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L-Area Wastewater Storage Drum Evaluation

P. R. Vormelker, D. Z. Nelson, C. N. Foreman, D. J. Hathcock, and D. W. Vinson
Savannah River National Laboratory
Materials Science and Technology

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Title: L-Area Wastewater Storage Drum Evaluation

MS&T APPROVALS

P. R. Vormelker, Author
Materials Application & Process Technology Group
Materials Science and Technology
Date: _____

D. Z. Nelson, Author
Materials Compatibility & Welding Technology Group
Materials Science and Technology
Date: _____

C. N. Foreman, Author
Materials Application & Process Technology Group
Materials Science and Technology
Date: _____

D. J. Hathcock, Author
Materials Application & Process Technology Group
Materials Science and Technology
Date: _____

D. W. Vinson, Author
Materials Application & Process Technology Group
Materials Science and Technology
Date: _____

P. E. Zapp, Technical Review
Materials Performance & Corrosion Technology Group
Materials Science and Technology
Date: _____

R. L. Sindelar, Manager
Materials Application & Process Technology Group
Materials Science and Technology Directorate
Date: _____

N. C. Iyer, Director
Materials Science and Technology Directorate
Date: _____

DOCUMENT: WSRC-STI-2008-00228

Title: L-Area Wastewater Storage Drum Evaluation

CUSTOMER APPROVALS

R. W. Deible, Engineer
SFP Operations Engineering
Spent Fuel Project

Date: _____

J. C. Guy, Manager
SFP Regulatory Engineering
Spent Fuel Project

Date: _____

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LIST OF ABBREVIATIONS

DOE	Department of Energy
GC/MS	Gas chromatograph/mass spectroscopy
ICP	Inductively Coupled Plasma
LANL	Los Alamos National Laboratory
MS&T	Materials Science and Technology
NFPA	National Fire Protection Association
PI	Principal Investigator
SRS	Savannah River Site
SRNL	Savannah River National Laboratory
XRD	X-Ray Diffraction

1.0 Summary

This report documents the determination of the cause of pressurization that led to bulging deformation of a 55 gallon wastewater drum stored in L-Area. Drum samples were sent to SRNL for evaluation. The interior surface of these samples revealed blistering and holes in the epoxy phenolic drum liner and corrosion of the carbon steel drum. It is suspected that osmotic pressure drove permeation of the water through the epoxy phenolic coating which was weakened from exposure to low pH water. The coating failed at locations throughout the drum interior. Subsequent corrosion of the carbon steel released hydrogen which pressurized the drum causing deformation of the drum lid.

Additional samples from other wastewater drums on the same pallet were also evaluated and limited corrosion was visible on the interior surfaces. It is suspected that, with time, the corrosion would have advanced to cause pressurization of these sealed drums.

2.0 Introduction

During the period 1999 to 2000, wastewater in K-Area was consolidated into a Tuff Tank, RD478 (vented container). The transportable Tuff Tank is a 330 gallon molded low density polyethylene square bottle inside a heavy-duty wire mesh cage. In 2000, the Tuff Tank was transferred from K Area to the L-Area Slug Vault Liquid Waste Staging Area. At this time, the Tuff Tank contained approximately 240 gallons of liquid, in three layers (primarily water), with an oil layer at the top, an aqueous layer, and a layer of solids/sludge at the bottom. The liquid contained a collection of water from the Crane Wash Tank, various skid pans, and sample bottles from the K-Area make-up room. Analysis of the water was performed in April 2006, including screening for radionuclides. Approximately a month later, the Tuff Tank was transferred to the -40' Second Sort Area (L-Area) for sampling and liquid transfer to 55 gallon drums for disposal. The Tuff Tank contents were pumped into five new drums during the last week of May or the first week of June 2006. Four of the drums contained aqueous material (No's SFP0001114, 1115, 1116, &1117) and a fifth drum contained oil. Some oil/sludge carryover into the aqueous drums may have occurred. SFP Operations work practices call for leaving a 10% head space in all liquid waste containers. The drums were relocated to the Slug Vault Liquid Waste Staging Area for storage.

Routine inspection is performed by Operations on a weekly basis in all liquid waste storage areas in L-Area. During weekly rounds on August 15, 2006, no unusual drum features were found. Approximately one week later, a bulge on one drum (No. SFP0001117) was found within a four drum pallet assembly and was reported during weekly rounds on August 22 (8 weeks storage). The drum was punctured at the top for pressure relief with wastewater remaining in the drum for approximately 7 months prior to liquid transfer to a new drum (1117(II)) per the timeline of events in Table 1. The pH was adjusted in all the drums at this time to 4.5<pH<8 (field measurements). The top of the deformed drum and adjacent drums are visible in Figure 1 to Figure 4. The NFPA hazard label was not visible in Figure 2 and therefore was reproduced in the lower right corner. A number one was indicated in the blue health hazard diamond which designates that a NFPA hazard determination was made for the wastewater in these drums.

The 55 gallon drums were manufactured by Skolnik Industries out of carbon steel with an epoxy phenolic coating on the interior as shown in Figure 5. The drums are approximately 35 inches tall and 23 inches in diameter. The epoxy phenolic coating (1 mil nominal thickness), applied by Skolnik, is produced by Delta Coatings.

The exterior of the drum was visually inspected by SRNL and SFP Engineering personnel in September 2006 and it was determined that the drum was pressurized. The following were directed by SFP Engineering:

- Depressurization of the drum
- Assay water from the drum
- Empty drum and transfer contents into same drum type with vented bung cap
- Vent remaining drums containing Tuff Tank contents by installing vented bung caps
- Raise pH of all drums to ≥ 4.0
- Inspection of the deformed drum interior
- Cut drum samples and ship to SRNL

This report documents a detailed characterization and analysis of drum coating/steel samples, and provides the most likely cause for drum pressurization.

3.0 Sample Analysis

The approximately 4 ½ inch diameter disks were cut from the bulged drum in positions indicated in Figure 6. The outside and inside surfaces of these disks are shown in Figure 7. Corrosion is very evident on the interior surface of the two lid samples. Corrosion was preceded by blistering which is shown on the sidewall sample shown in Figure 8. Additional samples were cut from the sample in Figure 8 where the cut lines are indicated. These samples were used for close-up metallography and XRD (X-ray diffraction) analysis (Figure 9). XRD analysis revealed the presence of hematite (Fe_2O_3), magnetite (Fe_3O_4), talc, $\text{Fe}(\text{OH})_2$ and the carbon steel base metal. Hematite is visible in sample 1 and 2 (Figure 7) with the normal rust color while magnetite is black and is visible in sample 2. Talc is probably from the gloves used to handle the samples. Close-up photos are shown in Figure 10 where the black oxide is clearly visible in the center of a burst blister.

Chemical analysis of the wastewater in the drums and the Tuff Tank (water sample left over from previous radiolysis analysis) was performed. The analytical results from inductively coupled plasma analysis (ICP-MS) are shown in Table 2. The highest elemental concentrations are sodium and phosphorus with levels from 3000 to 5000 ppm in the Tuff Tank, bulged and non-bulged drums. The only element in the bulging drum that is higher than that in the Tuff Tank or adjacent drum is Fe which indicates corrosion of the steel drum (SFP 0001117). Fe levels in drum 1114 are low at 29.1 ppm which is even lower than that in the Tuff Tank. Low level contamination in the wastewater is listed in Table 3. Tritium, Co-60, and Cs-137 were detected at low levels.

