

# Corrosion Testing Laboratories, Inc.

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CTL REF #31636

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## City of Gardner Leaking Copper Coils Failure Investigation

Presented herein are the results of the above referenced testing. This work was authorized per City of Gardner's PO #00009029-00.

### Conclusions

- Leaks in the provided coils were caused by localized pinholes that formed at the inside surface of the coil (exposed to potable drinking water).
- The attack that created the pinholes was likely caused by the water quality issues related to soft water low alkalinity, and/or low dissolved inorganic carbon. These parameters were more pronounced in the water distributed from Crystal Lake Water Treatment Facility (WTF). This facility uses surface/ground water as a source.
  - The coil failures are centralized around this distribution plant.
  - The water from this facility was soft, had low alkalinity and dissolved inorganic carbon (overall and relative to the other WTF), which is known as a cause of this type of pitting failure<sup>1</sup>.
    - These qualities reflect the waters buffering capacity and, relatedly, the ability of the copper to form a protective scale layer at its surface to prevent corrosion.
    - Surface water in the City's geographic region has been shown to have a generally low alkalinity.
  - Other qualities of water that can cause this type of attack in copper were not concerning in the provided water analysis report or in the laboratory analyses performed. There were no high levels of contaminants or corrodents identified at the failure sites (e.g., chlorides, sulfates, etc.).
- The fact that failures occurred in heating coils but not copper piping the same system could be attributed to the surface geometry of the coil. The scalloped inside surface could have provided sites for corrosion cells to initiate that were not present in the pipes.
- Laboratory findings during the metallurgical examination did not suggest that the failures were related to material quality.

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<sup>1</sup> EPA "Pitting Corrosion of Copper in High-pH and Low-Alkalinity Waters."  
[http://www.epa.gov/nrmrl/wswrd/cr/corr\\_res\\_copper\\_ai2.html](http://www.epa.gov/nrmrl/wswrd/cr/corr_res_copper_ai2.html)

## Background Information

In the past 15 years, an increasing number of homes in City of Gardener, Massachusetts have developed leaks in copper coils that are part of their water heating system. The coils are used to heat domestic potable water. The affected units are tankless coils, which use recycled steam or hot water from the home furnace to heat the potable water inside the coil. Leaks have occurred in systems using both steam boilers and hot water boilers. The leaks are reportedly confined to the heating units and hot water copper pipes in the homes have not leaked. Residences in neighboring cities that have similar units installed, but have different water service, are not having an issue.

There are two water treatment facilities (WTF) in City of Gardner: Crystal Lake WTF (that sources surface water) and Snake Pond WTF (that sources well water). Water provided to homes in the city is a mixture of water from both WTFs, with relative proportions from each WTF depending on the location. The failures appear to be centralized around the Crystal Lake WTF, **Figure 1**. The city uses chloramination to disinfect the water (a process that uses chlorine and ammonia).

In each home, the coils are located inside a cast iron vessel that is filled with water. The temperature of the water outside the coil (shell side), recycled from the boilers, is approximately 212 °F when from steam boilers or 170 to 190 °F from hot water boilers. The pressure on the outside of the coil is 15 to 20 psig. The potable water at the inside (ID) enters the coil at ~50 °F and exits coil at ~180 °F. The internal pressures are typical anywhere from 60 to 140 psig and the pH of the water should be 6.5 to 8.5. Typical households use approximately 2.5 to 7.5 gallons of heated water per minute.

## Laboratory Investigation

Three failed coils that varied in length of service life prior to failure were provided for analysis, **Figure 2**. Coil 1 (“301 Chapel Gardner”) was in service for 10 months before failure, Coil 2 (“41 Edgfil (?) Gard”, note that this label was not entirely legible) for 15 months, and Coil 3 (“2 Church St.”) for 36 months.

Each coil had two concentric layers of copper piping (an inner and an outer layer, see **Figure 2**) with external fins. The exposed surfaces of the coils were visually examined. The base plates that the copper coils were welded onto appeared corroded, most notably so on Coil 2, **Figure 3**. Deposits from the base plates of Coils 2 and 3 were analyzed for elemental composition by EDS<sup>2</sup>. They were composed primarily of iron and oxygen (i.e., “rust”), with low levels of silicon and, possibly, sulfur.

The outer surfaces of the coils were generally coated in a thin layer of dark colored deposits, **Figure 4**. These deposits were determined to be primarily iron, copper, and oxygen, with low levels of silicon, sulfur, and calcium detected. In some locations, the copper appeared shiny, which typically indicates a copper surface that does not have a passive layer. [Note: formation of this layer serves as copper’s inherent corrosion resistance mechanism, resulting in dull-looking material.]

Coil 1 was pressure tested to find leaks. At least five pinhole leaks were easily identified, primarily on the outer of the two coil layers. Coil 3 was also pressure tested and multiple leaks were found. It is uncertain if there were leaks present in the inner layer of the coil, as the tubing was not as exposed making identification difficult. Two sections were removed from Coil 1 and one section from Coil 3 that contained known leaks for closer examination, **Figures 5 through 7**. When viewed using the stereoptical microscope, the attacked area could easily be identified by the red tint of the copper and green-blue deposits, which is typical of copper corrosion. One of the two sections from Coil 1 had a visible hole at the leak, inside which reddish, crystalline deposits could be seen. Blue-green deposits surrounded the leak site. The second of

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<sup>2</sup> EDS = Energy Dispersive X-ray Spectroscopy, which is an analytical technique performed using a Scanning Electron Microscope (SEM)

the two leaks in Coil 1 did not have a visible hole. The leak in Coil 3 was covered in orange/brown-colored deposits at the outside and no hole was visible. Some green-blue deposits were also present on the outside surface at the leak.

Inside the coils, there were mounds of black deposits at the leaks. The remainder of the inside surfaces were coated in a uniform layer of black deposit. A sample of a black deposit mound from Coil 1 was analyzed by EDS and determined to be primarily copper and oxygen (i.e., copper oxide) with no other detectable contaminants (refer to **Figure 5**).

Additional sections from Coil 1 that did not include known leaks (from pressure testing) were split for examination, **Figure 8**. The inside surfaces were covered in a uniform layer of black deposit, similar to the sections that contained the leaks. There were some spots of blue and yellow colored deposits scattered within the black deposit. No pits were identified in these sections, even after scrubbing the inside surface with a soft nylon brush.

#### Microscopic Examination

Cross-sections were prepared through two leaks in Coil 1 (10 months to failure) and one leak in Coil 3 (36 months to failure), **Figures 9 through 13**. The attack at the leaks was similar in appearance in all three cross-sections in that it was in the form of a wide pit filled with oxide that originated at the inside surface. The copper in these pits had been converted into cuprous oxide ( $\text{Cu}_2\text{O}$ ), as was indicated by its characteristic red coloration (seen macroscopically at the failure and microscopically when the oxide was viewed using polarized light on the cross-sections). The composition of the oxide was also confirmed through analysis by EDS. There were no other contaminants detected by EDS in the corrosion product at the failure. Away from the leaks shallow, incipient attack at the inside surface was identified, **Figure 11**.

Metallurgical examination of the material revealed no evident differences between the two coils, **Figure 13**. The microstructures of the coils were similar between samples and overall typical of copper, with no obvious inconsistencies or defects.

