INTEROFFICE MEMORANDUM
South Plant PSL

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Subject: Corrosion Studies on GeoBrom™ 520
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Notebook: Great Lakes Solutions 3455-93
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Background Information

A 90 day total-immersion corrosion rate study was requested using GeoBrom™ HG 520 calcium bromide solution and six selected metals at 20° and 50° C. ASTM Method "Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens" G1 - 03 (reapproved 2011) was used to prepare, clean, and evaluate tests specimens.

The following six metals were evaluated:

- C-1018 ➔ mild carbon steel coupon
- 304-W ➔ 304SS welded coupon
- 316-LW ➔ 316SS, low iron, welded coupon
- 2205 ➔ Duplex 2205 coupon
- 304-LW ➔ 304SS, low iron, welded coupon
- 316 ➔ 316SS coupon

Objectives of the Study

1. Establish subsurface corrosion rates at 20° C and 50° C for each metal.
2. Visually document coupon condition before and after 90 day exposure.
3. Analyze solution for metal content before and after 90 day exposure to evaluate metals in test solution.

Executive Summary

All specimens were less than 2.0 mpy corrosion rate based on this 90 day total-immersion study. Mild carbon steel (C-1018) had the highest rates at 0.32 mpy at 20° C and 1.29 mpy at 50° C. All remaining specimens were under 0.05 mpy. ICP analysis indicated elevated iron content in test solutions at end of the 90 day period. General surface corrosion was observed on both C1018 coupons with some pitting at 50° C. There was no visible corrosion on remaining test specimens. The maximum allowable corrosion rate for each specimen with GeoBrom™ HG 520 depends on the application.

Description of Test Procedure

Metal test coupons with dimensions of ~ 2.0" x 0.75" x 0.125" were supplied by an outside vendor. The vendor prepared the coupons by abrading surfaces and stamping metal type and marking specimens with a unique identification number. Prior to using, coupons were cleaned using reagent grade aqueous HCl and a bristle brush followed by a thorough deionized water rinse, degreased using acetone, dried using hot air, then allowed to cool in desiccators. The clean, dry specimens were weighed and measured. Using forceps, a four place OHAUS Galaxy Model G160D analytical balance was used to attain initial weights for all coupons. Dimensions were established using a Starrett® Micrometer part # 436RL-1, EDP 51568 and a Starrett® Dial Caliper Part # 120Z, EDP 55951. Three measurements were taken on all dimensions and averaged for the length, width, and thickness. Pictures were taken to record coupon condition prior to beginning immersion tests.

Test coupons were split into two groups, containing specimens of each metal type, and placed into two glass one-liter bottles with Teflon® liners. One group was placed in a Yamato Model DVS600 drying oven to hold samples at 50° C and the second group placed in a controlled environment room held at 20° C. There was no agitation or aeration of the test specimens while in the glass bottles.

Duration of the test was 90 days or 2,160 hours. Prior to cleaning, pictures were taken to record coupon condition after the 90 day immersion test. After cleaning, pictures were taken again. None of the specimens were heavily corroded, so post immersion cleaning was simple and consisted of; (1) immersion in deionized water to remove test solution, (2) immersion and brushed in aq. HCl (for mild carbon steel), and nitric acid (for the stainless steels), (3) thoroughly rinsed with deionized water, then immediately dried. The C1018 coupon required scrubbing with a mild abrasive in deionized water. Table A1.1 in ASTM G1-03 was used as a guide to select cleaning procedure for removal of corrosion products. After drying test specimens with hot air and then allowing them to cool in desiccators, all specimens were re-weighed and the final weights recorded.

Spreadsheets were developed to capture data and to make calculations per ASTM method. Calculated metal densities and published metal densities were used in corrosion rate calculations for comparison.

The average corrosion rate calculation per ASTM G1-03 is:

Corrosion Rate = (K x W) / (A x T x D)

- K = a constant "(K) constant listed in ASTM G1-03, Section 8 for desired units"
- T = time of exposure in hours
- A = area in cm^2
- W = mass loss in grams
- D = density in gm/cm^3

Results and Discussion

Table #1 and Table #2 provide data on test specimens at 20° C and at 50° C respectively. Corrosion rates on all specimens were under 2.0 mpy rate. Mild carbon steel C-1018 gave the highest corrosion rate at 0.32 mpy at 20° C and 1.29 mpy at 50° C. General surface corrosion was observed on C-1018 coupons with some pitting on the C-1018 coupon at 50° C. Visibly, there was no surface corrosion or pitting observed on any remaining specimens.

Corrosion rates for each specimen were charted to reflect trends over the two temperatures 20° C and 50° C and data presented within Figures #1 and #2.

GeoBrom™ HG 520 test solutions were also submitted for inductively coupled plasma (ICP) analysis before and after the immersion test. ICP data contained in Table #3 provides metals concentrations in test fluids at start, at end, and the difference between the two. There is a significant increase in iron (Fe) concentrations in the post test solutions from the corrosion of the carbon steel coupons.

To visually document condition of test specimens, pictures were taken before immersion tests, after, then after cleaning. These are presented in Figures #3 to #10.

Table #4 presents the chemical composition of each test specimen.

Conclusion

C-1018 showed signs of corrosion in this test. There are a number of different corrosion standards depending on the application. Therefore, whether C-1018 is suitable for use with $CaBr_2$ depends on the application. These data are relevant only to the 52% CaBr2 solution. Dilute solutions or other uses of 52% solution may exhibit different corrosive behaviors.

Future Work

Additional corrosion tests using GeoBrom™ 520 and these same six metals are on-going at this time. Studies on above surface “vapor” exposure, as well as, half above and half below surface exposure at 20° and 50° C have been started. ICP analysis for metals before and after will be available and observations will be documented by pictures before and after.