Material was scraped from the surface of disk 5 (Figure 11) and analyzed by gas chromatograph mass spectroscopy (GC/MS). The results, shown in Table 4, reveal significant surface deposits from oil with smaller amounts from branched alkyl benzenes and tributyl phosphate. Oil in the original Tuff Tank was known to exist, the alkyl benzenes are probably from a scintillation cocktail, and the TBP (tributylphosphate) may be from the oil or from other contaminants from sampling of the water during analytical procedures. TBP is used to enhance oil film strength in lubricants.

Measurements of pH in the Tuff Tank and two drums reveal an acidic wastewater, shown in Table 5, with very little differences between the Tuff Tank, non-bulging and bulging drums. In fact, the pH in the Tuff Tank wastewater and the non-bulging drum (1114) is slightly more acidic than the bulging drum. Selected organic acids and their concentrations in Table 6 show that it does not take much acid to lower the pH to less than three.[1]

Samples were cut from a clean spare drum (same design and manufacturer as the bulged drum) and are shown in Figure 12. The top ring and middle ring samples were cut from the upper sidewall and middle sidewall section, respectively, as shown in Figure 6. Both sides of the lid are shown in the upper photos in Figure 12. The top ID surface shows surface stains that may be the result of condensation. The sidewall samples appear to be clean. Coating thickness measurements were performed with an Elcometer (model No. 246F) dry film thickness gauge and are shown in Table 7. Exterior coating thicknesses on the three samples averaged 0.37 mil while the interior coating thickness averaged 1.2 mils. Skolnik's interior coating process calls for a 1 mil nominal coating thickness. Coating vendors such as Carboline, Heresite Protective Coatings, International Protective Coatings, and Sherwin Williams prescribe a minimum of a 2 mil primer coat with a 2- 4 mil final coat for two coat coverage or 5 mils for single coat coverage per an internet search for epoxy phenolic type coatings. Based on vendor guidelines, Skolnik's interior drum coating nominal thickness of 1 mil may be insufficient for corrosion protection of carbon steel immersed in an acidic wastewater. This thin coating may contain too many holidays (coating defects) to be protective in immersion service.

The contents of each of the three original drums from the pallet and the new drum (SFP0001117(II)) were neutralized to pH levels shown in Table 8, prior to draining and then filling a new set of drums. This draining operation was performed to allow sample cutting of the original drums. The content in the new drums was further neutralized to higher pH levels shown in Table 9. Samples were cut from the three original drums to characterize the effects of wastewater on the ID coating of the drums. In addition, samples were also removed from the second drum (SFP0001117 (II)), which held the original contents of the bulged drum. The ID of the lid from drum SFP0001114 is shown in Figure 13. Staining is visible which is typical of the lids from the other two drums. The location of drum sidewall samples was chosen by SRNL to show typical surfaces within the drum. Figure 14 reveals the interior drum coating from drum SFP0001114 which appears to have been easily scraped from the surface during sample removal. The coating appears to be sufficiently softened by the wastewater to allow it to be scraped off. In Figure 15, the coating from drum SFP0001115 was also scraped off in the right photograph while blistering or shrinkage in the coating is visible in the left photo. A liquid/air interface is visible in the sample (right photo) from drum SFP0001116 (Figure 16). The sample on the left reveals more blistering/shrinkage than the right photo. Blistering is clearly visible in Figure 17 which showed samples from drum SFP0001117(II). Drum SFP0001117(II) was only exposed to wastewater with a pH of 3.76 (Table 8) for approximately 7 months per Table 1 and still blistered.

4.0 Discussion

Blistering is caused in paint coatings by water permeating through the coating and locating at the coating metal interface. Osmotic pressure drives water molecules to permeate through the coating.[2-5] The presence of micro-voids in the coating can also cause water molecules and acidic and/or caustic ions to penetrate through the coating. When the coating is penetrated, pressure builds up until pressure is equalized with that in the liquid. The result is a blister. At the same time, corrosion occurs in the base metal upon reaction with the unprotected carbon steel. The metal dissolution reaction, or anodic reaction, results in the loss of electrons, while

the coupled cathodic reaction results in a species gaining electrons. The reaction occurs electrochemically in an acidic and limited oxygen environment where iron is being oxidized to a ferrous species while hydrogen ions are being reduced so that hydrogen is released per the following reactions [6-8] :



The failure of the coating can advance as delamination progresses from ruptured blisters. Corrosion of the steel would continue until the acid water is spent or pH increases. Continued hydrogen evolution from corroding steel would cause pressurization of the drum which was probably the case for the bulging drum noted in L-Area. Radiolysis of the wastewater by the radioactive elements to cause H_2O_2 (which produces a more aggressive solution) is possible, but is not likely due to the low levels displayed in Table 3.

Calculations (Appendices A and B) were performed to show estimated pressures that can be produced from corrosion generated hydrogen.[8] The calculated pressures, based on an assumed corrosion rate of 0.5 mil/yr. (0.0005 in./yr.) over a period of 8 weeks, 6 months and one year, range from 7.9 to 51 psi per Tables 10, 11, 12 and 13 in Appendix A. Pressure calculations, in Appendix B, were also performed based on the Fe contents of two drums, the bulged drum (#1117) and an adjacent drum (#1114). Using the Fe content in these drums, per Table 2, pressure was calculated using the Fe corrosion reaction stoichiometry (one mole of Fe creates one mole of H_2) in acidic water and the ideal gas law. The calculated pressure, using 196 ppm Fe (in #1117-1), was 12.5 psi, versus 1.8 psi for the 29.1 ppm Fe in the # 1114 drum. This calculation may be high since there was existing Fe in the Tuff Tank. If one assumes that the actual Fe from corrosion were that value obtained by subtracting the Fe amount in the Tuff Tank (54 ppm) from the maximum # 1117 value (196 ppm), the calculated pressure is 8.9 psi. This pressure value is close to that calculated from steel corrosion rates based on 8 weeks exposure at a corrosion rate of 0.5 mpy but varies from 0.2 to 15.7 psi depending on corrosion rate. Based on DOE experience, open head 55 gallon mild steel drums can begin to exhibit bulging at approximately 6 psi internal pressure.[9] Bulging in tight head (also known as closed head) drums should occur at similar pressure values. Vertical movement of the top head of the bulged drum was estimated at 2 cm based on Figure 3. When compared to pressure testing data generated at LANL [10] on both closed and open head drums, as shown in Figure 18, a vertical deformation of 2 cm results from drum pressures ranging from 10 to 15 psi for a closed head drum. The LANL results are very similar to the calculated values in Table 12 and Table 15 from corrosion. Thus, bulging in drum SFP0001117 likely resulted from pressures generated by hydrogen released from corrosion.

The coating supplier stated that their epoxy phenolic coating would degrade in an acidic environment with $\text{pH} \leq 4$. Thus, in addition to blistering from water diffusion into the coating, the epoxy phenolic coating would be degrading from the acidic environment. The epoxy phenolic coating (70 % epoxy/30 % phenolic) is only recommended in an environment with $\text{pH} \geq 7$. [11] A 100% phenolic coating is recommended in a $\text{pH} \leq 4$ and a phenolic epoxy coating (70 % phenolic/30 % epoxy) is recommended in pH range between 4 and 7 per the coating supplier.[11] This recommendation is only for this supplier's coatings. Each supplier develops their own coating materials and no general guide was found to provide corrosion resistance of various coating materials. Each supplier would have to be contacted separately for their specific recommendations. The blistering and softening noted in the three additional drums sampled in this report and the bulged drum confirms that this epoxy phenolic coating was not compatible with the wastewater from the Tuff Tank. A second drum [SFP0001117(II)],

containing pH adjusted wastewater, also revealed blistering, an indication of coating incompatibility. A baked epoxy phenolic coating (EP-6308) from another supplier, Heresite Protective Coatings Inc., was rated only good in acid immersion service but excellent in alkaline immersion. The supplier's recommendations for this coating include a total dry film thickness of 5-7 mils for a 3-4 coat system. This thickness recommendation and those mentioned earlier are approximately twice the one mil nominal thickness of the Skolnik drum internal coating and the measurements made on an actual drum. Insufficient coating thickness for immersion service may have also contributed to this coating failure.