#### Corrodent Detection through Chemical Analysis

EDS and ion chromatography (IC) were used to analyze the deposits at the inside surface to identify potential corrodents that might be present. EDS did not detect any common corrodents, such as sulfur or chloride. IC of internal deposits also detected very low levels of contaminants: chloride was 3 ppm, sulfate was <1 ppm, acetate was 3 ppm and fluoride was 8 ppm. [Note: the value for fluoride was above the EPA recommended level for drinking water, but this value was based on analysis of deposits where it could have concentrated.]

#### Provided Water Analysis - Results Summary

Samples of the water distributed from the two water treatment facilities were analyzed by an external lab (New England Testing Laboratory, Inc., which is a local lab contracted by the City of Gardner). The results of these analyses, which were provided to CTL, are summarized in **Table 1**. Both water samples were soft, had moderate levels of dissolved solids, and low alkalinity. The inorganic carbon content in the Crystal Lake WTF was approximately one third that of the water from the Snake Pond WTF. The water was not analyzed for anions such as sulfate and chloride.

Table 1. Water Analysis			
Parameter	Crystal Lake Water Sample	Snake Pond Water Sample	EPA Standard <sup>3</sup>
pH	8.02	7.86	6.5 to 8.5
Alkalinity (mg/L as CaCO <sub>3</sub> )	20	52	N/A
Inorganic Carbon	45	140	N/A
Total hardness (as CaCO <sub>3</sub> ) (ppm)	35.8	47.6	0 to 60 = Soft 61 to 120 = Moderately hard 121 to 180 = Hard >180 ppm = Very hard <sup>4</sup>
Conductivity (µS)	371	535	N/A
Total Dissolved Solids (ppm)	244	320	500 ppm <i>secondary</i>

## Discussion and Conclusions

The leaks in the copper heating coils were the result of through-wall pitting that originated at the inside surface of the coils, which were exposed to potable water. The morphology of the attack appeared typical of localized pitting related to improper water quality (e.g., wide pit where the copper has been converted to cuprous oxide). Findings did not suggest that the failures were related to material quality, as the copper appeared typical from a metallurgical standpoint.

Failures were centralized around the water treatment facility (WTF) that uses surface water as a source (Crystal Lake WTF), with almost no instances around the WTF that sourced well water. A diagram provided of the distribution of the failures is shown in **Figure 1**. A report was provided with results from the analysis of the surface water and well water from the city (summarized in **Table 1**). There are specific parameters of water quality that have been related to the susceptibility of copper to pitting including the following: pH, alkalinity, hardness, total inorganic carbon, sulfate or chloride levels, and levels of aluminum or silica<sup>5,6</sup>. Pitting in copper tubing is often classified as Type I, II, or III. Type I pitting, also called cold water pitting, is typically associated with hard water conditions. Type II pitting is also called hot water pitting. It typically occurs when the water is above 140 °F in soft water. Type III pitting is called soft water pitting. It typically occurs in cold waters with pH above 8, low hardness and alkalinity and with higher levels of chloride and sulfate present. Review of the literature shows that the classifications are not hard and fast and that the mechanisms driving pitting corrosion in copper are not yet fully understood.

<sup>3</sup> Primary vs. secondary (<http://water.epa.gov/drink/contaminants/>) = “National Primary Drinking Water Regulations (NPDWRs or primary standards) are legally enforceable standards that apply to public water systems. National Secondary Drinking Water Regulations (NSDWRs or secondary standards) are non-enforceable guidelines that may cause cosmetic effects (such as skin or tooth discoloration) or aesthetic effects (such as taste, odor, or color) in drinking water. EPA recommends secondary standards to water systems but does not require systems to comply.”

<sup>4</sup> USGS Water Quality Information. Viewed online on 1/28/2015 at: <http://water.usgs.gov/owq/hardness-alkalinity.html>.

<sup>5</sup> EPA “Pitting Corrosion of Copper in High-pH and Low-Alkalinity Waters”. As viewed on 4/17/15 at: [http://www.epa.gov/nrmrl/wswrd/cr/corr\\_res\\_copper\\_ai2.html](http://www.epa.gov/nrmrl/wswrd/cr/corr_res_copper_ai2.html)

<sup>6</sup> Foundation for Water Research. “Causes of Copper Corrosion in Plumbing Systems.” As viewed on 4/24/15 at: <http://www.fwr.org/copper.pdf>

Based on the provided results of the water analyses from each facility, it is likely that the pitting is related to a combination of the soft water with low alkalinity and low dissolved inorganic carbon (DIC) content that is being distributed from the Crystal Lake (CL) WTF. Comparison of these factors with the classifications of pitting seems to suggest that the pitting in these coils is something of a hybrid between Types II and III, i.e., it shares characteristics of Type III (soft water with higher pH) and Type II (hot water).

Although hardness and alkalinity were relatively low at both water treatment plants, those parameters were lower for water from CL WTF. In the CL WTF water sample, the DIC content was overall low and only 32% what was measured in the SP WTF water sample. The EPA's drinking water regulations do not set limits for alkalinity or DIC. Although these parameters may not have significant health concerns, both are important with regards to corrosion. It has been suggested that increasing DIC increases both alkalinity and buffering capacity and, therefore, plays a role in corrosion prevention. Reduced buffering capacity of the water is related to a lack of carbonate, bicarbonate, or other carbon species. These are critical in the formation of a carbonate layer at the copper surface that serves as a protective barrier from corrosion. When water is devoid of these species, corrosion and pitting can more readily occur.

Water characteristics and qualities are sometimes related to geographic location. Surveys have shown that the City of Gardner is located in a region of the US that have water that is soft and surface water with a low alkalinity<sup>7</sup>. In addition, the City of Gardner reportedly uses chloramine treatment, which has also been associated with changing the alkalinity and dissolved inorganic carbonate levels in water<sup>8</sup>. Literature can provide some possible remedies related to low alkalinity and DIC (see references below <sup>9,10</sup>), including carbonate dosing. Increasing the hardness of the water could also be considered. Any changes to water treatment should be done under the supervision of a qualified water treatment specialist who is familiar with the history of the problems experienced by the City of Gardner. If desired, CTL would be happy to recommend a water treatment specialist suitable for this task. In addition, it may be possible to perform preventative simulated corrosion testing to determine the effectiveness of the water treatment regimen.

Reportedly, only copper heating coils, and not the copper pipes, have been attacked in these systems. This phenomenon could be attributed to the geometry differences and would tend to diminish the contribution of temperature (i.e., Type II or hot water pitting) as the primary mechanism. The scalloped inside surfaces of the heating coils could create locations favorable for initiation of a corrosion cell. In addition, the water inside the coil would be exposed to the maximum system temperatures, and higher temperatures generally accelerate corrosion. However, the locations of the failures were not directly correlated to areas that would be highest in temperature (e.g., the outlet). The failures, rather, were seemingly randomly distributed. In addition, the copper piping at the exit of the coil should also have been exposed to relatively high temperatures and some failures may be expected to have occurred in those pipes.

We appreciate the opportunity to assist you with this important investigation and look forward to your questions and comments.

