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Task 6: Supporting Studies

OTEC Heat Exchanger Program: 2016 Ultrasonic Scanning for Corrosion Monitoring Report

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OTEC HEAT EXCHANGER PROGRAM

ULTRASONIC SCANNING FOR CORROSION MONITORING

FINAL REPORT

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Prepared For

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1. SUMMARY

Seawater corrosion of aluminum alloys can adversely impact the lifetime and performance of aluminum Ocean Thermal Energy Conversion (OTEC) heat exchangers. Since uniform corrosion rates for the aluminum alloys being considered for use in OTEC heat exchangers are low, the primary corrosion mechanisms of concern are surface pitting and crevice corrosion at gasket interfaces. Makai Ocean Engineering has developed a system to observe pit growth in-situ using optical imaging and ultrasonic thickness measurements which allows corrosion development to be monitored over time without the removal and destruction of samples. Makai is also testing treatments that may prevent or mitigate pitting corrosion. Three treatments (warm seawater pre-treatment, acid treatment, and hypochlorite treatment) are being tested on three aluminum alloys (Al 1100-H112, Al 3003-H14, and Al 5086-H116) in flowing (1 m/s) and near-stagnant cold, deep seawater (6 samples total) provided by the National Energy Laboratory of Hawaii Authority in Kailua-Kona, Hawaii.

Pits have been identified on four samples – Al 5086 control in flowing seawater (after 477 days), Al 3003 control in near stagnant seawater (after 306 days), and Al 3003 warm seawater pre-treatment in both flowing (after 241 days in cold seawater) and near stagnant seawater (after 199 days in cold seawater).

There are only seven samples that do not have crevice corrosion: Al 1100 and Al 3003 warm seawater pre-treatment samples in flowing seawater, Al 5086 warm seawater pre-treatment sample in near stagnant seawater, and Al 3003 and Al 5086 hypo-chlorination samples in flowing and near stagnant seawater.

Hypochlorite treatment has been the most effective and preventing pitting and/or crevice corrosion in Al 3003 and Al 5086. Warm seawater pre-treatment samples also show improved performance over the control and acid treatment samples but both Al 3003 warm seawater pre-treatment samples have pits (but no crevice corrosion). Only the Al 1100 with warm seawater pre-treatment in flowing seawater does not have localized corrosion; Al 1100 was not expected to perform well in cold seawater but was included in this test to evaluate treatment efficacy.

All samples with OCPs in the pitting region also have localized corrosion, indicating that OCP is at least a good indicator of the presence of local corrosion. We discuss the implications of aluminum corrosion and preventative treatments on OTEC heat exchangers.

2. INTRODUCTION

Aluminum alloys have been proposed for use in Ocean Thermal Energy Conversion (OTEC) heat exchangers for their high thermal conductivity, comparatively low cost, and overall good general corrosion resistance (due to formation of a protective oxide layer) in seawater environments. Although uniform corrosion rates for aluminum alloys are low, aluminum alloys are susceptible to surface pitting and crevice corrosion at gasket interfaces which can initiate when local galvanic cells develop between alloying elements and deposit corrosion product on the surface of the metal. Corrosion product can encase the immediate area and change the local environment which acts to accelerate the corrosion process. It is important to quantify this phenomenon because, in time, pits or crevice corrosion can penetrate the wall of the heat exchanger and cause refrigerant to leak into the seawater. For heat exchangers, this is considered a catastrophic failure and must be avoided.

Makai Ocean Engineering has been studying and quantifying the development of corrosion on aluminum alloys being considered for OTEC heat exchangers. Makai has developed a setup in which pit growth can be observed in-situ by optical imaging and ultrasonic scanning. Pitting sites are identified and corrosion product accumulation on the metal surface is observed using imagery. However, once corrosion product encapsulates a pit, no accurate measurements of pit size or depth can be made with imaging alone. With the addition of ultrasonic thickness scanning, the surface underneath the corrosion product can be observed and the 3-dimensional structure of the pit can be measured. Pit development can now be monitored over time without removal or destruction of samples.

Makai tested three alloys (Al 1100-H112, Al 3003-H114 and Al 5086-H116) and three corrosion mitigation techniques (warm seawater pre-treatment, hypo-chlorination and exposure to a diluted sulfamic acid) in flowing (1 m/s) and near stagnant cold seawater for a total of 18 samples. Six control samples, one of each alloy in flowing and near stagnant cold seawater, were also tested.

3. INSTRUMENTATION

The testing apparatus consists of four components: multi-column imaging racks used to expose the samples to seawater flow and take daily images; ultrasonic thickness scanning equipment; open circuit potential measurement equipment; and a laser profilometer to measure a sample's surface features before and after being exposed to seawater.

3.1. MULTI-COLUMN IMAGING RACKS

Makai Ocean Engineering's Multi-Column Imaging Racks (MCIR, Figure 3-1) have been in operation for over 4 years and have provided valuable insight into the development of corrosion. Each MCIR has 16 columns. Three ultrasonic samples (one of each alloy) can be mounted in a single column. High-resolution images (27μm size pixels) are collected on a daily basis. Specified regions of interest (ROI) can be photographed at higher resolution (0.4 μm per pixel).

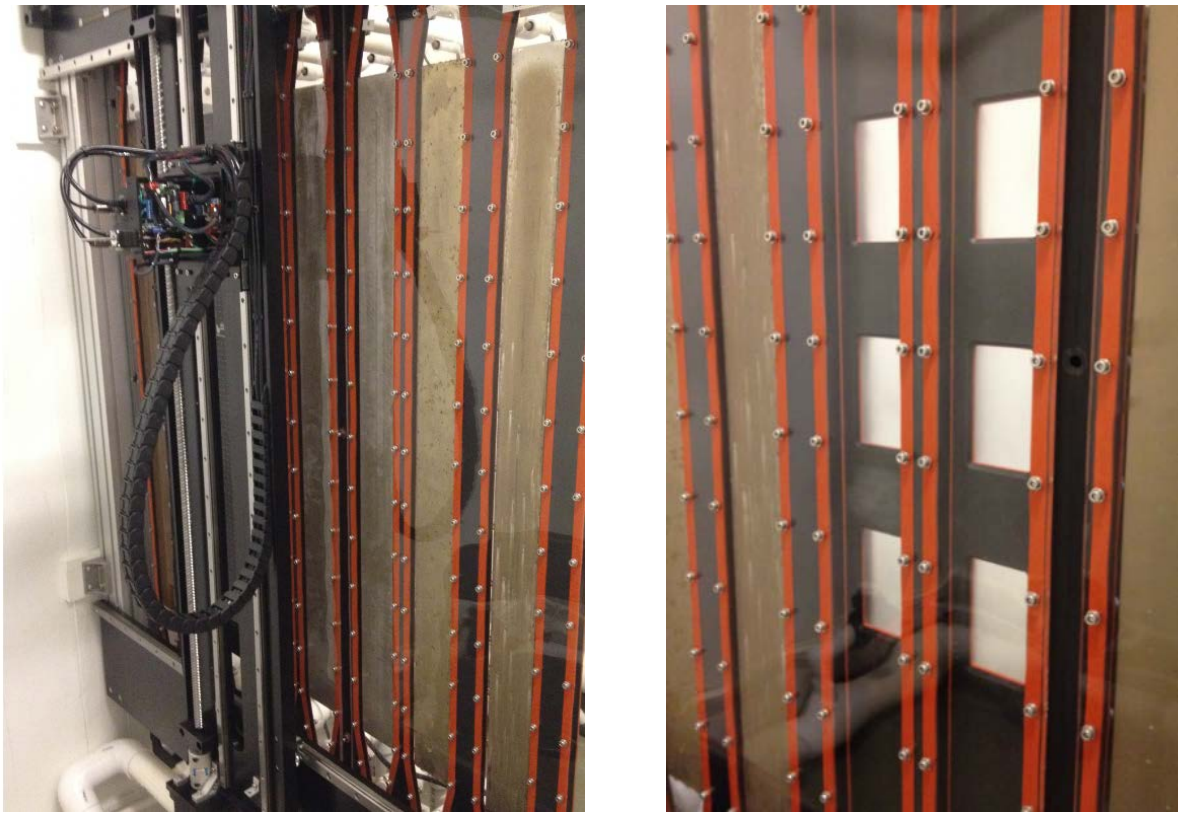

Figure 3-1. Left - Makai Ocean Engineering's corrosion imaging system. Right – several coupons of different alloys mounted in the imaging racks.

3.2. ULTRASONIC SCANNER

An ultrasonic scanner manufactured by NDT Systems which integrates a Raptor© Imaging Flaw Detector with a ¼" diameter 15 MHz ultrasonic transducer will be used in this study. Ultrasonic thickness measurements are performed by sending a high frequency sound pulse from the transducer placed on the back of a sample and measuring the time it takes for the sound reflection to return to the transducer. A fresh water source is provided to the face of the transducer as a sonic couplant and also functions as a lubricant. Thickness measurements across the sample are obtained with an NDT System's Tunnelscan© motorized X-Y stage with a 12" x 18" scan area. An X-Y stage allows a 3-dimensional surface to be created from individual thickness measurements. Mounting this stage to the back of the imaging racks permitted monitoring of several corrosion coupons at once (Figure 3-2).

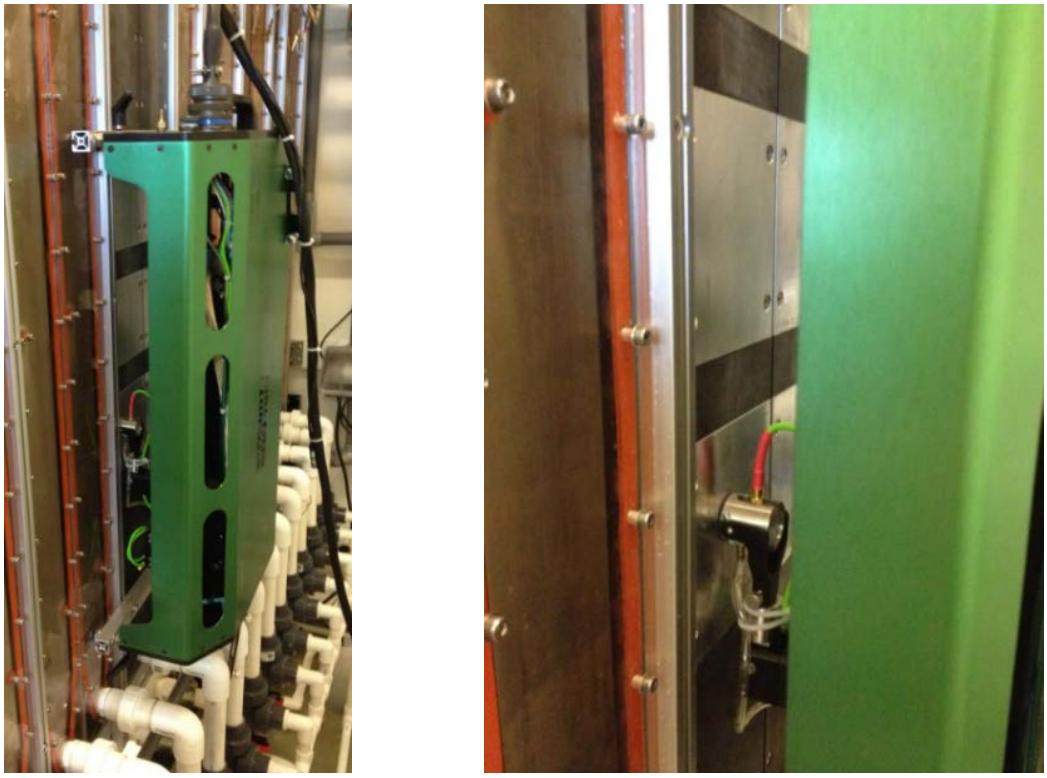

Figure 3-2. Left - Scanning stage mounted to the back side of the imaging racks. Right - Ultrasonic transducer in contact with a sample.

3.3. LASER PROFILOMETER

A CCS Prima® manufactured by Nanovea and a custom built motorized X-Y stage is used to create three-dimensional profiles of a sample surface. The laser profilometer uses chromatic confocal measurements to determine the distance to a surface from the laser head. The laser profiles can be obtained prior to seawater exposure and after the sample is removed from

seawater and corrosion product cleaned from its surface. The profilometer has high lateral and depth resolution, 8 μm and 1 μm respectively.

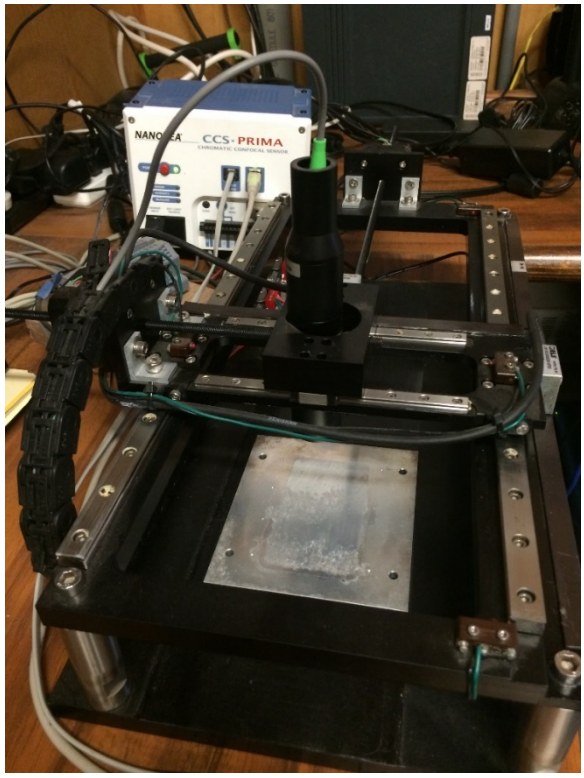

Figure 3-3. The laser profilometer scans the surface of a sample to measure corrosion depths.

3.4. ELECTROCHEMISTRY

Open circuit potential (OCP) is measured between a reference electrode and the sample. OCPs will be measured at least weekly (more frequently if warranted by sample performance) using a Fluke Multimeter. Changes in OCP may be indicative of localized corrosion and can be correlated with daily images and ultrasonic scans.

3.5. COMPARISON OF MEASUREMENT TECHNIQUES

There are advantages and disadvantages to each of three different measurement techniques (Table 3-1). The major drawback of the ultrasonic measurements is the large beam size of the transducer (13mm) makes pits look larger. Figure 3-4 compares ultrasonic and laser profilometer measurements of a pre-drilled flat-bottomed reference hole. Despite the difference in measured feature size, both techniques yield a consistent depth for the pre-drilled hole.

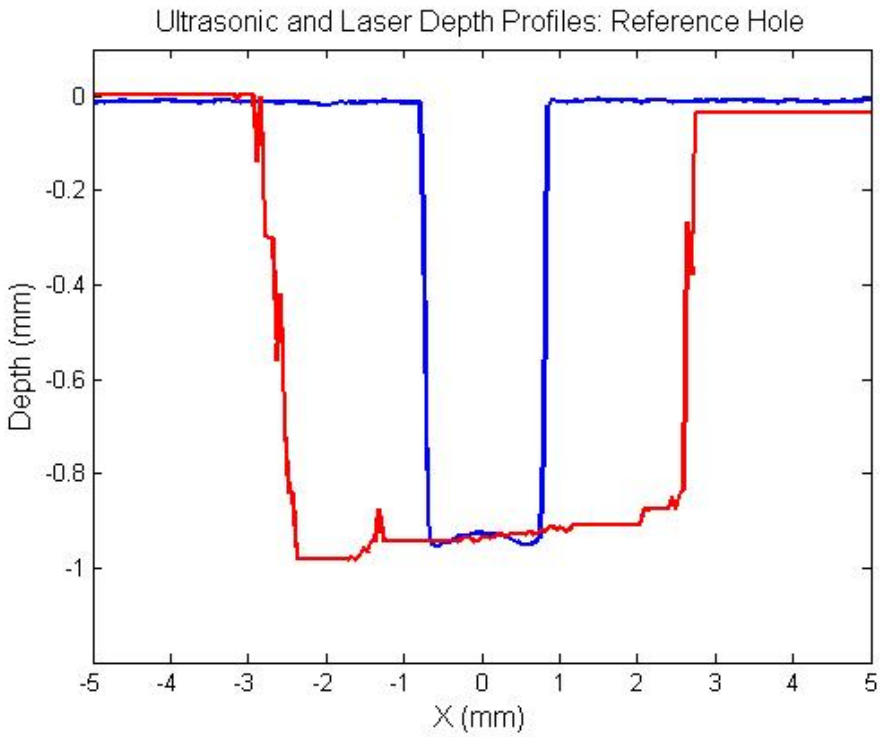

Figure 3-4. Comparison of a 0.76 mm diameter reference-hole profile measured ultrasonically (red) and with the laser profilometer (blue).

Ultrasonic measurements are ideal for in-situ measurements of heat exchanger wall penetration due to corrosion. This method can be implemented on an OTEC plant without disturbing operation. The maximum pit depth observed by the scanning will be instrumental in estimating lifetimes of OTEC heat exchangers.

The higher resolution laser profilometry helps us understand the mechanisms at work in the corrosion process. However, laser profilometry cannot be performed on heat exchangers without component removal.

Although imaging is non-destructive it is not easily implemented because it requires windows to view the interior surfaces of the heat exchanger or highly specialized imaging systems. Imaging is useful from an experimental point of view, correlations can be drawn between surface behavior and pit depth. Studying the build-up of corrosion product over time or as a function of pit depth allows us to estimate the loss of heat exchanger efficiency due to fouling by corrosion product.

Table 3-1. Comparison of measurement techniques.

Measurement	Type	Lateral Resolution	Depth Resolution	Can be implemented in an operating OTEC plant?
Ultrasonic Scanning	Non-destructive	3 mm	40 µm	Yes
Laser Profilometry	Destructive	8 µm	1 µm	No
Imaging	Non-destructive	27 µm, 0.4 µm	none	Difficult

4. TEST CONFIGURATION

Testing was conducted in cold, deep sea water (7ºC, 670 m) supplied by NELHA to Makai's corrosion testing facilities. One sample of each alloy was installed in a single column in the cold seawater (CSW) MCIR. Eight columns in the CSW MCIR were used for this test. Imaging and ultrasonic scanning systems were used to observe samples. Table 4-1 summarizes the test configuration.

Table 4-1. Test configuration.

Column	Sample IDs	Water Flow	Treatment
9	ut5-18, ut3-18, ut1-18	Near Stagnant	Control
10	ut5-1*, ut3-17, ut1-17	Flowing	Control
4	ut5-11, ut3-11, ut1-11	Flowing	Warm seawater pre-treatment
5	ut5-12, ut3-12, ut1-12	Near Stagnant	Warm seawater pre-treatment
6	ut5-16, ut3-16, ut1-16	Near Stagnant	Hypo-chlorination
7	ut5-15, ut3-15, ut1-15	Flowing	Hypo-chlorination
14	ut5-14, ut3-14, ut1-14	Near Stagnant	Acid Treatment
15	ut5-13, ut3-13, ut1-13	Flowing	Acid Treatment

4.1. ALLOYS

In previous tests, Al 6061 and Al 2024 corroded quickly and severely in cold seawater; neither alloy is suitable for use in OTEC heat exchangers. Al 3003 and Al 1100 have shown better performance in cold seawater (results of box coupon testing) and replaced Al 6061 and Al 2024 for this test. Al 5086 performed well in the previous test and was re-tested. Material certifications were provided for the raw material and can be found in Appendix A.

4.2. CORROSION MITIGATION TREATMENTS

Makai has been studying techniques to mitigate pit development and crevice corrosion. Preliminary results have been encouraging and the efficacy of three treatments – warm seawater pre-treatment, daily hypo-chlorination, and exposure to a diluted sulfamic acid based cleaner – were compared in this test. Treatments are expected to prevent and/or minimize pitting and crevice corrosion.

4.2.1. Warm Seawater Pre-treatment

In warm seawater, aluminum quickly builds up a uniform oxide layer that protects the metal against further corrosion. In contrast, this oxide layer does not develop as readily in cold seawater. The warm seawater pre-treatment protocol was developed on the hypothesis that corrosion resistance in cold seawater would improve if samples exposed in cold seawater had the same protective oxide layer as samples in warm seawater. Initially exposing samples in warm

seawater allows the oxide layer to develop and, when performed carefully, the developed oxide layer remains when samples are relocated to cold seawater. Previous testing established 40 days in warm seawater is sufficient time to build the oxide layer.

4.2.2. Hypo-chlorination

Biofouling develops on untreated sample surfaces exposed to seawater. Bacterial colonies have been observed on samples exposed to cold seawater. While the exact mechanism for pit initiation is unknown, any difference in the local surface environment is likely to accelerate corrosion; thus, bacterial colonies on a sample's surface may act as pit initiation sites. Samples will be exposed to 100 ppb chlorine for 1 hour daily to control the growth of bacterial colonies. This hypo-chlorination treatment routine is used in warm seawater and has been shown to eliminate biofouling.

4.2.3. Sulfamic Acid Based Treatment

Previous testing demonstrated a sample's open circuit potential (OCP) is correlated with corrosion activity. Samples have shown a marked change in OCP once pitting begins. Treatment of a sample with a mild acid will strip the oxide layer and possibly remove local environments that may have developed, essentially 'resetting' the surface to the condition it was in when first exposed to seawater. When treated, a sample's OCP will return to the pre-corrosion value and remain there for a period of time before pitting reinitiates (Figure 4-1). The interval between treatments varies and depends on the alloy being treated. Application of 5% sulfamic acid for 5 minutes when OCP reaches above -800 mV has been effective at stopping pitting in Al 6063. Acid treatments were performed every 2 months.

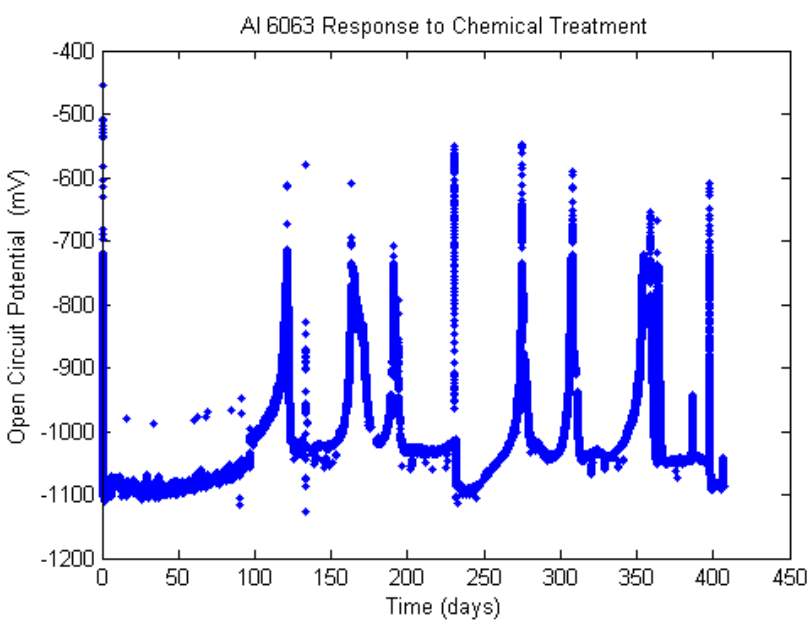

Figure 4-1. Open circuit potential of an AL 6063 sample that underwent periodic chemical treatments. Pitting starts when the OCP rises above -800 mV, treatments return the sample's OCP to the -1000 mV range, where pitting does not develop.

4.3. FLOWING VS NEAR STAGNANT SEAWATER

Each alloy/treatment combination was tested in seawater flowing at a velocity representative of the actual flow in a heat exchanger (~1 m/s) and near stagnant seawater flow since regions of dead flow inevitably develop in a heat exchanger. Comparing these two flow regimes will give us insight into required improvements to the design of heat exchangers.

4.4. SAMPLE PREPARATION

Several issues arose in sample procurement and installation. The samples were received with a sanded surface finish which was unacceptable for testing. Samples were returned for re-surfacing and received with tool marks on the surface. Although not ideal, we decided the finish was acceptable for testing. Samples also did not have countersunk holes as specified in the drawing. Countersinking was performed on-site by Makai, with care taken to ensure the exposed surface would not come into contact with metal or other contaminants. Finally, perhaps due to the re-surfacing, the non-exposed side (the side scanned by the ultrasonic scanner) of some samples did not lie flush with the mounting plate. A smooth transition is needed for the transducer to maintain adequate contact and not “catch” on edges. With the samples screwed into place, a sander was used to remove excess material from the mounting plate and create a smooth, even transition for the transducer. Some material may have also been removed from the back of the sample in the process.

Laser profilometer scans of the test surfaces were conducted prior to exposure for each sample. All corrosion samples were degreased, cleaned with simple green, and rinsed with ethanol before installation to remove surface contaminants.

Alloys in each column were arranged in the same order from top to bottom: Al 5086, Al 3003, and Al 1100. Warm seawater pre-treatment samples were exposed to warm seawater on 4/22/15 and moved to cold seawater on 6/15/15. Control, hypo-chlorination, and acid treatment samples were exposed to cold seawater on 5/21/15.

5. RESULTS

Warm seawater pre-treatment samples were exposed to warm seawater on 4/22/15 and moved to cold seawater on 6/15/15. Warm seawater pre-treatment samples have been exposed for 15 months. Control, hypo-chlorination, and acid treatment samples were exposed to cold seawater on 5/21/15. Control, acid treatment, and hypo-chlorination samples have been exposed for 14 months. Imaging has been performed daily, electrochemical monitoring has been performed on a weekly, and ultrasonic scans have been performed monthly.

5.1. OBSERVATIONS

Pitting and crevice corrosion observations are summarized in Table 5-1. Only six samples have no observed corrosion.

Table 5-1. Summary of observed localized corrosion on samples.

Sample	Treatment	Seawater	Pits?	Crevice?
ut1-11	**Warm seawater pre-treatment**	**Flowing**	**No**	**No**
ut1-12		Near-stagnant	No	Yes
ut1-13	Acid treatment	Flowing	No	Yes
ut1-14		Near-stagnant	No	Yes
ut1-15	Hypo-chlorination	Flowing	No	Yes
ut1-16		Near-stagnant	No	Yes
ut1-17	Control	Flowing	No	Yes
ut1-18		Near-stagnant	No	Yes
ut3-11	Warm seawater pre-treatment	Flowing	Yes	No
ut3-12		Near-stagnant	Yes	Yes
ut3-13	Acid treatment	Flowing	No	Yes
ut3-14		Near-stagnant	No	Yes
ut3-15	**Hypo-chlorination**	**Flowing**	**No**	**No**
ut3-16		**Near-stagnant**	**No**	**No**
ut3-17	Control	Flowing	No	Yes
ut3-18		Near-stagnant	Yes	Yes
ut5-11	**Warm seawater pre-treatment**	Flowing	No	Yes
ut5-12		**Near-stagnant**	**No**	**No**
ut5-13	Acid treatment	Flowing	No	Yes
ut5-14		Near-stagnant	No	Yes
ut5-15	**Hypo-chlorination**	**Flowing**	**No**	**No**
ut5-16		**Near-stagnant**	**No**	**No**
ut5-17	Control	Flowing	Yes	Yes
ut5-18		Near-stagnant	No	Yes

Pits have been observed on four samples – Al 5086 control in flow seawater (ut5-17), Al 3003 control in near stagnant seawater (ut3-18), and Al 3003 warm seawater pre-treatment in both flowing (ut3-11) and near stagnant seawater (ut3-12).

The pit on ut3-11 (Figure 5-1) is relatively small and has not been detected on ultrasonic scans. The pit initially looked similar to biofouling and surface discoloration and was not identified until recent images. By backtracking through the images, the pit was first distinguishable in images taken on 2/11/16.

The pit on ut3-12 (Figure 5-2) has been detected on ultrasonic scans. From the most recent images, the pit appears to be part of crevice corrosion, but backtracking through the images shows the pit developed first and some of the corrosion product buildup spread towards the gasket.

On ut3-18, the pit developed rapidly. No pits were identified in the 2/5/16 ultrasonic scan or image. A small pit first appeared on the 2/20/16 – Day 275 image (Figure 5-3). By the next scheduled ultrasonic scan on 3/22/16 – Day 306, the maximum pit depth was already -0.5 mm (Figure 5-14 and Appendix B).

On ut5-17, small pits were observed after 477 days via imaging. A pit (circled on Figure 5-4) was detected on the ultrasonic scan at Day 733 (Figure 5-15 and Appendix B). Biofouling began around Day 537 and became severe after Day 658. Images after 4/18/16 were indistinguishable due to biofouling coverage.

Crevice corrosion has observed on all except seven samples. Of the samples that received warm seawater pre-treatment, Al 5086 in near stagnant seawater (ut5-12), Al 1100 and 3003 in flowing seawater (ut1-11 and ut3-11, respectively) do not have crevice corrosion. Al 5086 in flowing seawater (ut5-11) has crevice corrosion identified on ultrasonic scans but not visible on images. Of the samples receiving daily hypo-chlorination treatment, only the Al 1100 samples (in flowing (ut1-15) and near stagnant seawater (ut1-16)) have crevice corrosion. All samples receiving acid treatment have crevice corrosion. All control samples have crevice corrosion, although, crevice corrosion did not occur on the Al 5086 until 477 days of total exposure. The Al 1100 and Al 3003 control samples in flowing seawater developed crevice corrosion before the Al 5086 sample. Except for Al 1100 in near stagnant seawater receiving daily hypo-chlorination treatment, samples with crevice corrosion identified in the images also have crevice corrosion identified in the ultrasonic scans.

The latest images, ultrasonic scans, and overlain images are shown below (Figure 5-5 through Figure 5-12). Time lapse ultrasonic scans of each sample are shown in Appendix B.

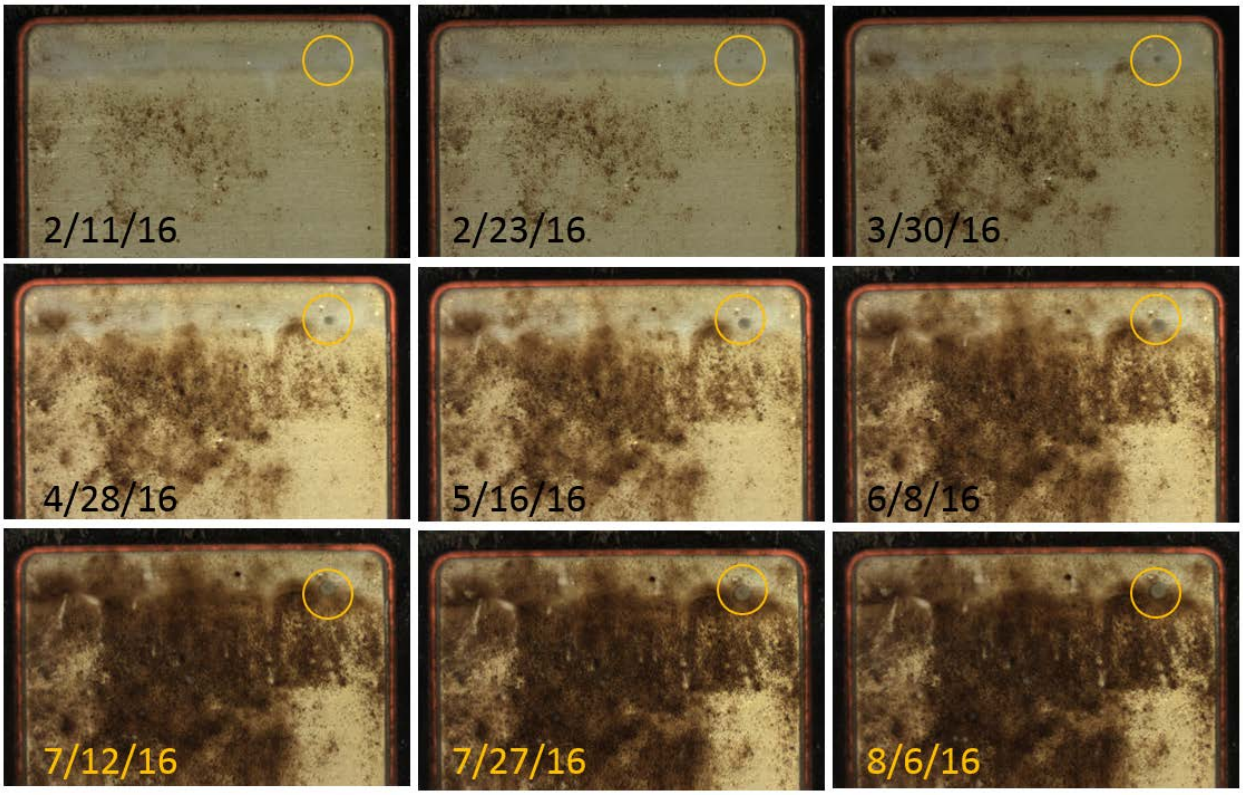

Figure 5-1. Pit development on ut3-11. Pit appears to be a biofouling spot initially. Pit has not been detected on ultrasonic scans.