5.0 Conclusions

Drum pressurization is due to a coating material (epoxy phenolic) which did not prevent osmotic blistering, coating degradation, and subsequent corrosion of the carbon steel drum in the acidic wastewater. Early coating degradation may also be the result of insufficient coating thickness. It is recommended that future drum choices be made after chemical analysis and pH measurement of intended contents are performed. Other specific drum coatings could be used but would have to be special ordered. A stainless steel drum is the preferred choice for acidic wastewater, especially when specific contents are not known prior to use. The second choice is a high density polyethylene drum. Adjustment of pH to levels >7 is also possible. Caution is advised since neutralization of acidic liquids causes heat generation and high temperatures if neutralized too quickly. Coating supplier recommendations for the proper coating and its thickness should be closely followed to achieve the desired corrosion resistance for future storage of waste materials in new drums.

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Table 1. Bulging Drum Activity Timeline

Filling of Tuff Tank in K Area	1999 – 2000
Tuff Tank moved to L Area	2000
Tuff Tank Sampled	April 2006
Aqueous layer transferred to drums (SFP0001114, 1115, 1116, & 1117)	Late May/early June 2006
Observation of bulge in drum SFP0001117	August 22, 2006
Bulging drum vented by puncture	September 19, 2006
Contents of SFP0001117 Transferred to new drum (II) pH adjusted on all drums 4.5 <pH< 8 (field measurements)	January 25, 2007
Samples cut from bulged drum	February 27, 2007
All drum contents transferred to new drums with pH adjustment 7 <pH<10 (field measurements)	August 21, 2007
Coupons cut from original drums (1114, 1115, and 1116) and 1117(II)	September 19, 2007

Table 2. Inductively Coupled Plasma analysis of wastewater chemistry from original wastewater Tuff Tank, bulging drum, and adjacent non-bulging drum. Analysis was performed by SRNL Analytical Labs in 2006 (Tuff Tank) and in 2007 (drums).

Analyte	Original Tuff Tank (ppm)	Bulging Drum		Non-Bulging Drum 1114 (ppm)
		1117-1 (ppm)	1117-2 (ppm)	
Al	37.1	21.8	20.4	32.4
B	64.8	66	66.1	66.4
Ba		0.952	0.824	1.21
Ca	31.1	31.5	32	30.8
Cu				0.56
Fe	54.4	196	152	29.1
Gd	3.73			0.929
K	405	369	369	398
Mg	5.66	5.9	5.88	5.88
Mn	7.32	8.31	8.23	5.11
Na	3430	3420	3340	3090
P	5150	5230	5130	5280
S	301	335	332	319
Si	48.5	50.7	50.3	49.9
Sr	5.85	6.54	6.62	6.42
V	6.4	6.64	5.52	7.35
Zn	96.9	100	98.7	103

Table 3. Radioactive contamination in original wastewater Tuff Tank, bulging drum, and adjacent non-bulging drum.

Analyte	Unit	Original Tuff Tank	Bulging Drum		Non-Bulging Drum 1114
			1117-1	1117-2	
Alpha	dpm/ml	2.02	0.152	0.275	0.702
Non-Vol. Beta	dpm/ml	156	67.1	69.4	76.5
H-3	μCi/ml	209	224	230	240
Co-60	dpm/ml	181	166	162	180
Cs-137	dpm/ml	38.6	42.6	43	40.8
Am-241	dpm/ml	<7.11	<3.17	<3.2	<3.39

Table 4. GC/MS Analysis of Scrapings from Disk 5.

Description	Result	Units
Hydrocarbon oil	40,000	mg/Kg
Branched Alkyl Benzenes	6700	mg/Kg
Tributyl phosphate	230	mg/Kg

Table 5. Measurements of pH from Tuff Tank and Drums.

Tuff Tank	Bulging Drum		Non-Bulging Drum 1114
	1117-1	1117-2	
2.89	2.97	2.99	2.86

Table 6. Selected Acid Concentrations and pH

Acid	Concentration	pH
Acetic (CH ₃ CO ₂ H ₂)	0.2 M	2.4
	0.02 M	2.9
	0.002 M	3.4
Carbonic (H ₂ CO ₃)	Saturated	3.8
Oxalic (H ₂ C ₂ O ₄)	1.0 M	0.8
	0.5 M	1.6
	0.1 M	2.1
Nitric (HNO ₃)	0.4 M	0.4
	0.05 M	1.3
	0.005 M	2.1
	0.003 M	2.5
	0.001 M	3.0
	0.0003 M	3.3

Table 7. Coating thickness measurements, mils (0.001 in.) of new 55 gallon drum from Skolnik (measurements by MS&T's NDE group).

Lid		Top Ring		Middle Ring	
OD	ID	OD	ID	OD	ID
0.37	0.90	0.33	1.00	0.36	1.28
0.38	1.14	0.36	1.01	0.36	1.31
0.39	1.35	0.37	1.12	0.39	1.40
0.41	1.41	0.41	1.20	0.40	1.47
Average		Average		Average	
0.39	1.20	0.37	1.08	0.38	1.37

Table 8. Adjusted pH of original drums after venting of drum 1117.

Drum ID	Lab pH*
SFP0001114	6.11
SFP0001115	6.11
SFP0001116	5.6
SFP0001117(II)**	3.76

* Laboratory measured pH

** Replacement drum with contents from original bulged drum

Table 9. New drums with adjusted pH of transferred liquid.

Drum ID	Lab pH*
SFP0001114(II)	10.4
SFP0001115(II)	8.25
SFP0001116(II)	11.1
SFP0001117(III)**	7.25

* Laboratory measured pH

** 2nd Replacement drum with contents from original bulged drum



Figure 1. Bulged lid of 55 gallon wastewater drum stored in L-Area.



Figure 2. Bulged drum (A) on pallet along with three additional drums containing wastewater. The NFPA hazard label is reproduced in lower right corner.



Figure 3. Close-up view of normal depressed lids on two adjacent drums compared with bulged drum lid to the left. Bulged drum number is SFP000117.



Figure 4. The drum lid crease is shown below dotted line. Drum Label reveals PO No. KM53842A” with the United Nations uniform drum designation “1A1/X1.8/300/05/USA/SDCC.” The designation “SDCC” identifies Skolnik Industries as the manufacturer.



Figure 5. Exterior view of new 55 gallon carbon steel tight head drum (A) in left photo with red epoxy phenolic lined drum (B) shown in right photo (Vendor photographs). Note that the B drum has an extra rolled hoop near the top. SRS drums have two roll hoops as shown in A.