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<sup>7</sup> <http://water.usgs.gov/owq/hardness-alkalinity.html>

<sup>8</sup> <http://www.epa.gov/ogwdw/disinfection/chloramine/pdfs/chloramine2.pdf>

<sup>9</sup> *Ibid.*

<sup>10</sup> <http://www.awwa.org/publications/journal-awwa/table-of-contents/articleid/15141/issueid/33541993.aspx?getfile=/documents/dcdfiles/15141/waternet.0060846.pdf>

Respectfully submitted by,

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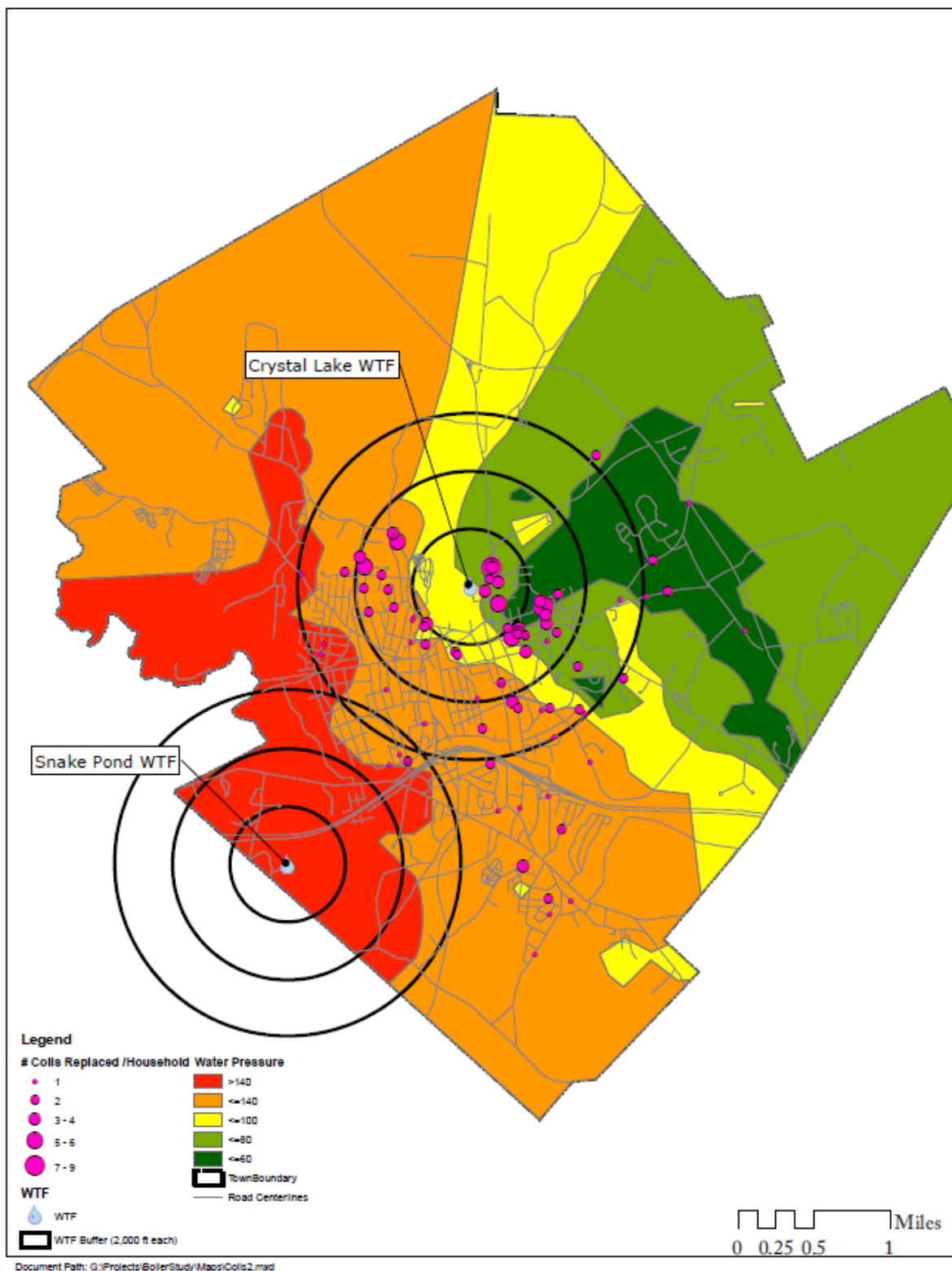


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**Policy Statement**

*This study was performed and this report was prepared based upon specific samples and/or information provided to Corrosion Testing Laboratories, Inc. (CTL) by the City of Gardner. The information contained in this report represents only the materials tested or evaluated. Such work was performed in accordance with CTL's Quality Assurance Manual, Revision 13, issued 22 June 2009. The conclusions and opinions provided were developed within a reasonable degree of scientific certainty and are based upon materials and information provided to date. Should additional information become available (e.g., on further continued review of the material received or submission of additional samples for examination), we reserve the right to adjust our professional opinions.*

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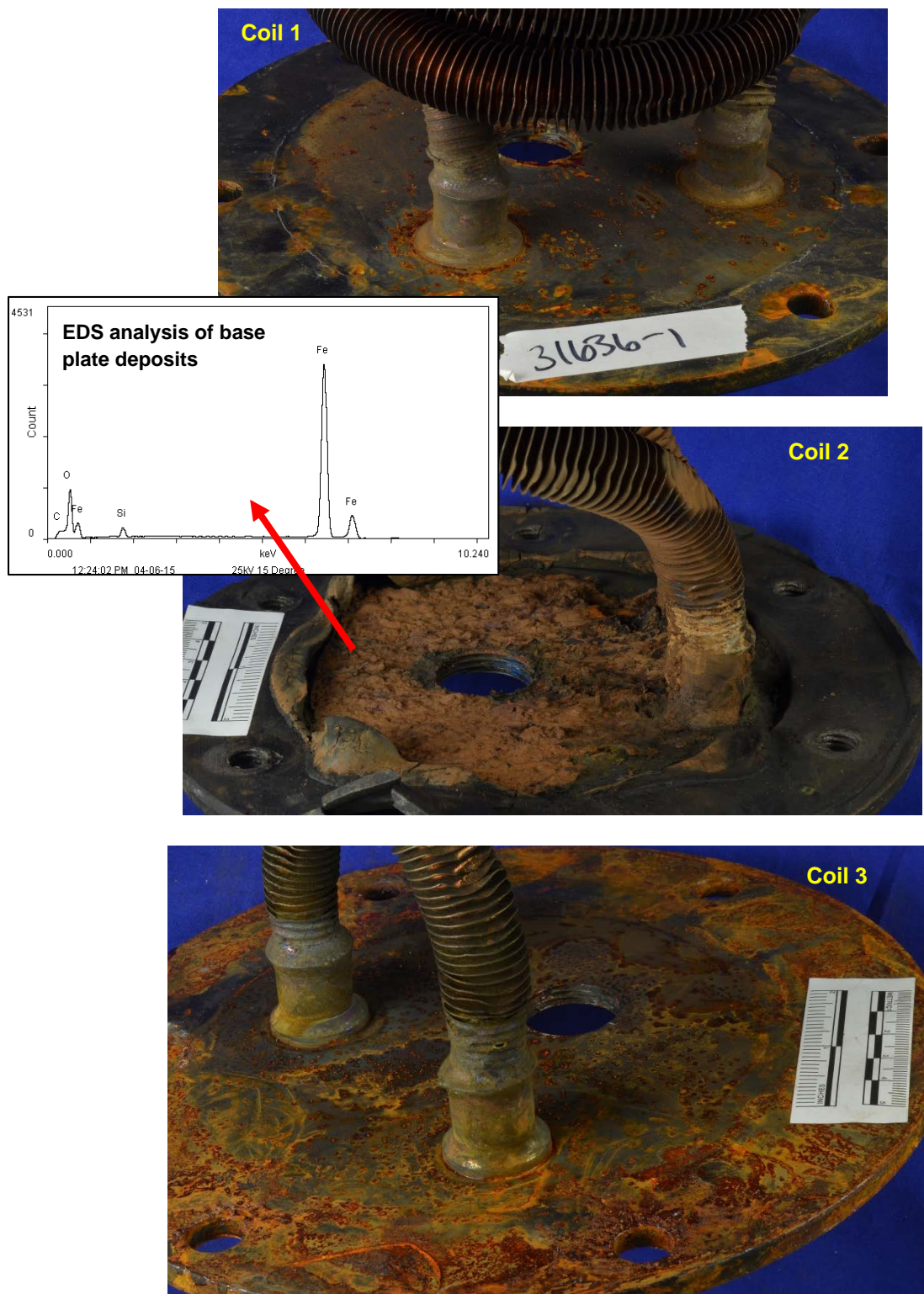
**Figure 1.** Map provided by the City of Gardner demonstrating the distribution of coil failures relative to the location of the water treatment facilities. Snake Pond WTF uses well water as their source and Crystal Lake WTF uses surface water.