Table #1 Subsurface at 20° C

Corrosion Coupons Testing in PSL in GeoBrom 14.2 ppg Solution ==> Below Surface at 20° C

May 31, 2013 to August 29, 2013 T. G. Ray

Total exposure time was 90 days

Using ASTM Designation: G1 - 03 (reapproved 2011)Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens

				Duplex		
Coupon Type	**C-1018**	**304-W**	**316-LW**	**2205**	**304-LW**	**316**
ID	**A1686**	**A0023**	**A8151**	**single dot**	**A0012**	**A1170**
Weight (grams)	22.1947	22.8463	20.0253	21.9995	22.9181	19.7559
Length (inches)	2.017	2.003	2.003	2.017	2.008	1.989
Width (inches)	0.771	0.756	0.746	0.763	0.759	0.750
Thickness (inches)	0.123	0.129	0.115	0.123	0.130	0.112
Hole dia. (inches)	0.376	0.375	0.377	0.377	0.375	0.380
Calculated Density (gm/cc)	7.627	7.674	7.719	7.674	7.641	7.792
Published Density (gm/cc) ASTM	7.86	7.94	7.94	7.805	7.94	7.98
Calculated Surface Area (Sq. cm)	23.991	23.714	22.776	23.757	23.844	22.607
Date in Oven (MDY)	5/31/2013	5/31/2013	5/31/2013	5/31/2013	5/31/2013	5/31/2013
Time in oven (hours)	14:35	14:35	14:35	14:35	14:35	14:35
Date out of oven (MDY)	8/29/2013	8/29/2013	8/29/2013	8/29/2013	8/29/2013	8/29/2013
Time out of oven (hours)	14:35	14:35	14:35	14:35	14:35	14:35
Temperature (°C)	20	20	20	20	20	20
Exposure Time (hours)	2,160	2,160	2,160	2,160	2,160	2,160
Ending Weight (grams)	22.1585	22.8455	20.0233	21.9992	22.9161	19.7551
Loss in Weight (grams)	0.0362	0.0008	0.002	0.0003	0.002	0.0008
Rate of Corrosion (mpy) using calculated Density	0.3160	0.0070	0.0182	0.0026	0.0175	0.0073
Rate of Corrosion (mpy) using Published Density	0.3066	0.0068	0.0177	0.0026	0.0169	0.0071

Observations :

(1) Mild Carbon Steel shows the highest corrosion rate at 0.316 mpy at 20° C based on a 90 day exposure time.

(2) Coupons of 304-W, 316-LW, Duplex 2205, 304-LW, and 316 were all below 0.05 mpy.

Table #2 Subsurface at 50° C

Corrosion Coupons Testing in PSL in GeoBrom 14.2 ppg Solution ==> Below Surface at 50° C

May 31, 2013 to August 29, 2013 T. G. Ray

Total exposure time was 90 days

Using ASTM Designation: G1 - 03 (reapproved 2011) Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens

Coupon Type	C-1018	304-W	316-LW	Duplex 2205	304-LW	316
ID	A1685	A0024	A8153	double dot	A0013	A1169
Weight (grams)	22.3493	23.0076	20.17	21.9338	22.7433	19.9863
Length (inches)	2.018	2.005	2.000	2.017	2.006	2.001
Width (inches)	0.773	0.760	0.749	0.762	0.758	0.750
Thickness (inches)	0.124	0.130	0.115	0.122	0.129	0.113
Hole dia. (inches)	0.375	0.373	0.377	0.378	0.375	0.380
Calculated Density (gm/cc)	7.574	7.637	7.694	7.697	7.657	7.757
Published Density (gm/cc) ASTM	7.86	7.94	7.94	7.805	7.94	7.98
Calculated Surface Area (Sq. cm)	24.127	23.867	22.870	23.702	23.760	22.797
Date in Oven (MDY)	5/31/2013	5/31/2013	5/31/2013	5/31/2013	5/31/2013	5/31/2013
Time in oven (hours)	14:35	14:35	14:35	14:35	14:35	14:35
Date out of oven (MDY)	8/29/2013	8/29/2013	8/29/2013	8/29/2013	8/29/2013	8/29/2013
Time out of oven (hours)	14:35	14:35	14:35	14:35	14:35	14:35
Oven Temperature (°C)	50	50	50	50	50	50
Exposure Time (hours)	2,160	2,160	2,160	2,160	2,160	2,160
Ending Weight (grams)	22.2015	23.0066	20.1696	21.9322	22.7382	19.9855
Loss in Weight (grams)	0.1478	0.001	0.0004	0.0016	0.0051	0.0008
Rate of Corrosion (mpy) using calculated Density	1.2918	0.0088	0.0036	0.0140	0.0448	0.0072
Rate of Corrosion (mpy) using Published Density	1.2448	0.0084	0.0035	0.0138	0.0432	0.0070

Observations:

(1) Mild Carbon Steel shows the highest corrosion rate at 1.2918 mpy at 50° C based on a 90 day exposure time.

(2) Coupons of 304-W, 316-LW, Duplex 2205, 304-LW, and 316 were all below 0.05 mpy.