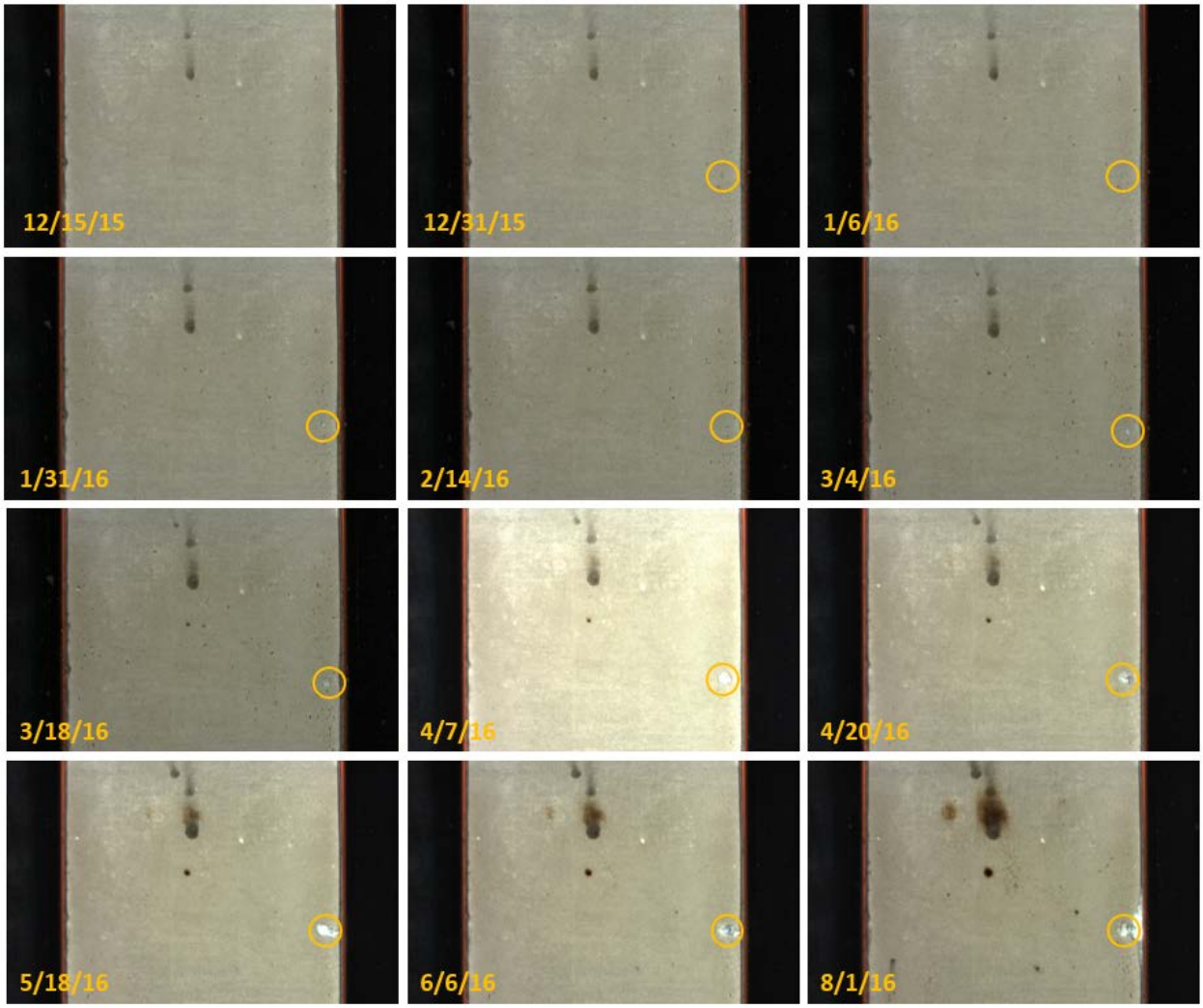

Figure 5-2. Pit development on ut3-12. In images after 4/20/16, the pit appears to be related to crevice corrosion but earlier images confirm that the pit developed first.

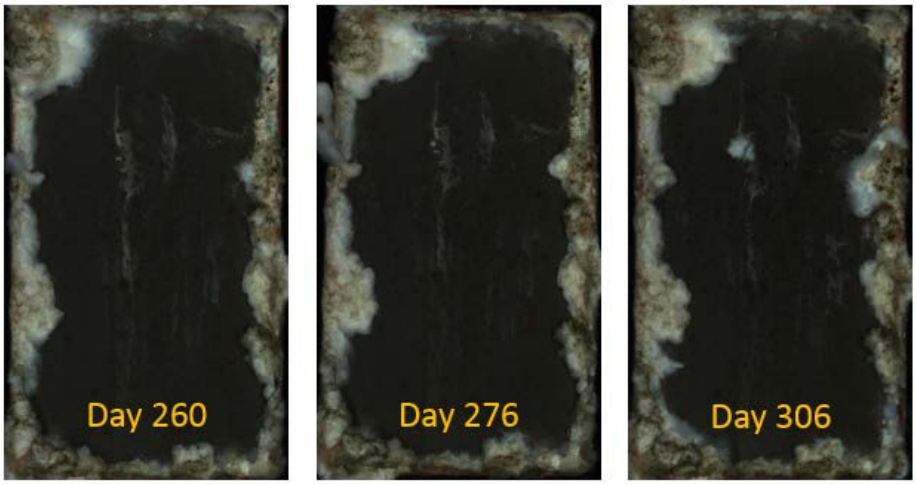

Figure 5-3. Pit initiation on ut3-18. Pit was barely detectable at Day 260 but -0.5 mm deep by Day 276 according to ultrasonic scan.

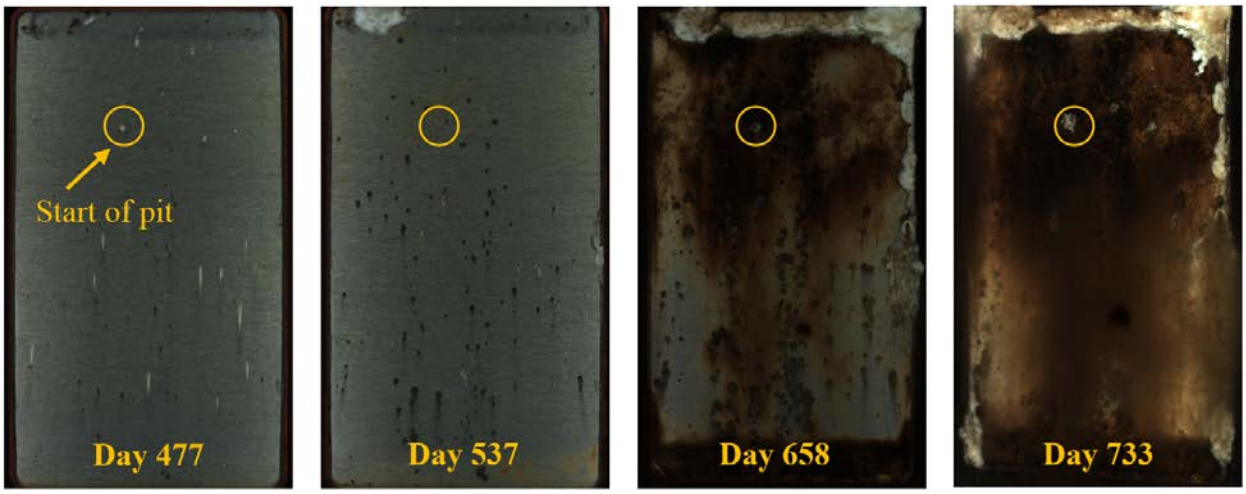

Figure 5-4. Pit development on ut5-17. Pit is small and not detected on ultrasonic scans until Day 733. Corrosion product buildup becomes noticeable by Day 658. Crevice corrosion and biofouling also worsen between Day 537 and Day 658.

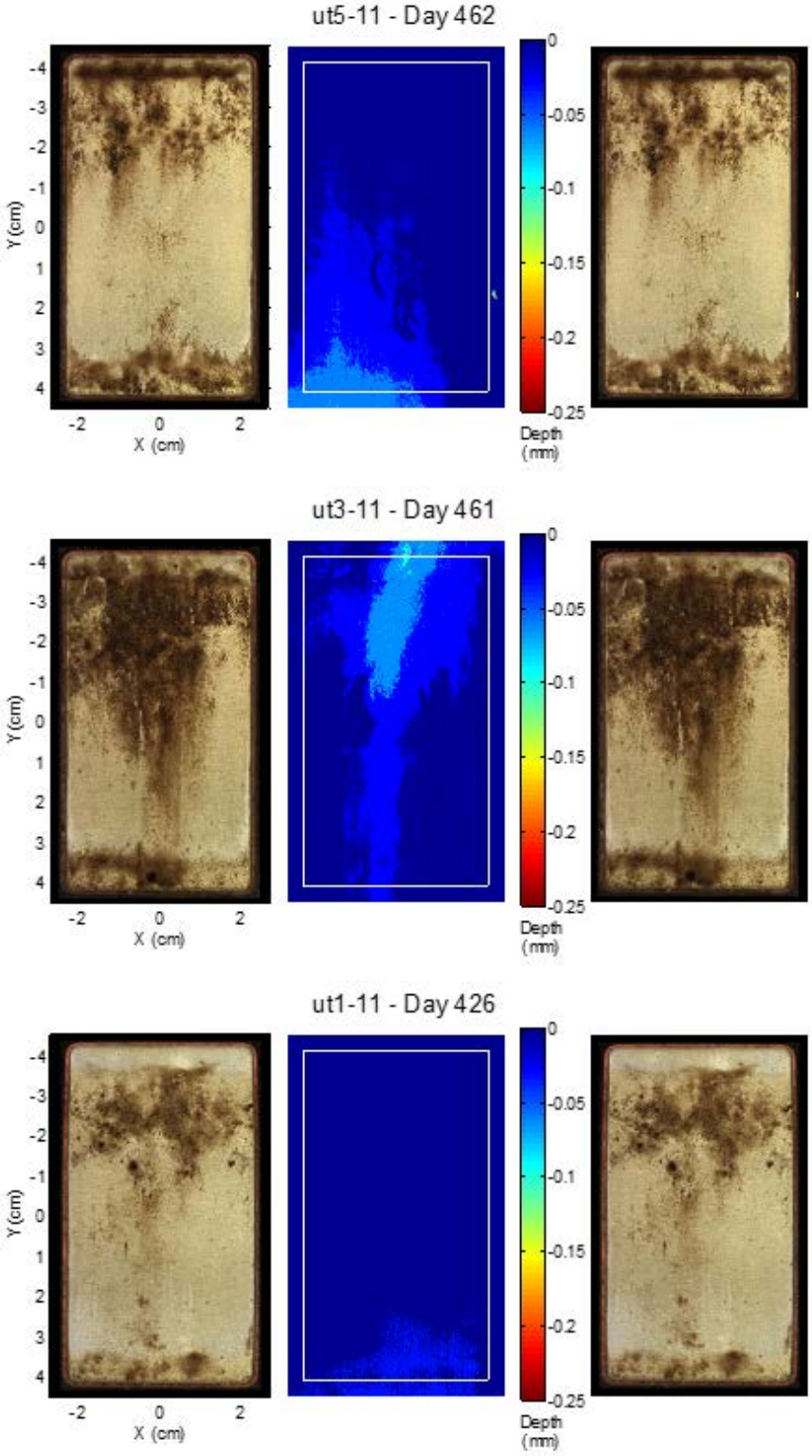

Figure 5-5. Warm seawater pre-treatment samples in flowing seawater. No corrosion features are observed in images but ut5-11 has crevice corrosion detected by ultrasonic scan.

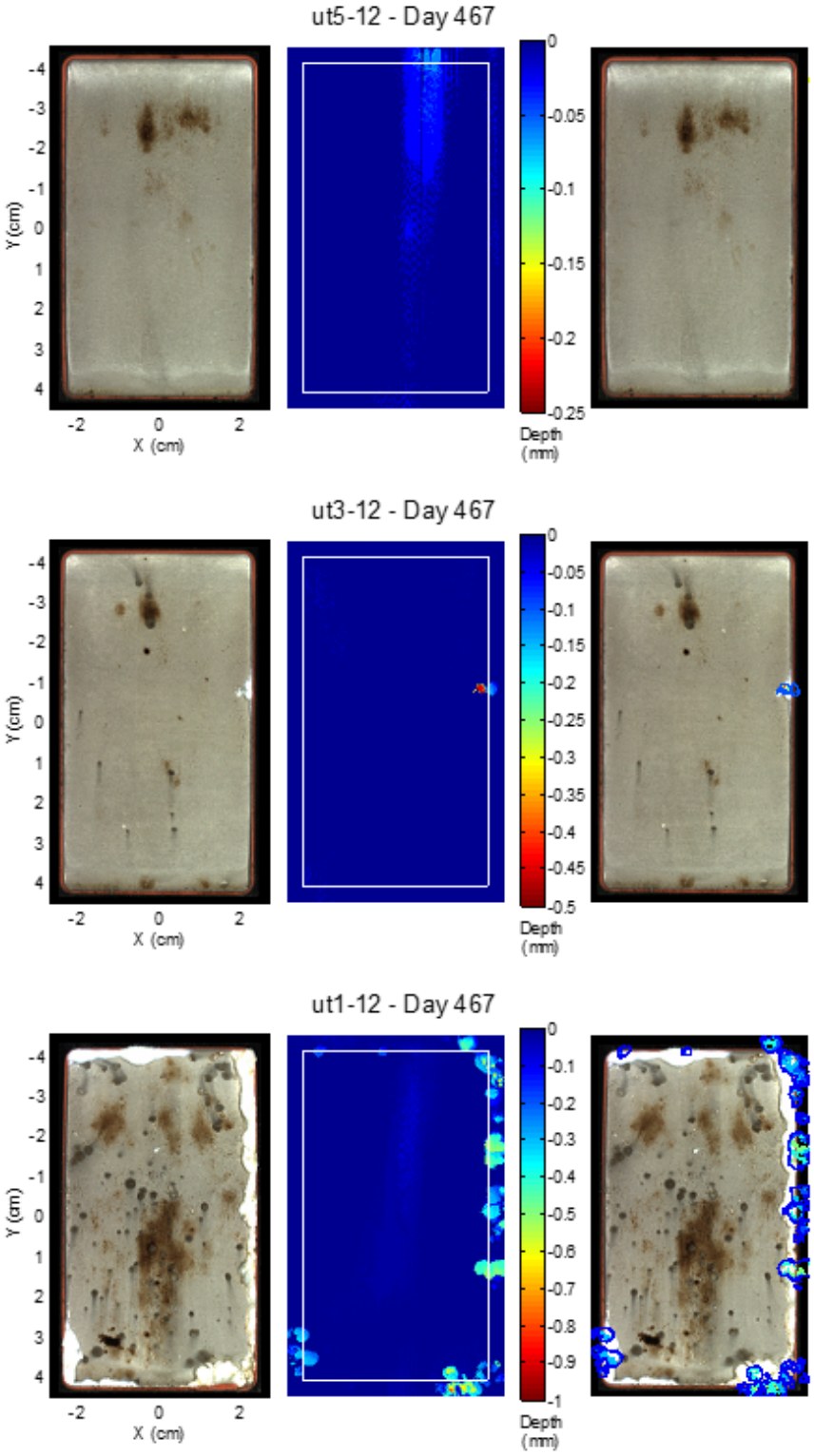

Figure 5-6. Warm seawater pre-treatment samples in near stagnant seawater. Crevice corrosion observed in images and ultrasonic scans on ut3-12 and ut1-12. A pit is visible on ut3-12.

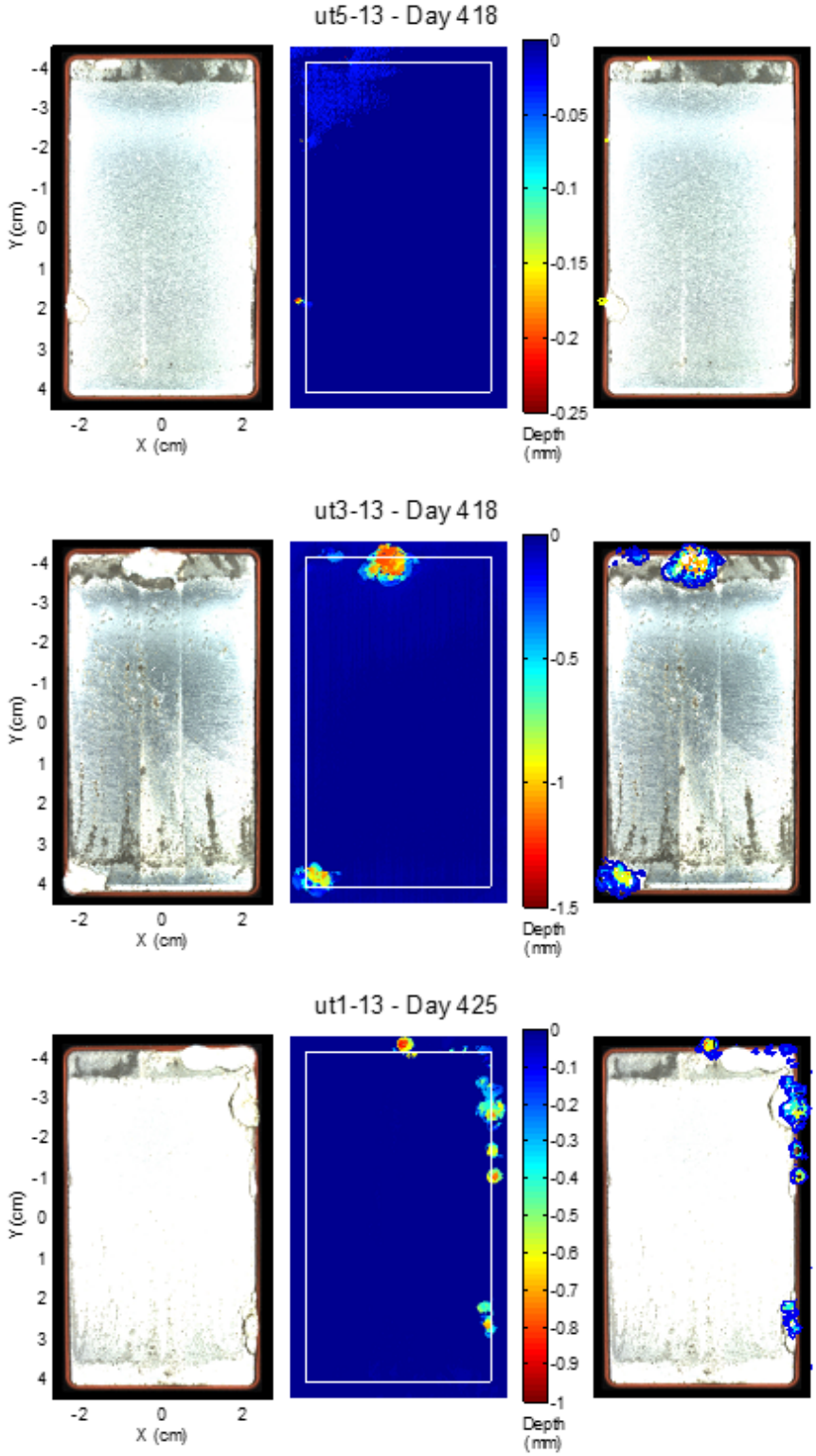

Figure 5-7. Acid treatment samples in flowing seawater. Crevice corrosion is visible in images and ultrasonic scans for all samples.

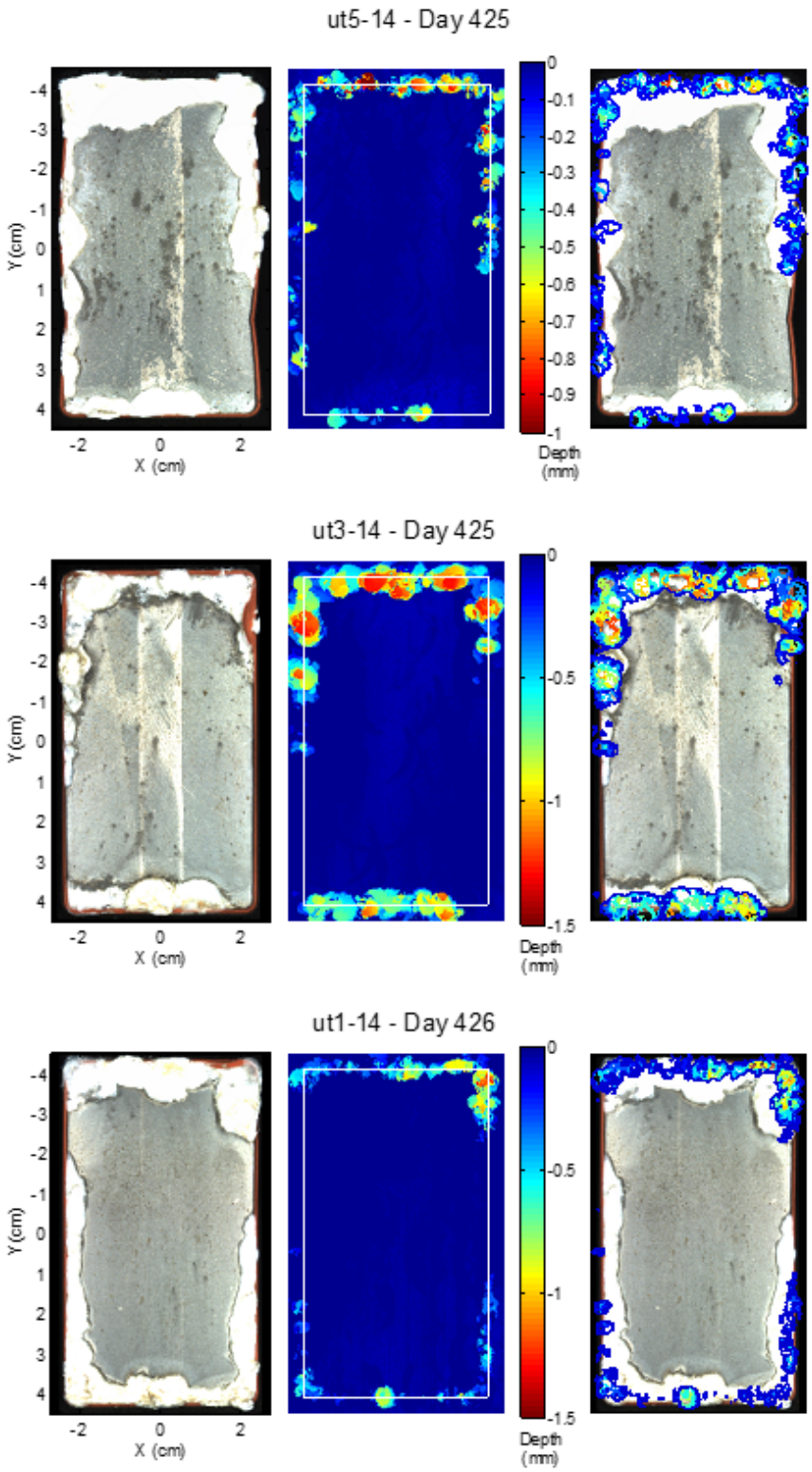

Figure 5-8. Acid treatment samples in near stagnant seawater. Crevice corrosion is severe and visible in imaging and ultrasonic scans for all samples.

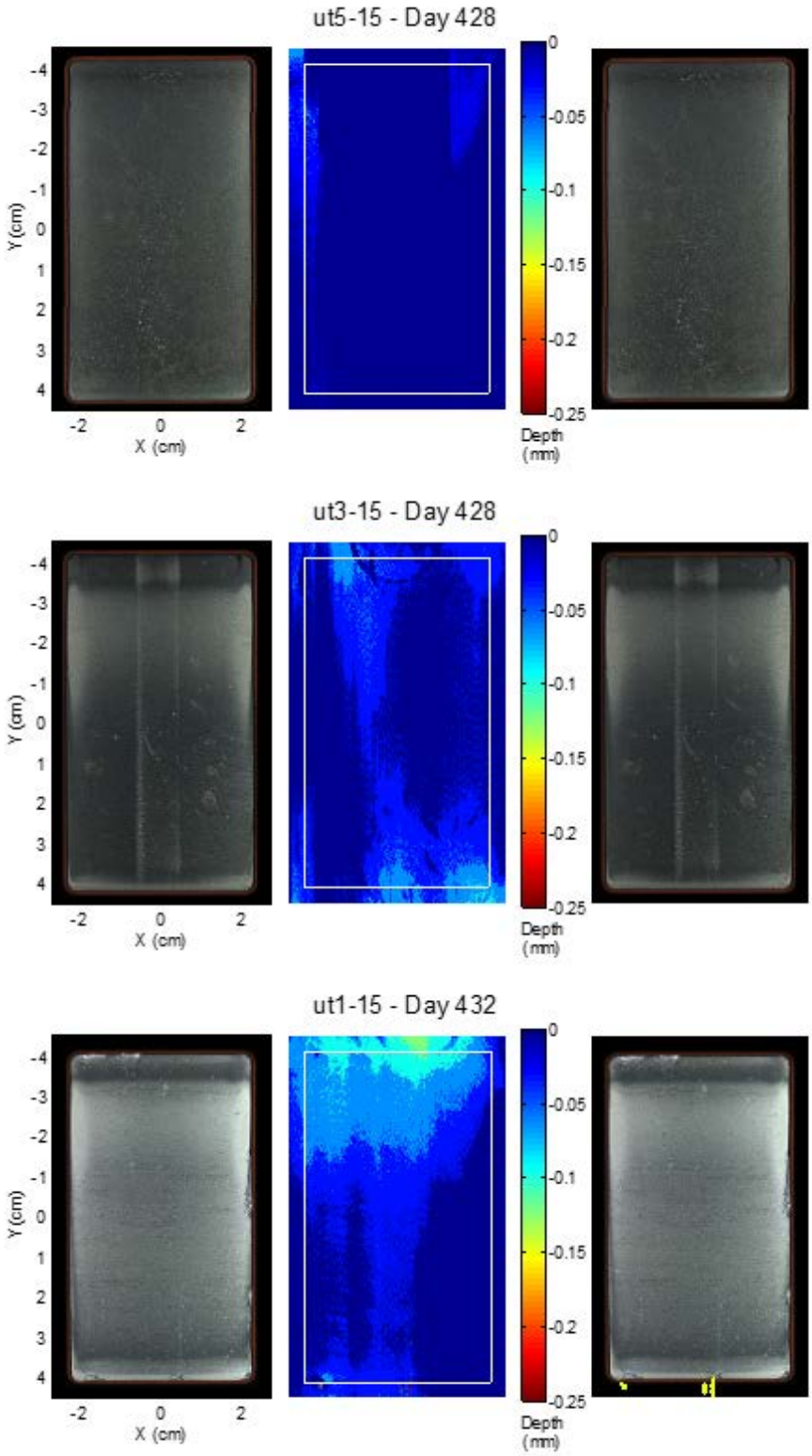

Figure 5-9. Hypo-chlorination treatment in flowing seawater. Crevice corrosion is visible in images and detected on the ultrasonic scan for ut1-15. ut3-15 and ut5-15 do not have observable corrosion features. Surfaces appear new and shiny.

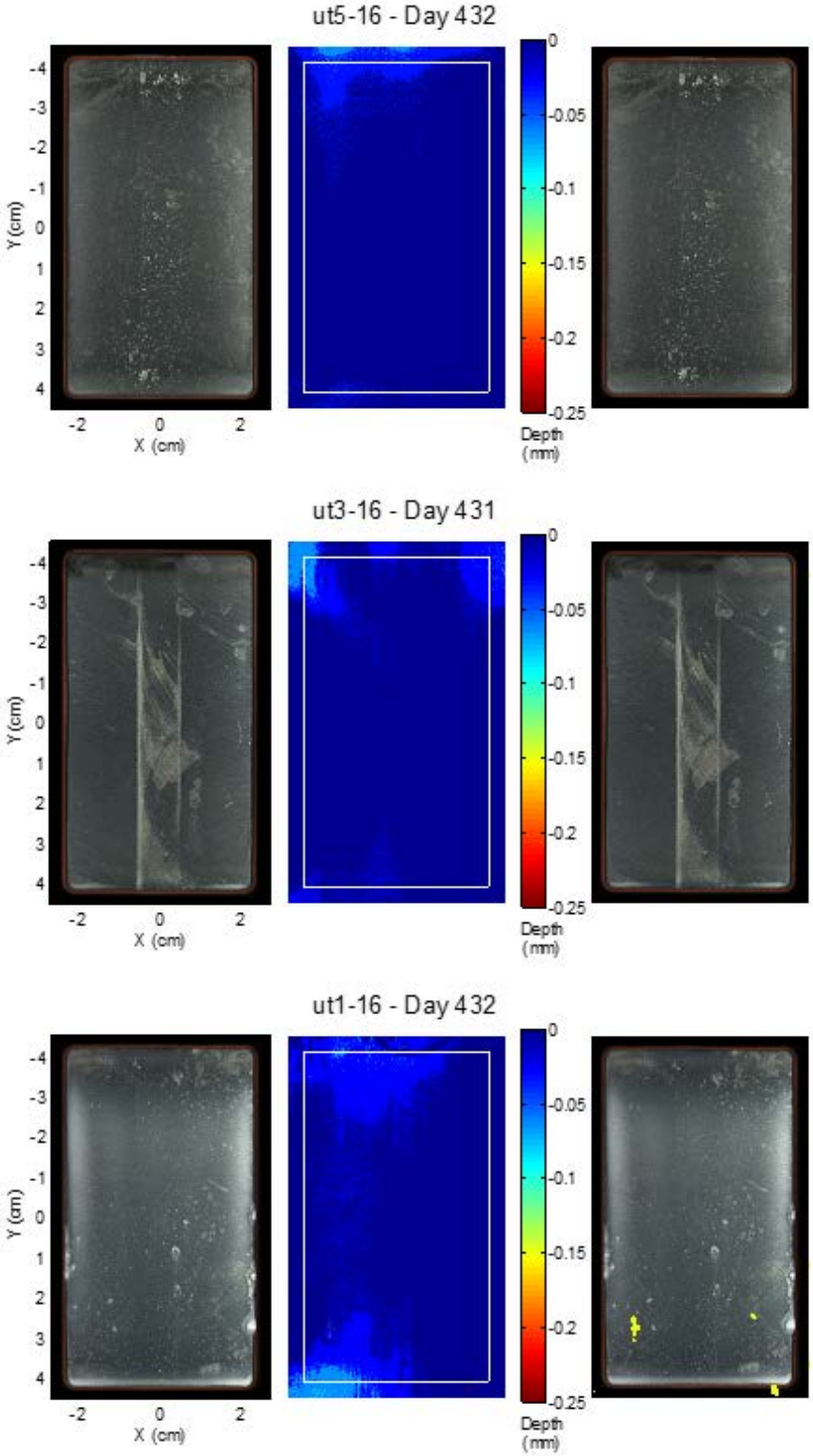

Figure 5-10. Hypo-chlorination samples in near stagnant seawater. The beginning of crevice corrosion is visible in images and on the ultrasonic scan for ut1-16. ut3-16 and ut5-16 do not have observable corrosion features.