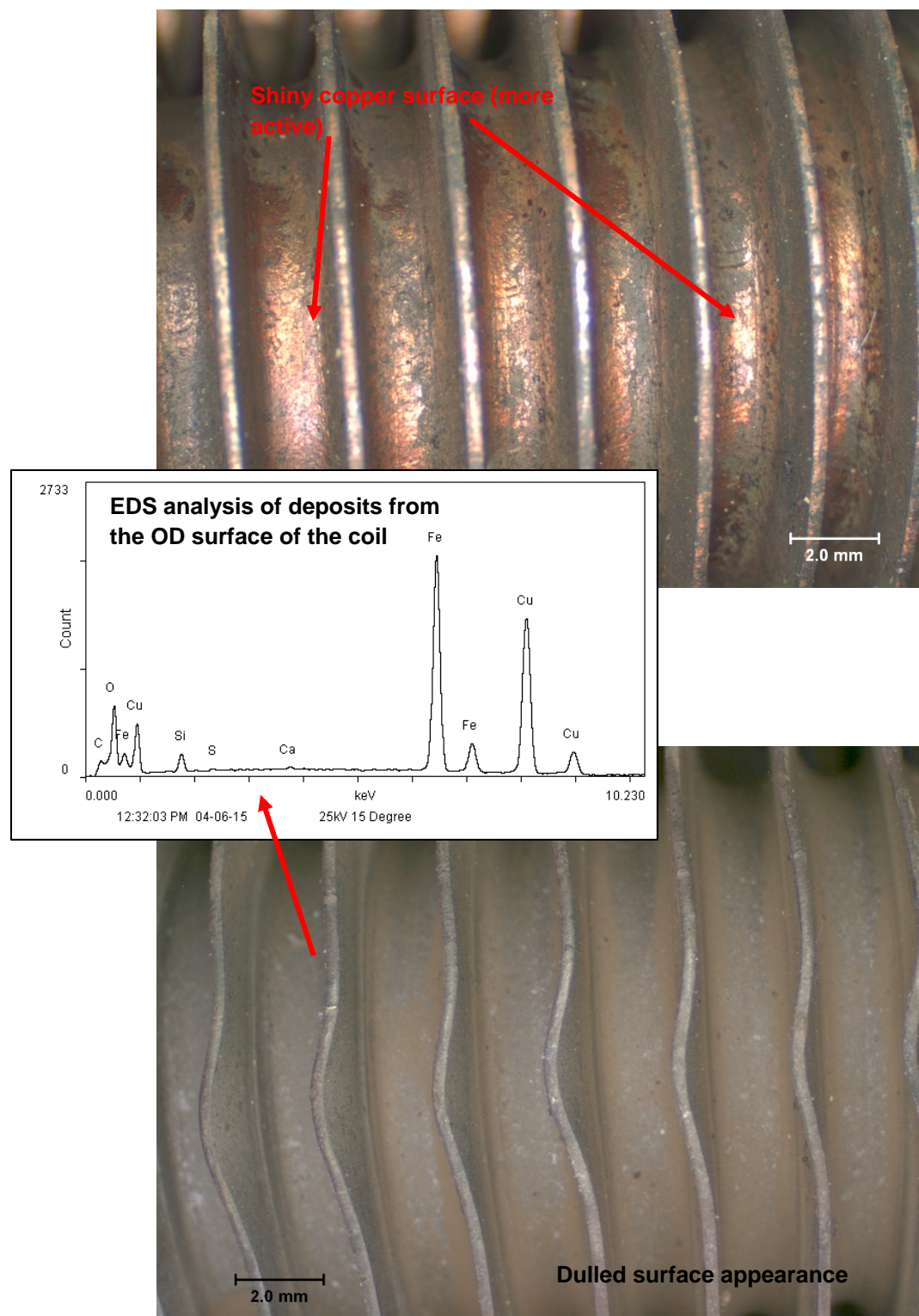


Figure 2. Coils, as received, and their provided tags.