Table #3 Metals in Test Fluid

ICP Analysis Before and After 90 day Total-Immersion Corrosion Rate Study

All results in mg/L		ref ICP spl #1 Metals in sample	ref ICP spl #3 Metals in sample	20° C Test	ref ICP spl #2 Metals in sample	ref ICP spl #4 Metals in sample	50° C Test
Metal ID		**B-04 before**	**B-04 after at 20° C.**	**Difference**	**B-05 before**	**B-05 after at 50° C.**	**Difference**
Ag	(Silver)	4.23	4.85	0.62	4.26	4.81	0.55
Al	(Aluminum)	3.78	4.75	0.97	3.89	4.42	0.53
As	(Arsenic)	8.77	0.00	-8.77	3.55	5.12	1.57
B	(Boron)	0.92	1.05	0.13	1.04	1.11	0.07
Ba	(Barium)	5.72	5.88	0.16	5.78	5.93	0.15
Be	(Beryllium)	0.00	0.00	0.00	0.00	0.00	0.00
Bi	(Bismuth)	10.97	9.97	-1.00	11.97	11.83	-0.14
Ca	(Calcium)	very high	very high	#VALUE!	very high	very high	#VALUE!
Cd	(Cadmium)	1.14	2.24	1.10	1.70	2.93	1.23
Ce	(Cerium)	13.64	15.37	1.73	16.25	15.56	-0.69
Co	(Cobalt)	3.25	3.12	-0.13	3.41	3.17	-0.24
Cr(II)	(Chromium)	6.69	5.17	-1.52	5.78	8.86	3.08
Cu	(Copper)	1.50	1.45	-0.05	1.40	1.54	0.14
Fe(II)	(Iron)	3.25	53.95	50.70	6.39	139.86	133.47
K	(Potassium)	168.11	166.39	-1.72	149.46	184.31	34.85
La	(Lanthanum)	61.13	61.93	0.80	66.21	62.88	-3.33
Li	(Lithium)	6.15	6.41	0.26	6.48	6.29	-0.19
Mn	(Manganese)	3.51	4.47	0.96	3.58	7.00	3.42
Mo	(Molybdenum)	11.03	11.99	0.96	9.44	10.15	0.71
Na	(Sodium)	3.36	3.49	0.13	3.34	3.75	0.41
Ni	(Nickel)	3.55	2.40	-1.15	3.29	2.71	-0.58
Pb	(Lead)	4.22	4.83	0.61	6.30	12.99	6.69
Rb	(Rubidium)	4.74	4.32	-0.42	4.74	5.09	0.35
Sb	(Antimony)	5.27	4.63	-0.64	3.28	7.96	4.68
Se	(Selenium)	uncal	uncal	#VALUE!	uncal	uncal	#VALUE!
Sn	(Tin)	6.57	6.48	-0.09	6.66	10.79	4.13
Sr	(Strontium)	52.08	61.19	9.11	52.39	68.60	16.21
Ti	(Titanium)	2.93	3.03	0.10	2.90	3.03	0.13
Tl	(Thallium)	uncal	uncal	#VALUE!	uncal	uncal	#VALUE!
U	(Uranium)	48.57	29.68	-18.89	43.04	38.00	-5.04
V	(Vanadium)	18.32	21.79	3.47	21.39	29.99	8.60
Zn(I)	(Zinc)	0.00	0.46	0.46	0.00	3.98	3.98

