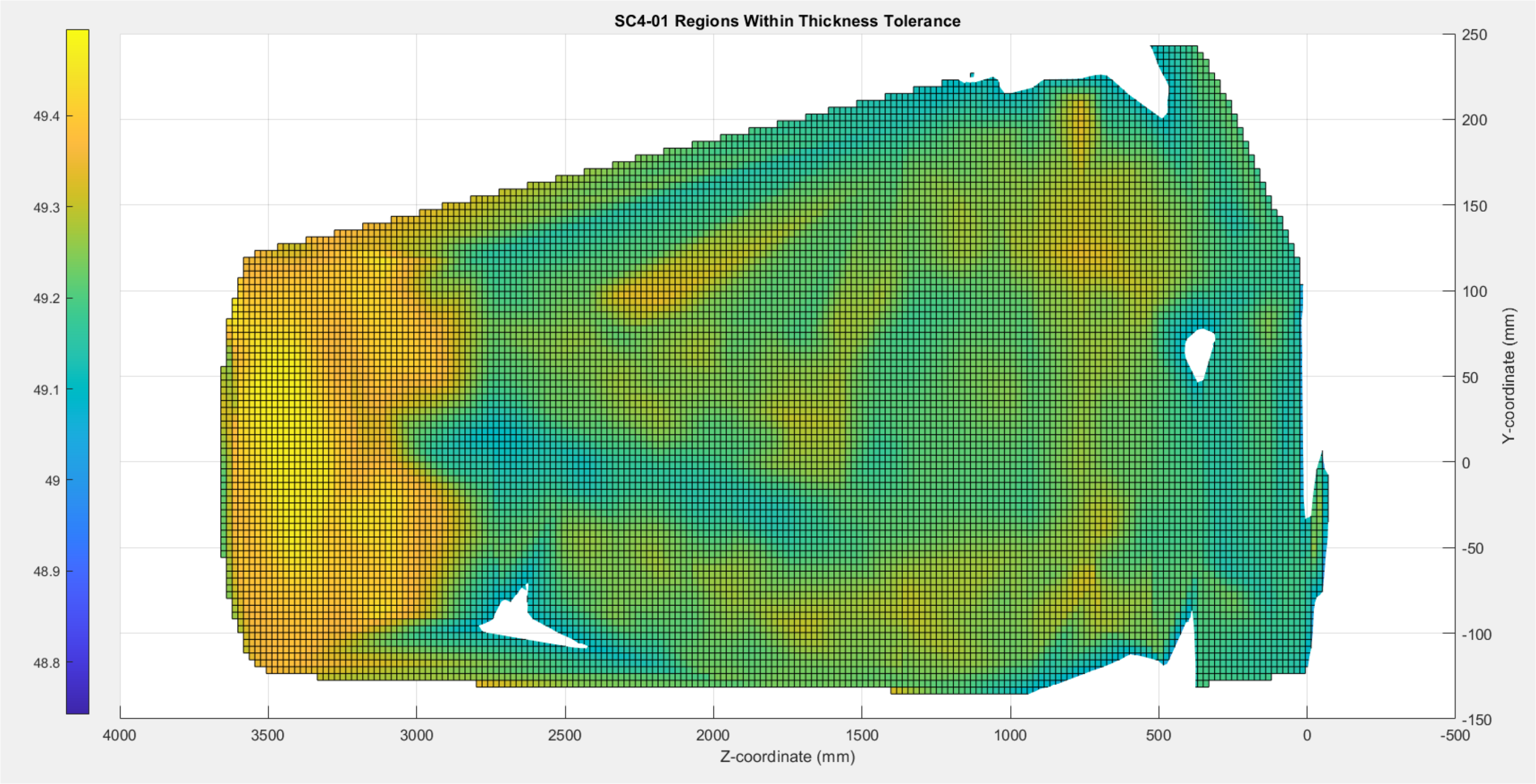


Figure 99 - SC4-01 Regions Within Tolerance