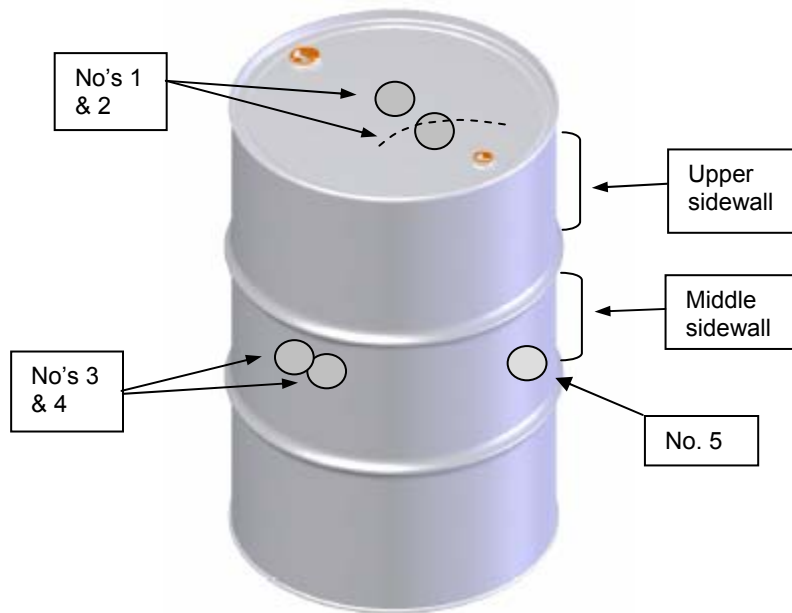


Figure 6. Location of five disks cut from bulged drum (SFP0001117).

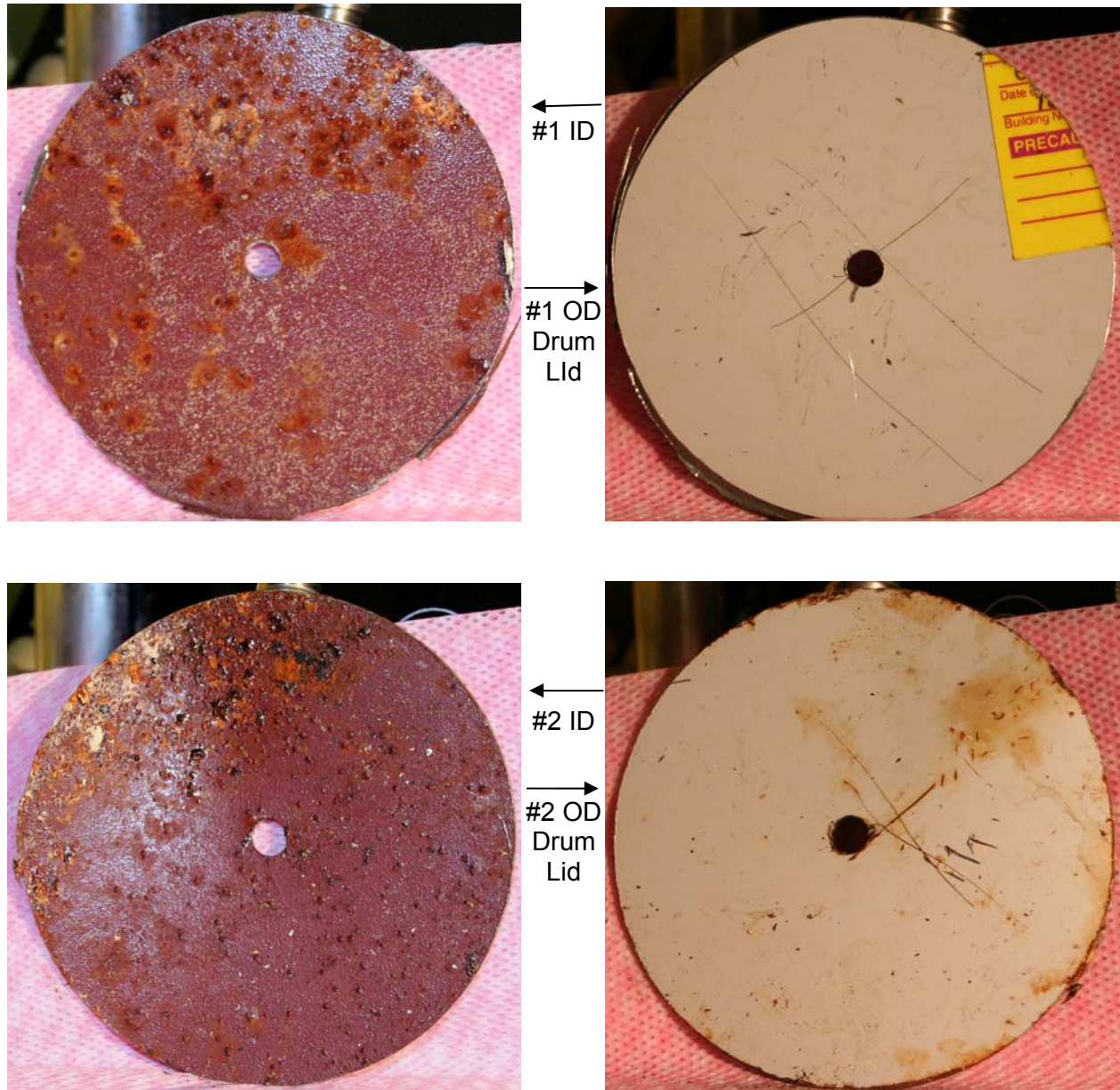


Figure 7. ID and OD of two disks cut from drum head revealing visible corrosion in ID surface of both samples. Minor corrosion was visible on the OD of the number 2 sample, from Figure 6.

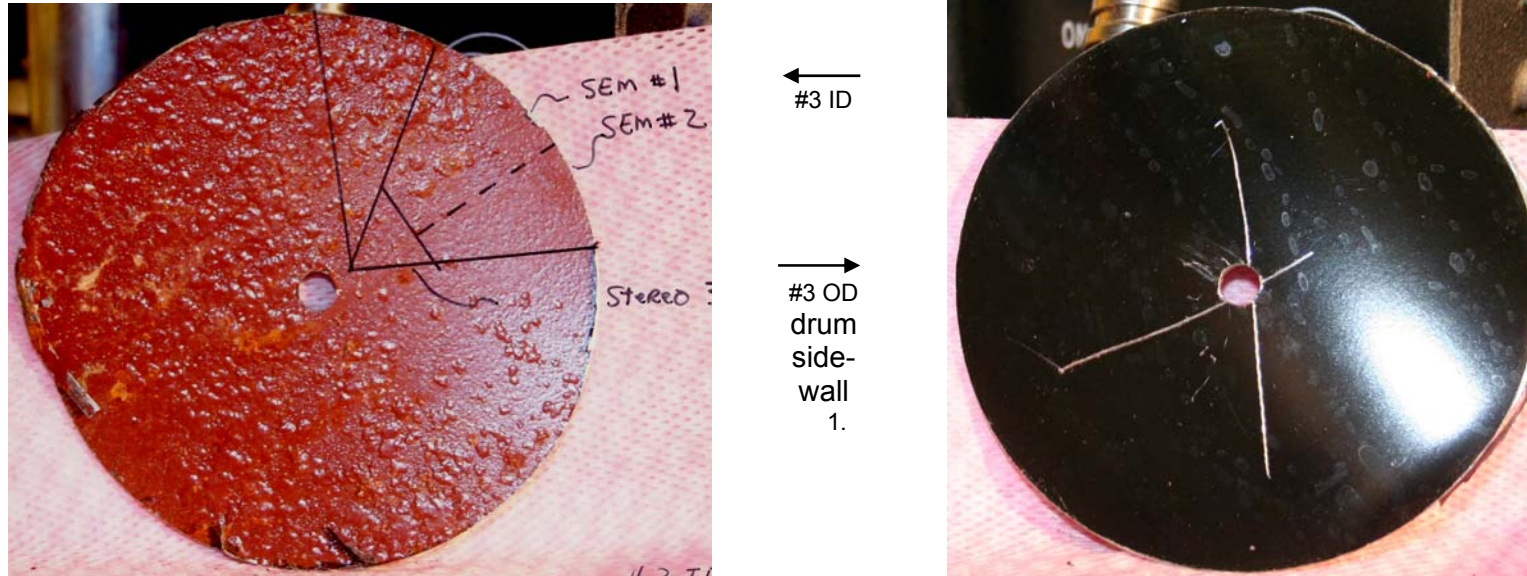


Figure 8. ID and OD surfaces of the number 3 disk (See Figure 6) cut from the drum sidewall. The ID surface also reveals the areas cut from the disk for SEM evaluation.