Figure #1 ➔ Corrosion Rate Trend Chart w/ Y axis at 0 to 1.4 mpy scale

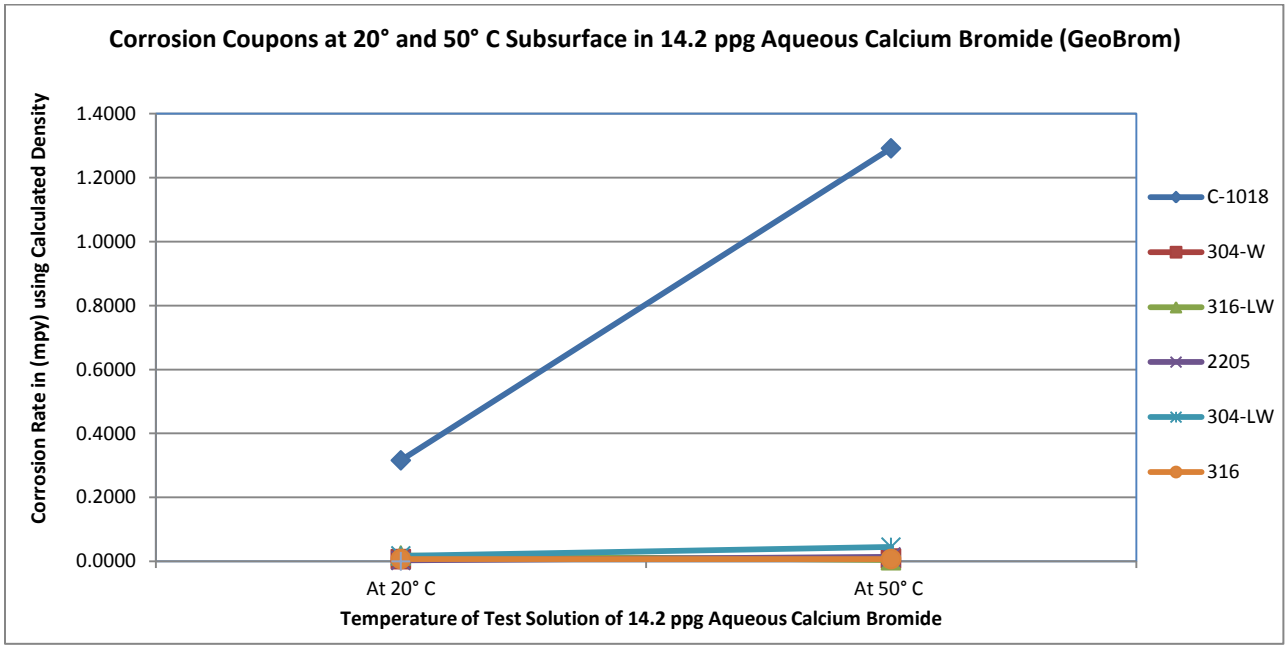

Figure #2 ➔ Corrosion Rate Trend Chart w/ Y axis at 0 to 0.07 mpy scale

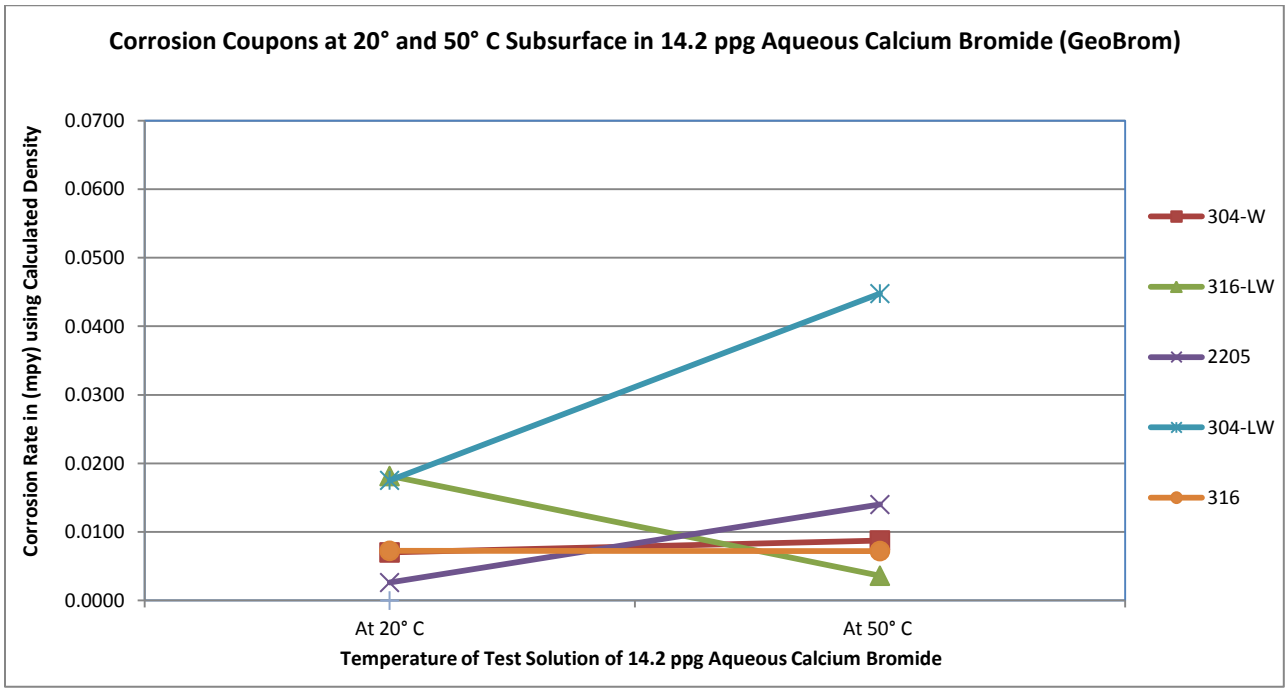

Figure #3 ➔ Test Coupons before 90 day subsurface exposure