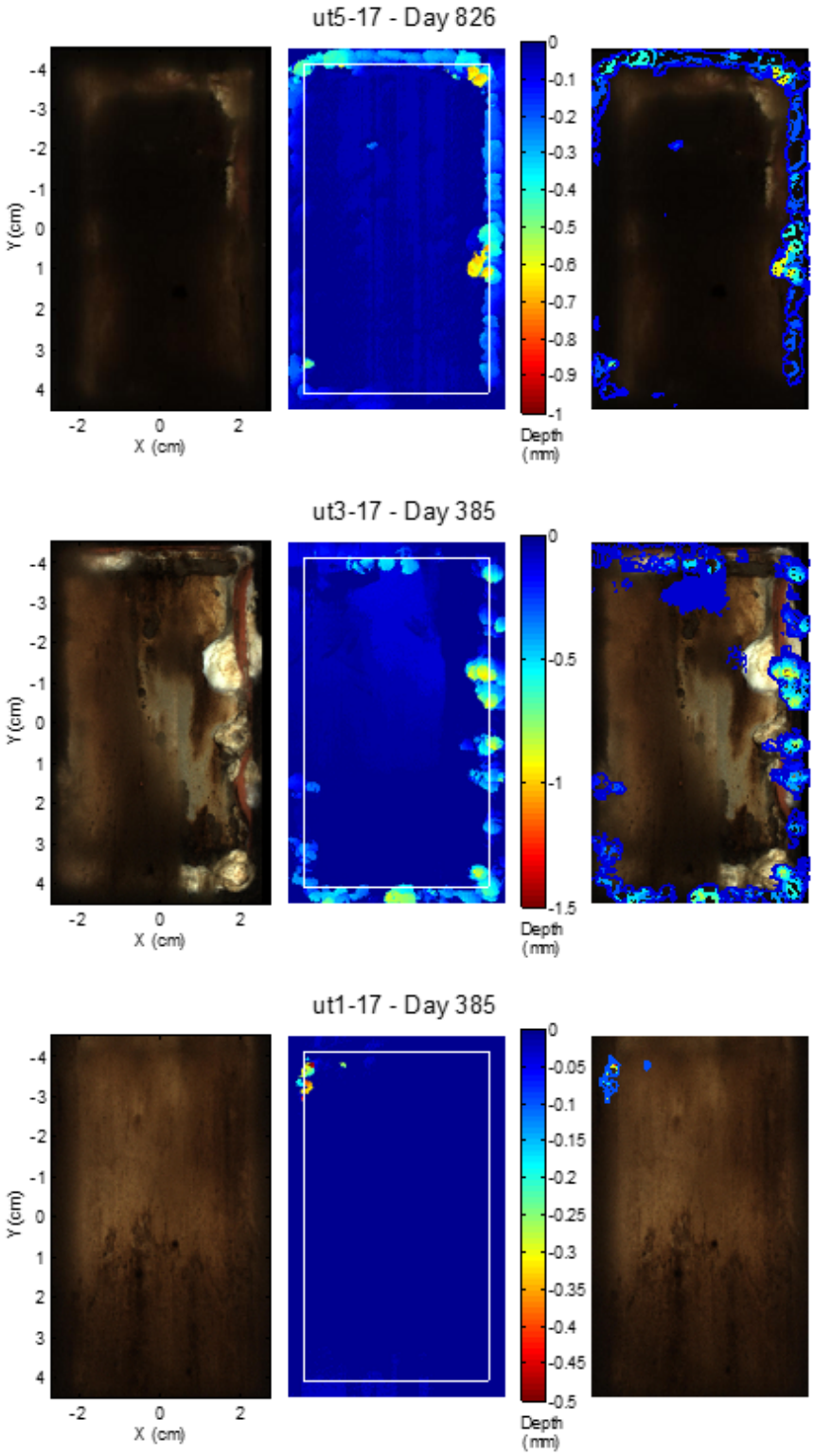

Figure 5-11. Control samples in flowing seawater. Sample surfaces and testing column window is severely biofouled. Crevice corrosion is most severe on ut3-17; the right side of the gasket is distorted from corrosion product. Three pits were visible on earlier images of ut5-17, but now obscured by biofilm. Only one pit is detected on ultrasonic scans.

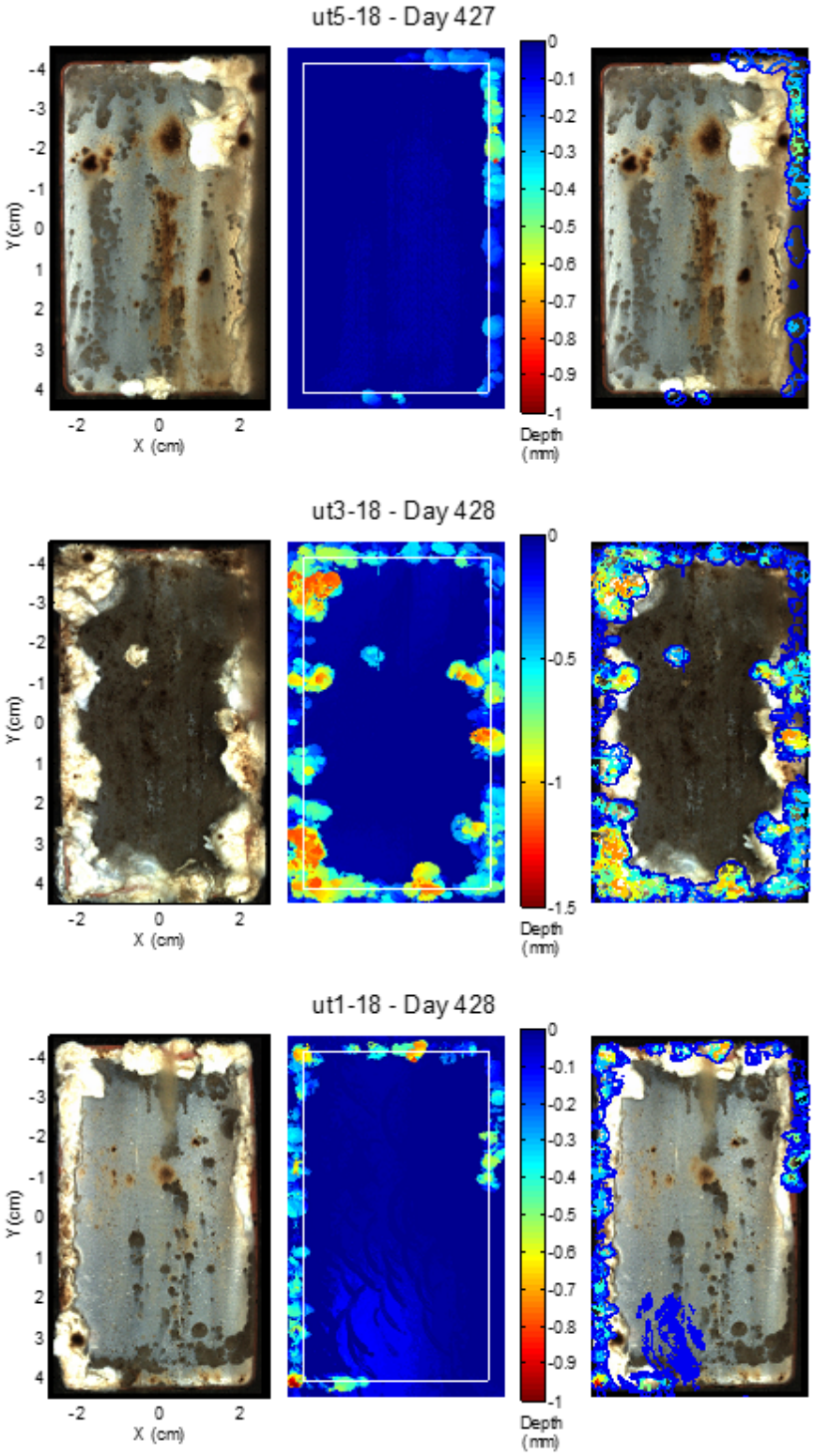

Figure 5-12. Control samples in flow near stagnant seawater. Crevice corrosion is observed on images and ultrasonic scans of all samples; corrosion (and biofouling) is most severe on ut3-18. There is a large pit on in the middle of ut3-18.

5.2. PITTING MEASUREMENTS

Ultrasonic measurements of pit depth and pitted surface area were used to establish pit growth and crevice corrosion rates which are crucial in establishing the lifetime of an OTEC heat exchanger. To separate the effect of crevice corrosion, only data from a 1.5” x 2.75” rectangle at the center of the sample (68.6% of the total exposed surface area) was used to determine pit depth and coverage. In these regions, areas with depths greater than 0.05 mm were considered pits. The maximum pit depth, average pitted depth, and pitted area were tabulated.

The average pitted depth (proportional to the total volume of material removed) was calculated from the pit-depth and pitted area measurements. Because area measurements determined by the ultrasonic scans are biased due to the large beam size, the values were normalized by dividing by the total area and multiplying by a scale factor (determined previously by comparing ultrasonic and post-processing laser profilometry scans). The % corroded surface area was calculated by dividing the number of pixels with depths greater than 0.05 mm (pit threshold) by the number of pixels in the pit analysis area. The corroded volume per unit area was calculated by multiplying the average depth of the pitted pixels by the number of pitted pixels divided by the total number of pixels in the pit analysis area.

The maximum pit depths on ut3-12 and ut3-18 are over 0.5 mm deep but do not appear to be getting deeper whereas the maximum pit depth on ut5-17 continues to get deeper (Figure 5-13 through Figure 5-15). The corroded volume per unit area and % corroded surface area has plateaued for ut3-18 but continues to increase for ut3-12 and ut5-17 (Figure 5-16).

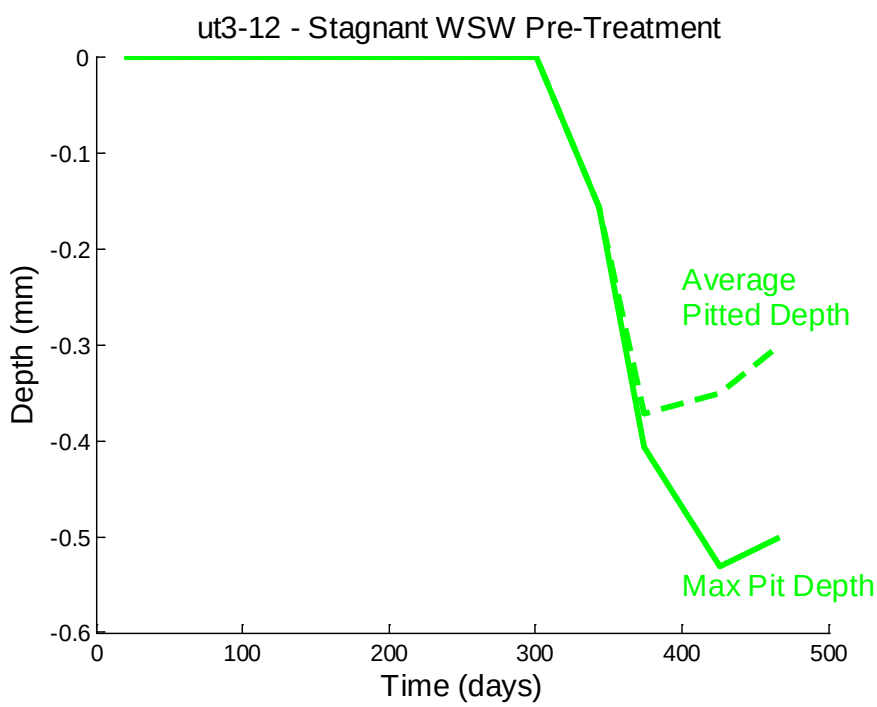

Figure 5-13. Maximum and average pitted depth for ut3-12.

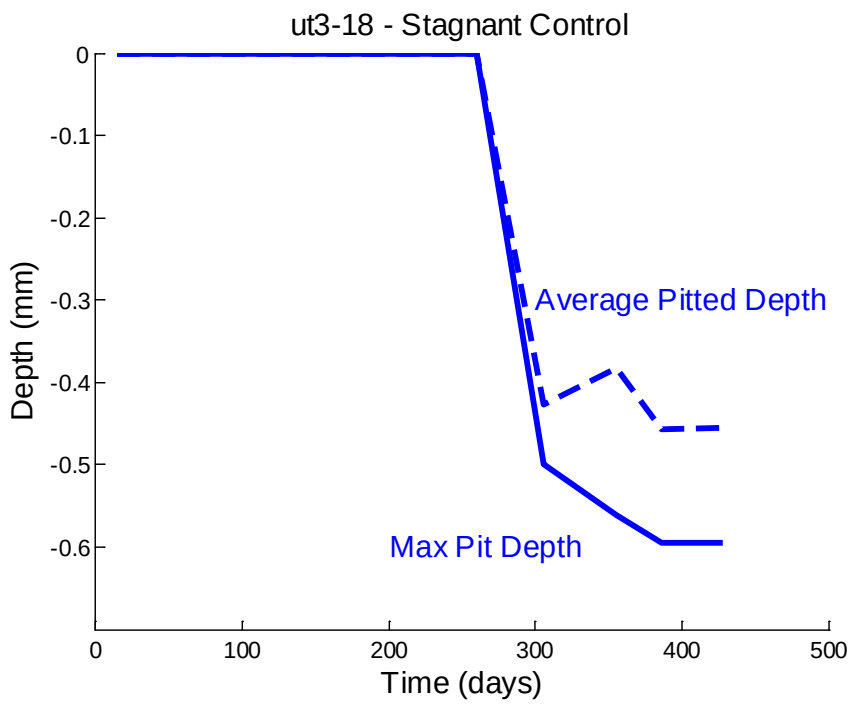

Figure 5-14. Maximum and average pitted depth for ut3-18.

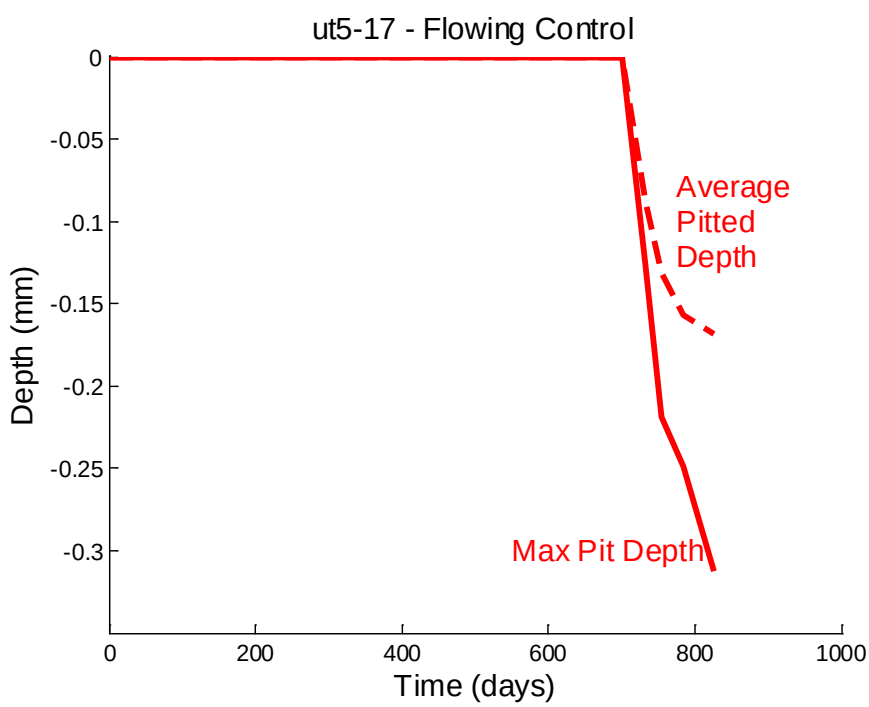

Figure 5-15. Maximum and average pitted depth for ut5-17.

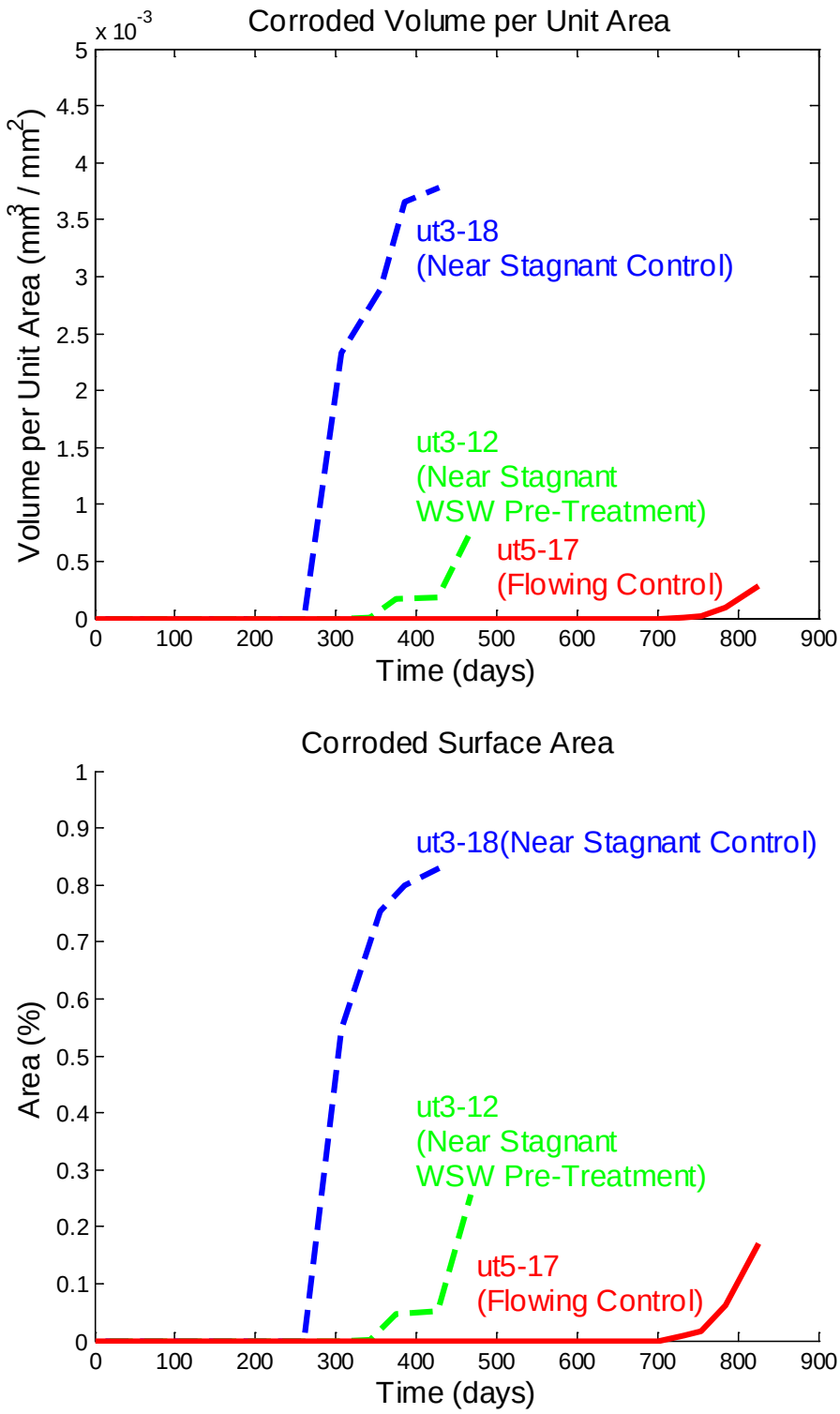

Figure 5-16. For comparison only, the total corroded volume per unit area and percent corroded area. Because the ultrasonic beam is wide, a correction factor was applied to area measurements. Pitting in ut3-18 has plateaued while pits continue to expand and deepen on ut3-12 and ut5-17.

5.3. CREVICE CORROSION

Only 7 out of 24 samples do not have crevice corrosion. Except for Al 1100 in near stagnant seawater receiving daily hypo-chlorination treatment, samples with crevice corrosion identified in the images also have crevice corrosion identified in the ultrasonic scans.

Crevice corrosion was severe in four samples – ut1-18, ut3-14, ut3-17, and ut3-18. Corrosion product from crevice corrosion has displaced the gasket; corrosion product is visible on both sides of the gasket. There is now a path available for seawater to get to the non-exposed surfaces. Once initiated, crevice corrosion progresses rapidly and severely for Al 3003 samples. Crevice corrosion is more severe in near stagnant conditions compared to flowing seawater conditions. This is notable because crevices and interfaces/gasketed regions are most likely to have lower seawater flow rates.

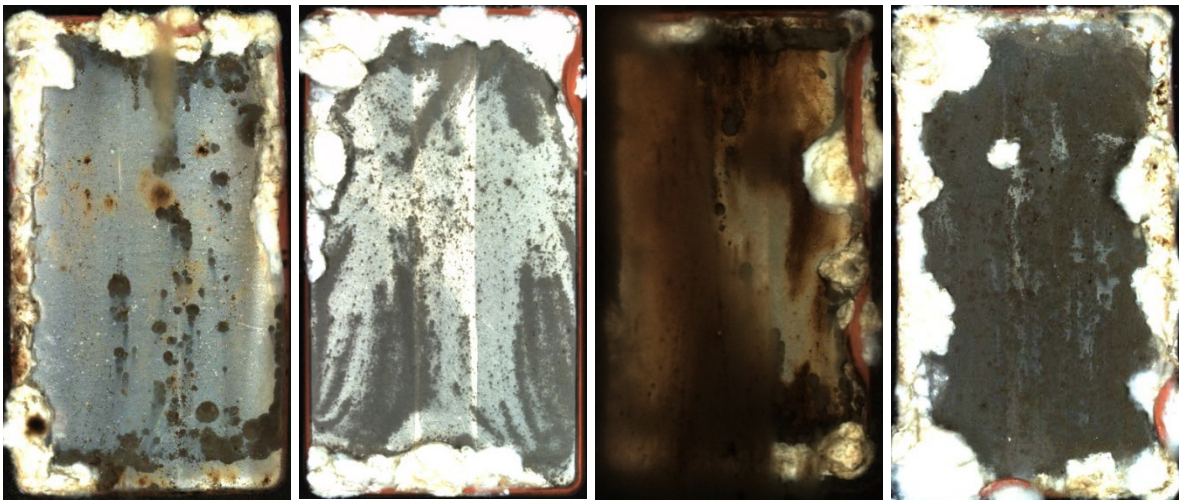

Figure 5-17. Corrosion product buildup from severe crevice corrosion has displaced the gasket in (left to right) ut1-18, ut3-14, ut3-17, and ut3-18. Once initiated, Al 3003 is particularly susceptible to developing severe crevice corrosion.

Lateral gasket corrosion not as catastrophic as pitting corrosion, which would result in working fluid leaking into the seawater. In shell-and-tube heat exchangers, gaskets are located on non-heat transferring surfaces, so a wider gasketed area and thicker base material can compensate for under-gasket corrosion.

The extent of crevice corrosion penetration and maximum depth under the gasket was measured ultrasonically (Table 5-2). The maximum depth and maximum lateral penetration were not necessarily in the same location.

Table 5-2. Crevice corrosion at the gasket interface. Lateral penetration is the distance from the inner edge of the gasket to the furthest extent of corrosion. The maximum corrosion depth underneath gasket is not necessarily in the same location as the maximum lateral penetration.

Water Flow	Treatment	Sample	Present on image?	Lateral Penetration [mm]	Maximum Depth under Gasket [mm]
Near Stagnant	Control	ut5-18	Yes	4.0	0.5
		ut3-18	Yes	11.2	1.2
		ut1-18	Yes	7.0	1.0
Flowing	Control	ut5-1	No[a]	-	-
		ut3-17	Yes	7.5	1.2
		ut1-17	Yes	2.7	0.4
Near Stagnant	Hypochlorination	ut5-16	No	-	-
		ut3-16	No	-	-
		ut1-16	Yes	n.d.	n.d.
Flowing	Hypochlorination	ut5-15	No	-	-
		ut3-15	No	-	-
		ut1-15	Yes	2	0.3
Near Stagnant	Acid treatment	ut5-14	Yes	5.4	1.2
		ut3-14	Yes	6.7	1.3
		ut1-14	Yes	5.4	1.3
Flowing	Acid treatment	ut5-13	Yes	2.0	0.2
		ut3-13	Yes	7.2	1.2
		ut1-13	Yes	3.6	0.9
Near Stagnant	Warm seawater pre-treatment	ut5-12	No	-	-
		ut3-12	Yes	4.0	0.5
		ut1-12	Yes	4.4	0.8
Flowing	Warm seawater pre-treatment	ut5-11	No	2	0.1
		ut3-11	No	-	-
		ut1-11	No	-	-

n.d. = not detected on ultrasonic scans.

[a] For the same exposure time, no crevice corrosion or pits were detected on the Al 5086 control sample in flowing seawater. Crevice corrosion was detected on images after 477 days.

5.4. OPEN-CIRCUIT POTENTIALS

Open-circuit potential (OCP) relative to an Ag/AgCl reference electrode was monitored for all samples. OCP is a qualitative indicator of the state of a sample, changes can be indicative of the onset of corrosion. OCP in the pitting region (around -700 mV), has been a strong indicator of the presence of local corrosion. OCP monitoring of OTEC heat exchangers could be a non-destructive technique to identify corrosion development.

OCPs of the samples are shown in Figure 5-18. OCP is most closely correlated to the onset of corrosion for Al 3003. OCP changes were within days of pits and crevice corrosion being identified on images. Based on the current trend, some corrosion is likely for ut3-16 (Al 3003 receiving daily hypo-chlorination in near stagnant seawater). ut3-16's OCP has been noisy and the overall trend is OCP is climbing towards -700 mV. Similar noise was observed in ut5-17 (Al 5086 control sample in flowing seawater) prior to the observation of pits in images. For Al 1100 and Al 5086, OCP did not correspond as closely to the onset of localized corrosion but this could be due to lack of resolution – more frequent OCP measurements may have captured a change. However, the current OCPs for Al 1100 and 5086 samples are indicative of the presence or absence of localized corrosion. The one Al 1100 and three Al 5086 samples without localized corrosion are the only samples to have OCPs not in the pitting region.

Acid treatments lowered OCP of all samples, but did not have the protective effect observed in previous testing. OCP typically returned to pre-treatment levels within 30 days of treatment. More frequent treatments or OCP-based treatments may have been necessary for acid treatment to be effective. OCP-based treatments are difficult in the current test setup because all samples in a column must be treated at the same time; an individual sample cannot be isolated for treatment.

OCPs were also affected by the warm seawater pre-treatment. Once moved to cold seawater, OCPs immediately jumped to -700 mV although no corrosion was observed. OCPs generally lowered to -800 mV after 210 days in flowing cold seawater and 90 days in near stagnant cold seawater. Two samples, ut5-11 and ut3-12 (Al 5086 sample in flowing seawater and Al 1100 sample in near stagnant seawater), that received the warm seawater pre-treatment had OCPs that remained ~ -700 mV and both have crevice corrosion. Although the OCPs of both Al 3003 samples dropped to -800 mV, the OCPs eventually returned to -700 mV and the time of return to -700 mV coincided with detection of pits on the daily images.

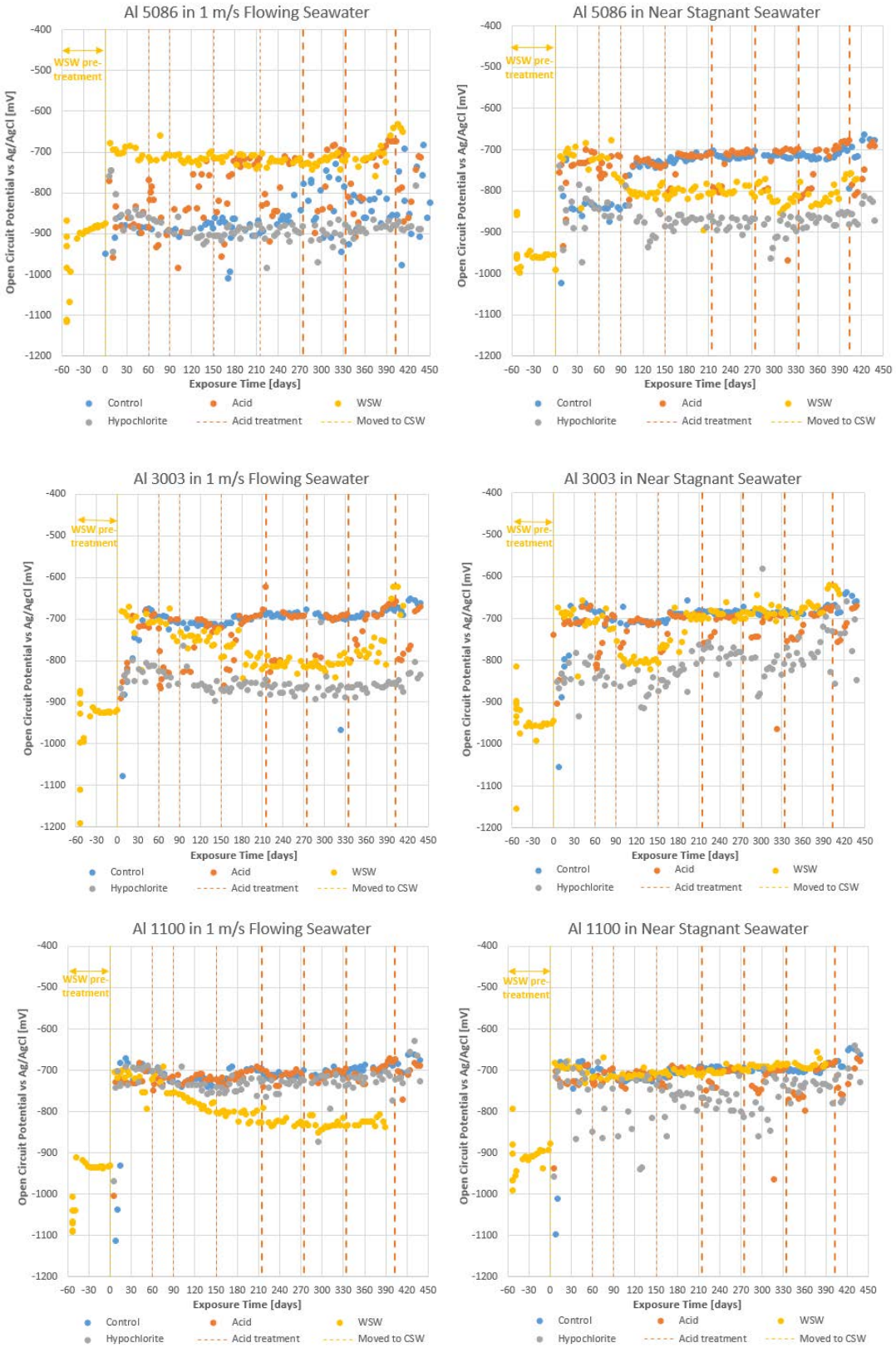

Figure 5-18: Open-circuit potentials against an Ag/AgCl reference electrode.