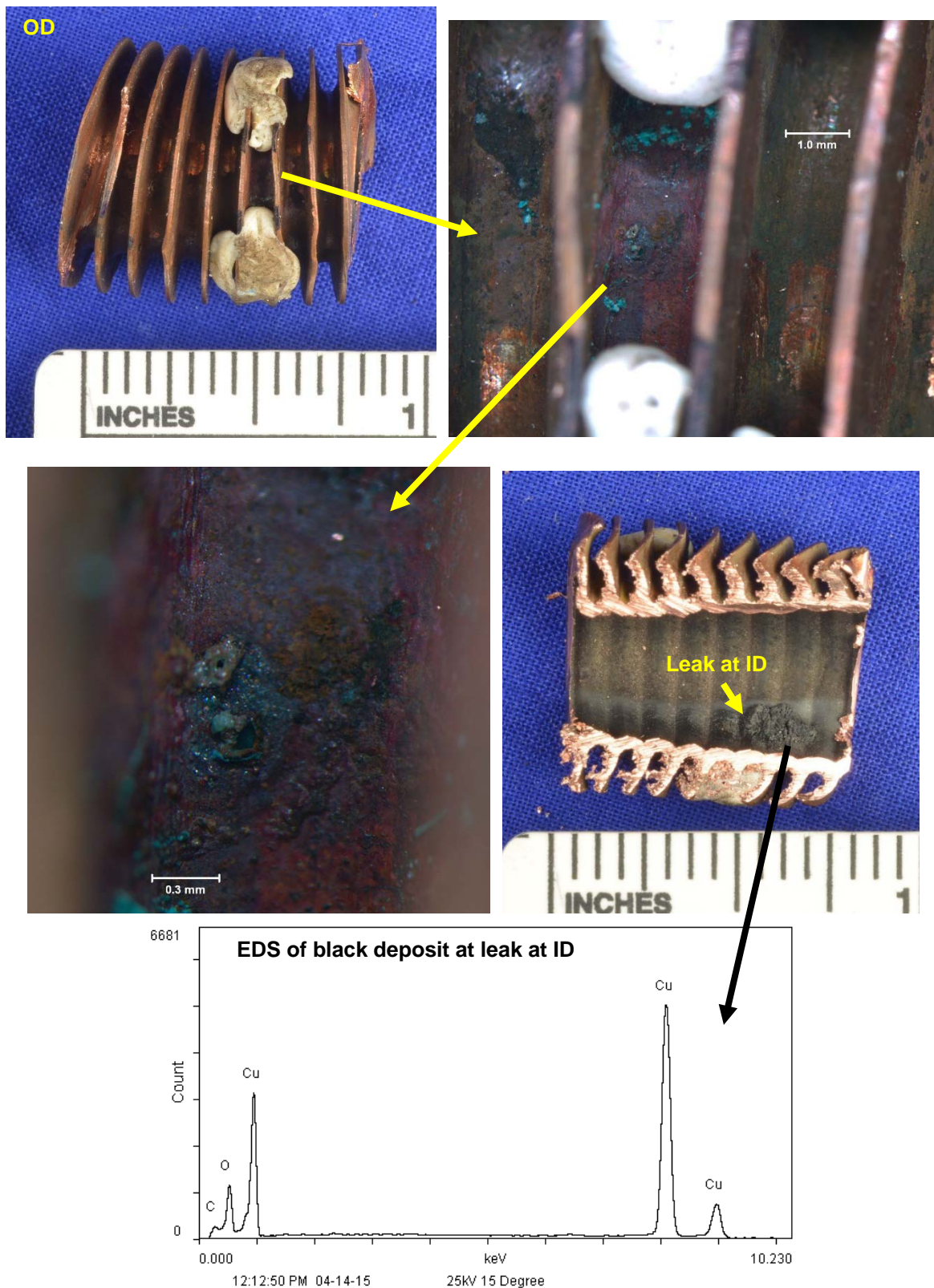


**Figure 3.** Corrosion on the base plates of the three coil samples. Deposits from Coils 2 and 3 were analyzed by EDS and were determined to be primarily iron and oxygen.

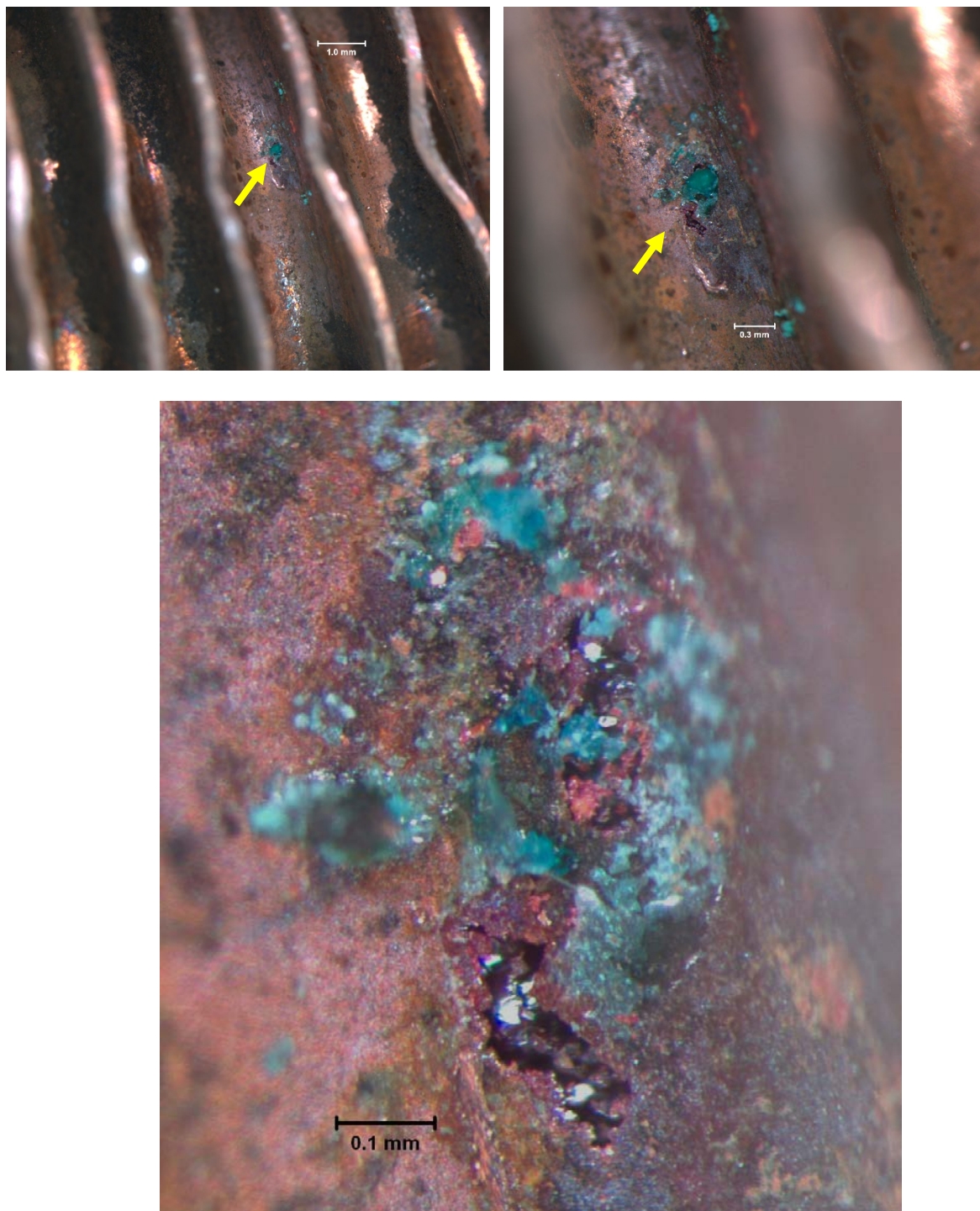


**Figure 4.** Representative images of the exterior surface conditions of the copper coils. In many locations, the surface was dull and covered in deposits, which were analyzed by EDS to determine their elemental composition (bottom image). In some locations, the copper surface was shiny.