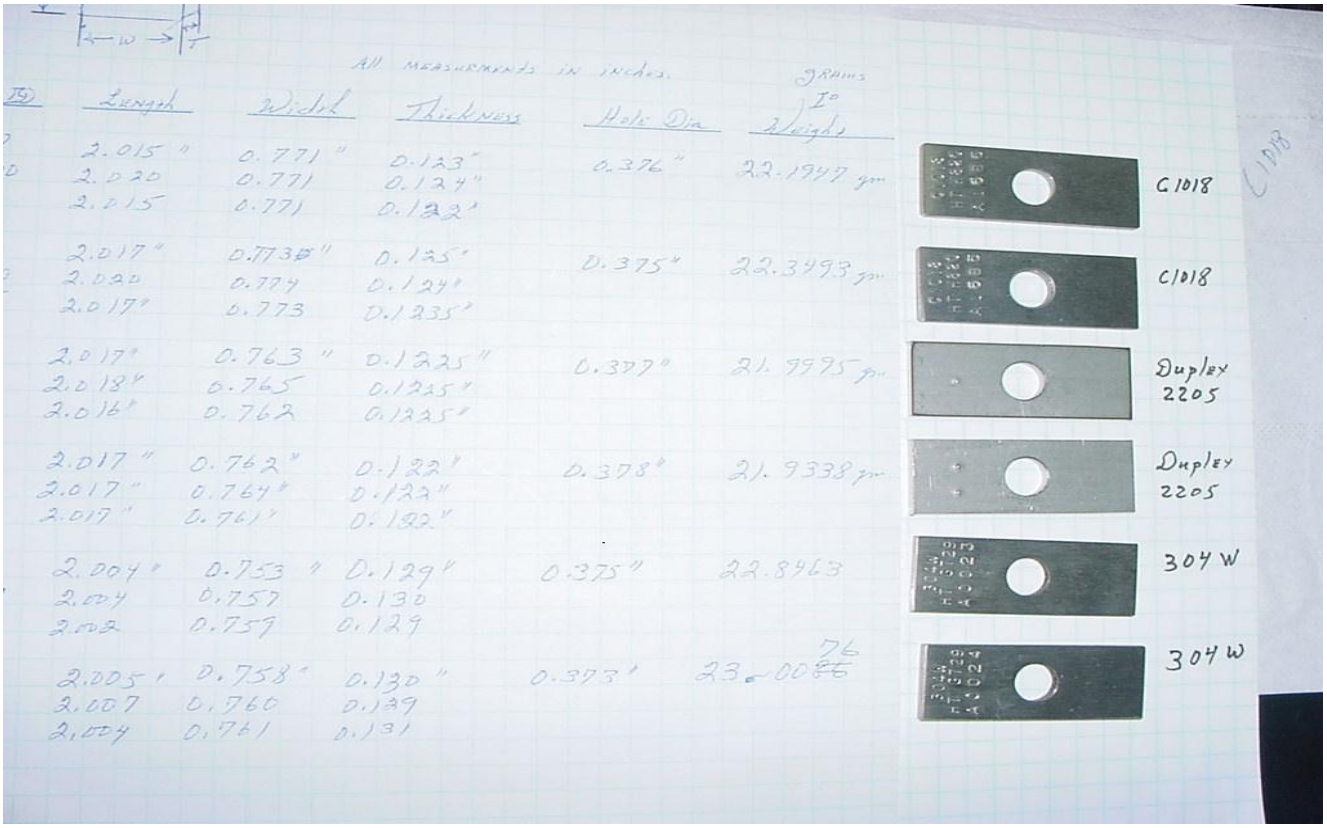

Figure #4 ➔ Test Coupons before 90 day subsurface exposure

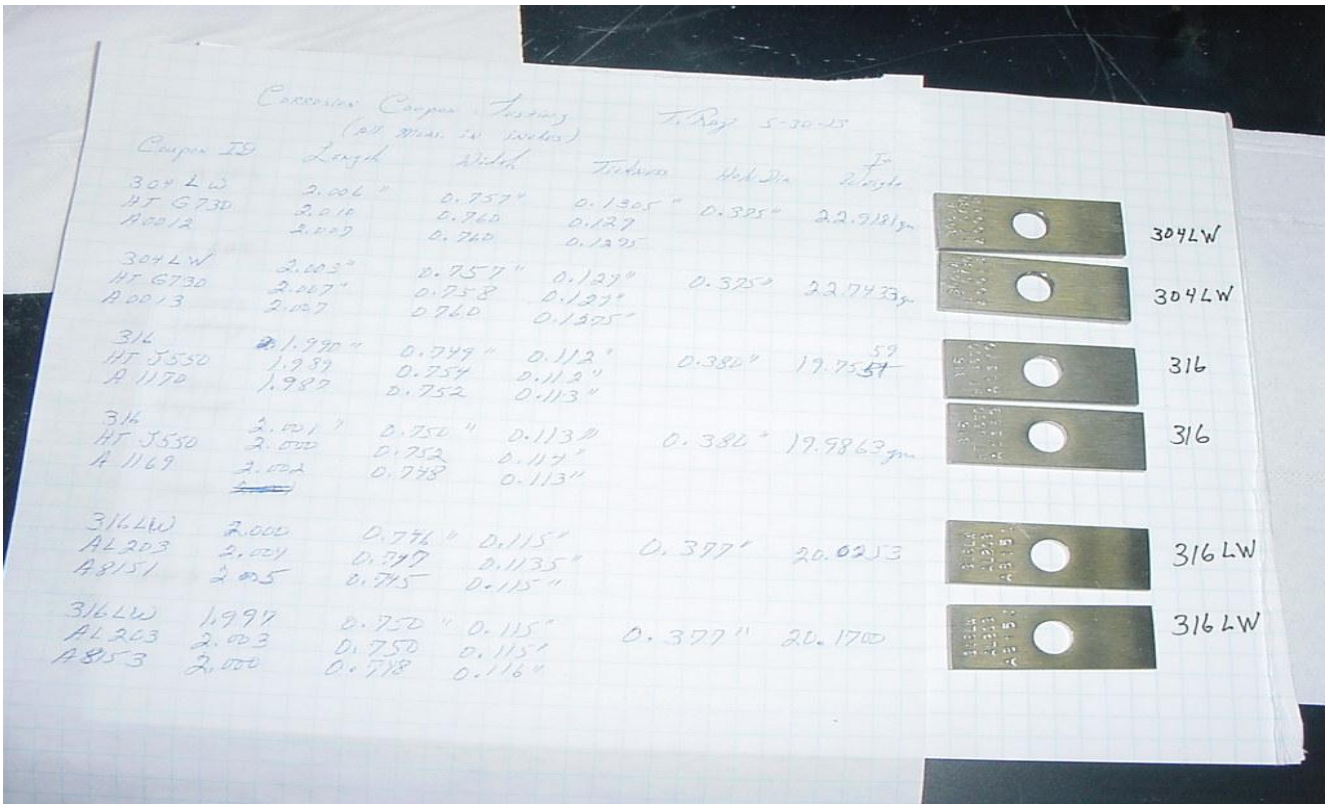

Figure #5 ➔ Test Coupons after 90 day subsurface exposure at 20° C (before cleaning)