5.5. BIOFOULING

The extent of biofouling on the samples was unexpected. Bacterial colonies have been previously observed in cold seawater as dark gray spots or patches, but in this test, the slimy, rust colored film typically observed in warm seawater was observed in several samples. The biofilm attached to the acrylic viewing/imaging windows on the MCIR in addition to the sample surfaces.

Previous studies concluded that biofouling in cold seawater consists of bacterial colonies and extra-cellular polymeric substances excreted by the bacteria. No algal cells or multi-cellular organisms were found. The bacteria are found in the seawater itself; although contamination from warm seawater is possible, it is unlikely the primary source for biofouling. Makai also believes there is biofouling in the cold seawater supply lines. Cold seawater is supplied to Makai's corrosion testing facility in white PVC piping that is above ground in some sections. Makai previously determined there is enough light penetration through the PVC wall to support growth and subsequently shielded (darkened) Makai-maintained pipe sections. Any growth in the piping, especially during no-flow maintenance periods, could be carried into the corrosion test during flow resumption.

6. DISCUSSION

Three treatments were tested for their efficacy at preventing and/or mitigating pitting and crevice corrosion on three alloys in two cold seawater flow conditions.

Crevice corrosion was more severe in near-stagnant samples than in flowing seawater samples. Since low-flow areas are likely at boundaries, interfaces, and transitions, this is an important consideration in heat exchanger design. In several samples, corrosion product buildup from crevice corrosion displaced the gasket and was visible on both sides of the gasket, essentially creating a pathway for seawater to flow to surfaces not intended for seawater exposure.

Shortly after samples were installed in cold seawater, the samples were inadvertently kept in stagnant cold seawater overnight. It is possible this adversely affected the samples in this test, essentially introducing an extended stagnant condition for the flowing seawater samples. For samples with crevice corrosion, the onset of corrosion was observed at nearly the same time for samples in flowing seawater and near-stagnant seawater. This is noted because the only Al 1100 sample without crevice corrosion is the warm seawater pre-treatment sample in flowing seawater; it was not exposed to stagnant cold seawater because it was receiving the warm seawater pre-treatment. The corresponding Al 1100 warm seawater pre-treatment sample in near-stagnant cold seawater developed crevice corrosion within 15 days in cold seawater, which is comparable to the onset of crevice corrosion in the other Al 1100 samples. It is possible the overnight period in stagnant cold seawater shortly after exposure accelerated the initiation of crevice corrosion in the flowing seawater samples.

Pitting was observed in four samples. In three Al 3003 samples, pits appeared within one year. Pitting was deeper in stagnant seawater and although the pit depth increased quickly, it also appeared to passivate within 150 days. At least three pits were observed via images of the Al 5086 control sample; only one pit has been detected on ultrasonic scans. Ultrasonic scans have only detected the pit for ~ 100 days; it will be interesting to see whether the pit continues to deepen (as previously observed in Al 6061) or passivates as observed in Al 3003.

Acid treatment was not effective at preventing corrosion; samples of all three alloys had crevice corrosion that is comparable to the control samples. Acid treatment was effective at removing biofouling, although the biofilm would redevelop prior to the next treatment. Acid treatments lowered OCPs but the effect was not as long lasting as observed in previous tests. Treatment intervals may need to be modified for acid treatment to be effective.

Warm seawater pre-treatment appears to be somewhat effective. No corrosion has been observed on two of the warm seawater pre-treatment samples, Al 1100 in flowing seawater and Al 5086 in near stagnant seawater. However, the two Al 3003 samples that received the warm seawater pre-treatment both have pits.

Although not effective for Al 1100, hypo-chlorination was the most effective treatment for Al 3003 and Al 5086. None of the Al 3003 and Al 5086 samples receiving hypo-chlorination have crevice corrosion or pitting. In general, sample surfaces also look shiny and new. Some biofouling has started on the Al 3003 sample in near stagnant seawater. The start of biofouling appears around Day 193 and corresponds to a slight rise in OCP. OCP of the sample becomes noisier after Day 360 and has increased into the pitting region, although it occasionally returns to < -800 mV. This sample may show corrosion in the near future.

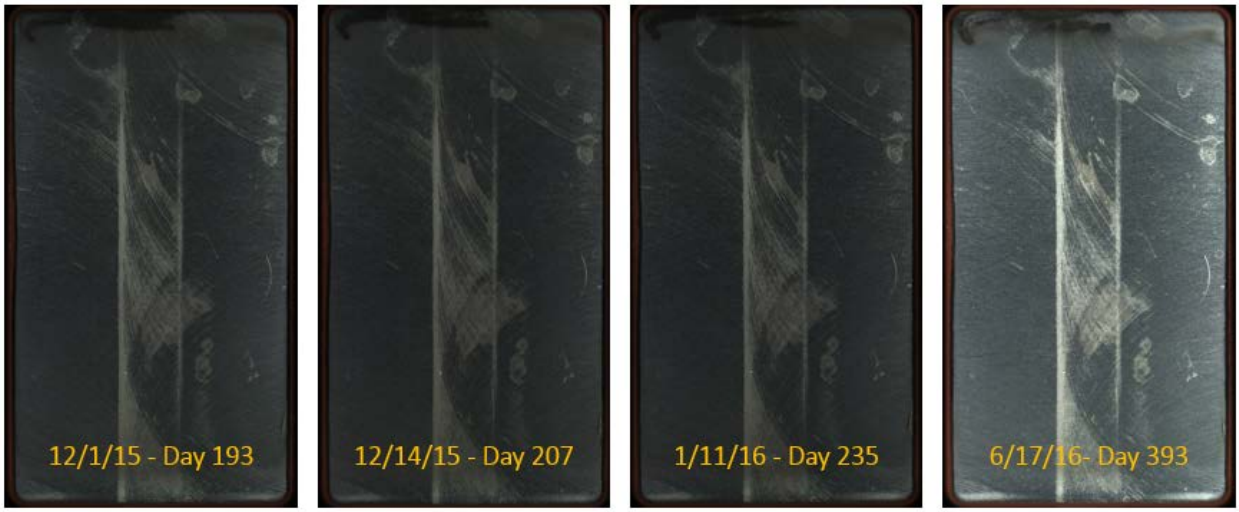

Figure 6-1. Biofouling observed on Al 3003 receiving daily hypo-chlorination treatment in near stagnant cold seawater.

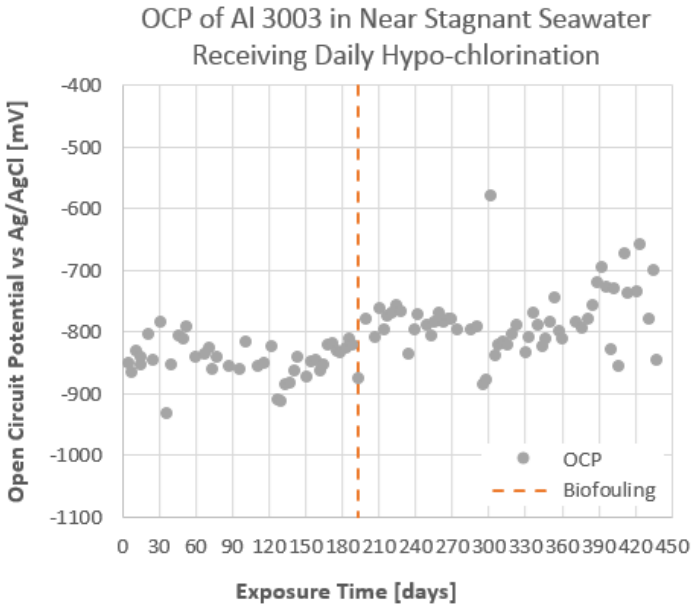

Figure 6-2. OCP of Al 3003 receiving daily hypo-chlorination treatment in near stagnant cold seawater. A slight change in OCP coincides with the observation of biofouling.

In light of the improved performance of samples receiving hypo-chlorination treatment, biofouling may contribute more to corrosion in cold seawater than previously anticipated.

Crevice corrosion may be addressed in the design phase by reducing low flow areas as much as possible and using thicker materials and gaskets to extend the usable lifetime. Since crevices and interfaces are usually associated with non-heat transfer surfaces, designing with larger safety factors may be the most economical solution to addressing seal integrity issues associated with crevice corrosion.

Pitting corrosion can occur on heat transfer surfaces where it is not practical to increase wall thicknesses. Pitting corrosion can result in the working fluid entering the environment, which is considered a catastrophic failure and must be avoided.

Cumulative findings of Makai's ongoing corrosion testing program are summarized in Table 6-1. Box coupon testing data was also used in the analysis presented in Table 6-1. One major limitation is that box coupon data collection is discrete and destructive. It is not possible to determine if observed pits were established and continued to deepen over time (as observed for Al 6061) or levelled off and remained at a stable depth (as for Al 2024) or if the observed pits or crevice corrosion could be traced back to a singular disturbance.

Compared to previous studies, the major advantage of Makai's current research is the ability to provide continuous, in situ monitoring. The ability to follow the development of the same pit is crucial and eliminates errors in extrapolating discrete measurements of *different* pits over time to determine pit development rate. The major obstacle in statistically extrapolating our data to provide an expected pit depth over time is our limited sample size. Both the sample area (size of exposed surfaces) and sample size (number of samples) is very small compared to areas expected in OTEC plant-sized heat exchangers. For this test, the sample area is 4.125 in^2 (0.0027 m^2) with a sample size of N = 1. The minimum heat transfer area of the 2 MW heat exchangers at the OERC ranges is 135 m^2, which is on the order of 10^4 times greater than the sample area. In order to apply extreme value statistics, the sample size should be at least 30.[1]

It is also important to keep in mind that many variables can affect pitting corrosion, and therefore the life expectancy of a heat exchanger. Manufacturing processes must be carefully controlled and scrutinized because small deviations can become corrosion initiation sites. Quality control is crucial and must be maintained on scale required for OTEC-sized heat exchangers.

Makai believes an evaporator constructed from Al 3003 or Al 5052 can be expected to last up to 15 years with little risk of failure. Extending lifetime beyond 15 years increases the risk for failure. A condenser constructed from Al 3003 or Al 5052 can be expected to last 10 years with little risk of failure. Makai believes extending a condenser lifetime beyond 10 years

[1] Shibata, T. *Application of Extreme Value Statistics to Corrosion*. J. Res. Natl. Inst. Technol. **99**, 327 (1994)

will significantly increase the risk for failure. Al 3003 and Al 5052 box coupons have been tested in cold seawater for over 6 years with maximum pit depths of 0.75 mm.

Makai will continue to test the control, warm seawater pre-treatment, and daily hypo-chlorination treatment samples. The acid treatment samples have so much crevice corrosion that no useful data is likely from continued testing. The control samples are also have severe crevice corrosion but the pit development on Al 5086 warrants continued study.

Table 6-1. Cumulative findings corrosion suitability of bare aluminum alloys for use in OTEC heat exchangers.[1]

Alloy	Evaporator	Cumulative Test Exposure	Expected Life Cycle[2]	ANL 1980's Test Results	Condenser	Cumulative Test Exposure	Expected Life Cycle[2]	ANL 1980's 5-years Test Results
3003	Yes[4]	ongoing, ~6 years	at least 6 years	Yes	Yes with caution [5]	ongoing, ~6 years	at least 6 years	Yes with caution
3003 (treated[3])	Not Tested	Not Tested	Not Tested	-	Yes with caution[8]	ongoing, ~6 years	at least 6 years	-
5052	Yes[6]	ongoing, ~6 years	at least 6 years	Yes	Yes with caution [7]	ongoing, ~6 years	at least 6 years	Yes
5052 (treated[3])	Not Tested	Not Tested	Not Tested	-	Yes with caution[8]	ongoing, ~6 years	at least 6 years	-
6063-T5	Yes	ongoing, ~6 years	at least 6 years	Yes	No (pitting)	ongoing, ~6 years	Not suitable	Yes
6063 (treated[3])	Not Tested	Not Tested	Not Tested	-	No (pitting)	ongoing, ~6 years	Not suitable	-
6061	Not Tested	Not Tested	Not Tested	Not Tested	No	~1 year	Not suitable	Not Tested
5086	Not Tested	Not Tested	Not Tested	Not Tested	TBD[9]	ongoing, ~1.5 years	TBD	Not Tested
5086 (treated[3])	Not Tested	Not Tested	Not Tested	Not Tested	TBD	ongoing, ~1.5 years	TBD	Not Tested
1100	No	ongoing, ~6 years	at least 6 years	Not Tested	No (pitting)	ongoing, ~6 years	Not suitable	Not Tested

1. These alloys are solely evaluated based on their corrosion and pitting characteristics as determined at Makai Ocean Engineering's Marine Corrosion Lab when coupons are exposed to flowing seawater (~ 1 m/s) ranging from 24 to 28 °C for evaporator uses and 6 to 7 °C (CSW from 674-m) for condenser uses. Alclad alloys are not acceptable for OTEC HXs.
2. Makai believes an Al 3003 or Al 5052 evaporator can reasonably be expected to last 15 years, 10 years for a condenser. The risk for failure increases rapidly with extended lifetime. More data would reduce the risk. Makai considers the risk beyond 15 years for an evaporator and 10 years for a condenser to be unacceptably high given the data we have to date.
3. Warm seawater pre-treatment is tested on Alloys 3003, 5052, 6063, and 5086. Acid treatment is tested on Alloys 3003, 5086, and 6063. Hypo-chlorination is tested on Alloys 3003 and 5086.
4. 3003 WSW – Some pitting has been observed. Pits initially observed after 2 years, maximum pit depths have not increased in 5 year samples. Maximum pit depth observed is less than 0.1 mm (0.004").
5. 3003 CSW - Some pitting has been observed. Pits initially observed after 1.5 years, pit depths have not significantly increased between samples removed at 3 years and samples removed at 5 years. Maximum pit depth observed is ~ 0.6 mm (0.024").
6. 5052 WSW - Some pitting has been observed. Pits initially observed after 1.5 years, pit depths have not significantly increased in samples removed at 5 years. Maximum pit depth observed is ~ 0.125 mm (0.005").
7. 5052 CSW - Some pitting has been observed. Pits initially observed after 1.5 years, pit depths have not significantly increased between samples removed at 2 years and samples removed at 5 years. Maximum pit depth observed is ~ 0.75 mm (0.030").
8. 3003 and 5052 WSW pre-treatment: Some pitting has been observed. Pits initially observed after 1 year, pit depths have not significantly increased in samples removed at 5 years. Maximum pit depth observed is ~ 0.2 mm (0.008").
9. 5086 CSW – Pitting observed after 1.3 years. Current maximum pit depth is 0.3 mm with increasing trend.

Caveats:

1. To avoid pitting of braze joints in evaporators, silicon must be removed from surface by, for example, machining off the top layer.
2. Braze joints fabricated using commercial fluxes <u>are not acceptable in the condenser.</u>
3. Avoid stagnant water especially near gaskets. Crevice corrosion is severe in stagnant cold seawater, especially for Alloy 3003.
4. Care must be taken during manufacturing to avoid defects such as extrusion lines or concentrated areas of cold work, e.g., during roller expansion.

7. CONCLUSION

The corrosion development of Al 1100, Al 3003 and Al 5086 in flowing and near-stagnant cold seawater has been observed for 15 months. Corrosion development was observed with three measurement techniques – ultrasonic scanning, imaging, and measurements of open circuit potential. Ultrasonic scanning is a non-destructive test method that allows measurements of corrosion in-situ without disturbing the samples. Simultaneous in-situ imaging of the corroding surface shows a clear correlation between the accumulation of corrosion product and pitting locations. Open circuit potential measurements also correlated with observation of corrosion product in imaging and ultrasonic scans. Previous testing showed ultrasonic measurement of pit depth and areas were in agreement with and likely more accurate than laser profilometry measurements.

In the current test, four samples developed pits and all but seven samples developed crevice corrosion. Pitting and crevice corrosion are more severe in the near-stagnant seawater samples than the flowing seawater samples. Since crevices are not typically found on heat transfer surfaces, crevice corrosion can likely be compensated for with increased thicknesses for components in the heat exchanger design.

Pitting corrosion is more difficult to solve. Untreated aluminum alloys are unlikely to be suitable for use in long-term (20+ year) OTEC heat exchangers. Some samples of Al 3003, 5052, and 5086 have performed well but, even in warm seawater, no alloy has performed without pits. Pitting has been attributed to material and manufacturing defects – such as extrusion defects or poor surface finishes; operational oversights – such as missed treatments or flow disturbances; and experimental bias – such as poor gasket/interface design. However, Makai believes the manufacturing and operational anomalies experienced were not atypical and could easily occur during the production and operation of aluminum-based heat exchangers, especially at the scales required in an OTEC plant.

Provided that efforts are taken to ensure material and manufacturing quality and no operational anomalies, Makai considers the risks associated with using untreated aluminum alloys for pilot plant heat exchangers or limited lifetime heat exchangers (10 years for a condenser, 15 years for an evaporator) to be acceptable. However, as there is also no definitive "warning" prior to failure, Makai believes the risks associated with extending the life time of untreated aluminum alloy heat exchangers will increase rapidly and outweigh potential savings.

Makai believes that treated aluminum alloys show more promise to last 20+ years, but more thorough and longer testing is required. Warm seawater pre-treatment and acid treatment samples have shown promise in other tests and it may be that the pits in this test will passivate and remain at their current depth. Only six samples have received hypo-chlorination treatment in cold seawater. While promising for Al 3003 and Al 5086, the small sample area, limited number of samples, and relatively short test time (445 days) make it difficult draw conclusions for heat exchanger surfaces expected to be on the order of 1000 m^2 and lasting at least 10-20 years.

Future work should focus on treatments and corrosion detection methods. Makai has previously suggested an ultrasonic measurement system could be used to monitor a sample from the same lot/manufacturing process and exposed to the exact same conditions as the functional heat exchanger.

8. APPENDIX A

MATERIAL CERTIFICATIONS

CERTIFICATE OF CONFORMANCE

Novelis, Inc.
Oswego, NY 13126

CUSTOMER:

ALLOY: 3003 TEMPER: H14

ITEM	WGT.	GAUGE	WIDTH	LENGTH	ORDER NUMBER	CUST P.O.	Novel S.O.	REF. NO.
116995101	16,740	.3750	48.0000	COIL	03P03285			

TOTAL: 16,740 LB MECHANICAL PROPERTIES

	LOT NO	COIL/ TRACE NO	GAUGE IN	TENSILE STRNGTH PSI ULTIMATE	.2% YIELD	GAUGE LENGTH	ELONGATION %
OD	04867624	03285-1	.3635	20040	17840	2.0 in	29.59
ID	04867624	03285-1	.3635	20210	17750	2.0 in	27.3

NOTES

MATERIAL MEETS SPECIFICATIONS:
ASTM B209/AMS QQ-A-250/2

BEND TEST RESULTS:
BEND DIAMETER:

THE CHEMICAL COMPOSITION IS GUARANTEED BY Novelis, TO CONFORM TO THE REQUIREMENTS OF SPECIFICATION

CHEMICAL COMPOSITION (%)

AL	SI	FE	MN	MG	ZN	CU	CR	TI	NI	BE
98.0	.21	.59	1.09		.01	.07	.01	.01		.0001

I HEREBY CERTIFY THAT THE ITEMS OR MATERIAL COVERED BY THIS DOCUMENT HAVE BEEN INSPECTED AND TESTED AND CONFORM TO THE APPROVED SPECIFICATIONS. REVIEWED ON BEHALF OF Novelis,.

BY:

CERTIFIED INSPECTION REPORT **Alcoa Inc.** DAVENPORT WORKS 4879 State Street Bettendorf, IA 52722

Ship From: RIVERDALE, IA.

We hereby certify that the material covered by this certificate has been inspected with, and has been found to meet the applicable requirements described therein, including any specifications forming a part of the description and that samples representative of the material met the composition limits and had the mechanical properties shown on the face of this sheet.

This test report shall not be reproduced except in full, without the written approval of the Quality Department. No alteration, addition or other change is authorized to be made to this certificate. The recording of false, fictitious , or otherwise fraudulent statements or entries on this certificate by any recipient may be punished as a felony under applicable law.
Per:

Rob Woodall
Director of Manufacturing Davenport Works

Terrence Thom
Quality Assurance Manager

1621141	0			
Ship Date	B.L. No.	Invoice No.	Alcoa No. Item	
2013-09-27	8805550	00000	1000520473-1	DP-20473-1
P.O. No./Govt Contract No.		Customer	Alcoa Item	
	Ln#: 1		G041130640R01	

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Lot: 559551 - Mechanical, Physical, Metallograpy, Quantometer Results (cont.) ----------

14.7	9.9	35.9
14.6	9.8	34.7
14.4	10.1	36.5

Cast Number	Chemical - OES	CU	MN	ZN	FE	SI
13M03682	Actuals	0.14	0.00	0.00	0.62	0.08

This material was melted in the United States or a Qualifying Country [REF DFARS 225.872.1(a)]; it was manufactured in the United States

Metal Suppliers Online, LLC.
certifies that this is a true copy
of the original mill test report
now on file Received & Inspected

CERTIFIED INSPECTION REPORT **Alcoa Inc.** DAVENPORT WORKS 4879 State Street Bettendorf, IA 52722

Ship From: RIVERDALE, IA.

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Rob Woodall
Director of Manufacturing Davenport Works

Terrence Thom
Quality Assurance Manager

Page 2 of 2

Lot: 605961 - Mechanical, Physical, Metallograpy, Quantometer Results (cont.) ----------
Lot: 605961 - Mechanical, Physical, Metallography, Quantometer Results ----------

Tmpr	Dir	No-> Test	UTS KSI	TYS KSI	EL4D PCT
H116	Longitudinal	5	42.4	30.8	17.3
			42.7	32.4	19.2
			43	32.3	19.1
			42.7	33.3	19.6
			43.7	33.3	18

H116 Exfoliation Corrosion PASS

Cast Number	Chemical - OES	SI	FE	CU	MN	MG	CR	ZN	TI
H3617012	Actuals	0.08	0.26	0.07	0.41	4.0	0.09	0.03	0.01

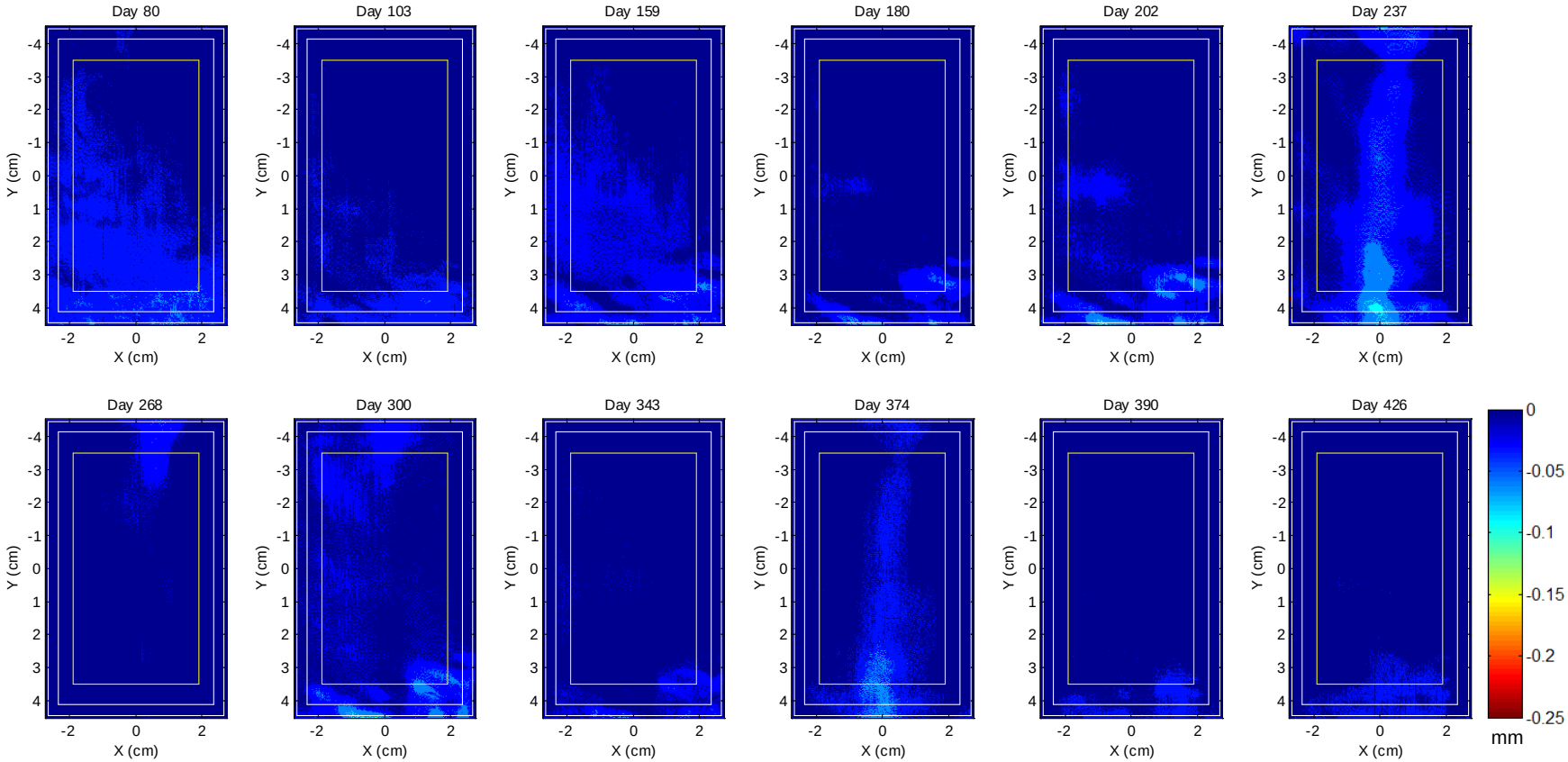
This material was melted in the United States or a Qualifying Country [REF DFARS 225.872.1(a)]; it was manufactured in the United States