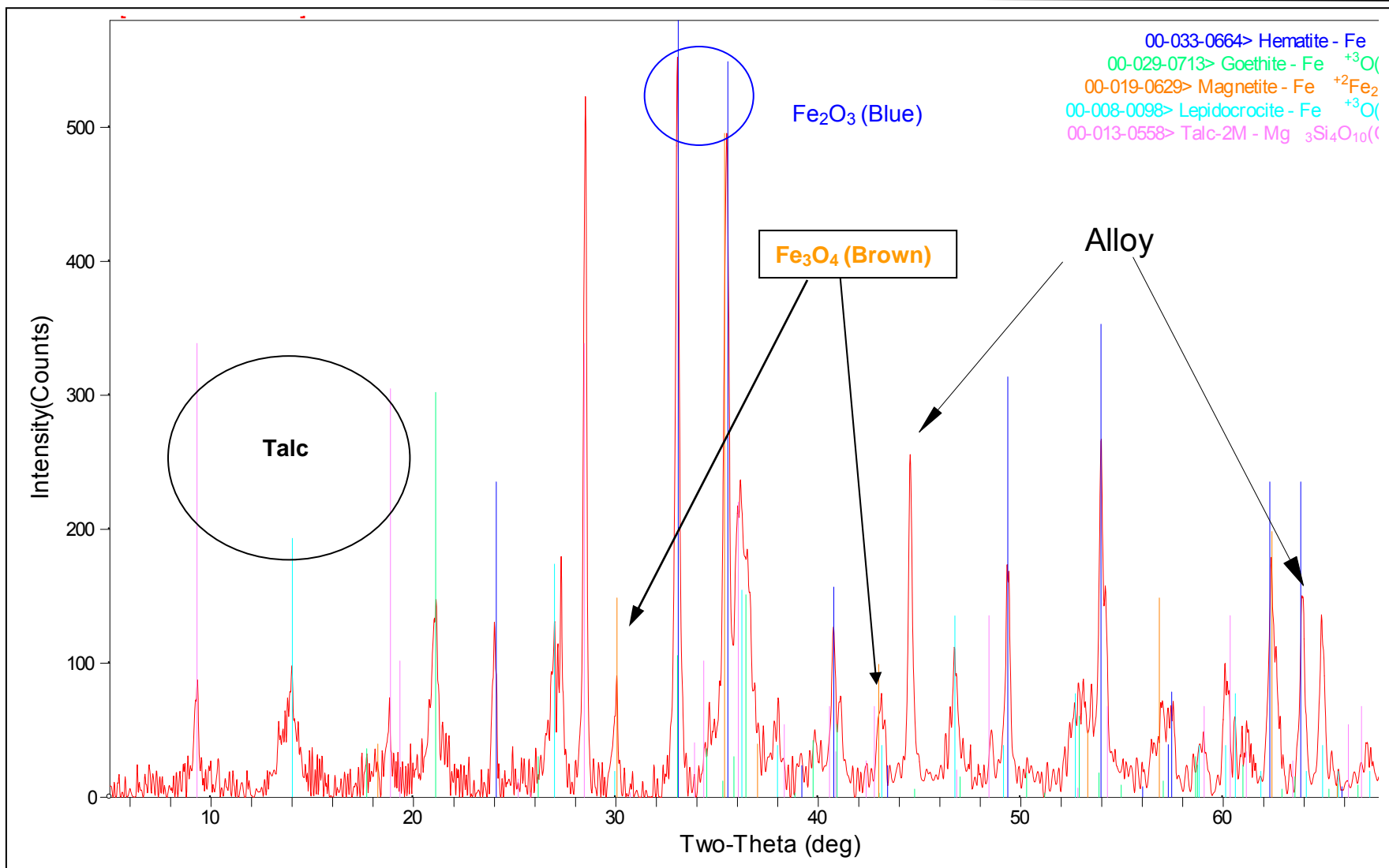


Figure 9. XRD analysis of the surface from sample 2 revealing the presence of Fe₂O₃, Fe₃O₄, Talc, FeOH, and the FeC base carbon steel.

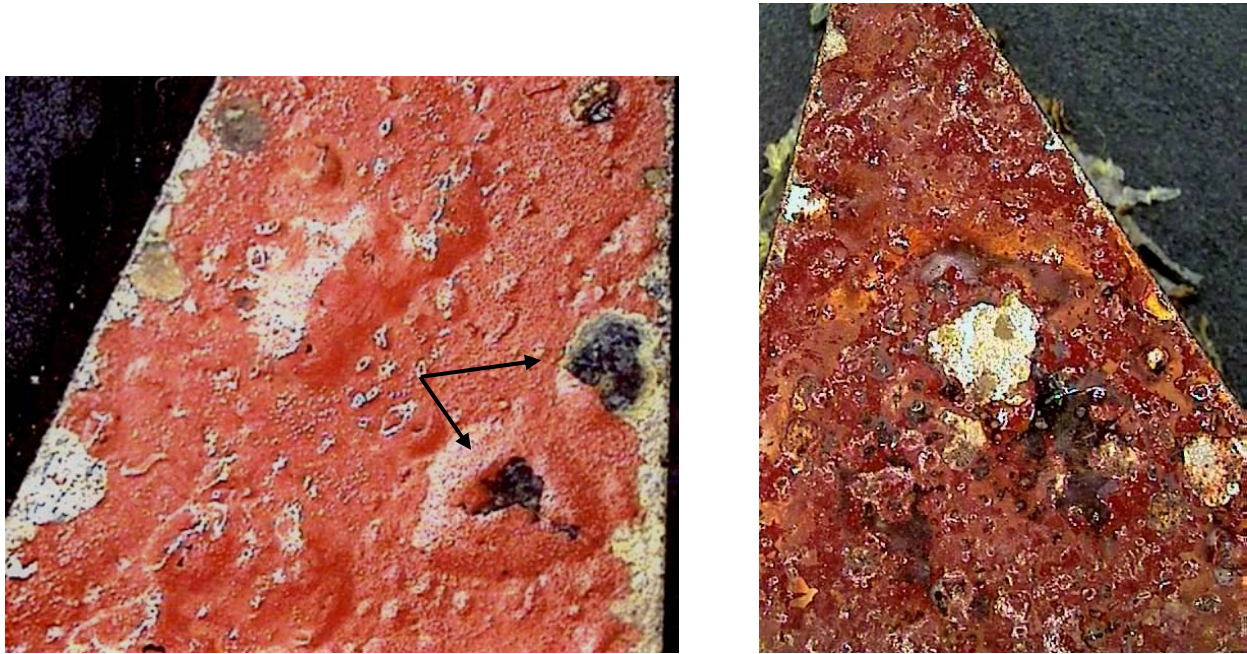


Figure 10. Close-up of surface of cut samples from the ID of Figure 8 revealing blisters that burst with black oxide in the middle.