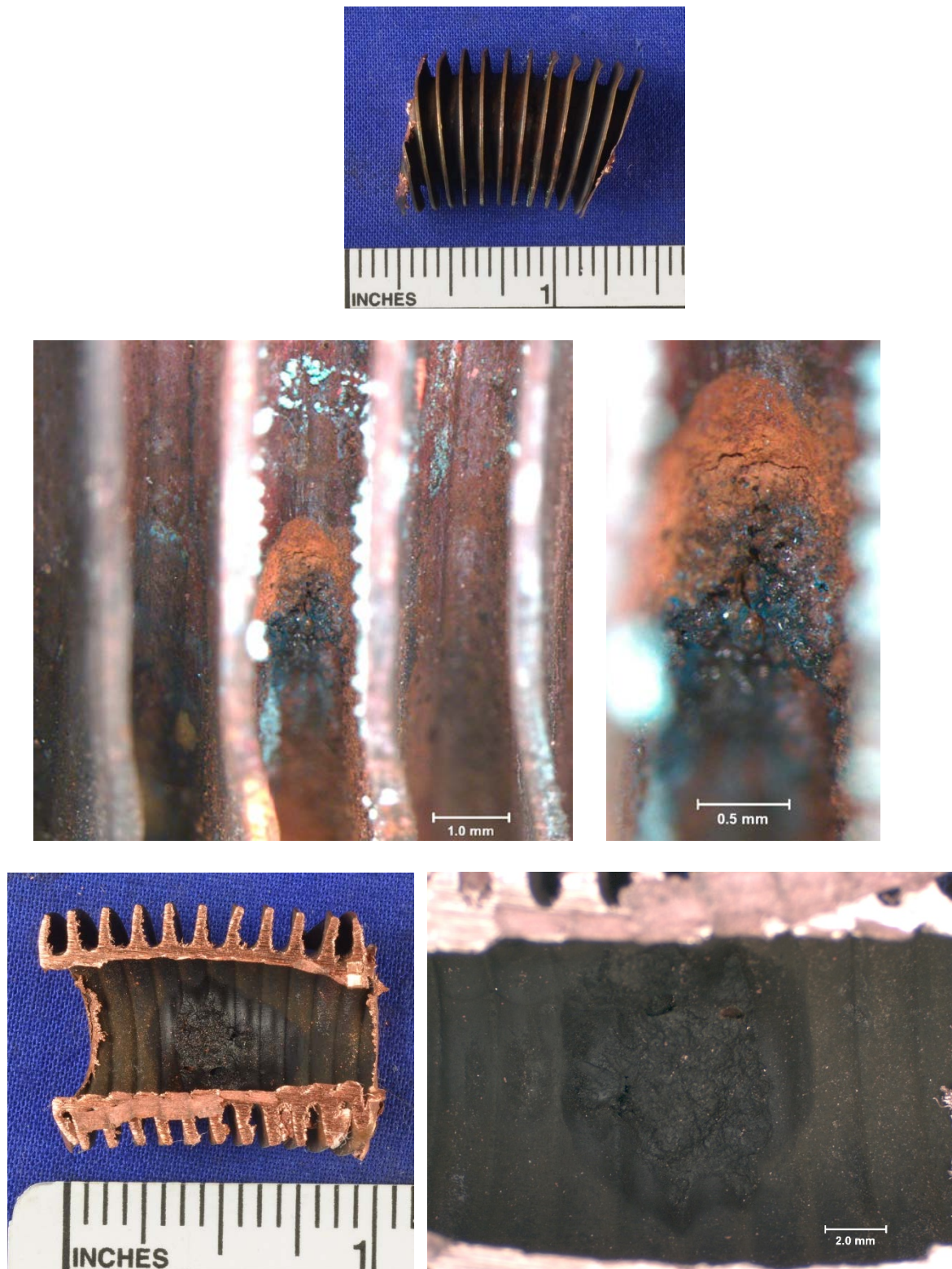


**Figure 5.** Leak A on Coil 1 identified by pressure testing. At the outside surface, the material at the leak was red in color and there were green-blue deposits. At the inside surface, the leak was covered by a mound of black deposits, which were analyzed by EDS.



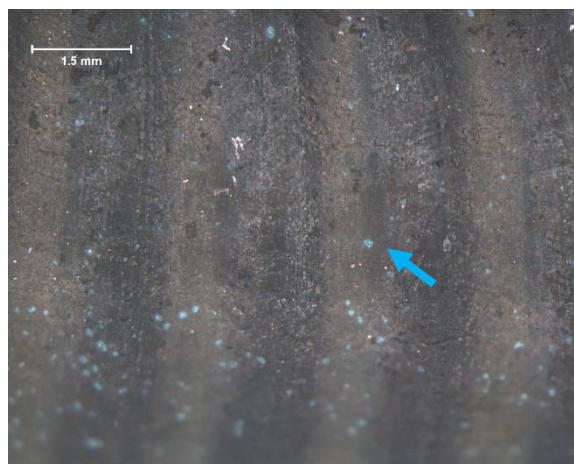
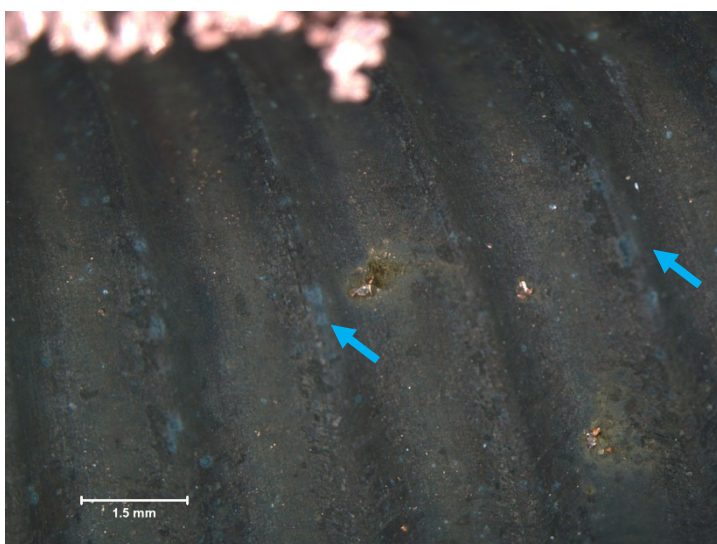
**Figure 6.** Leak B (yellow arrow) on Coil 1 identified by pressure testing. There was a visible hole at the outside surface, inside which there were reddish, crystalline deposits. There was green-blue colored deposits surrounding the attack.