9. APPENDIX B

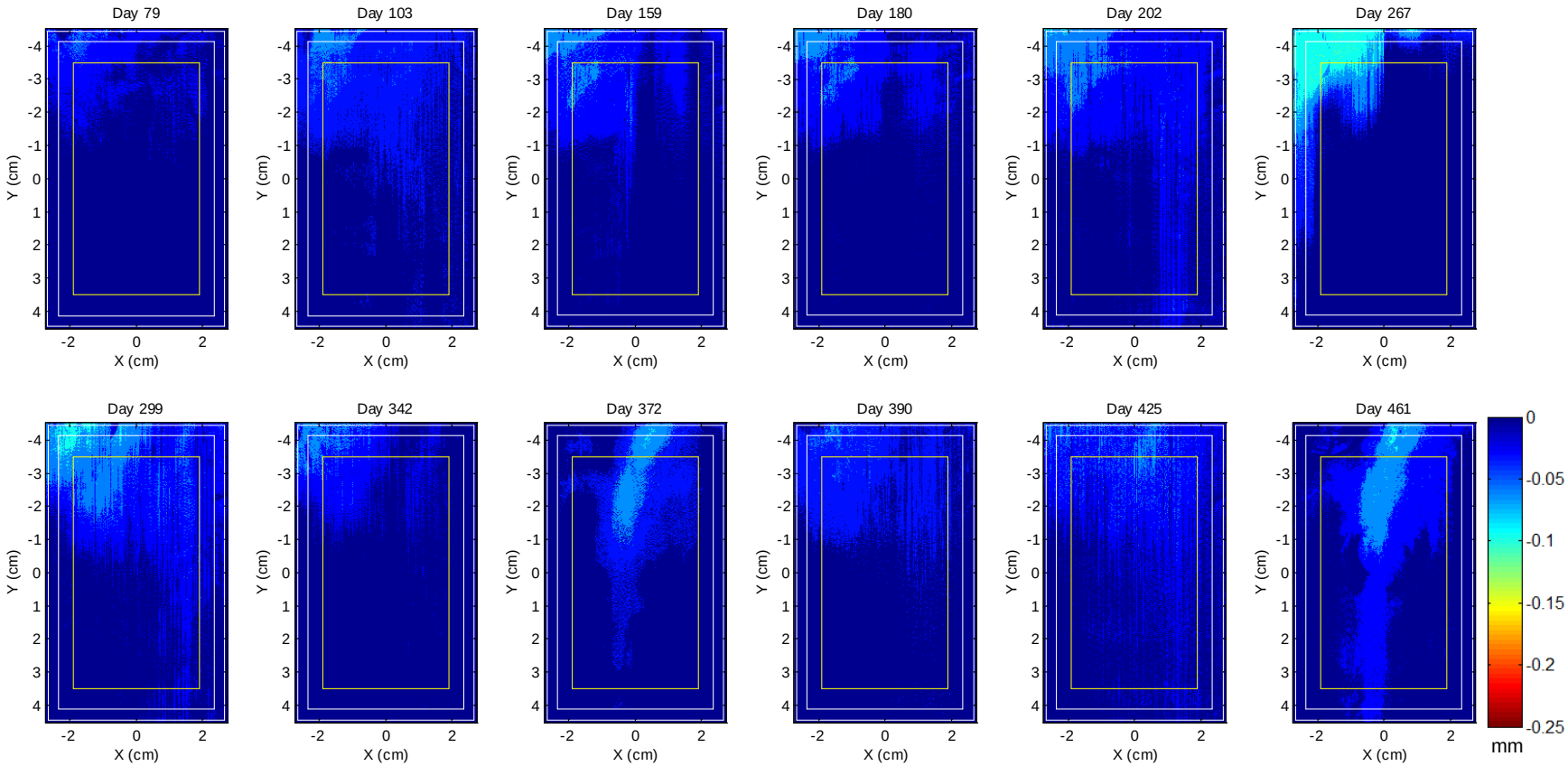
COMPILATION OF ULTRASONIC SCANS

9.1. WARM SEAWATER PRE-TREATMENT IN FLOWING SEAWATER

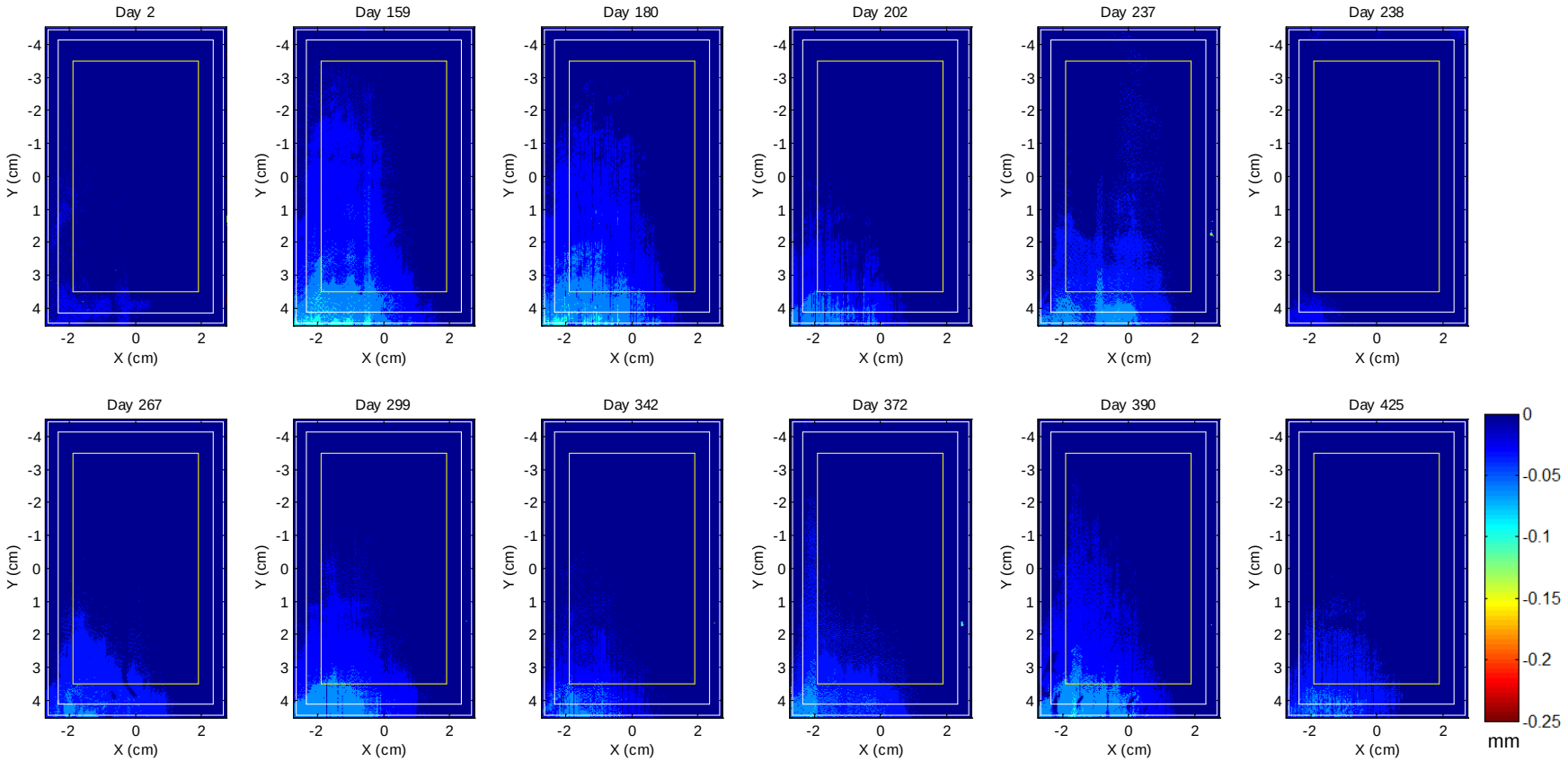
9.1.1. Alloy 1100 – ut1-11

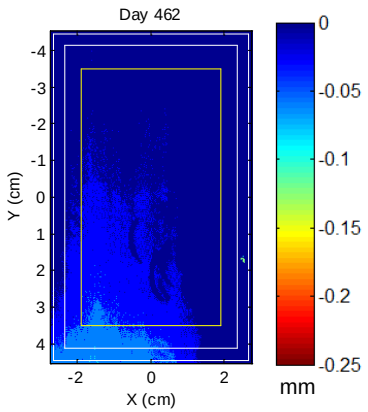


9.1.2. Alloy 3003 – ut3-11



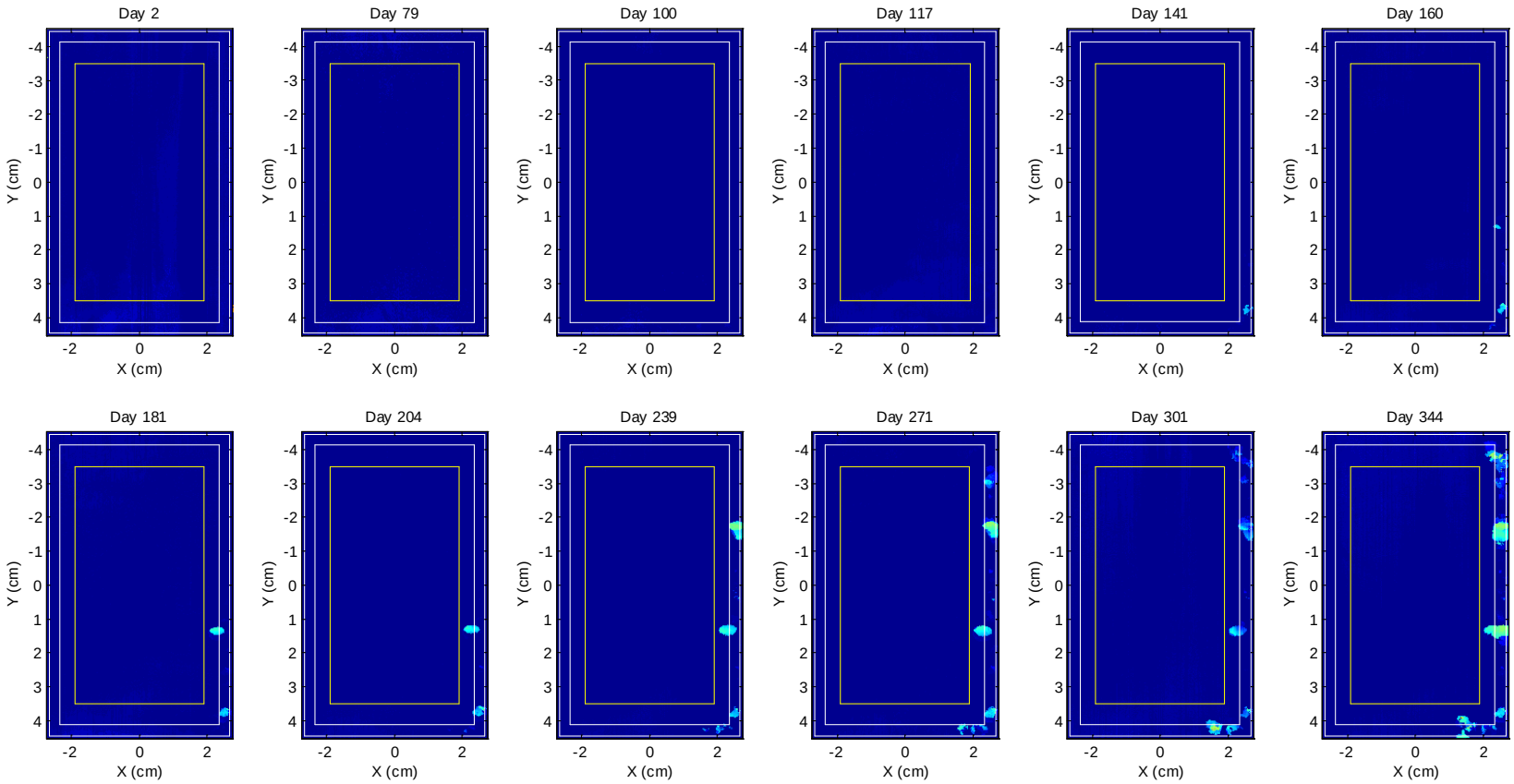
9.1.3. Alloy 5086 – ut5-11

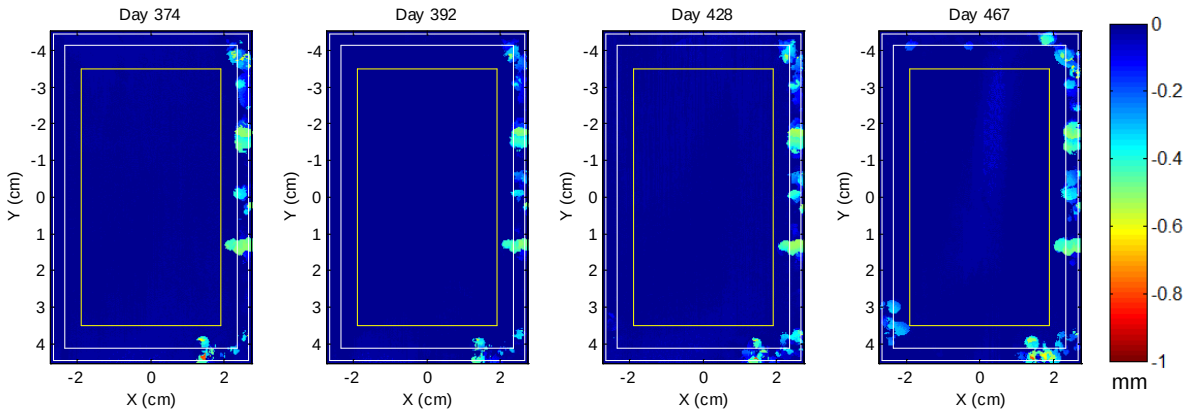



Day 462
Y (cm)
X (cm)
-4
-3
-2
-1
0
1
2
3
4
-2
0
2
0
-0.05
-0.1
-0.15
-0.2
-0.25
mm

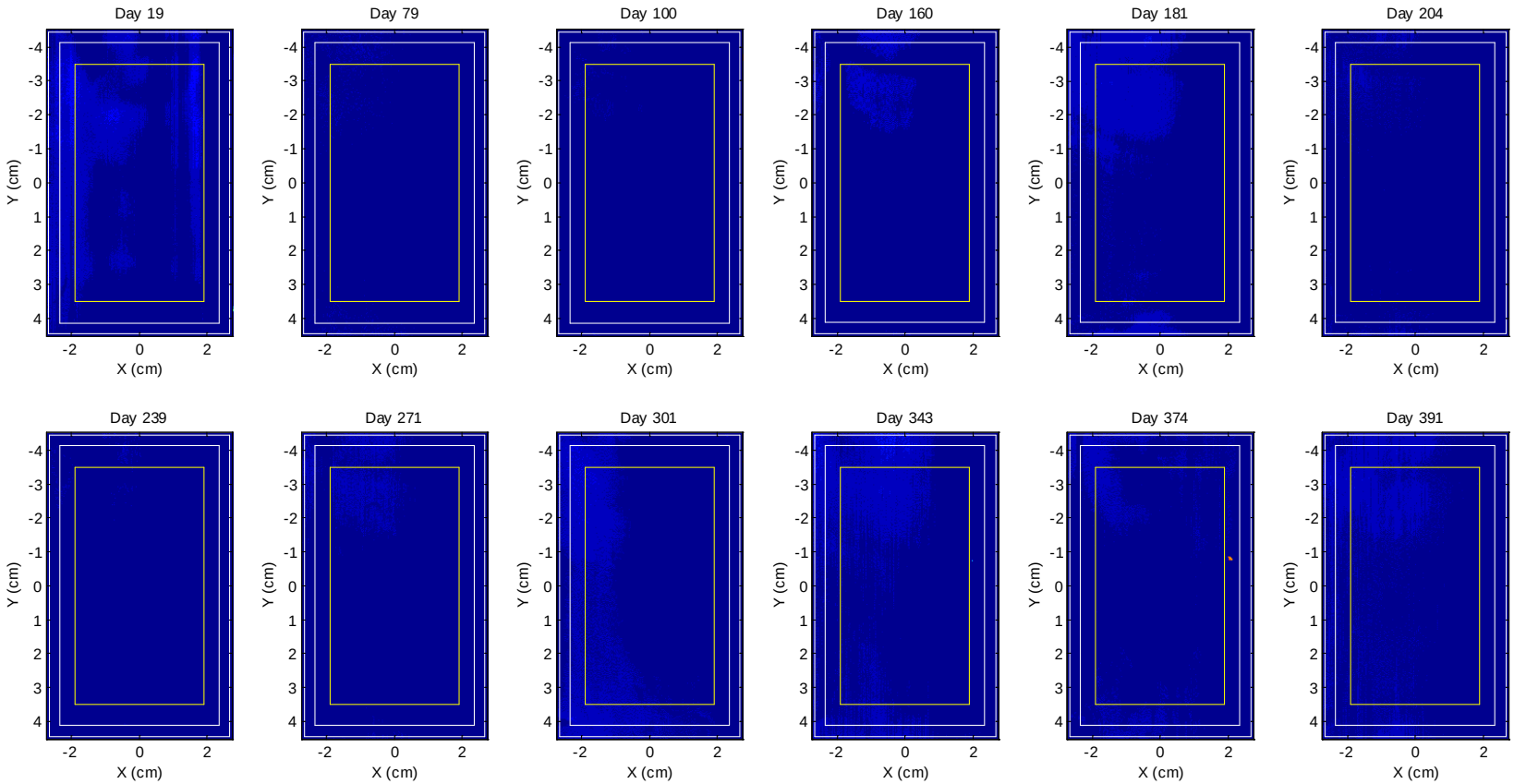
9.2. WARM SEAWATER PRE-TREATMENT IN NEAR STAGNANT SEAWATER

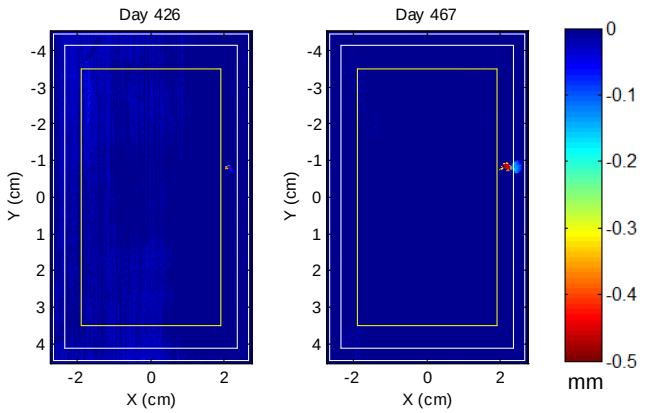
9.2.1. Alloy 1100 – ut1-12



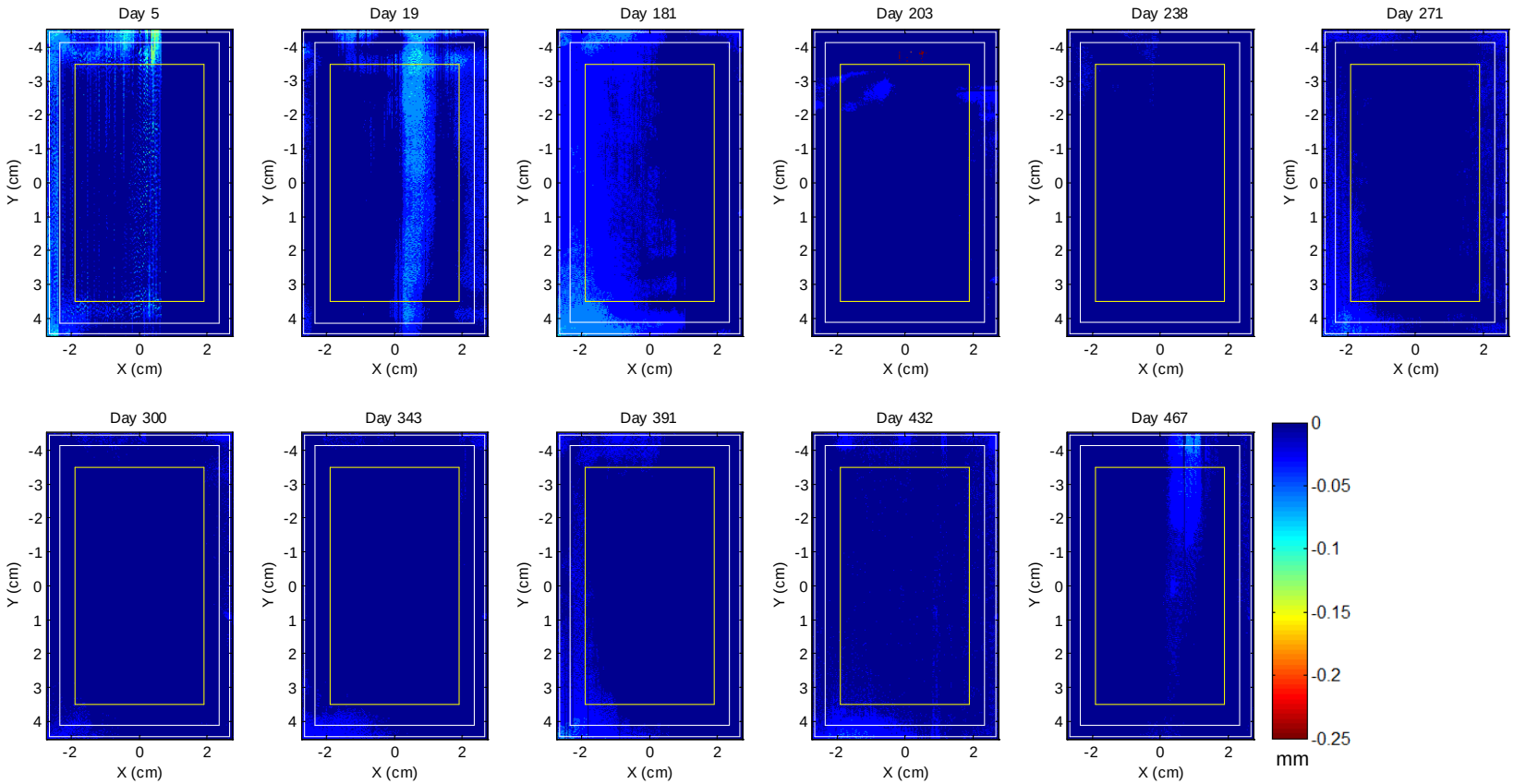

Day 374
Day 392
Day 428
Day 467
Y (cm)
X (cm)
-4
-3
-2
-1
0
1
2
3
4
-2
0
2
0
-0.2
-0.4
-0.6
-0.8
-1
mm

9.2.2. Alloy 3003 – ut3-12



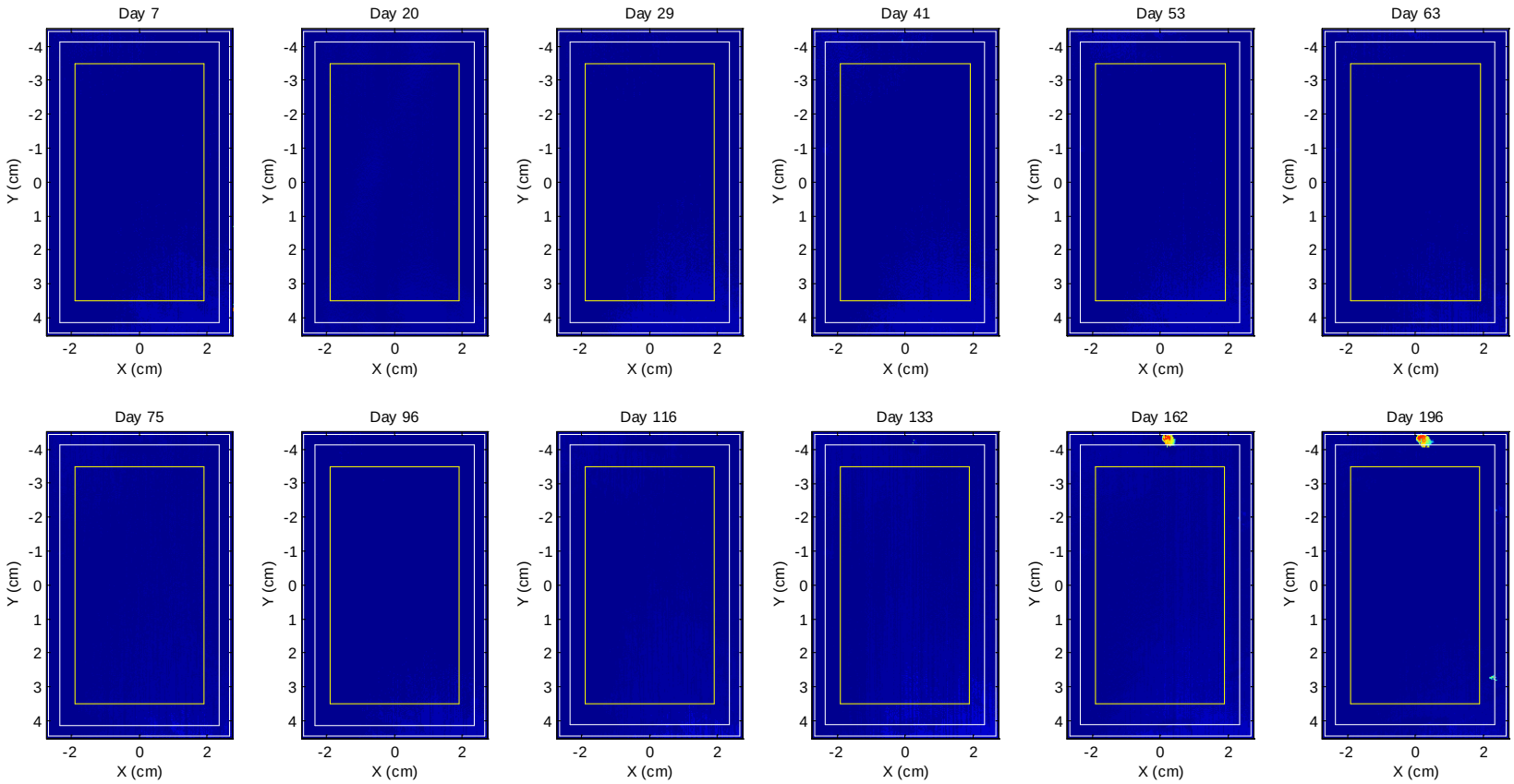

Day 426
Day 467
Y (cm)
X (cm)
-4
-3
-2
-1
0
1
2
3
4
-2
0
2
0
-0.1
-0.2
-0.3
-0.4
-0.5
mm

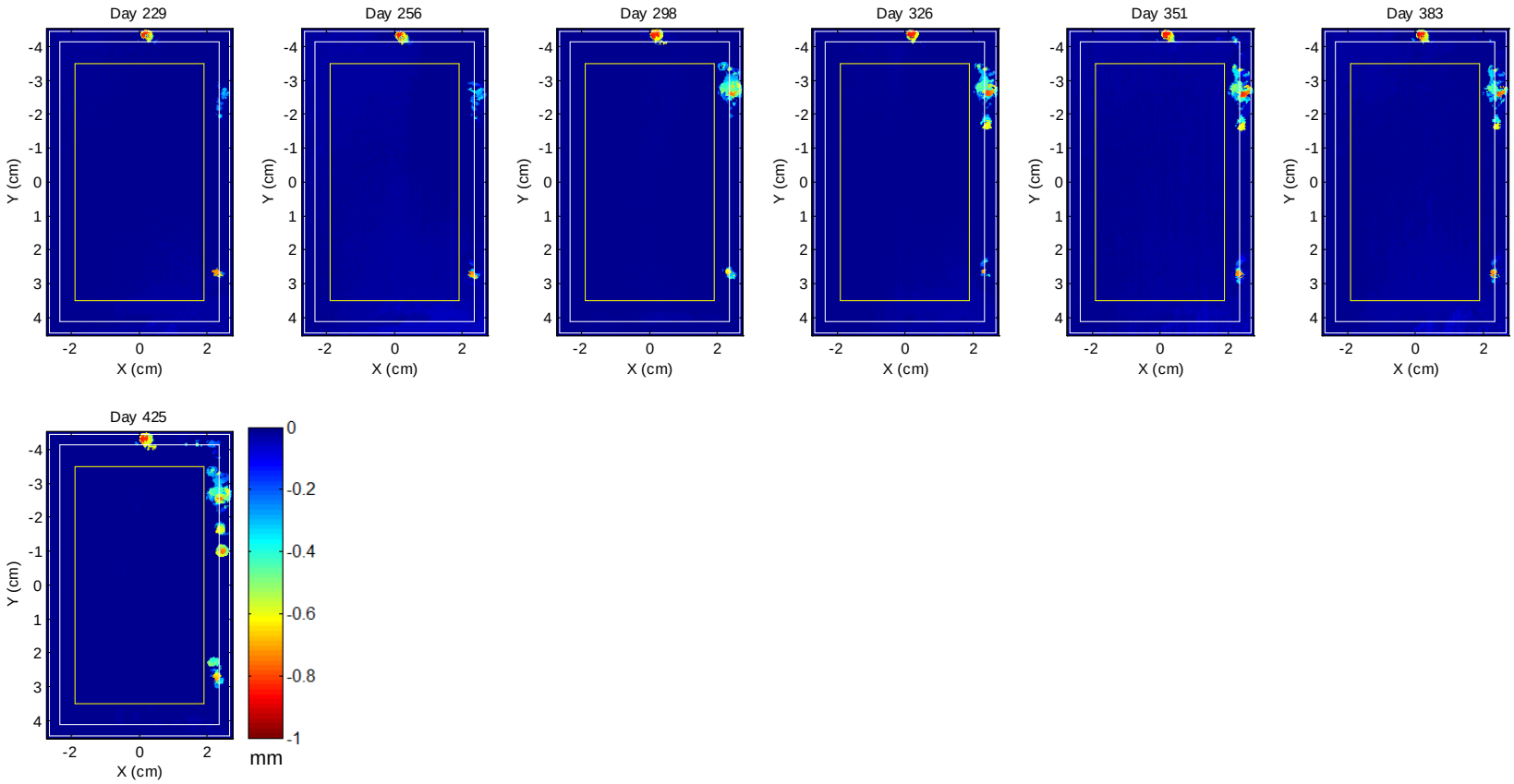
9.2.3. Alloy 5086 – ut5-12



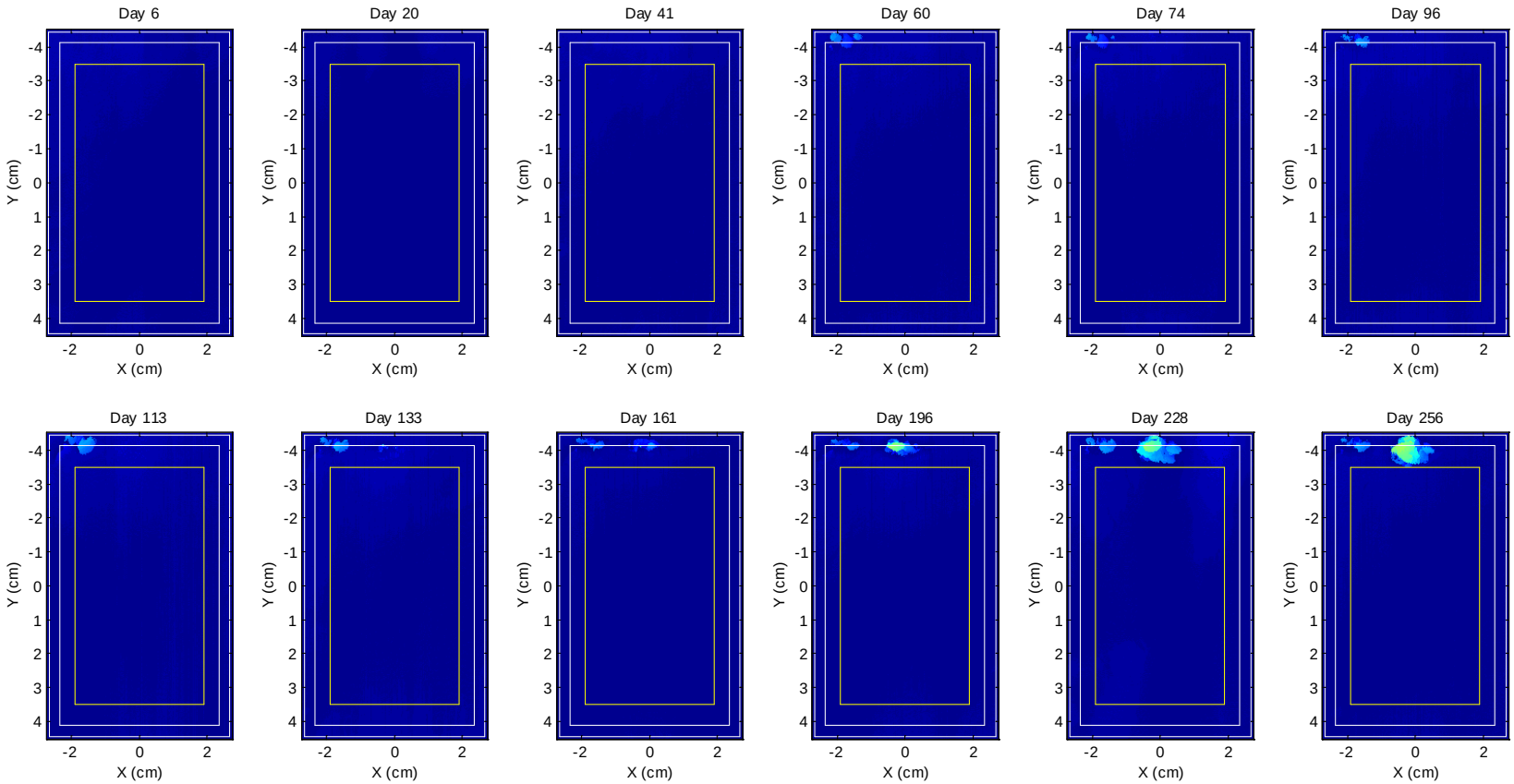
9.3. ACID TREATMENT IN FLOWING SEAWATER

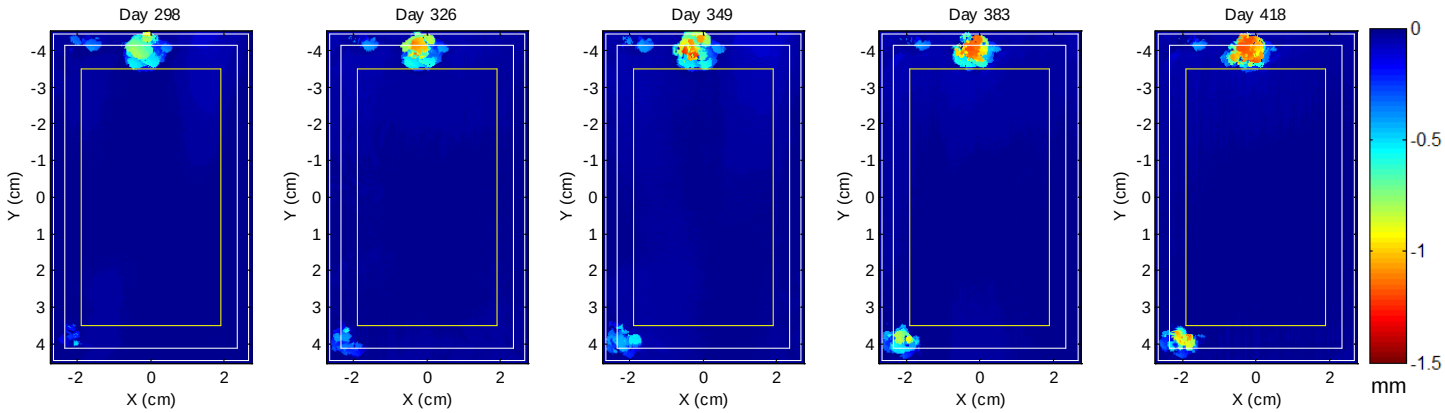
9.3.1. Alloy 1100 – ut1-13



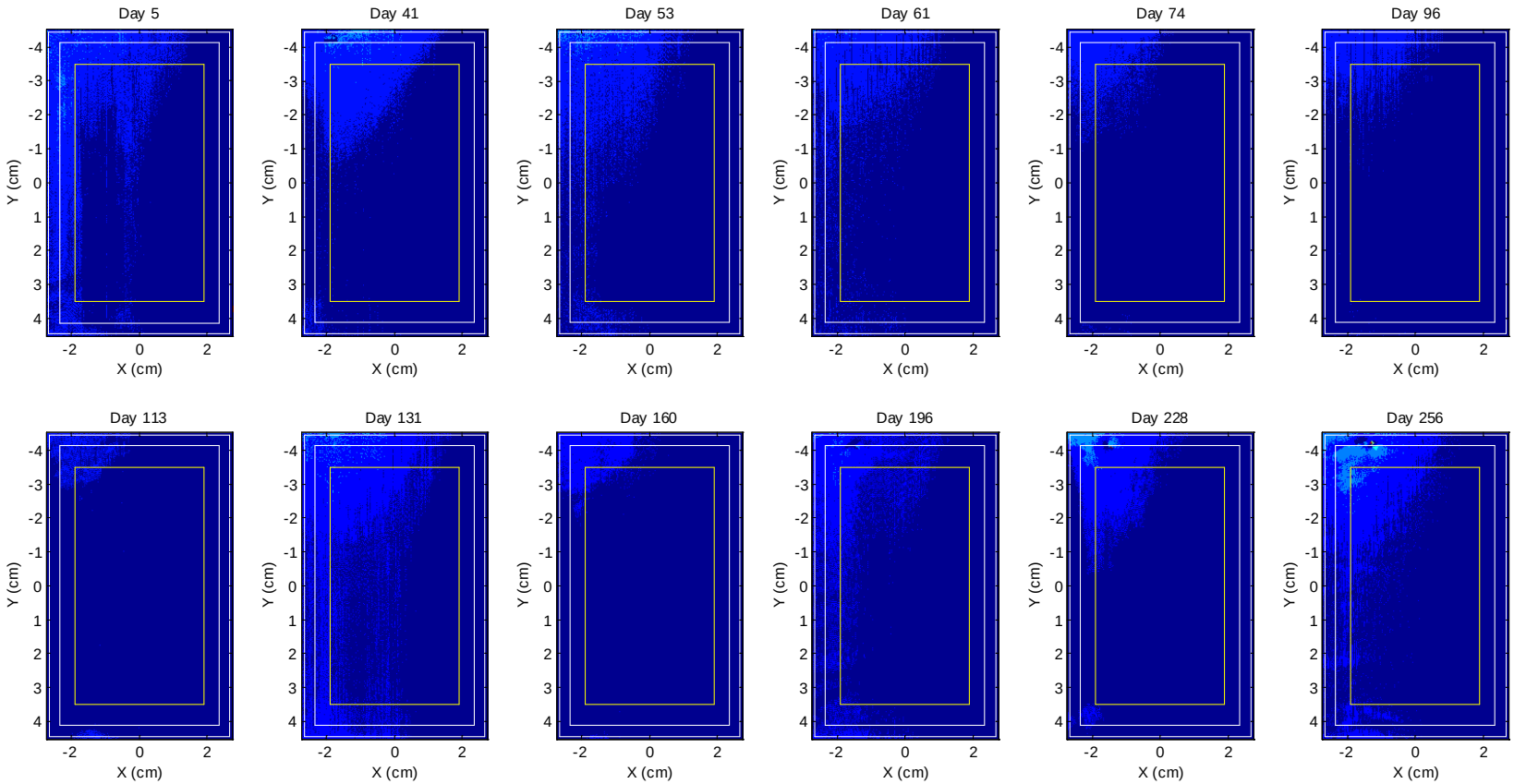

Day 229
Day 256
Day 298
Day 326
Day 351
Day 383
Day 425
Y (cm)
X (cm)
-4
-3
-2
-1
0
1
2
3
4
-2
0
2
0
-0.2
-0.4
-0.6
-0.8
-1
mm