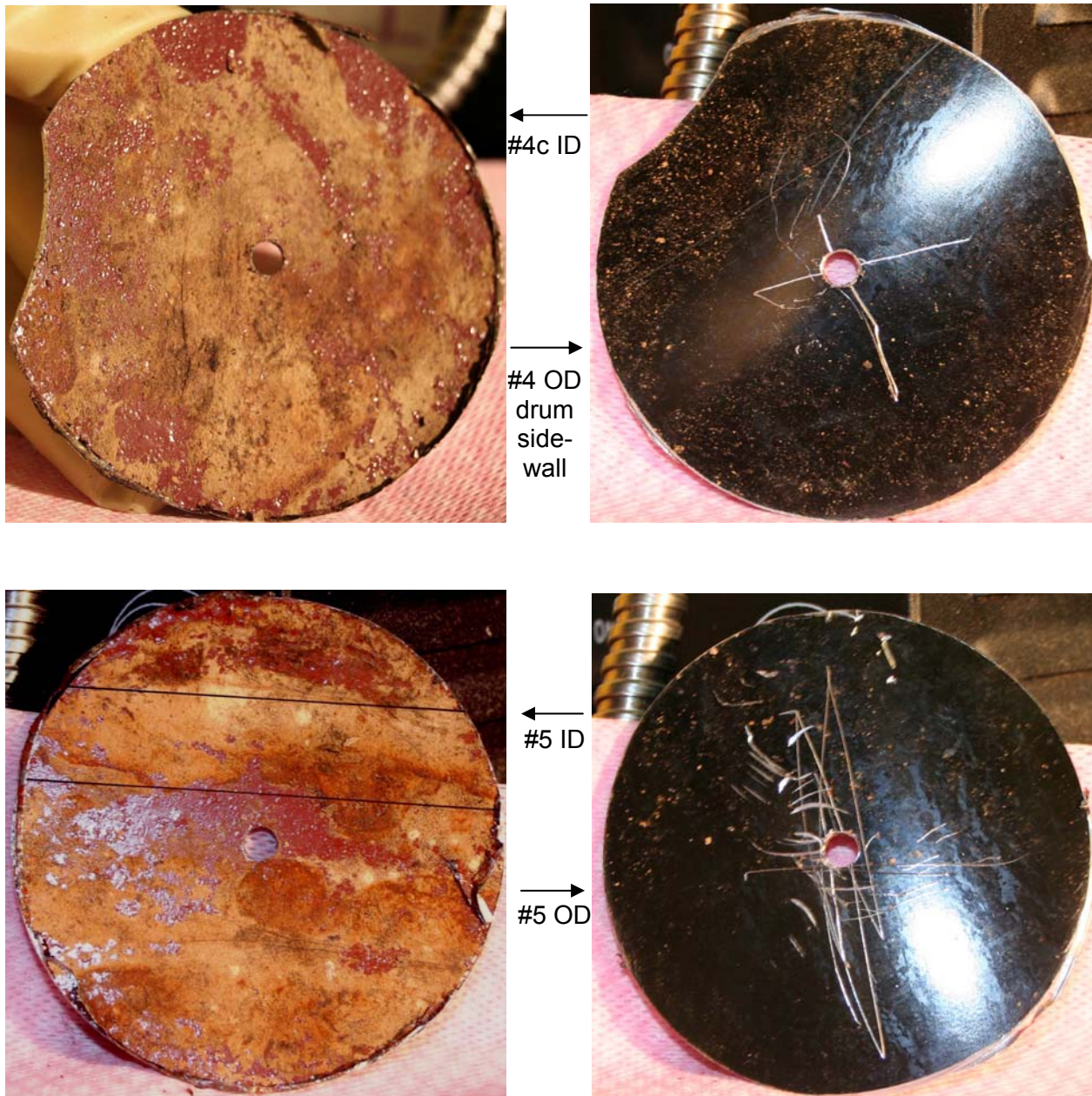


Figure 11. ID and OD surfaces of the number disk numbers 4 and 5 (see Figure 6) which were also cut from the drum sidewalls. Disk number 5 has two parallel lines within which the surface was scraped for analysis. The ID surface on both disks is blistered but is not as visible in these photographs (compared to previous photos) due to surface deposits.

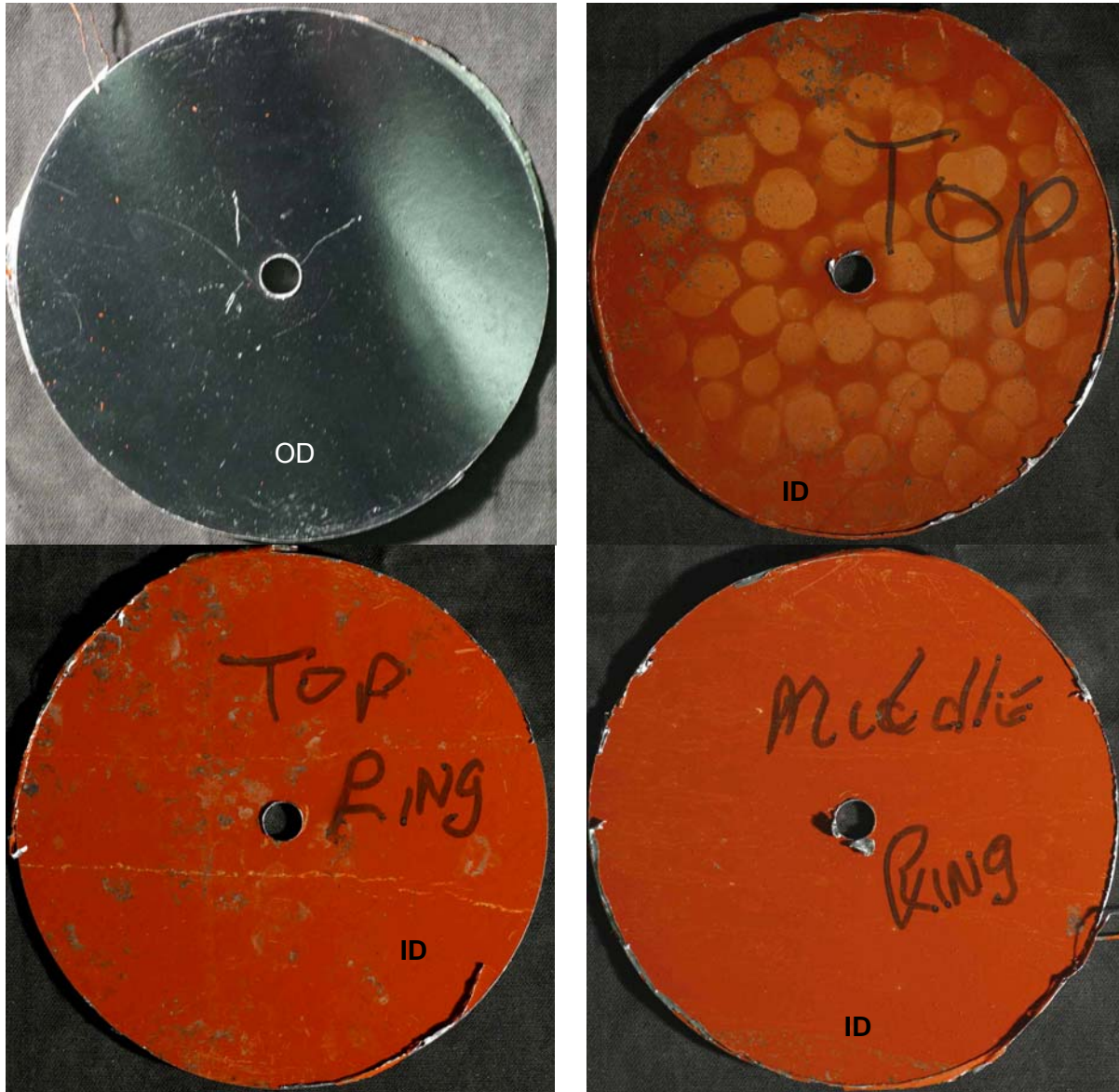


Figure 12. Photos of samples cut from a spare drum of same type as bulged drum and was unused prior to sample cutting. Some cutting debris are visible on the surface of the Top Ring sample.