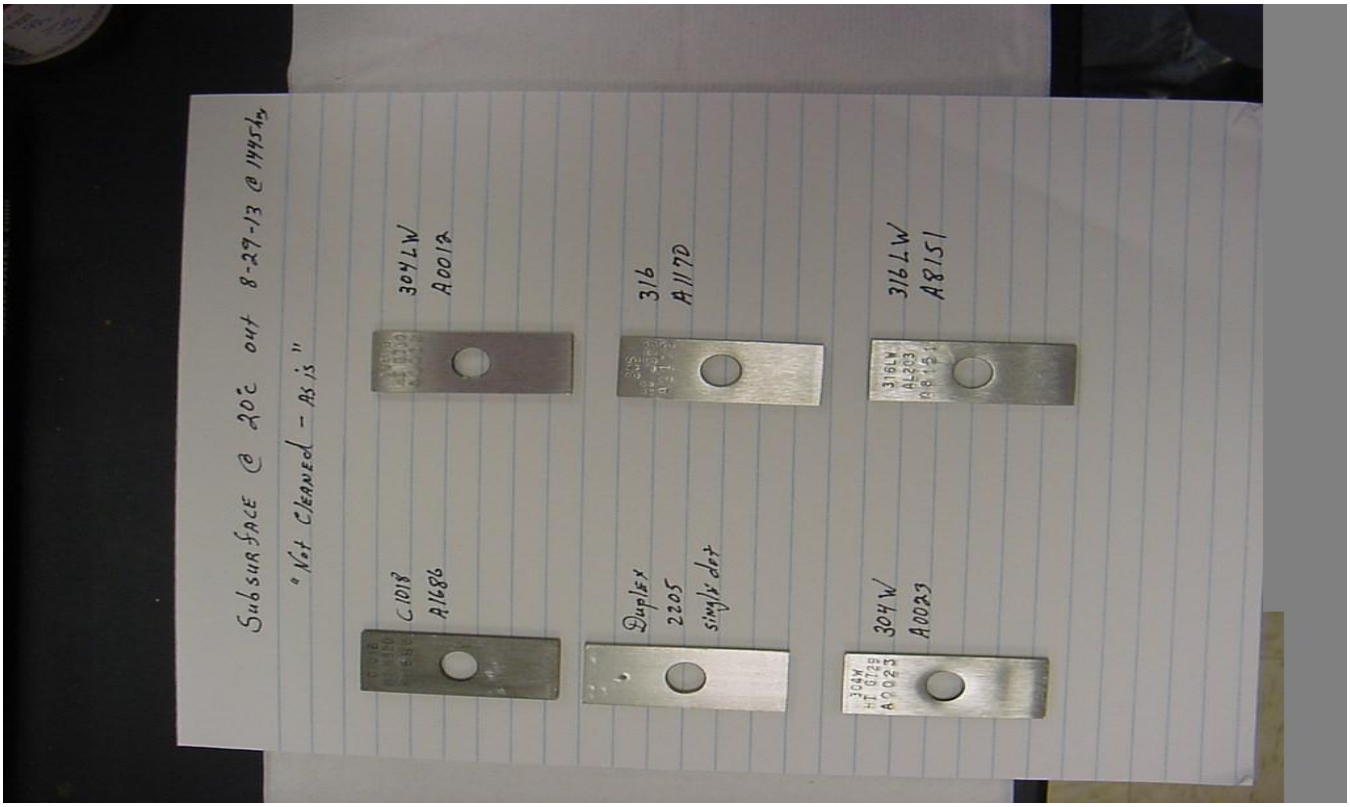

Figure #6 ➔ Test Coupons after 90 day subsurface exposure at 50° C (before cleaning)

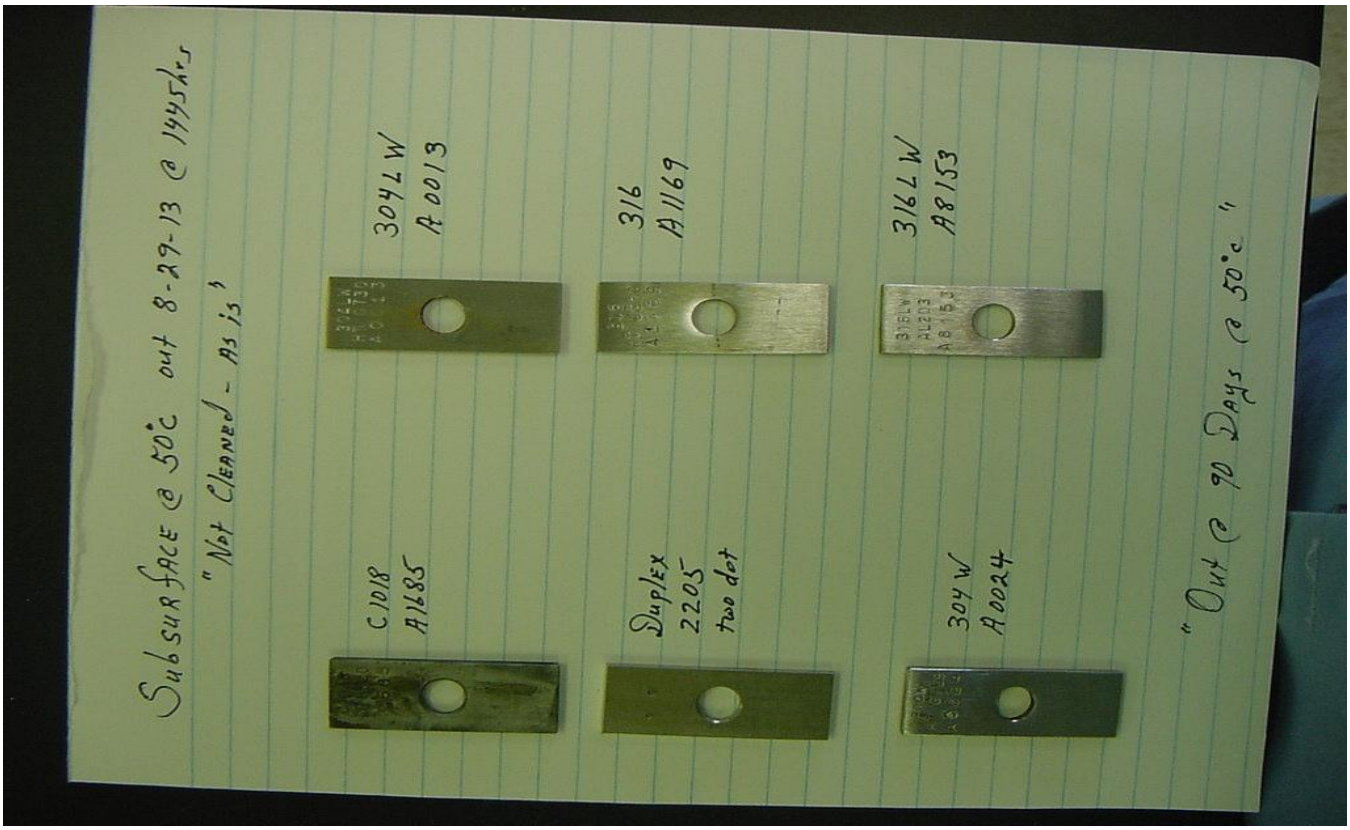

Figure #7 ➔ Front side of C1018 Coupon after 90 day subsurface exposure at 50° C (before cleaning)