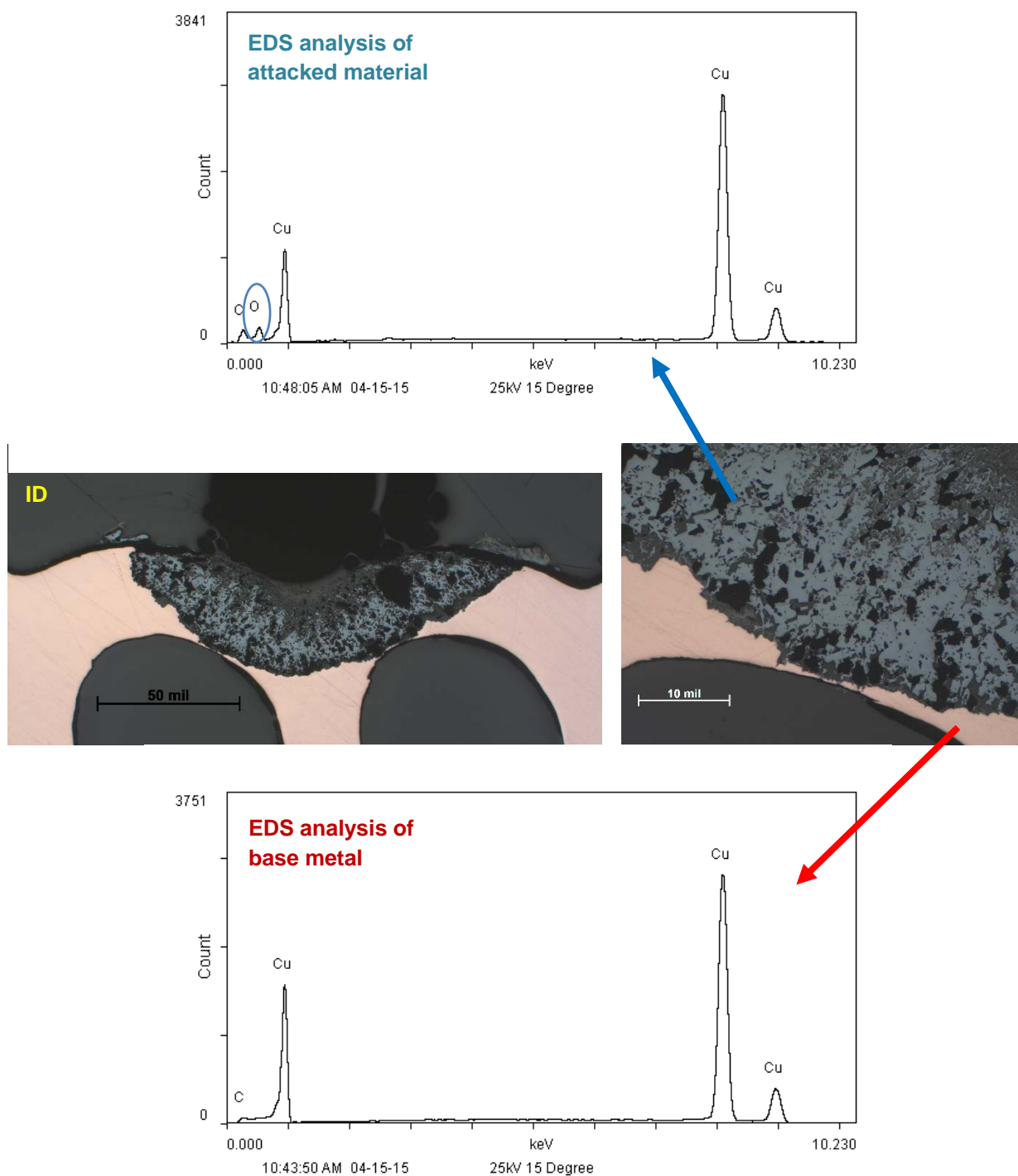


**Figure 7.** Leak on Coil 3 identified by pressure testing. The leak at the outside surface was covered by orange/brown deposits. There were also green-blue deposits present. At the inside surface, there was a mound of black deposits covering the leak.

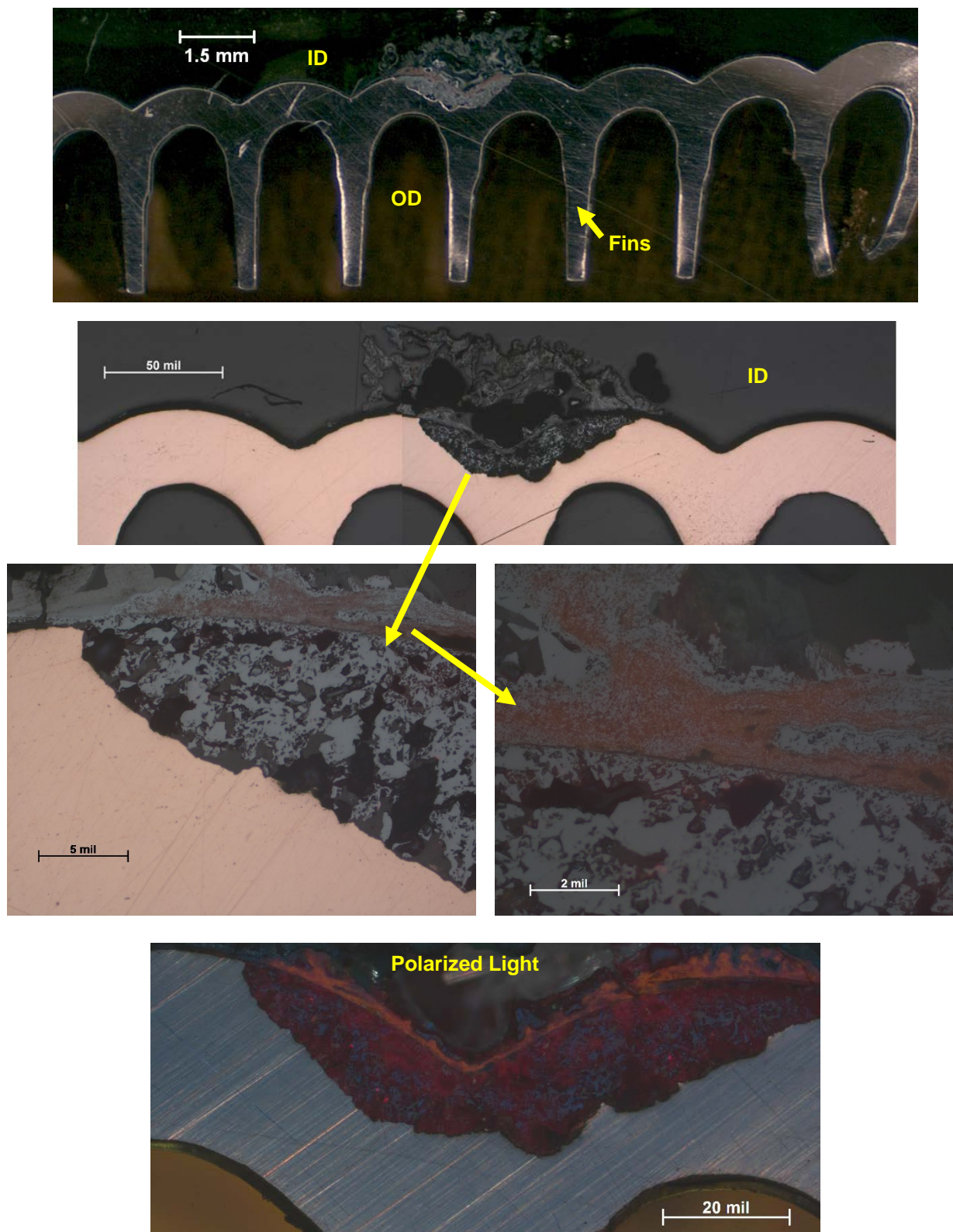




**Figure 8.** Sections of coil that were split and inspected that had no known leaks. The surfaces were covered primarily in black deposits, with some blue and yellow colored deposits scattered throughout (see arrows). No pits were identified in any of these sections.

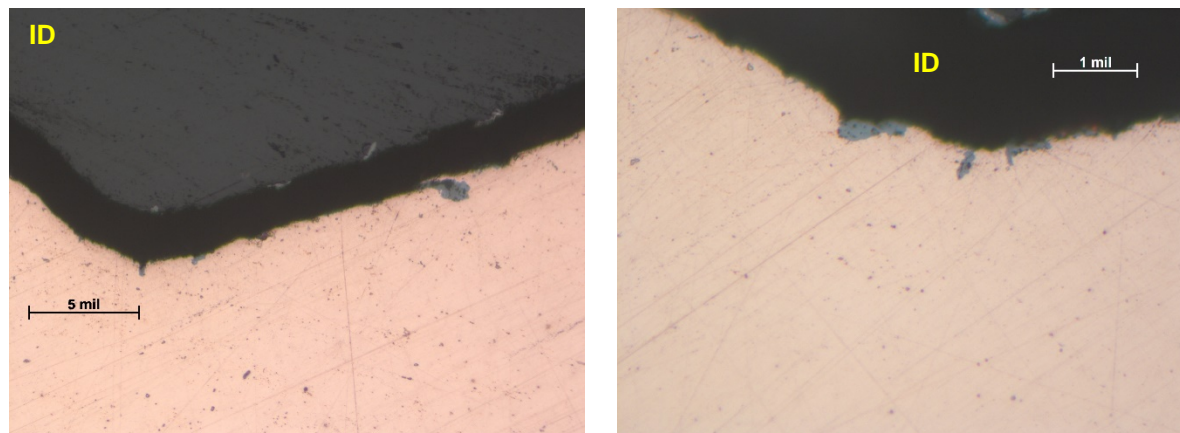


**Figure 9.** Cross-section prepared through Leak A in Coil 1. EDS analysis of the base metal and attacked material inside the pit are shown. 25X and 100X original magnifications. No metallurgical etchant used.