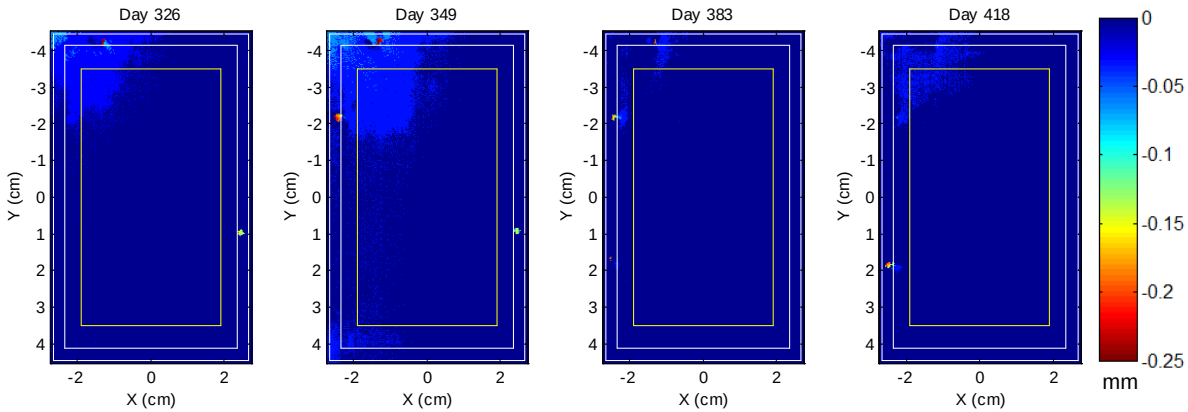
9.3.2. Alloy 3003 – ut3-13




Day 298
Day 326
Day 349
Day 383
Day 418
Y (cm)
X (cm)
-4
-3
-2
-1
0
1
2
3
4
-2
0
2
0
-0.5
-1
-1.5
mm

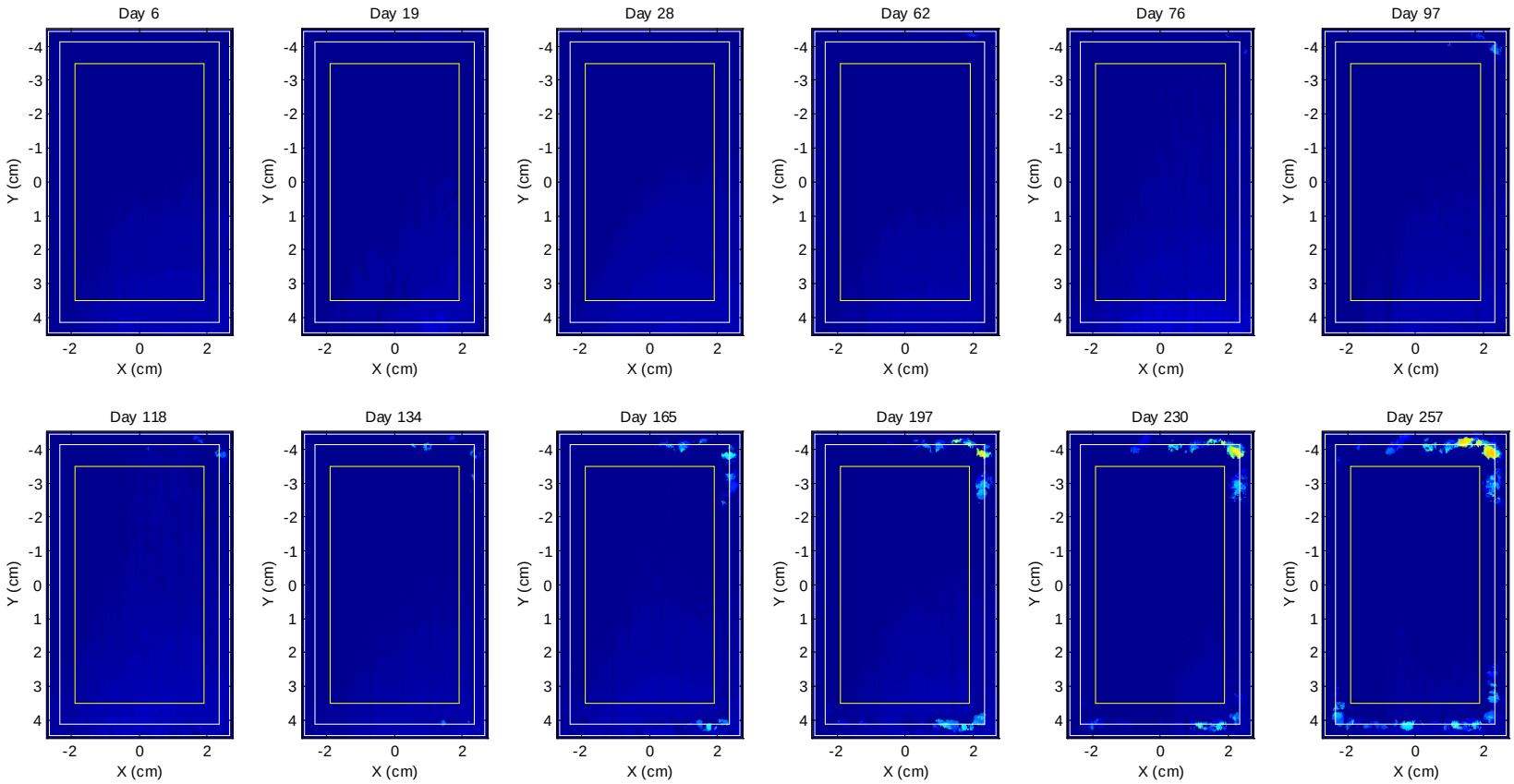
9.3.3. Alloy 5086 – ut5-13

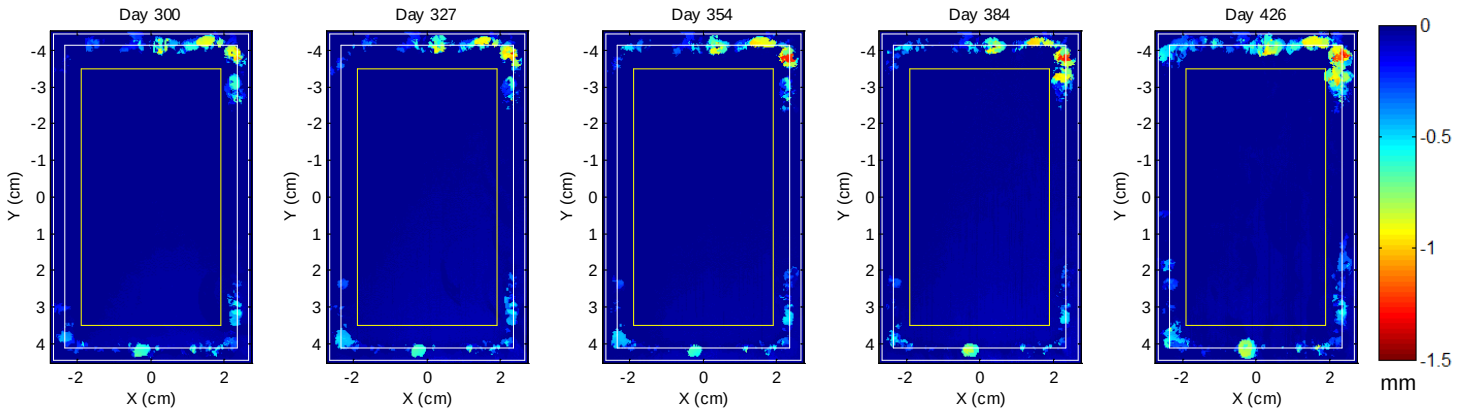



Day 326
Day 349
Day 383
Day 418
Y (cm)
X (cm)
-4
-3
-2
-1
0
1
2
3
4
-2
0
2
0
-0.05
-0.1
-0.15
-0.2
-0.25
mm

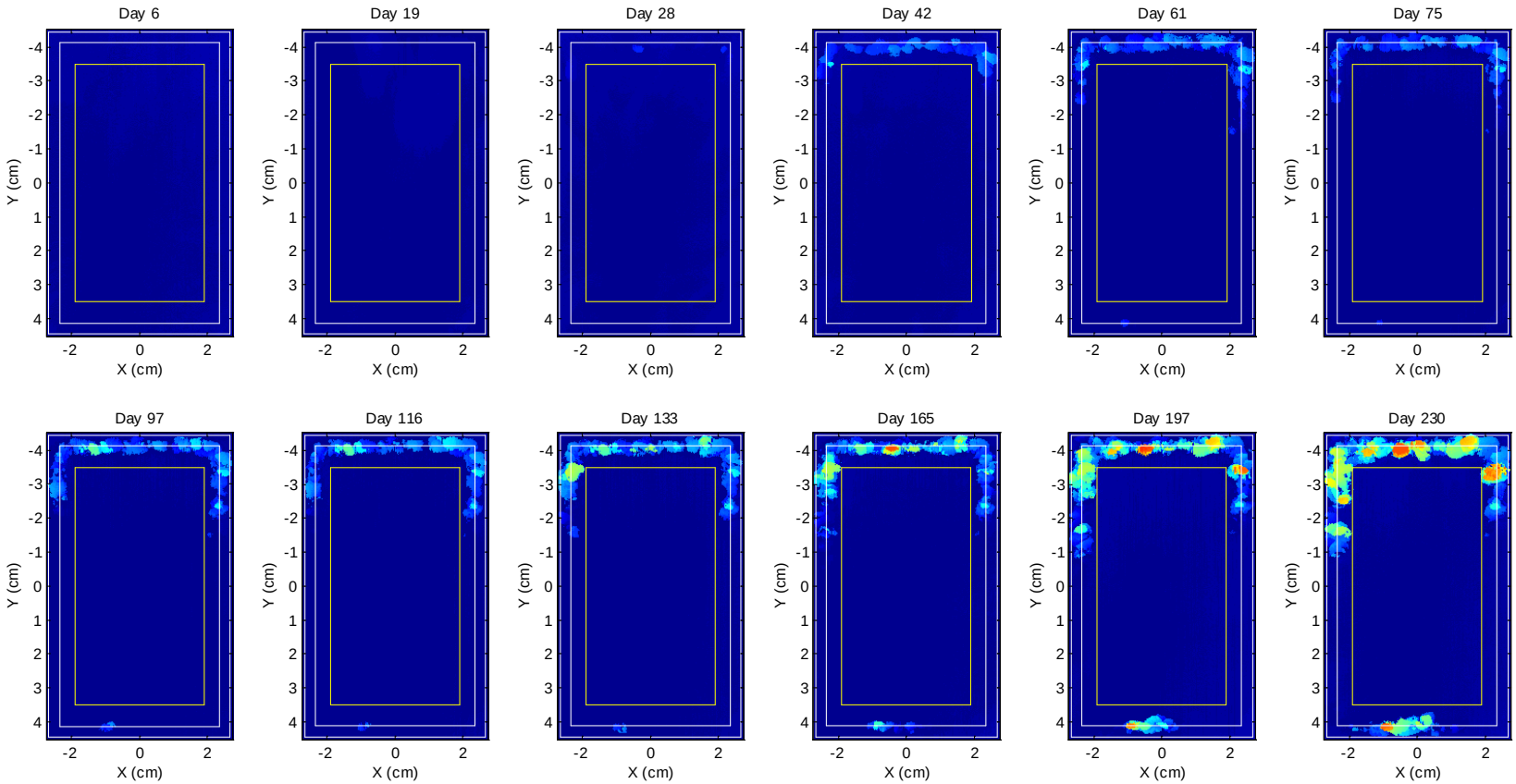
9.4. ACID TREATMENT IN NEAR STAGNANT SEAWATER

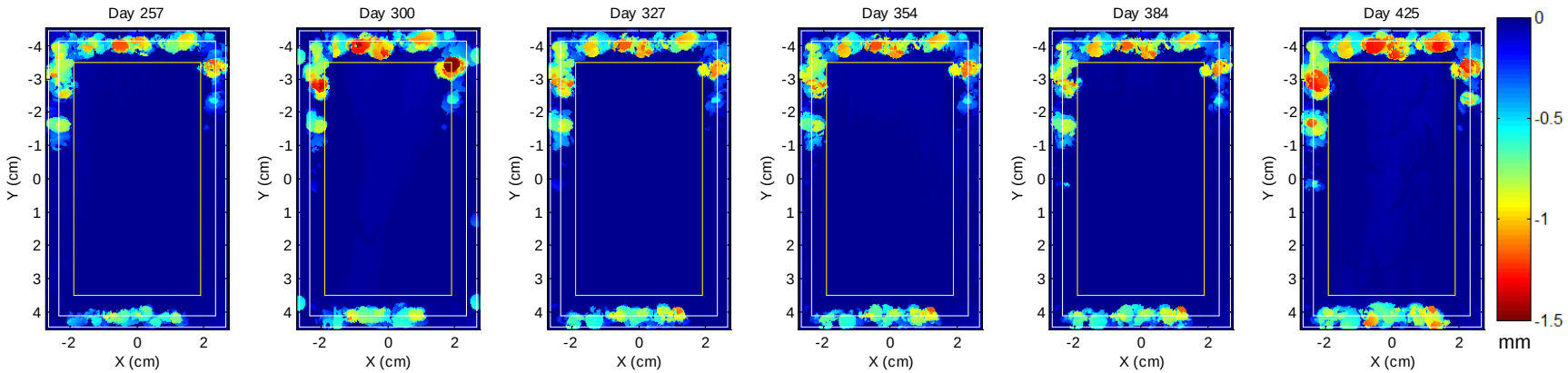
9.4.1. Alloy 1100 – ut1-14



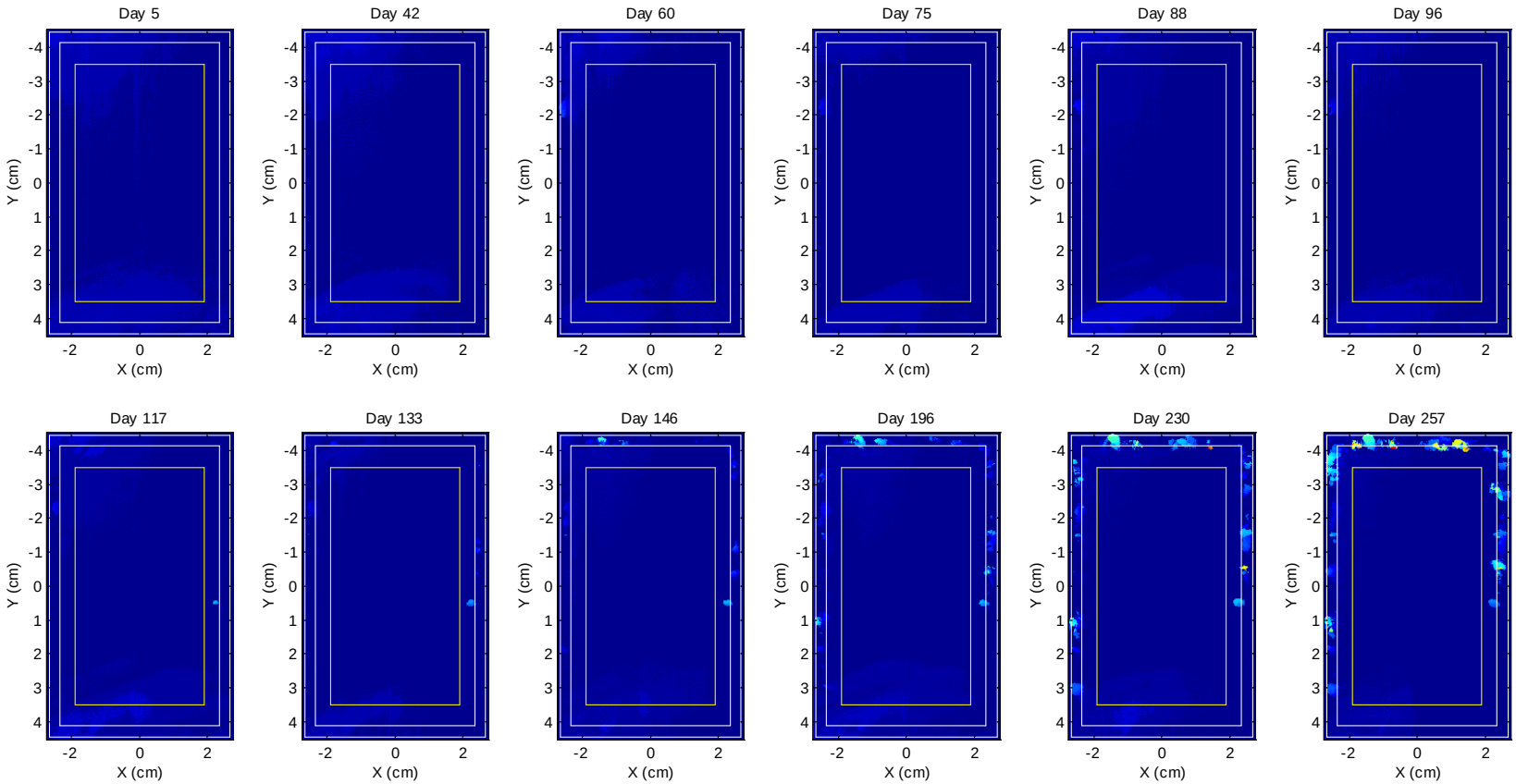

Day 300
Day 327
Day 354
Day 384
Day 426
Y (cm)
X (cm)
-4
-3
-2
-1
0
1
2
3
4
-2
0
2
0
-0.5
-1
-1.5
mm

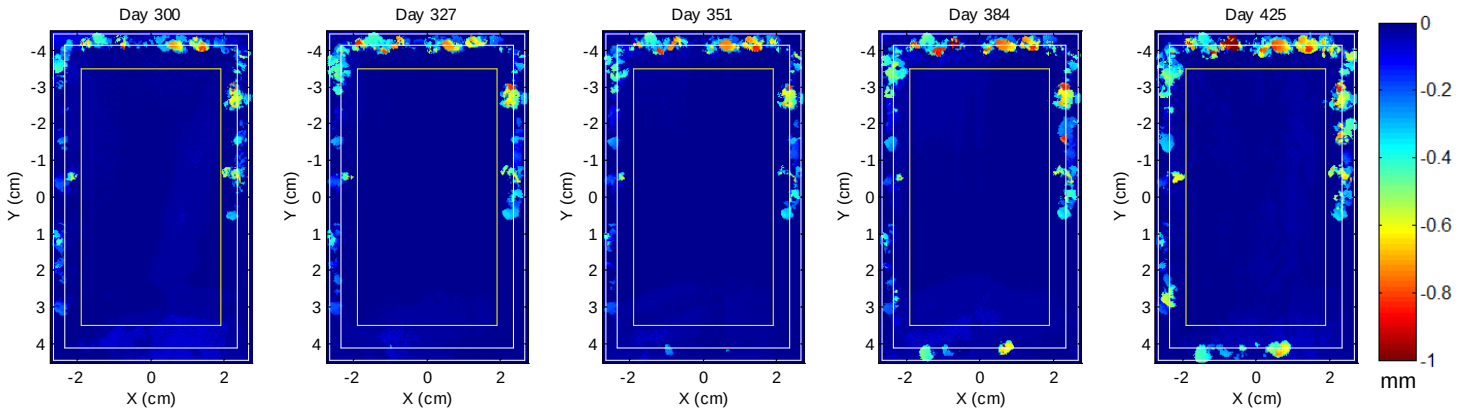
9.4.2. Alloy 3003 – ut3-14




Day 257
Day 300
Day 327
Day 354
Day 384
Day 425
Y (cm)
X (cm)
-4
-3
-2
-1
0
1
2
3
4
-2
0
2
0
-0.5
-1
-1.5
mm

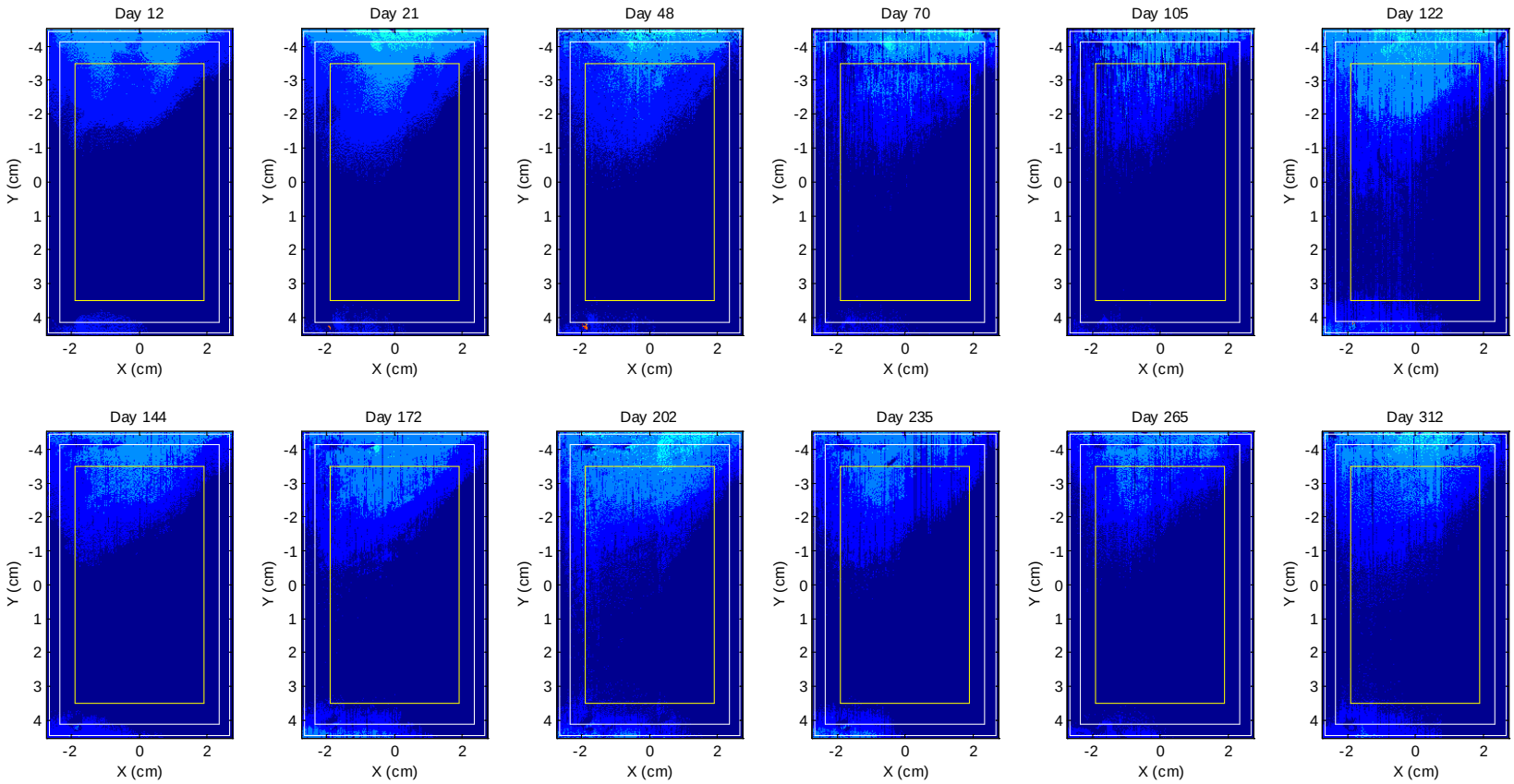
9.4.3. Alloy 5086 – ut5-14

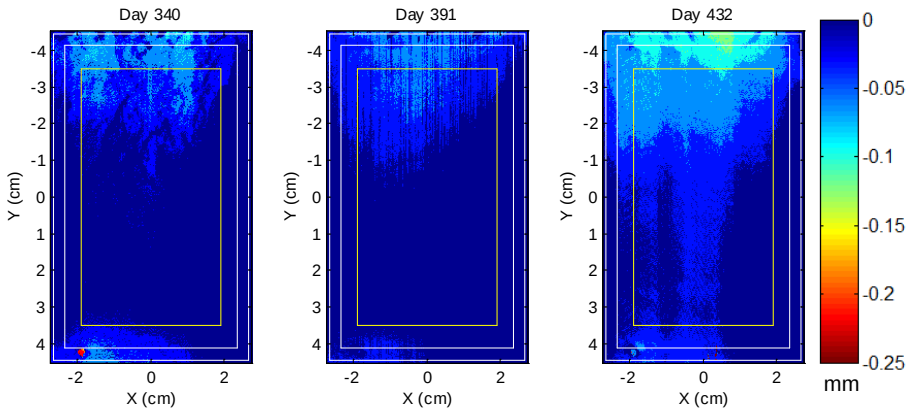



Day 300
Day 327
Day 351
Day 384
Day 425
Y (cm)
X (cm)
-4
-3
-2
-1
0
1
2
3
4
-2
0
2
0
-0.2
-0.4
-0.6
-0.8
-1
mm

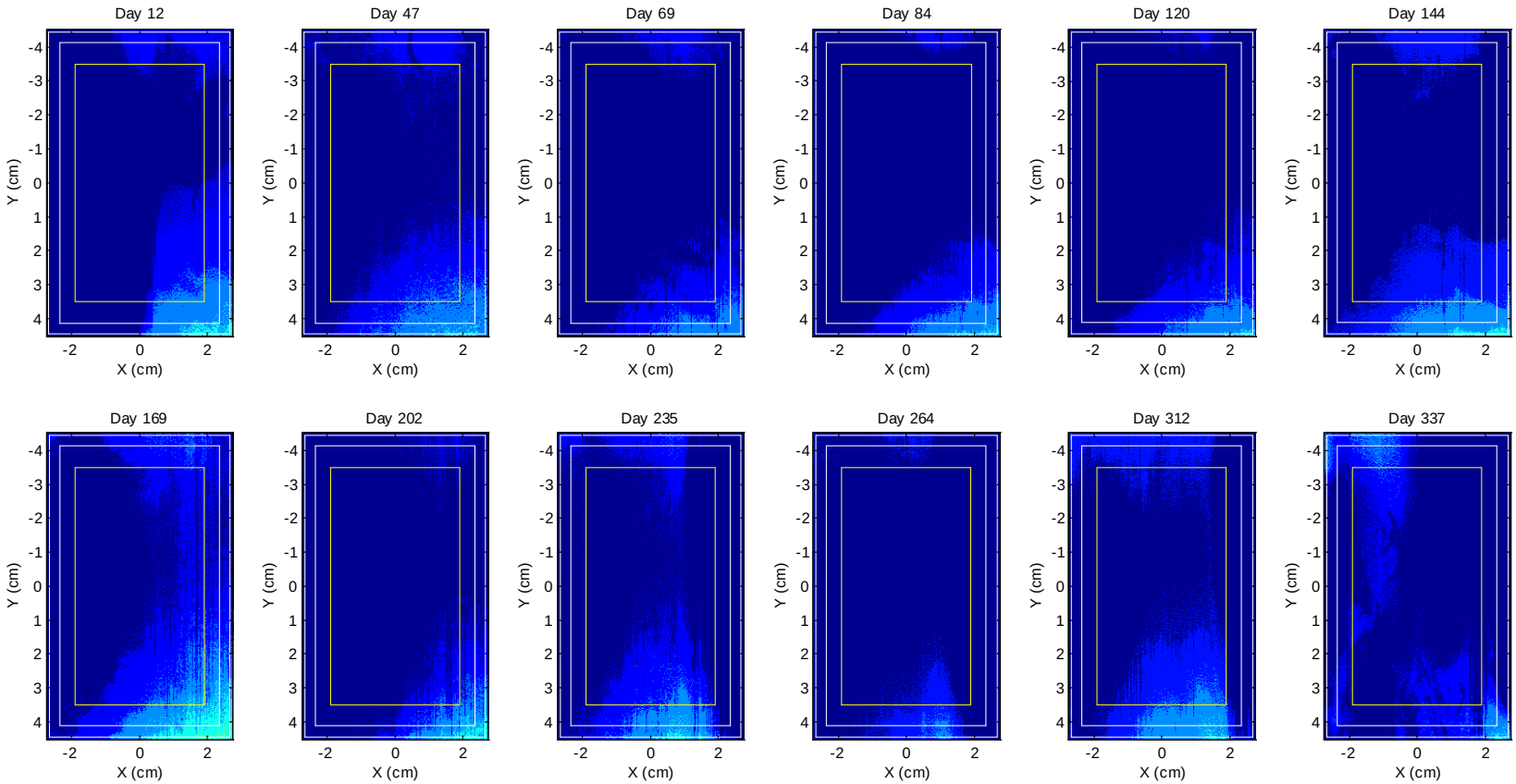
9.5. HYPO-CHLORINATION IN FLOWING SEAWATER