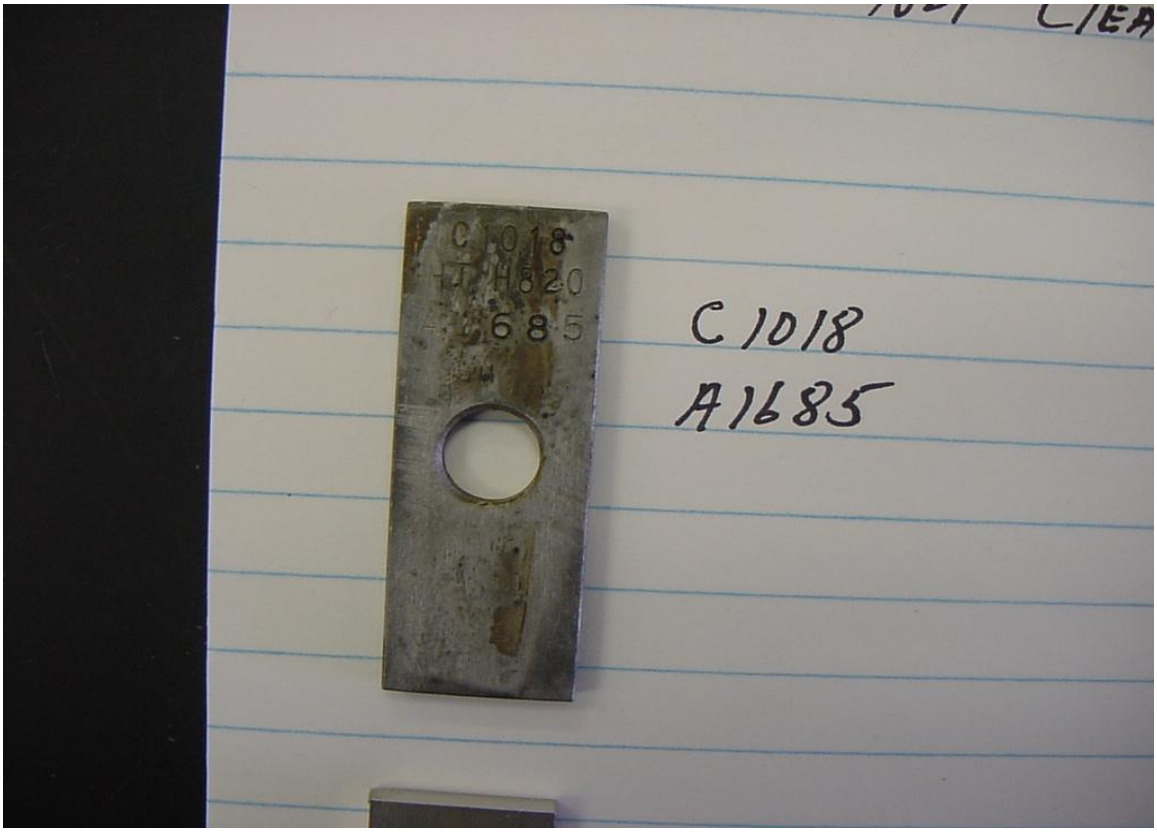

Figure #8➔ Back side of C1018 Test Coupon after 90 day subsurface exposure at 50° C (before cleaning)

Figure #9 ➔ Test Coupons after 90 day subsurface exposure at 20° C (after cleaning)