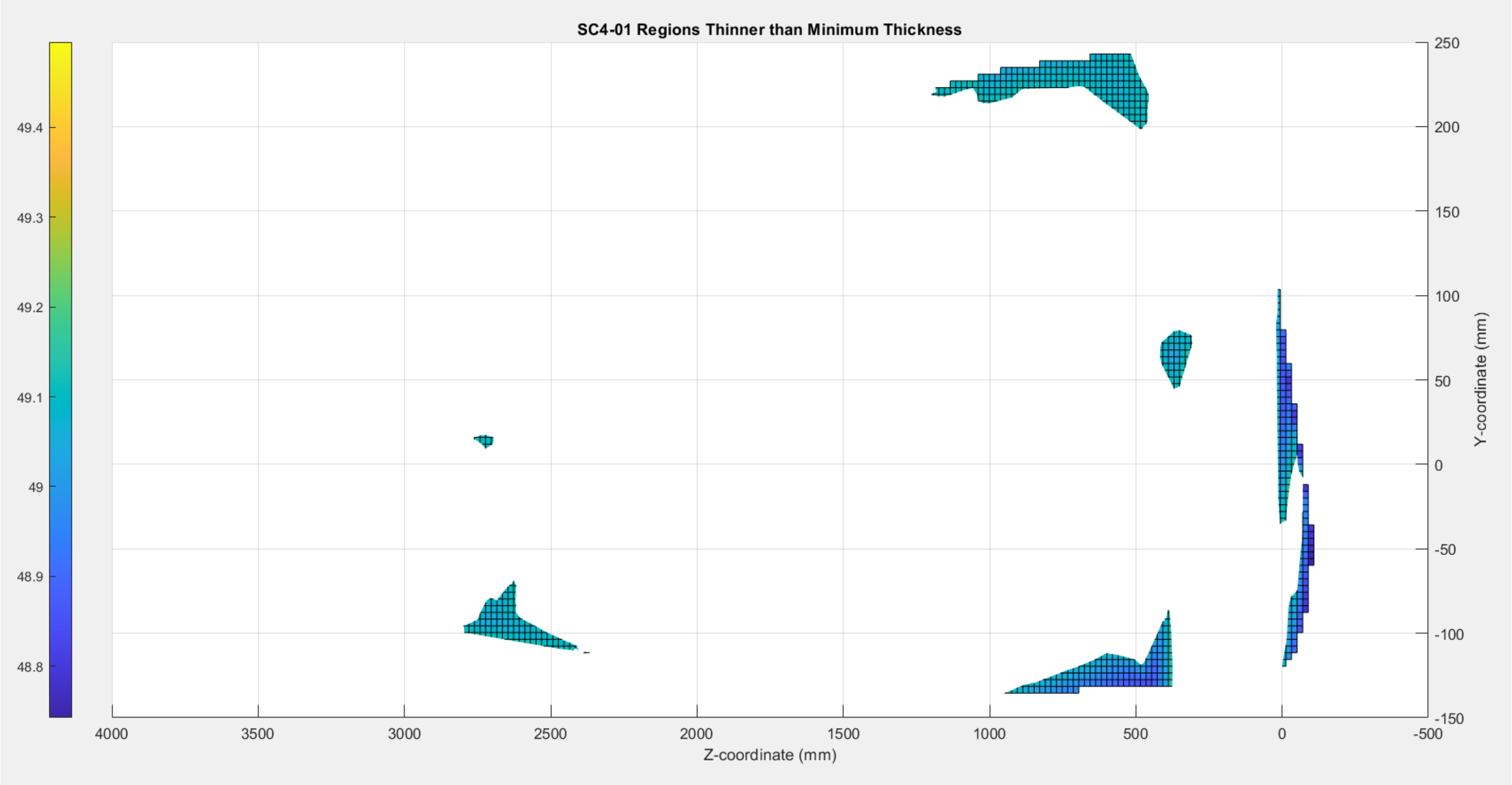


Figure 100 - SC4-01 Out of Tolerance Regions, Thin