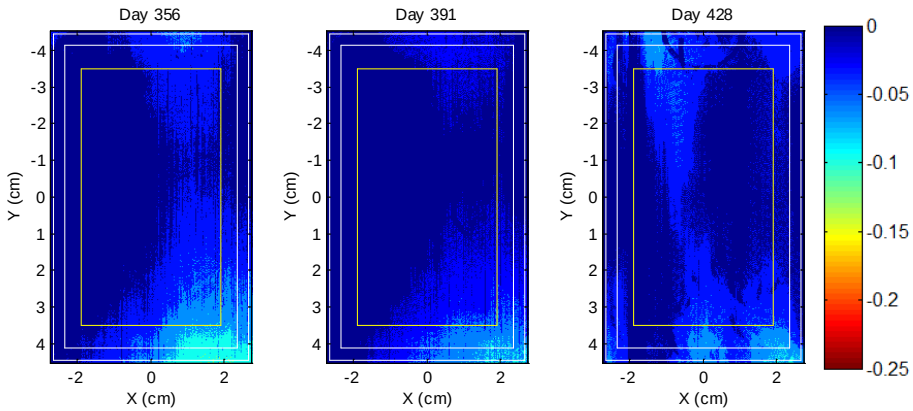
9.5.1. Alloy 1100 – ut1-15



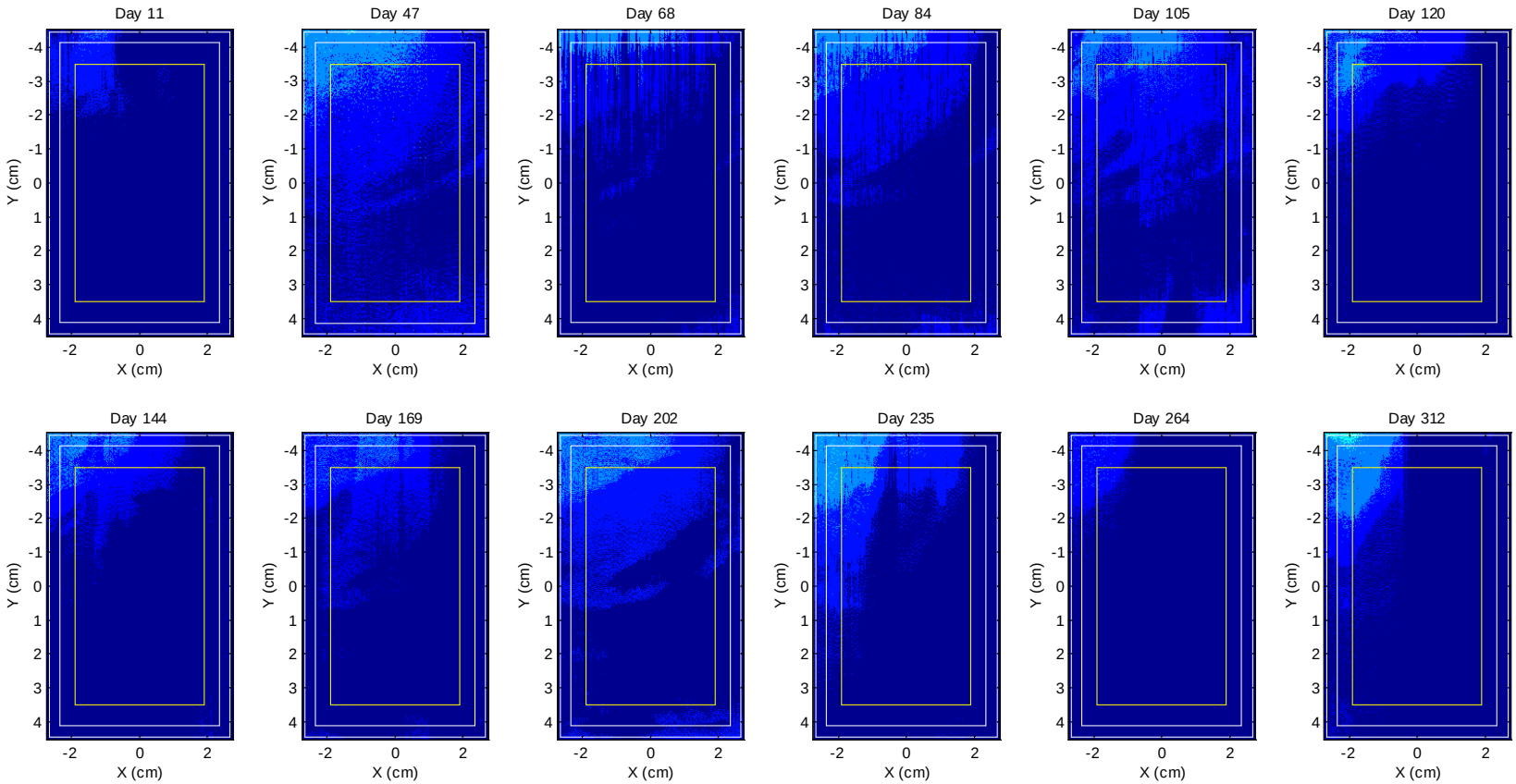

Day 340
Day 391
Day 432
Y (cm)
X (cm)
-4
-3
-2
-1
0
1
2
3
4
-2
0
2
0
-0.05
-0.1
-0.15
-0.2
-0.25
mm

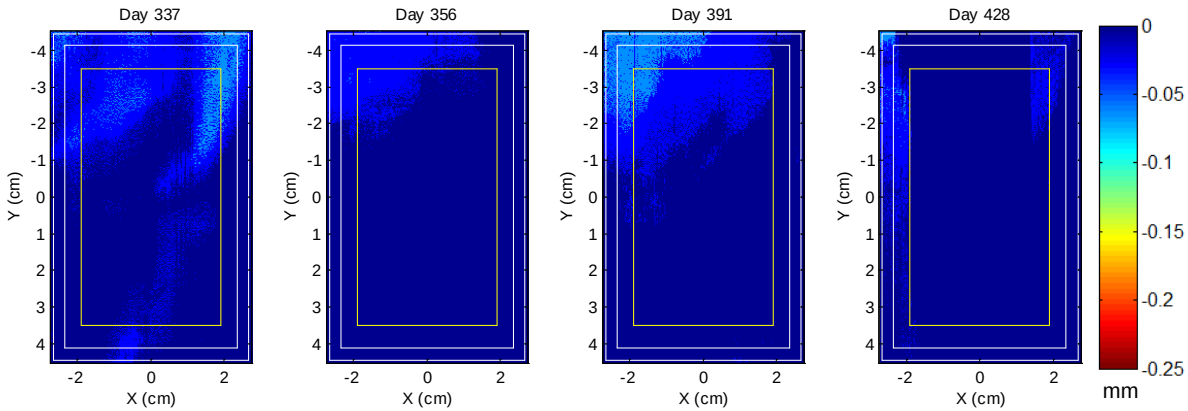
9.5.2. Alloy 3003 – ut3-15




Day 356
Day 391
Day 428
Y (cm)
X (cm)
-4
-3
-2
-1
0
1
2
3
4
-2
0
2
0
-0.05
-0.1
-0.15
-0.2
-0.25

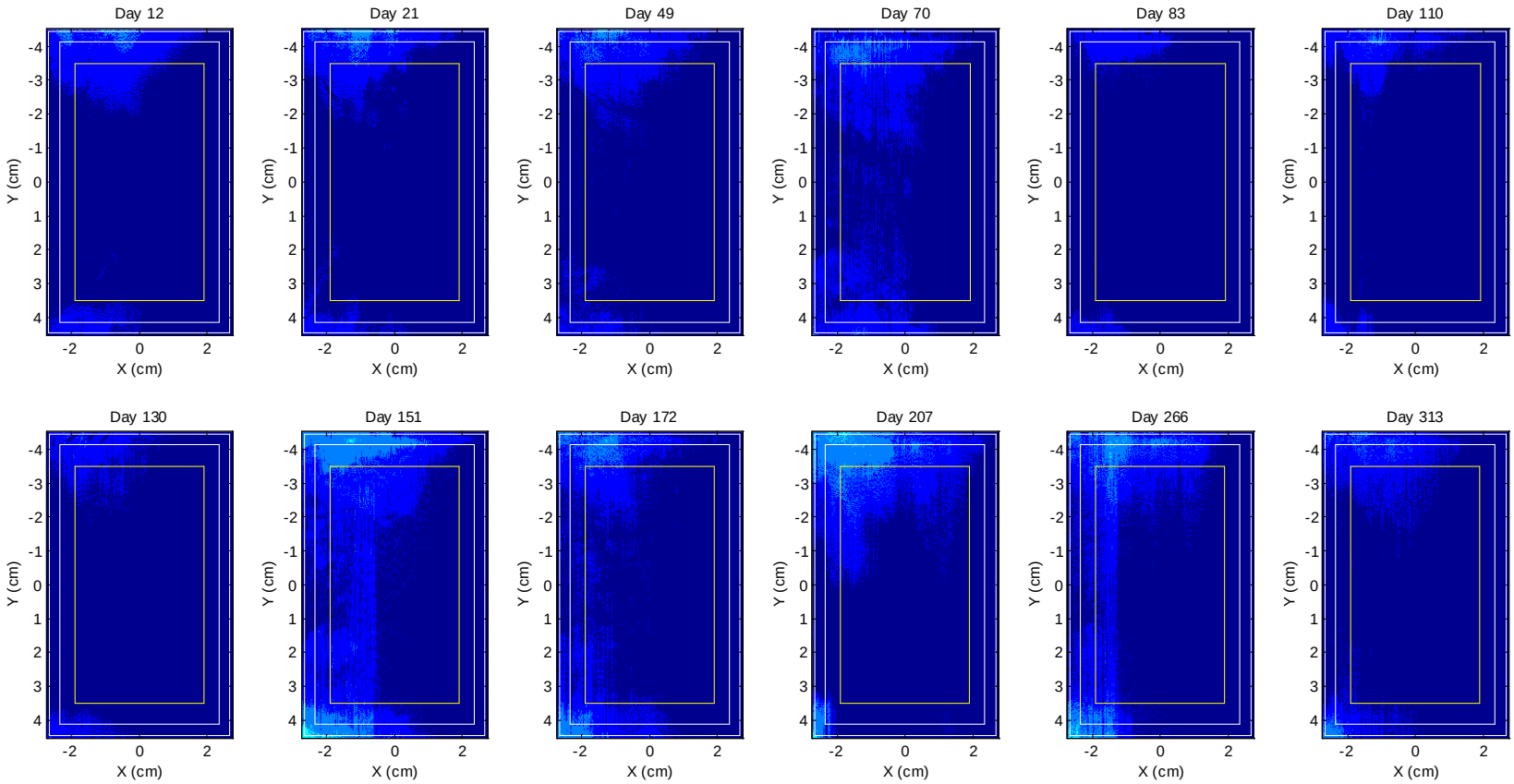
9.5.3. Alloy 5086 – ut5-15

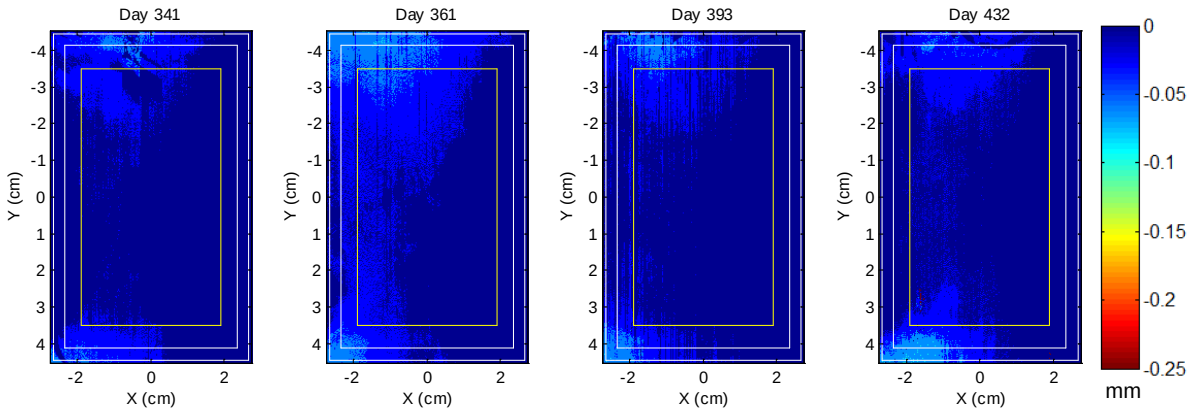



Day 337
Day 356
Day 391
Day 428
Y (cm)
X (cm)
-4
-3
-2
-1
0
1
2
3
4
-2
0
2
0
-0.05
-0.1
-0.15
-0.2
-0.25
mm

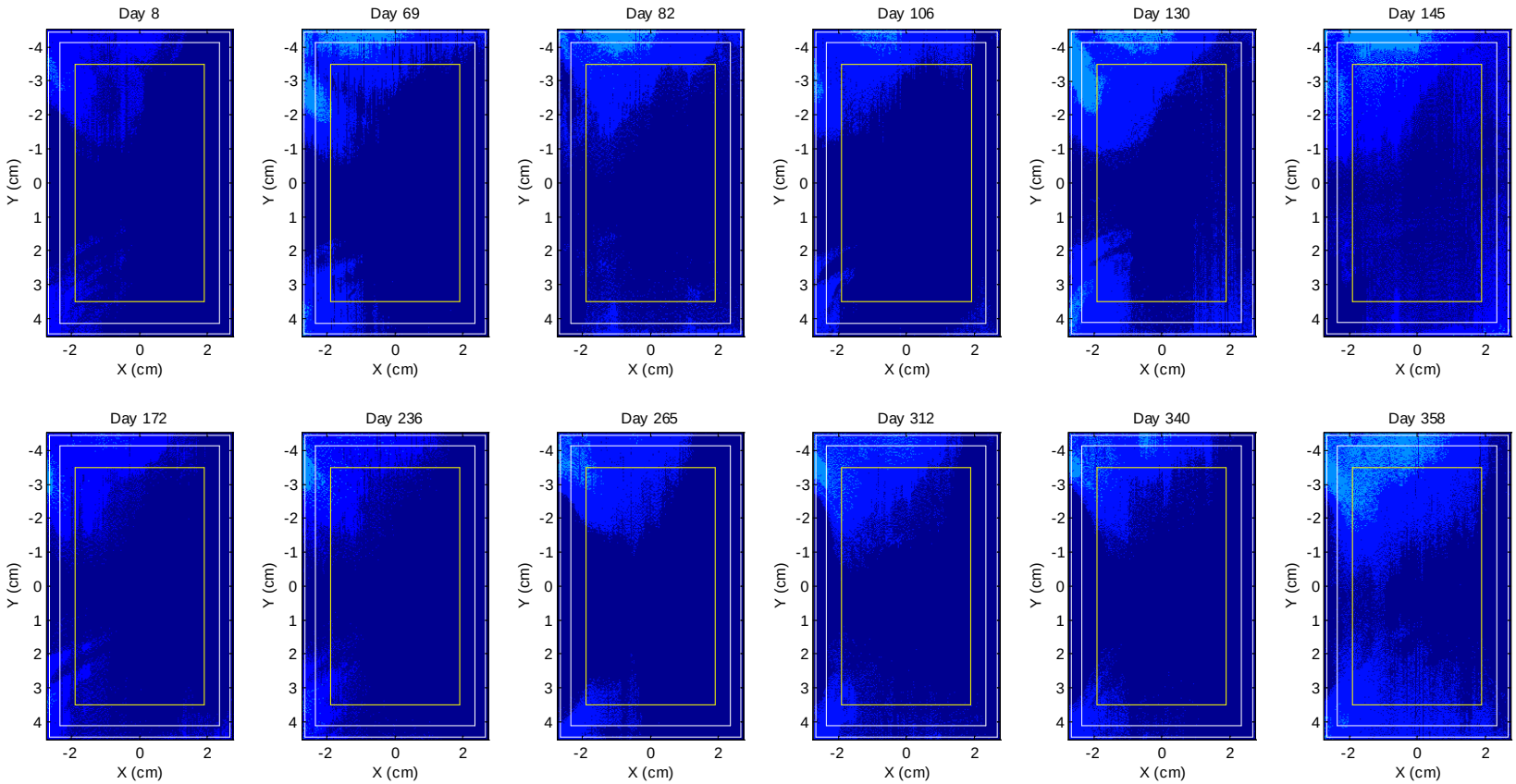
9.6. HYPO-CHLORINATION IN NEAR STAGNANT SEAWATER

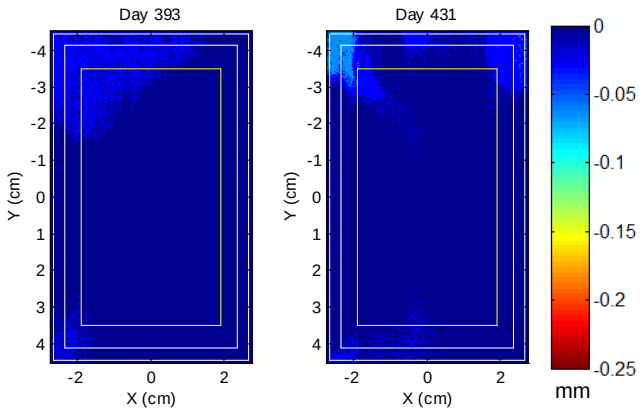
9.6.1. Alloy 1100 – ut1-16



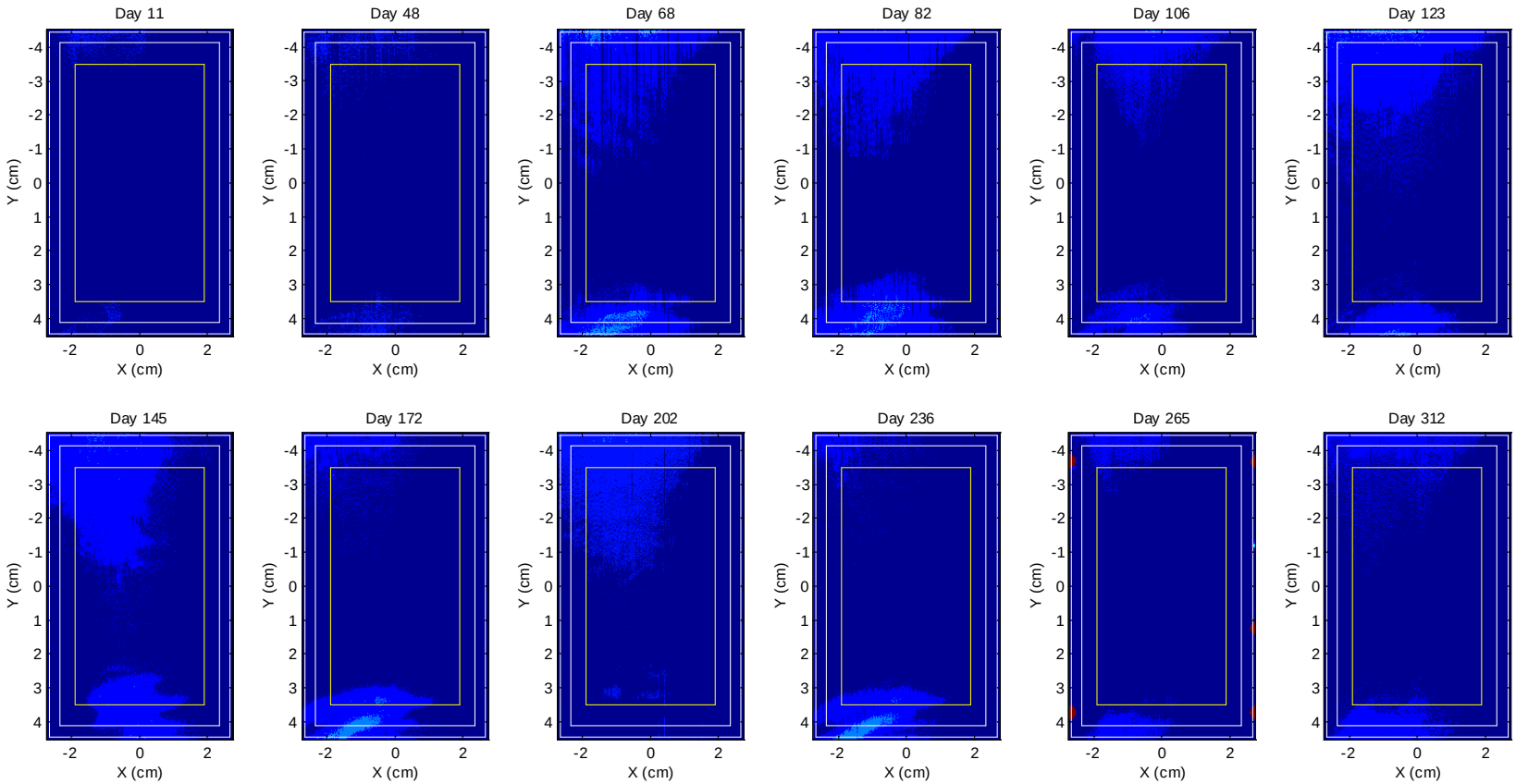

Day 341
Day 361
Day 393
Day 432
Y (cm)
X (cm)
-4
-3
-2
-1
0
1
2
3
4
-2
0
2
0
-0.05
-0.1
-0.15
-0.2
-0.25
mm

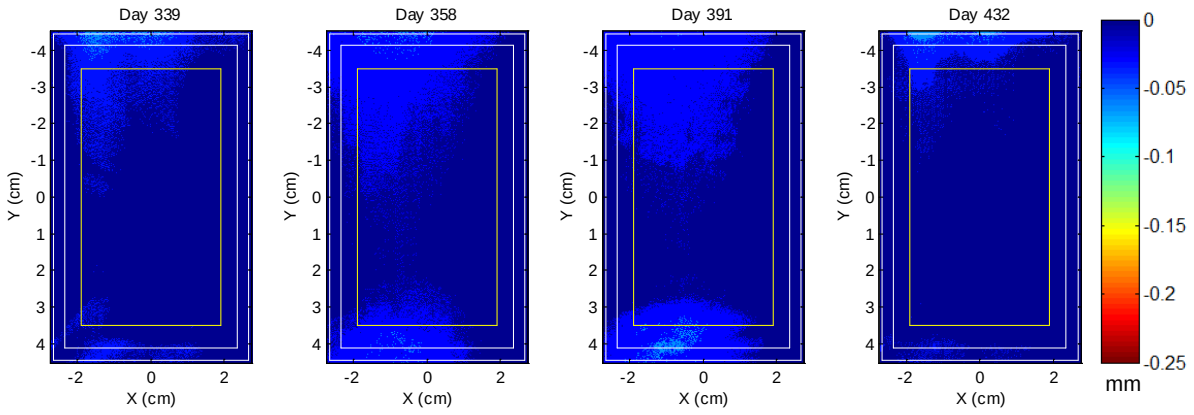
9.6.2. Alloy 3003 – ut3-16




Day 393
Day 431
Y (cm)
X (cm)
-4
-3
-2
-1
0
1
2
3
4
-2
0
2
0
-0.05
-0.1
-0.15
-0.2
-0.25
mm

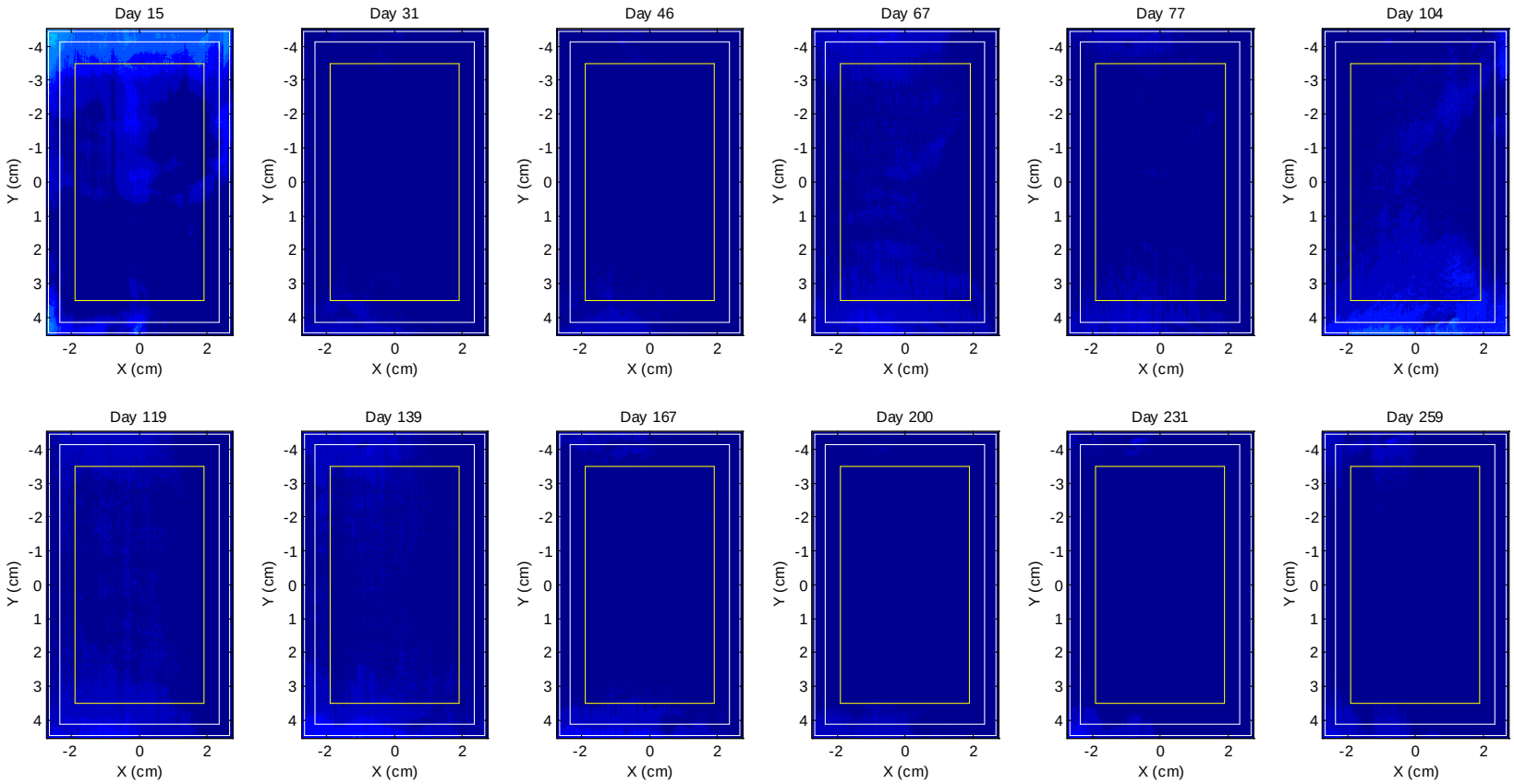
9.6.3. Alloy 5086 – ut5-16

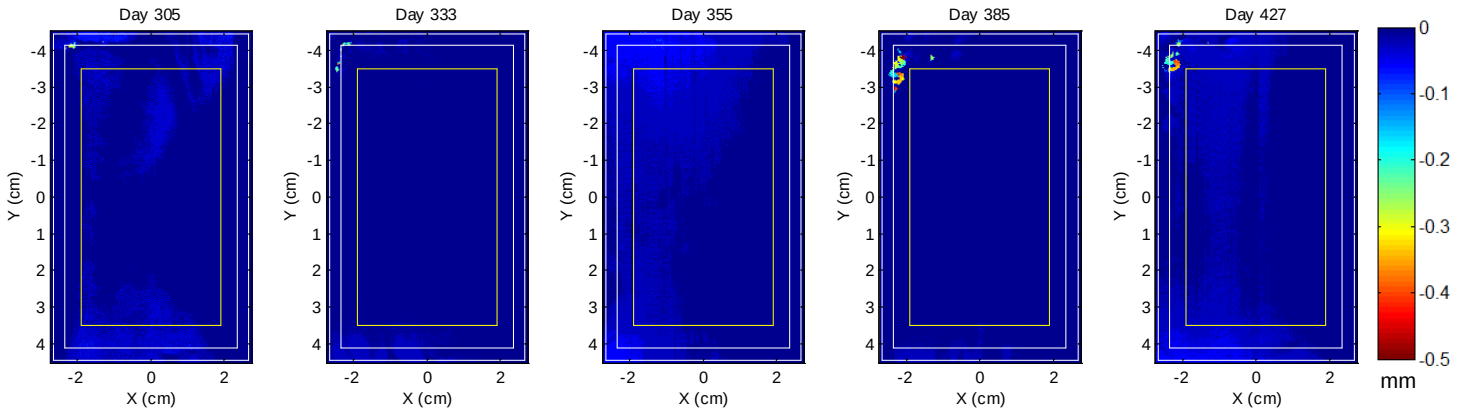



Day 339
Day 358
Day 391
Day 432
Y (cm)
X (cm)
-4
-3
-2
-1
0
1
2
3
4
-2
0
2
0
-0.05
-0.1
-0.15
-0.2
-0.25
mm