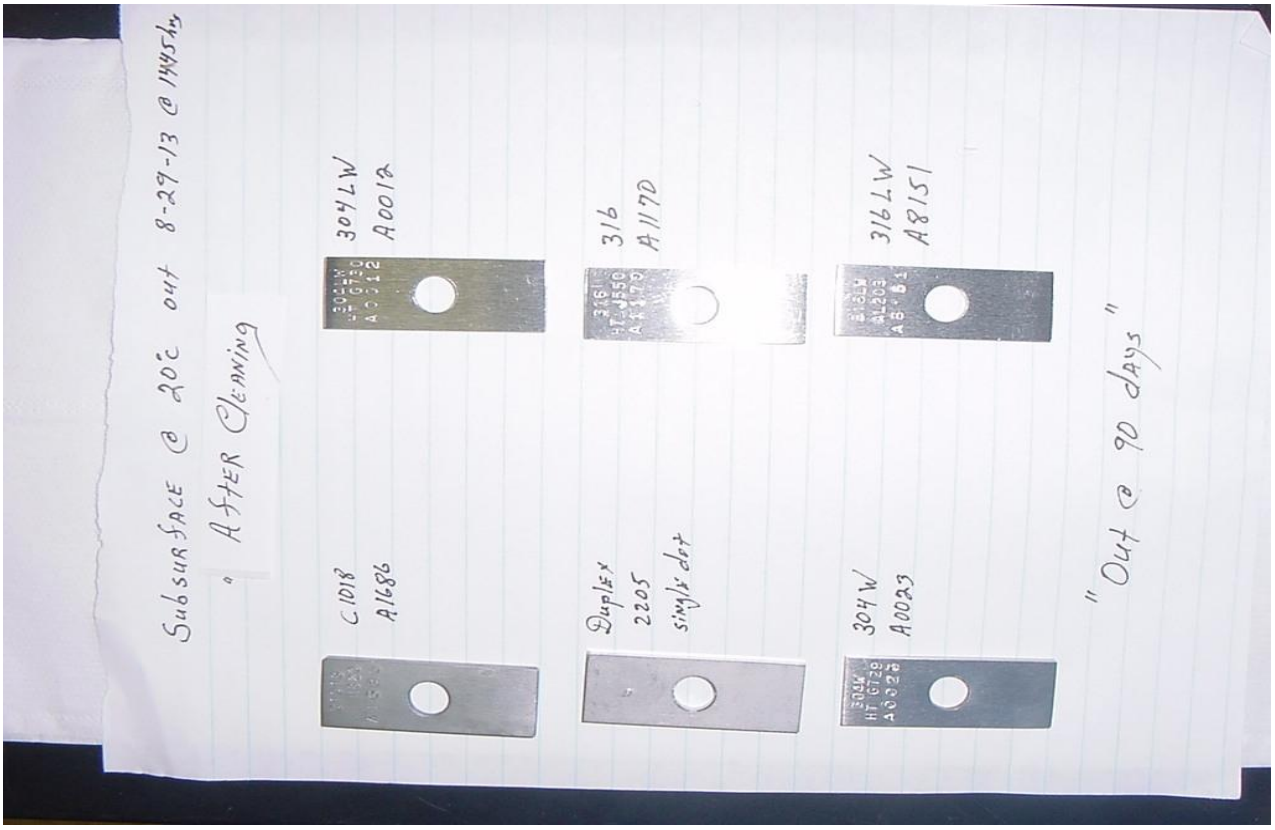

Figure #10 ➔ Test Coupons after 90 day subsurface exposure at 50° C (after cleaning)

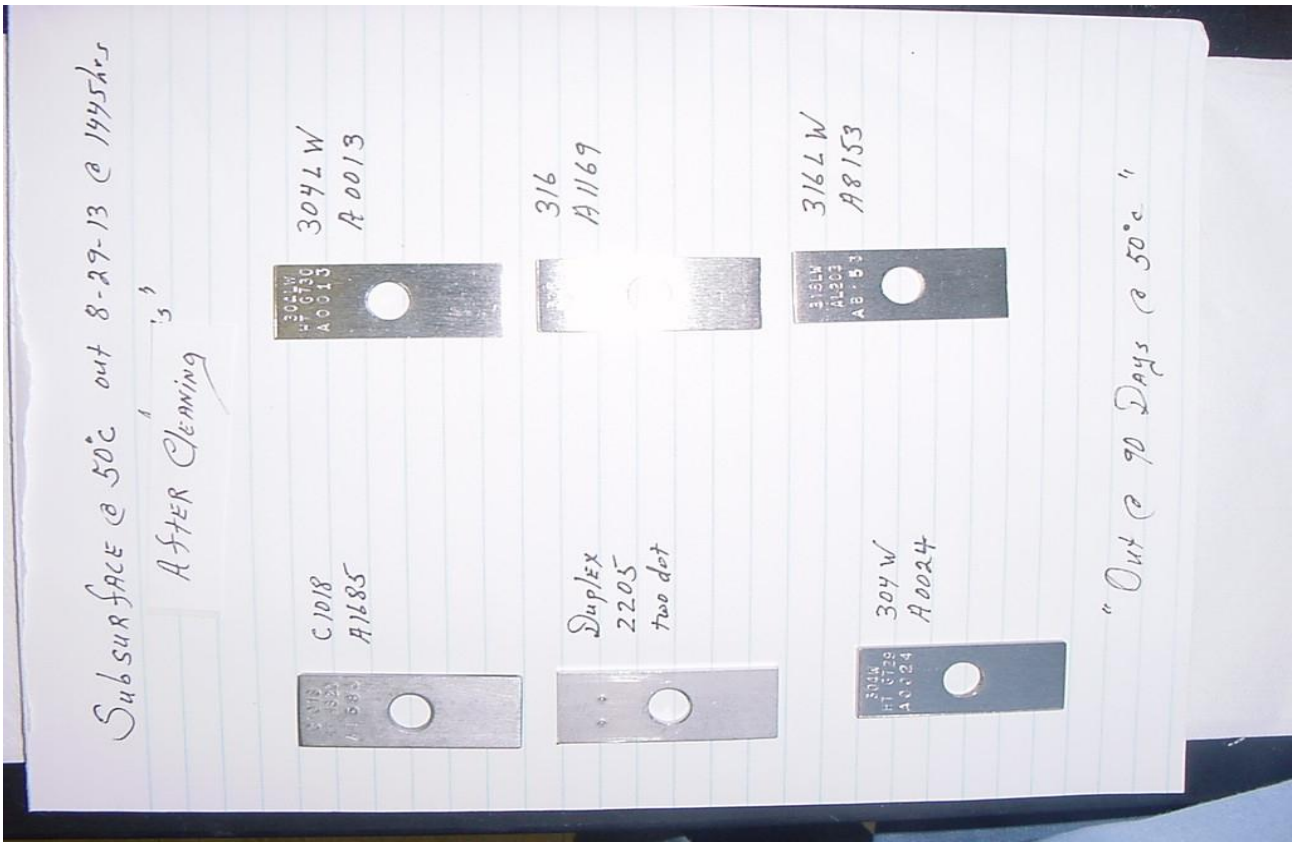

Table #4 Composition of Specimens

Chemical Composition of Specimens Tested during 90 day Total Immersion Study

AISI = American Iron and Steel Institute Data in % by weight

Metal Type	**AISI 1018**	**AISI 304**	**AISI 304-L**	**AISI 316**	**AISI 316-L**	**Duplex 2205**
Carbon	0.15 - 0.20	0.08 max	0.03 max	0.08 max	0.03 max	<0.03
Manganese	0.60 - 0.90	2 max	2 max	2 max	3 max	< 2
Phosphorous	0.040 max	0.045 max	0.045 max	0.045 max	0.045 max	< 0.03
Sulfur	0.050 max	0.03 max	0.03 max	0.03 max	0.03 max	< 0.02
Silicon	0.15 to 0.30	0.75 max	0.75 max	1 max	2 max	< 1
Chromium		18 - 20	18-20	16 - 18	17 - 18	21 - 23
Nickel		8 to 12	8 to 12	10 to 14	11 to 14	4.5 - 6.5
Molybdenum				2 to 3	3 to 3	2.5 - 3.5
Nitrogen		0.10 max	0.10 max			0.8 - 2.0
Iron	balance	balance	balance	balance	balance	balance