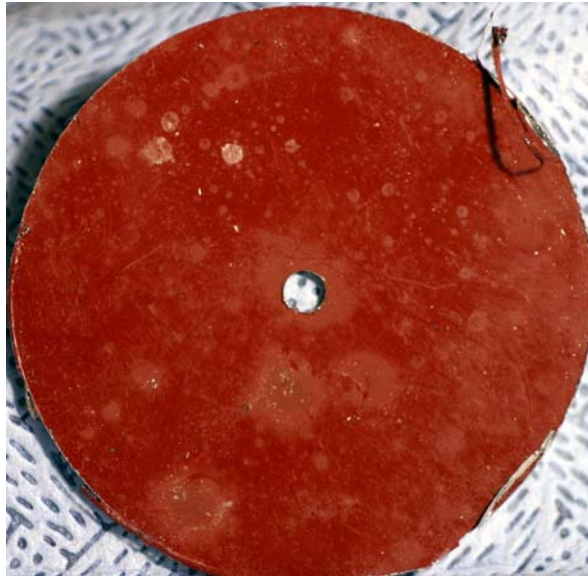


Figure 13. ID of Lid sample from drum 1114. This is also typical of lid samples from drums 1115, 1116, and 1117-2. Some staining is visible.

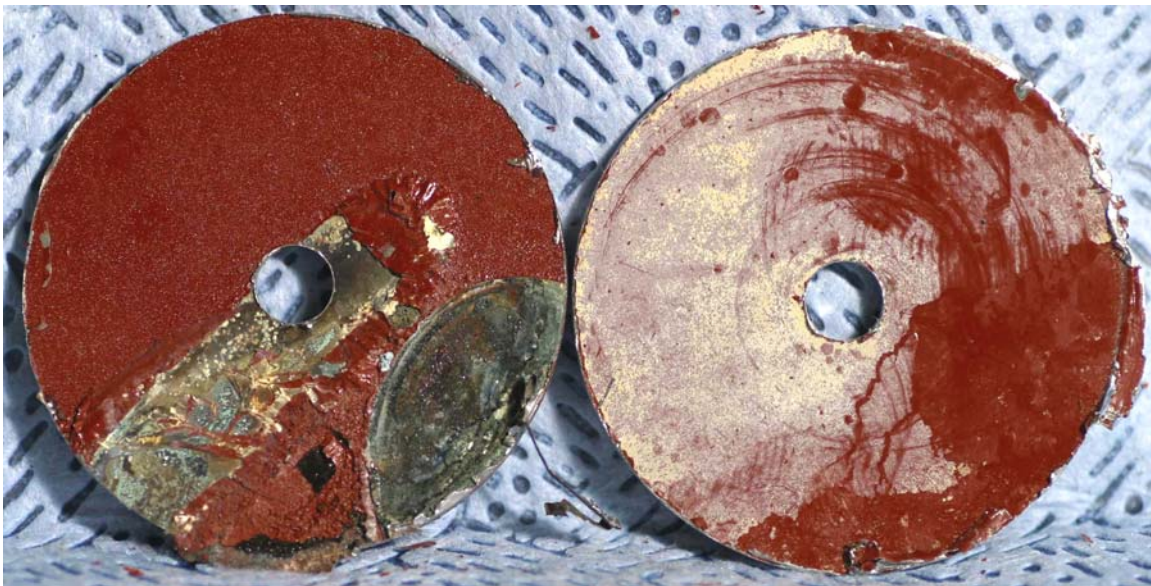


Figure 14. Drumwall ID samples from drum 1114.

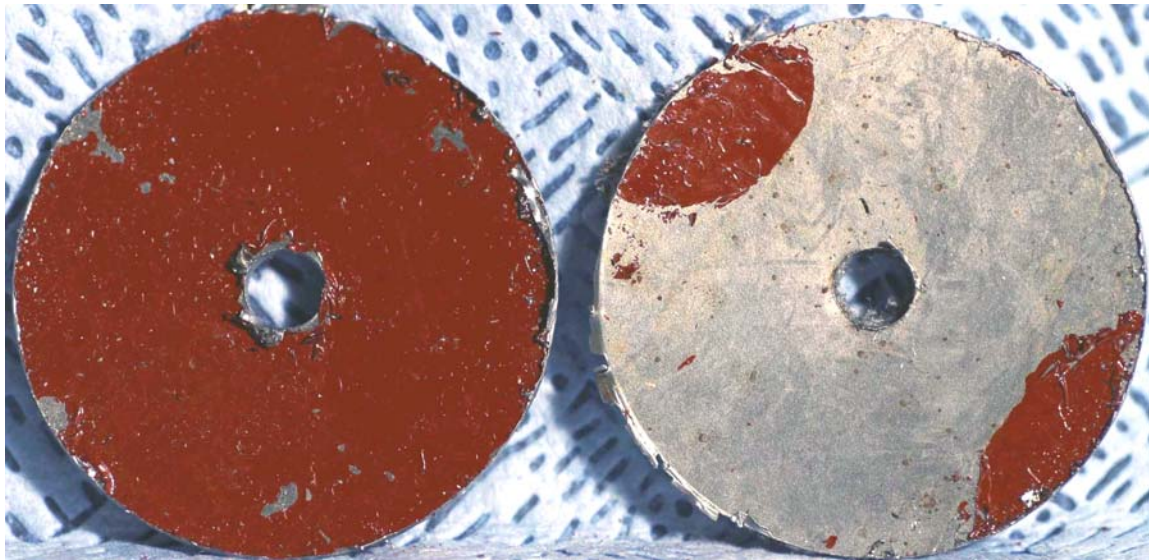


Figure 15. Drumwall ID samples from drum 1115.



Figure 16. Drumwall ID samples from drum 1116.



Figure 17. Drumwall ID samples from drum 1117 (II).