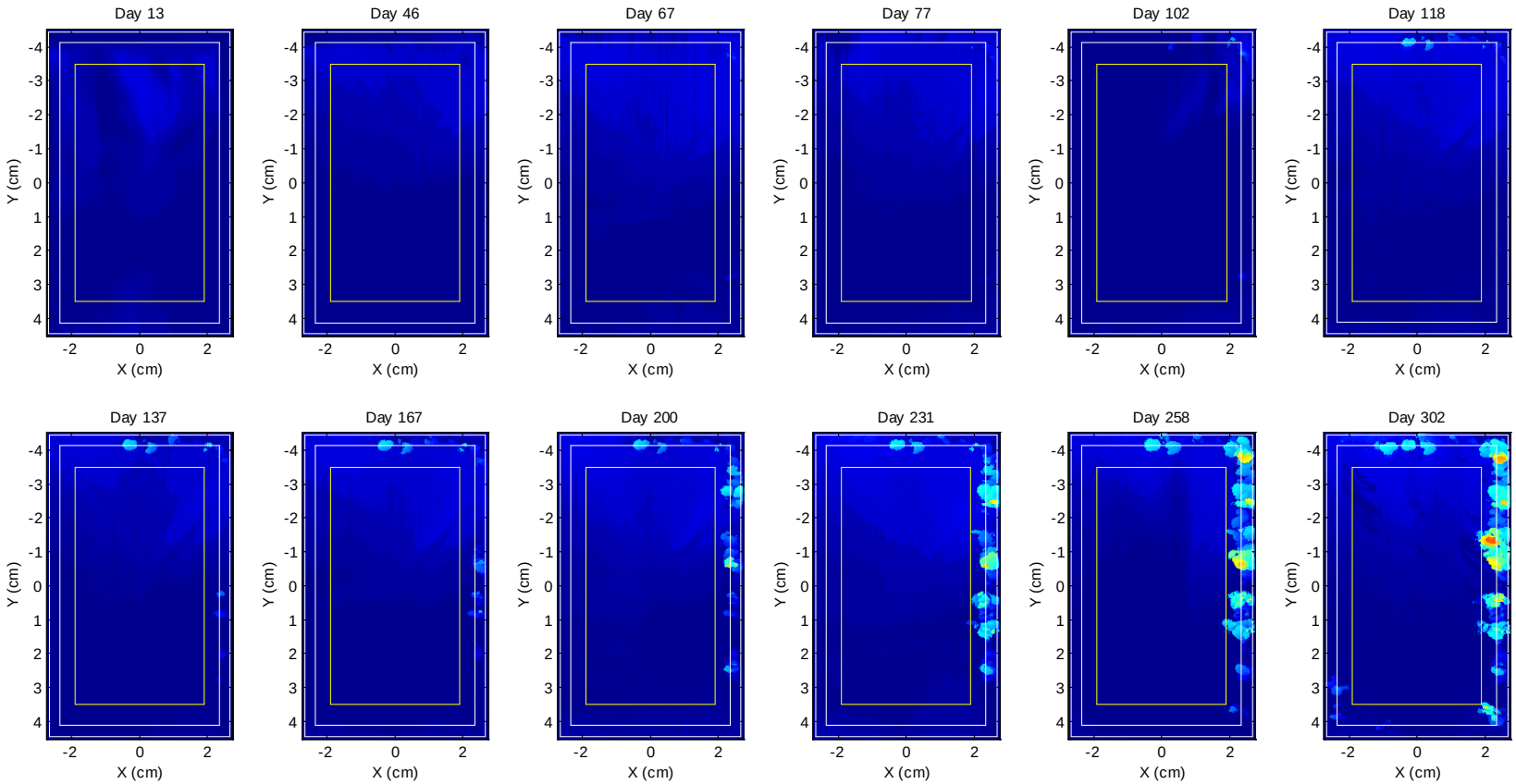
9.7. CONTROL IN FLOWING SEAWATER

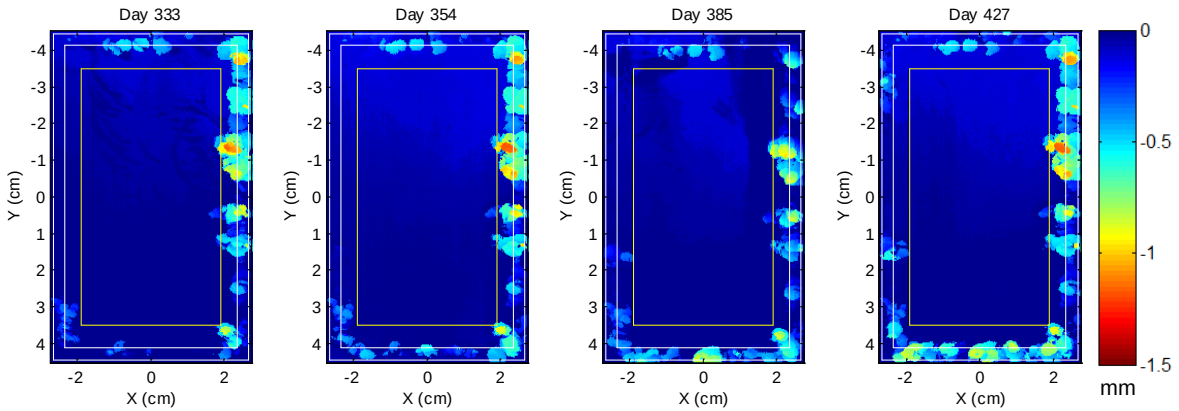
9.7.1. Alloy 1100 – ut1-17



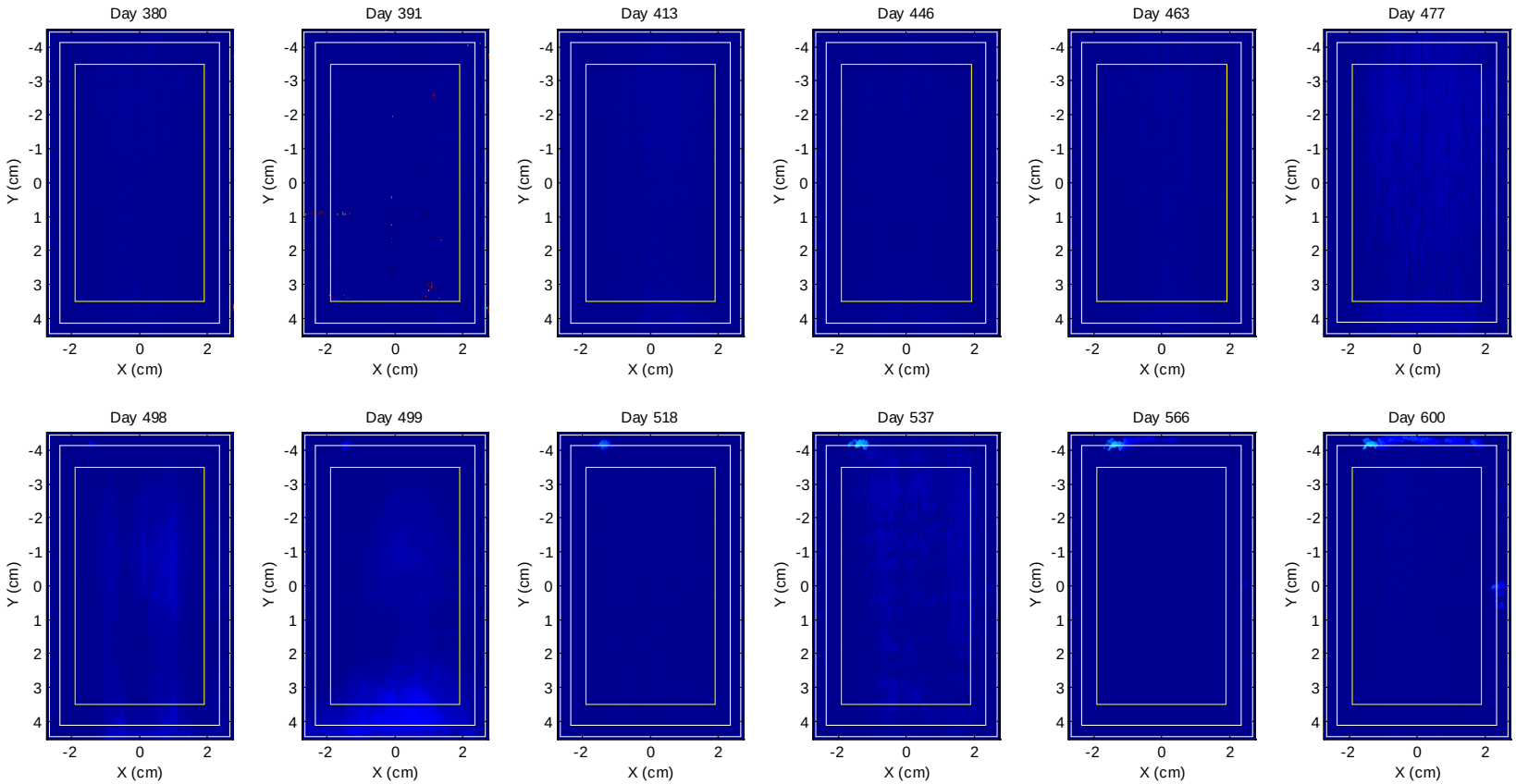

Day 305
Day 333
Day 355
Day 385
Day 427
Y (cm)
X (cm)
-4
-3
-2
-1
0
1
2
3
4
-2
0
2
0
-0.1
-0.2
-0.3
-0.4
-0.5
mm

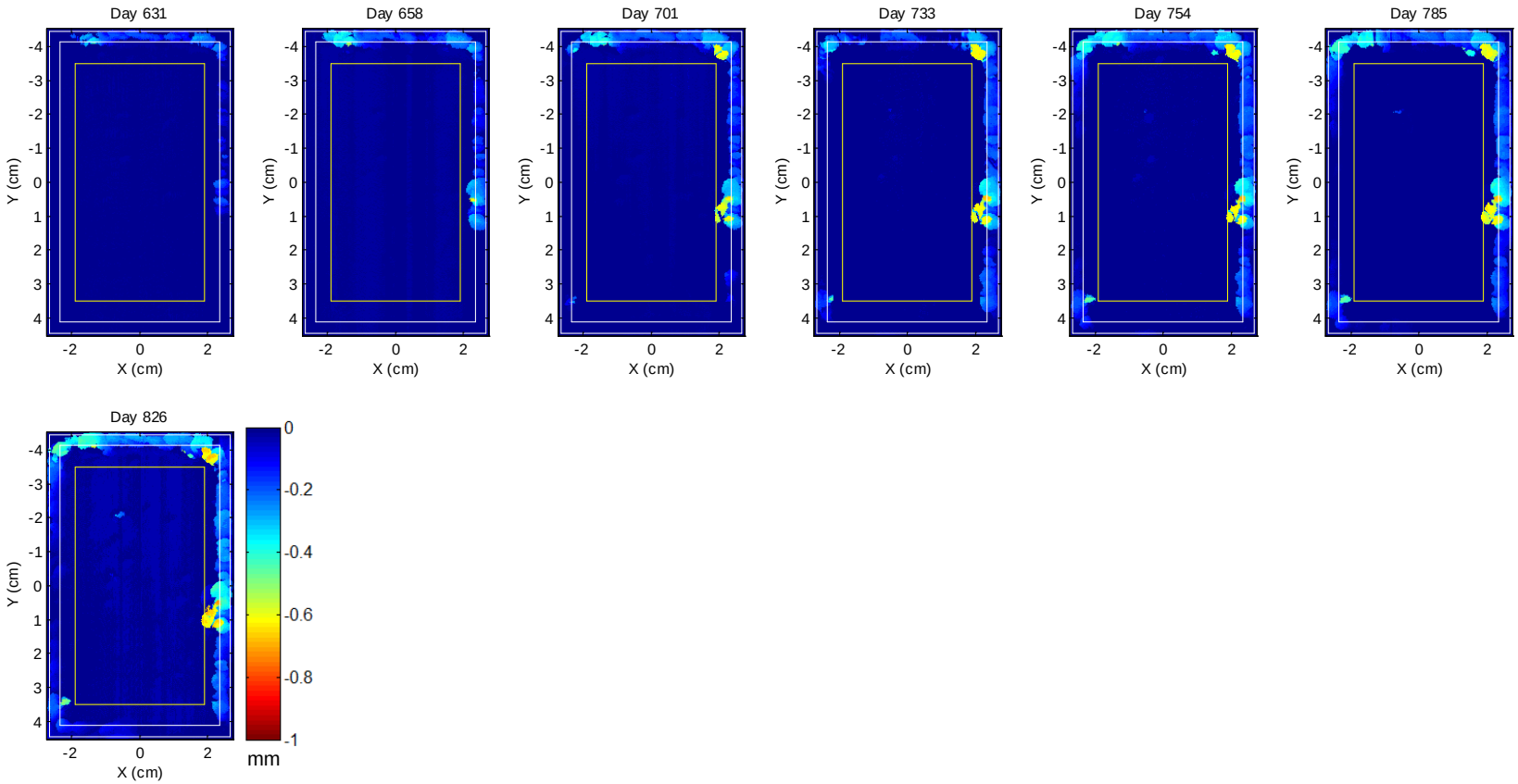
9.7.2. Alloy 3003 – ut3-17




Day 333
Day 354
Day 385
Day 427
Y (cm)
X (cm)
-4
-3
-2
-1
0
1
2
3
4
-2
0
2
0
-0.5
-1
-1.5
mm

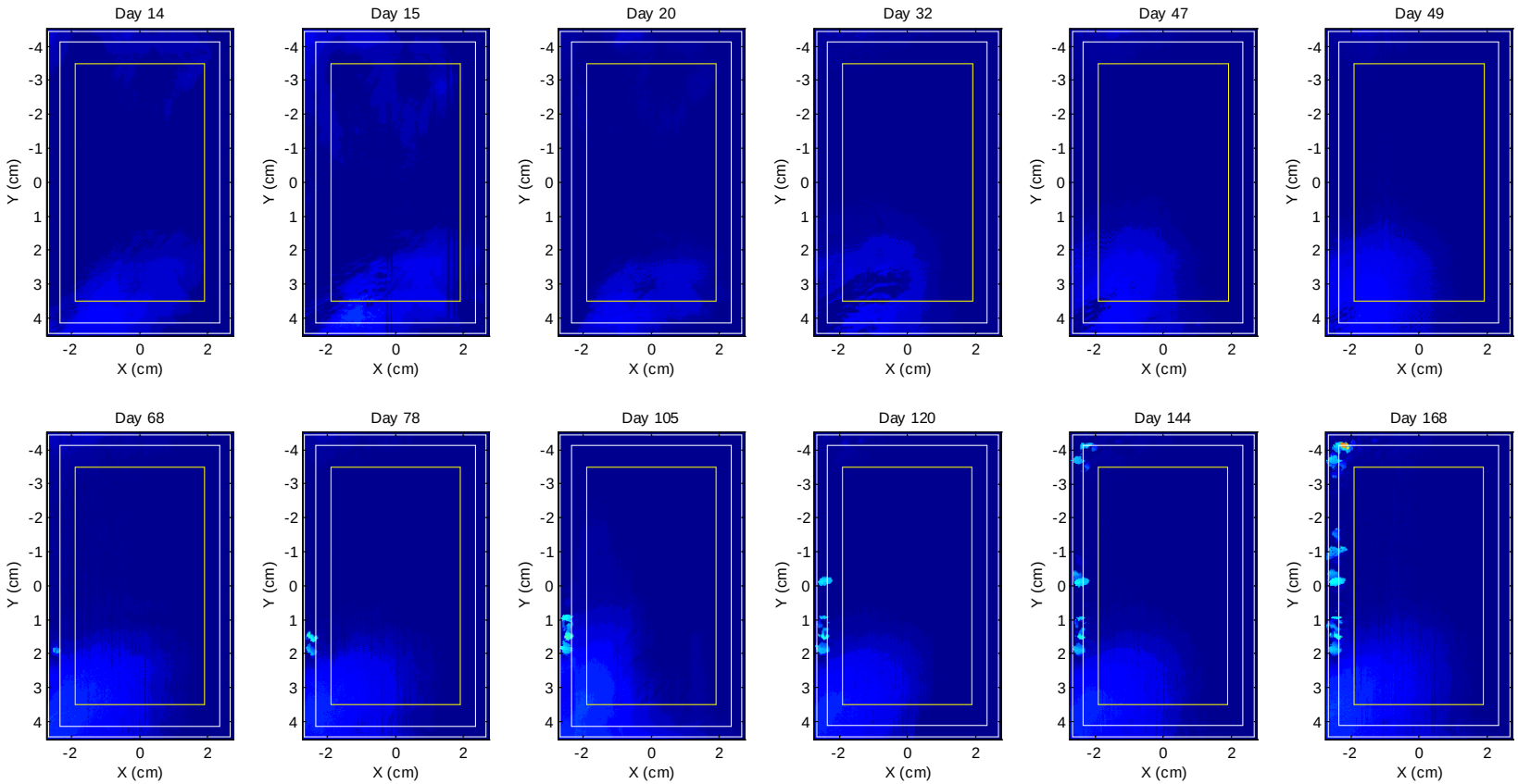
9.7.3. Alloy 5086 – ut5-17

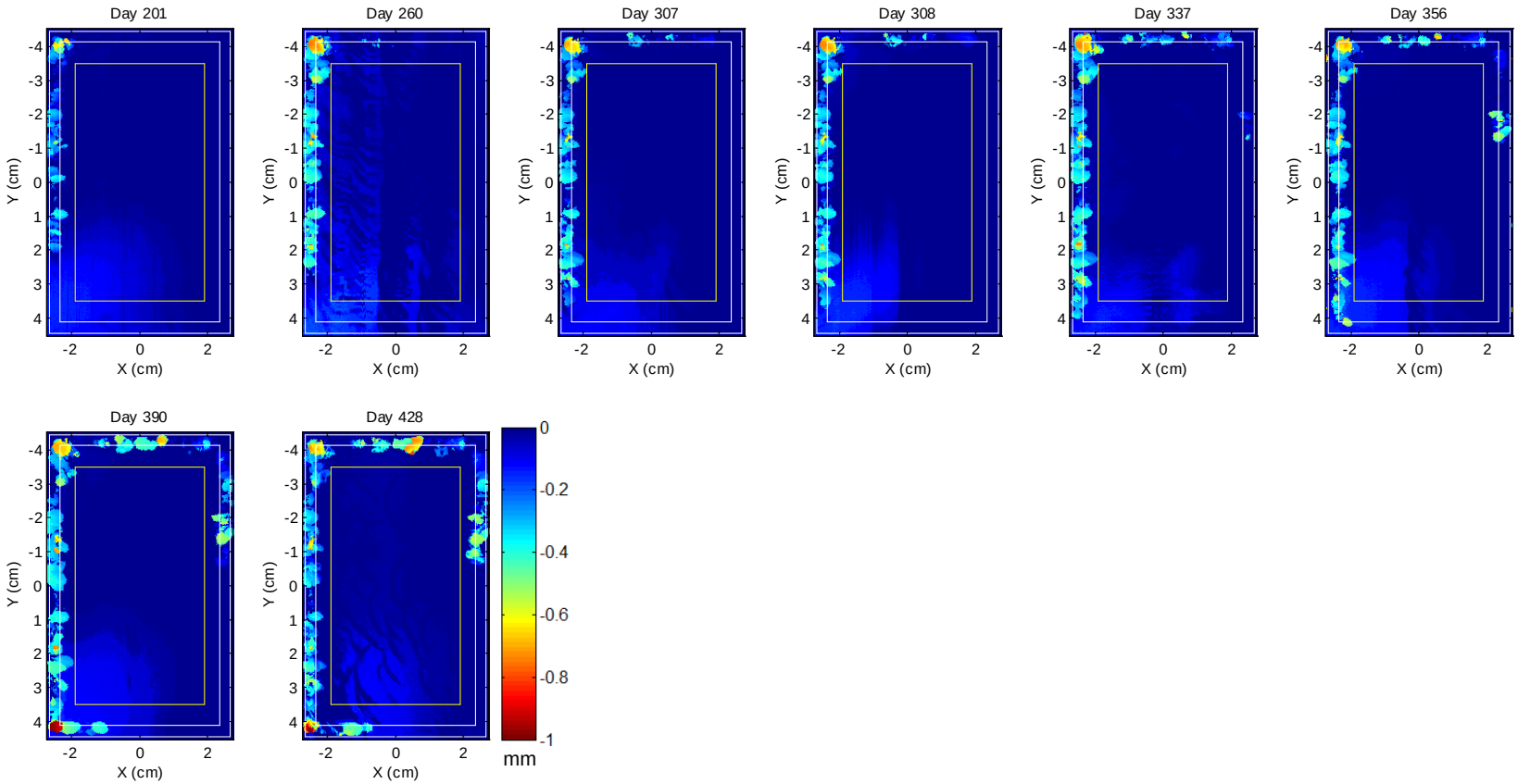



Day 631
Day 658
Day 701
Day 733
Day 754
Day 785
Day 826
Y (cm)
X (cm)
-4
-3
-2
-1
0
1
2
3
4
-2
0
2
0
-0.2
-0.4
-0.6
-0.8
-1
mm

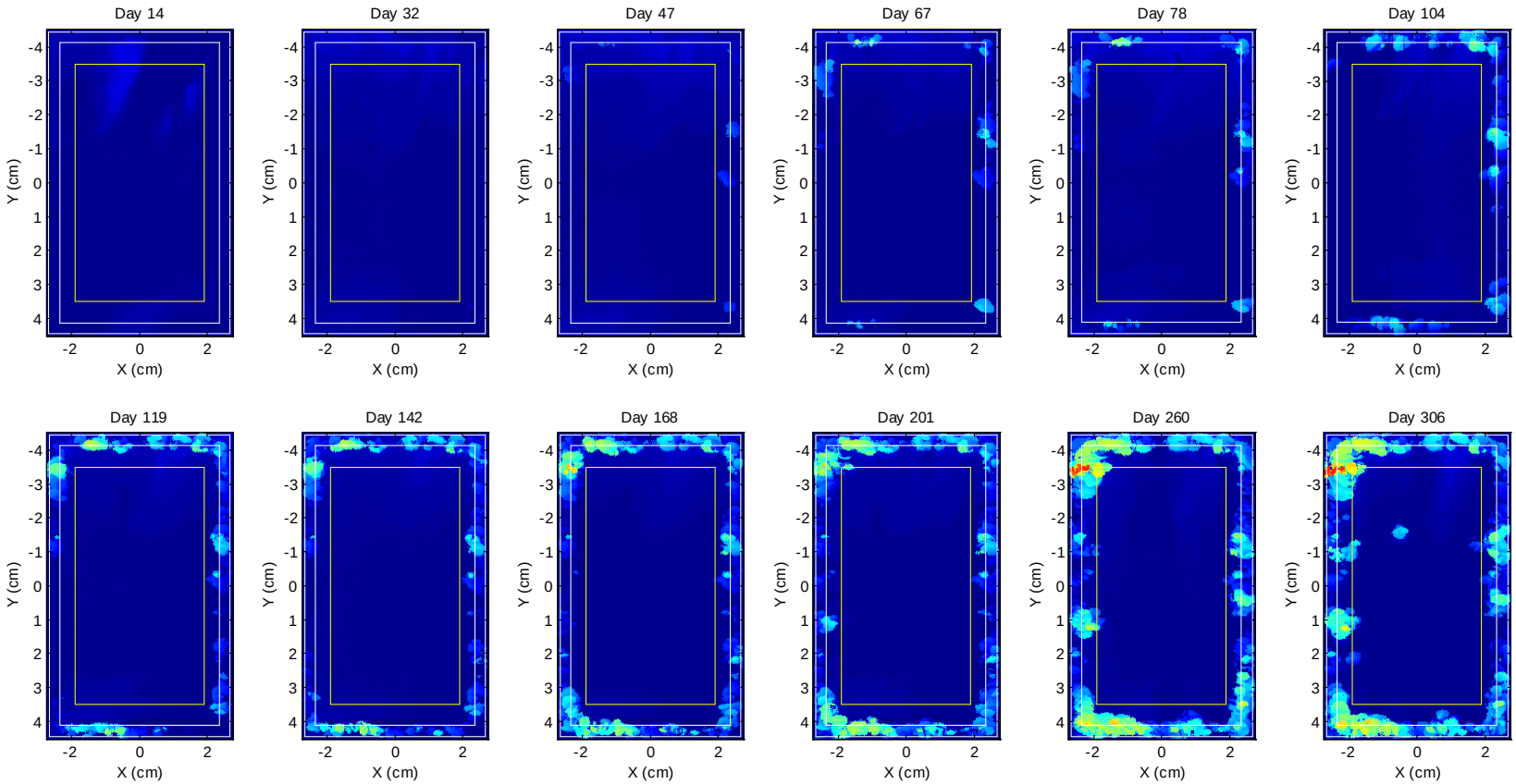
9.8. CONTROL IN NEAR STAGNANT SEAWATER

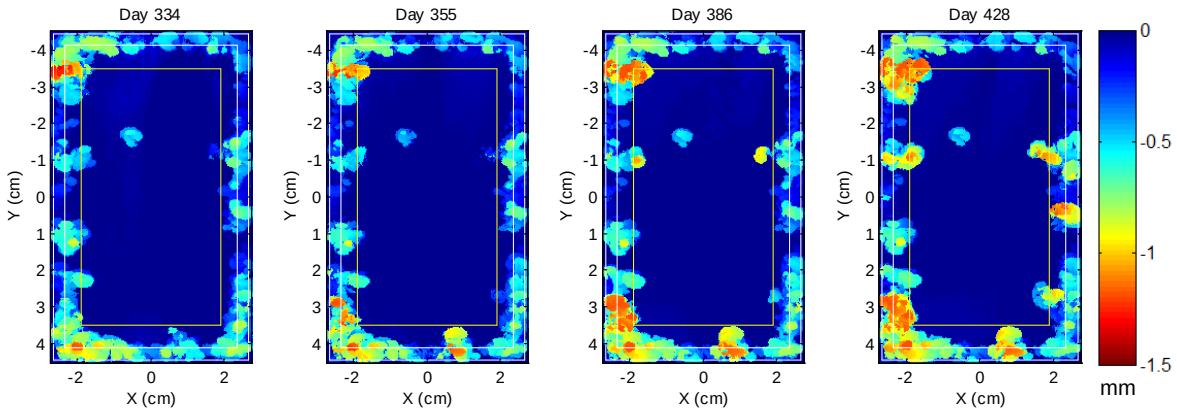
9.8.1. Alloy 1100 – ut1-18



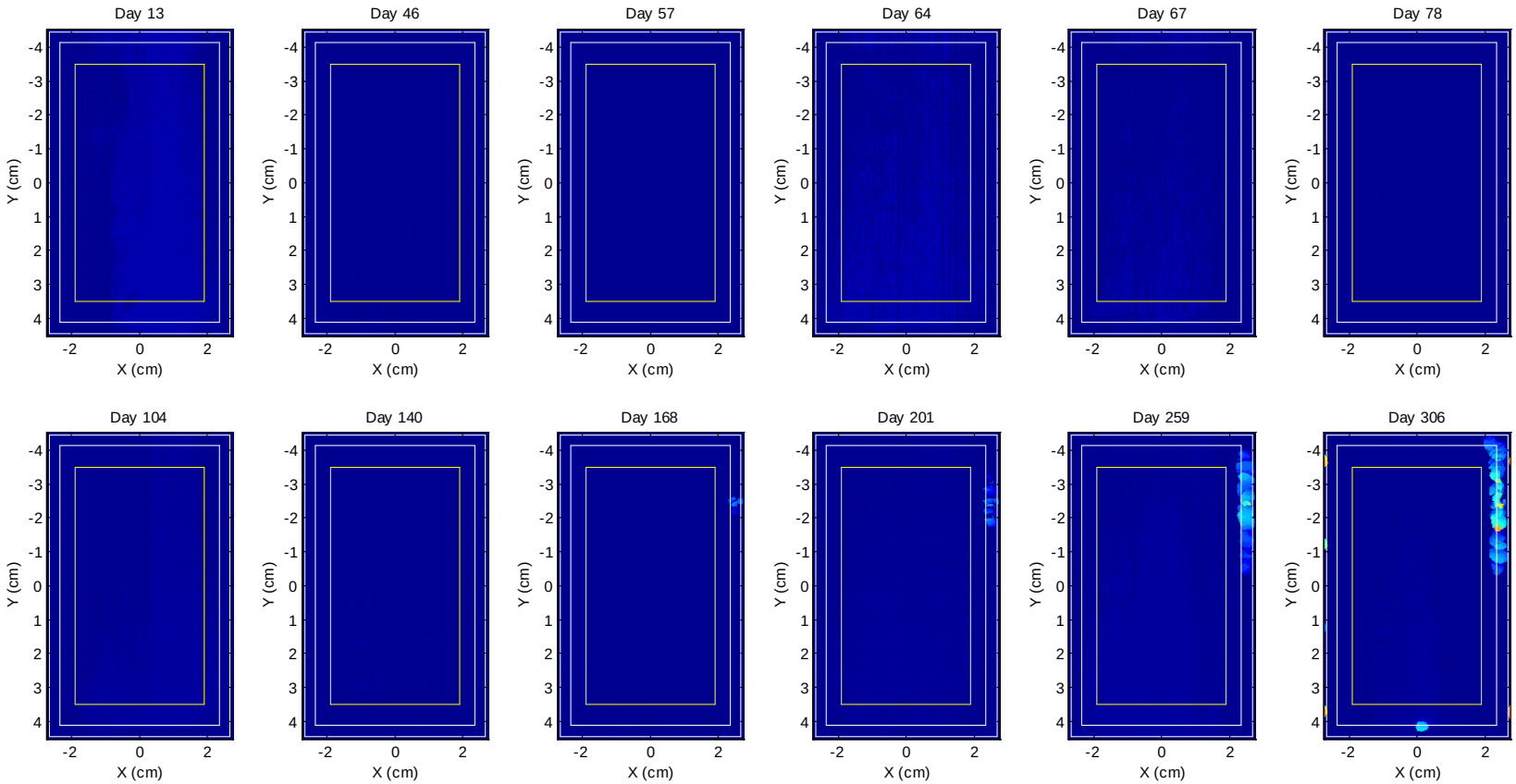

Day 201
Day 260
Day 307
Day 308
Day 337
Day 356
Day 390
Day 428
Y (cm)
X (cm)
-4
-3
-2
-1
0
1
2
3
4
-2
0
2
0
-0.2
-0.4
-0.6
-0.8
-1
mm

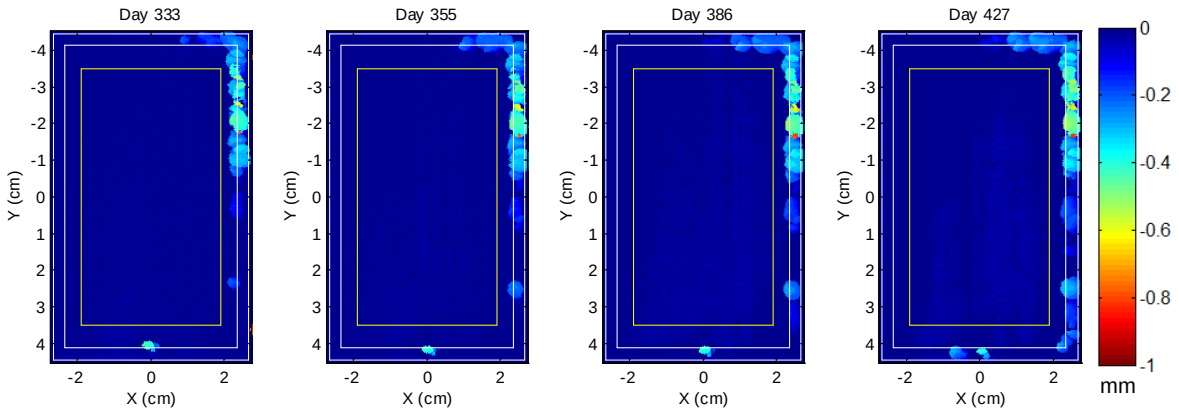
9.8.2. Alloy 3003 – ut3-18




Day 334
Day 355
Day 386
Day 428
Y (cm)
X (cm)
-4
-3
-2
-1
0
1
2
3
4
-2
0
2
0
-0.5
-1
-1.5
mm

9.8.3. Alloy 5086 – ut5-18




Day 333
Day 355
Day 386
Day 427
Y (cm)
X (cm)
-4
-3
-2
-1
0
1
2
3
4
-2
0
2
0
-0.2
-0.4
-0.6
-0.8
-1
mm