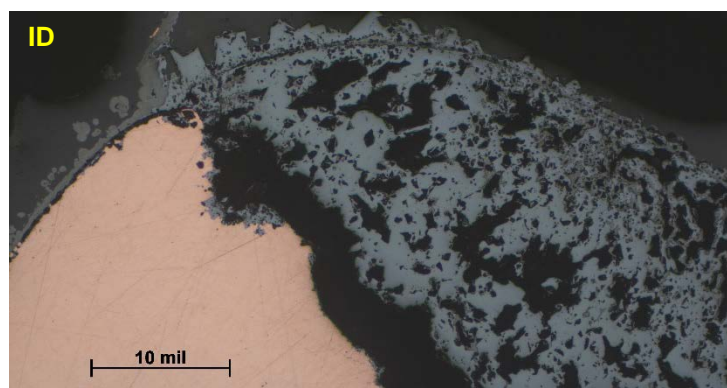
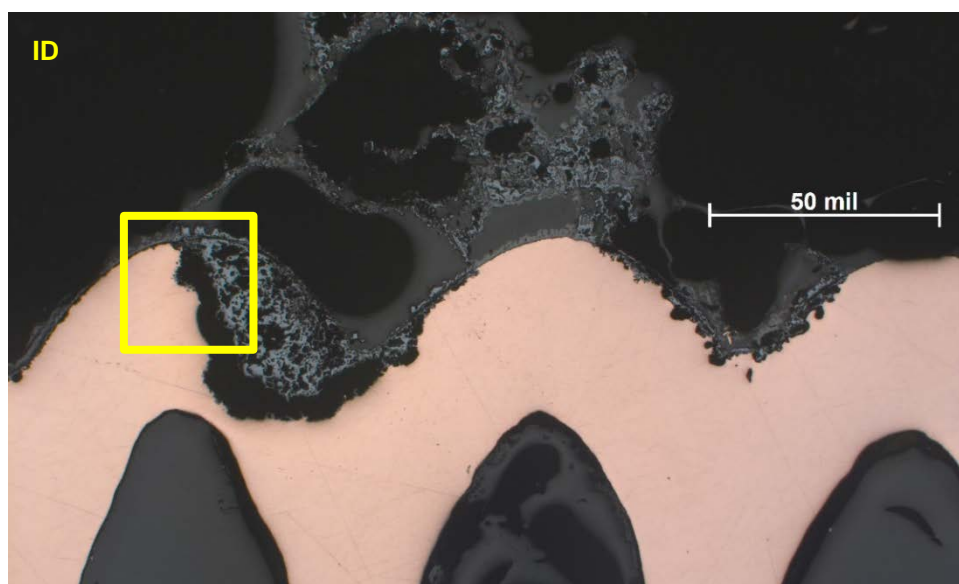


**Figure 10.** Cross-section through Leak B on Coil 1. Bottom image shows attacked area using polarized light. The deposits at the attack appeared red, as is typical of cuprous oxide ( $\text{Cu}_2\text{O}$ ). 25X, 50X, 100X, and 200X original magnifications. No metallurgical etchant used.

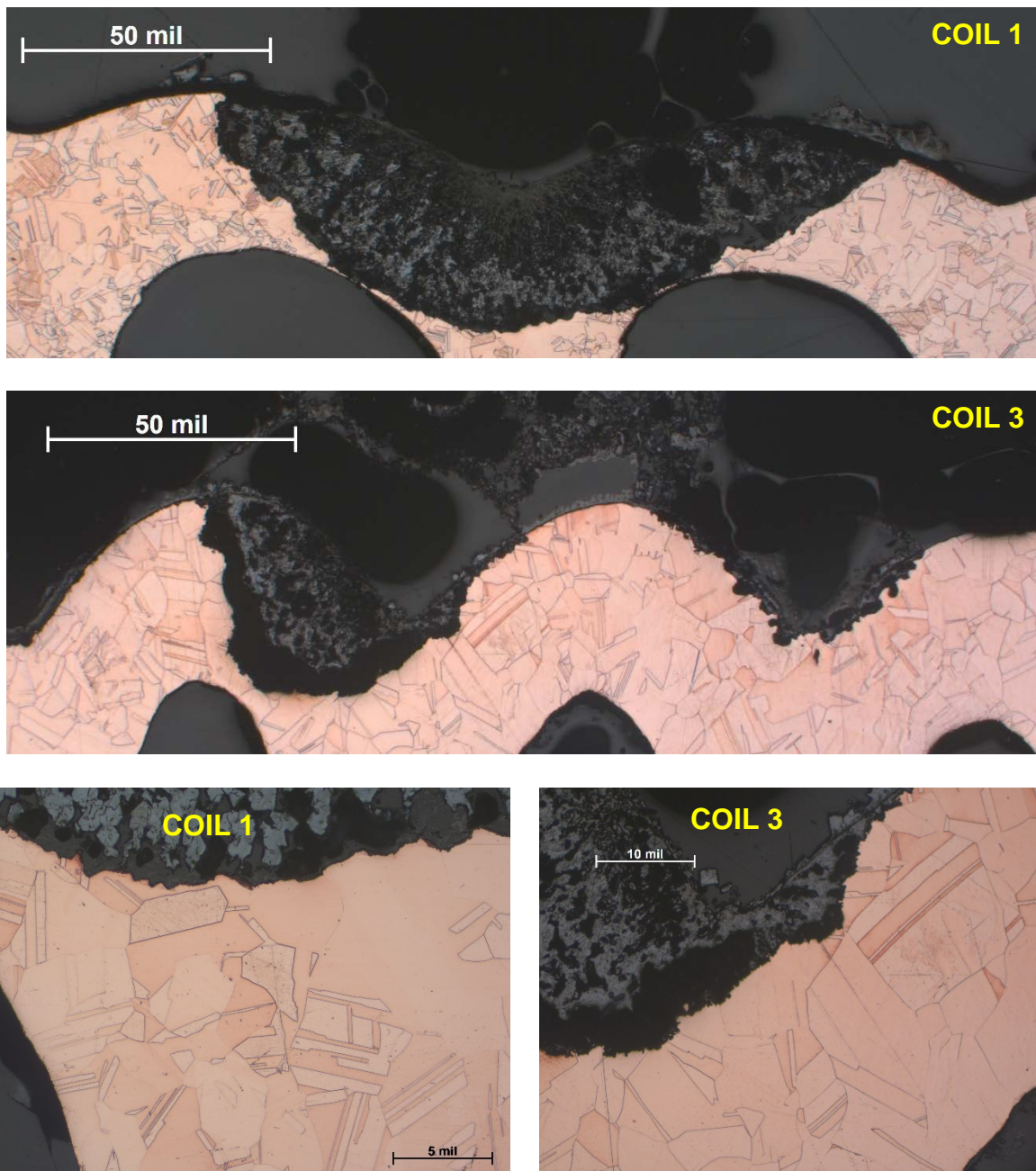




**Figure 11.** Shallow incipient attack at the ID away from the leak in the cross-section prepared at Leak B from Coil 1. 100X and 500X original magnification. No metallurgical etchant used.



**Figure 12.** Attack on cross-section through Coil 3 leak, which was very similar in appearance to the attack in Coil 1. 25X and 100X original magnifications. No metallurgical etchant used.



**Figure 13.** Etched cross-sections showing that the microstructure of the material from Coils 1 and 3 were similar and typical of copper. 25X, 100X, and 200X original magnifications. Potassium dichromate etchant used to reveal microstructure.