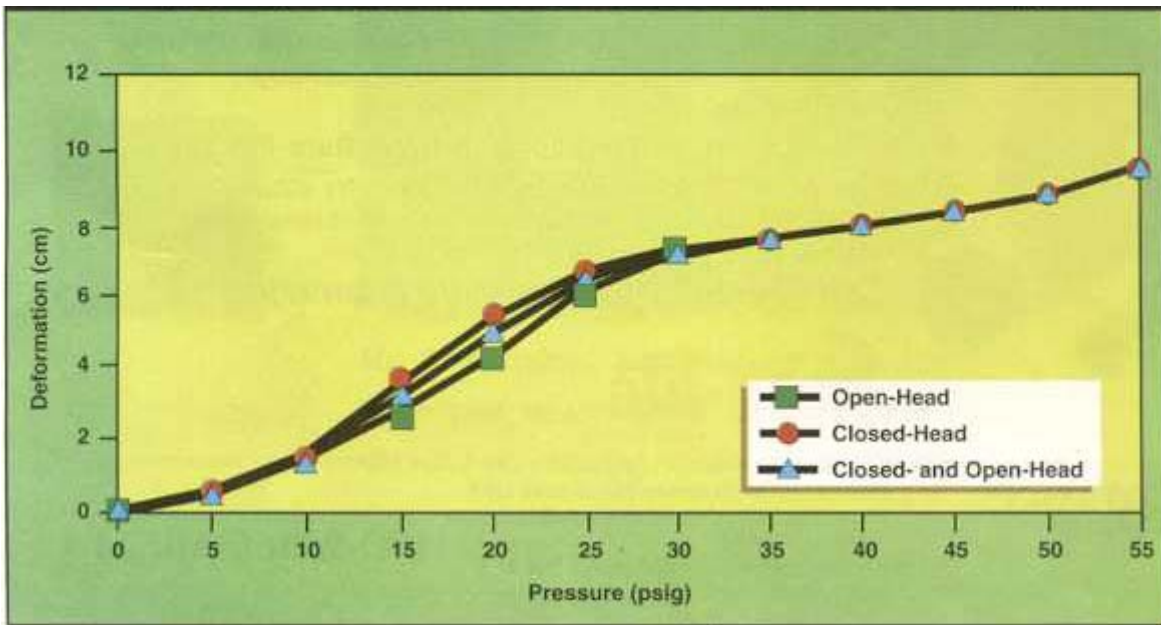


Figure 18. Open-head vs. closed-head drum top deformation averages versus pressure curve (upper graph) for 55 gallon steel drums.[10] The curves overlap each other at low and high pressures, except between 10 and 30 psi.

APPENDIX A

Hydrogen Evolution & Pressure Calculation from Steel Corrosion Rates

Hydrogen generation rate, $G_r = 3.8 \times 10^{-5} (K) (S_A) (F)$ moles H₂/hr (Ref. 8)
 Where K = Corrosion Rate (mpy), S_A = Surface Area (ft²), and F = fraction of total corrosion generating H₂ (assumed to be 1), G_r = H₂ generation rate, moles H₂/hr.

Drum internal surface area

Height = 35.0625 in. less 1/2 in. on each head for convexity (1 in. total)
 = 34.0625

Diameter = 22.5 in. (144 sq in. per sq. Ft).

Circumf. Area + bottom head area = $\pi * d * h + \pi * (d/2)^2 = 2805$ sq. in.

Volume = $\pi * (d/2)^2 * h = 13941.1$ in³

less 10% Vol. = 1394 in³

Area = 2805 sq in/144 sq. in./sq. ft.

Area = 19.48 sq ft

19.5 sq. ft.

For 90% surface (12 months) 10% air space

1 in³ = 1.64E-02 liters

PV = nRT 1394 in³ = 2.28E+01 liters

1 Kpa * 0.145 = psi

Table 10. H₂ Generation Rate.

K, mpy (corr. Rate)	H ₂ gen rate moles H ₂ /hr.	H ₂ gen rate moles H ₂ /yr
0.01	7.41E-06	6.49E-02
0.02	1.48E-05	1.30E-01
0.05	3.71E-05	3.25E-01
0.10	7.41E-05	6.49E-01
0.25	1.85E-04	1.62E+00
0.50	3.71E-04	3.25E+00
1.00	7.41E-04	6.49E+00

Table 11. Pressure vs. Corrosion Rate - 1 Yr.

Corrosion Rate(mpy)	n (# moles) H ₂ 1 year	P (Kpa)	P (psi)
0.01	6.49E-02	7	1
0.02	1.30E-01	14	2
0.05	3.25E-01	35	5
0.10	6.49E-01	70	10
0.20	1.30E+00	141	20
0.25	1.62E+00	176	26
0.50	3.25E+00	352	51
1.00	6.49E+00	704	102

Table 12. Pressure vs. Corrosion Rate
- 6 months

Corrosion Rate(mpy)	n (# moles)	P (Kpa)	P (psi)
0.01	3.25E-02	3.5	0.5
0.02	6.49E-02	7.0	1.0
0.05	1.62E-01	17.6	2.6
0.10	3.25E-01	35.2	5.1
0.20	6.49E-01	70.4	10.2
0.25	8.11E-01	88.0	12.8
0.50	1.62E+00	176.0	25.5
1.00	3.25E+00	352.0	51.0

Table 13. Pressure vs. Corrosion Rate
- 8 weeks

Corrosion Rate(mpy)	n (# moles)	P (Kpa)	P (psi)
0.01	9.99E-03	1.1	0.2
0.02	2.00E-02	2.2	0.3
0.05	4.99E-02	5.4	0.8
0.10	9.99E-02	10.8	1.6
0.20	2.00E-01	21.7	3.1
0.25	2.50E-01	27.1	3.9
0.50	4.99E-01	54.2	7.9
1.00	9.99E-01	108.3	15.7

Note: Corrosion rates are assumed values to enable calculations.

APPENDIX B

Hydrogen Evolution & Pressure Calculation from Fe Content in Drum Wastewater

Table 14. Max. Fe content in drums, ppm

Bulged Drum #1117-1	Good Drum #1114
196	29.4

one mole Fe creates one mole H₂ in acidic water

Fe Atomic weight = 55.8 g/mole

H₂ Atomic weight = 2 g/mole

Note: 1 ppm = 0.001 g/L

Fe content Drum # 1117-1 196 ppm * 0.001 g/L = 0.196 g/L

Fe content Drum # 1117 alt. 142 ppm * 0.001 g/L = 0.142 g/L

Fe content Drum # 1114 29.1 ppm* 0.001 g/L = 0.029 g/L

55 gal. drum less 10% = 49.5 gal.

1 gal. = 3.79 L

Thus 1 drum wastewater estimated at 49.5*3.79 = 187.61 liters (L)

Drum # 1117-1 0.196 g/L * 187.6 L = 36.77058 or 36.8 g Fe

Drum # 1117 alt. 0.142 g/L * 187.6 L = 26.63920 or 26.6 g Fe

Drum # 1114 0.029 g/L * 187.6 L = 5.44054 or 5.4 g Fe

Drum # 1117-1 36.8 g Fe/55.8 g/mole = 0.659 or 0.7 moles Fe

Drum # 1117 alt. 26.6 g Fe/55.8 g/mole = 0.477 or 0.5 moles Fe

Drum # 1114 5.4 g Fe/55.8 g/mole = 0.097 or 0.1 moles Fe

PV = nRT

where n = # moles of H₂ gas

T = room temperature ~25° C or 298 K

P = pressure resulting from the gas, Pa

kPa = 1000 x P

R = gas constant = 8.314 L kPa/mol K

V = free volume (10%) = 5.5 gal.x 3.79 g/L = 20.845 liters

Table 15. Pressure vs. Fe Content

Drum #	Fe ppm	# moles Fe	P, kPa	Conversion to psi	P, psi
#1117-1	196	0.7	83.2	x 0.15 psi/Kpa =	12.5 psi
# 1114	29.1	0.1	11.9	x 0.15 psi/Kpa =	1.8 psi
# 1117 alt.	142	0.5	59.4	x 0.15 psi/Kpa =	8.9 psi

Note: Pressure Calculation (P = nRT/V = H₂ pressure from Fe content)