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March 16, 2020

Captain Marc Delao
Commander Navy Region Hawaii
850 Ticonderoga St., Suite 110
Joint Base Pearl Harbor Hickam, Hawaii 96860-5101

Re: Response to Corrosion and Metal Fatigue Practices, Destructive Testing Results Report, Red Hill Bulk Fuel Storage Facility (Red Hill), Joint Base Pearl Harbor-Hickam, Oahu, Hawaii

Dear Captain Delao,

The United States Environmental Protection Agency ("EPA") and the Hawaii Department of Health ("DOH"), collectively the "Regulatory Agencies," have reviewed the *Corrosion and Metal Fatigue Practices, Destructive Testing Results Report* ("Results Report"), July 7, 2019 submitted by the U.S. Department of the Navy ("Navy") and Defense Logistics Agency ("DLA") to satisfy the requirements in section 5.3.3 of the Red Hill Administrative Order on Consent ("AOC").

The Regulatory Agencies, in consultation with our experts in fuel storage management and corrosion, interpret the results of the destructive testing exercise performed in Tank 14 at the Facility differently than the findings presented in the Results Report. Specifically, the Regulatory Agencies do not concur that the "NDE results are validated, both by Destructive Testing and thorough, case-by-case analysis.[1]" As a result, and pursuant to section 7(b) of the Red Hill AOC, the Regulatory Agencies are disapproving the Results Report.

To clarify, the Regulatory Agencies are not requiring the resampling of Tank 14 under section 5.3.2 of the Red Hill AOC Scope of Work ("SOW"). For the most part, the data collected for the Results Report enabled the Regulatory Agencies to arrive at several important conclusions, although some of the data collection and analysis deviated from expectations and the originally approved workplan. However, further work shall be performed to the Regulatory Agencies' satisfaction to address differences in interpretation and data gaps found in the initial Destructive Testing Study. This additional work should include both 1) further effort to improve the non-destructive testing protocol as generally envisioned in Section 5.4 of the AOC SOW, and 2) further destructive testing to address data deficiencies identified by the Regulatory Agencies and their experts, and to evaluate the proposed improvements to the non-destructive testing protocol.

[1] U.S. Navy, *Corrosion and Metal Fatigue Practices, Destructive Testing Results Report*, July 7, 2019. p.61

More detailed comments that outline the Regulatory Agencies' specific concerns can be found in Enclosures 1 and 2 attached to this letter. Enclosure 3 includes detailed comments that the Regulatory Agencies received from the Honolulu Board of Water Supply, which the Navy should also consider when proceeding with the additional work.

As part of the terms of this disapproval, within 60 days of receipt of this letter, the Navy and DLA are required to hold a scoping meeting with the Regulatory Agencies to determine the further work needed as related to the improvement of non-destructive testing protocols and subsequent destructive testing.

If you have any questions, please contact us.

Sincerely,

Steven Linder, P.E.
Red Hill Project Coordinator
EPA Region 9

Roxanne Kwan
Interim Red Hill Project Coordinator
State of Hawaii, Department of Health

Enclosures
1. Regulatory Agencies Interpretation of Destructive Testing Data
2. Hihara Corrosion Consulting (HCC) LLC, Corrosion Report on Red Hill Bulk Fuel Storage Facility, February 5, 2020
3. Board of Water Supply Letter, Honolulu Board of Water Supply Comments on Navy's "AOC SOW Section 5 Corrosion and Metal Fatigue Practices, Destructive Testing Results Report" dated July 7, 2019 and IMR's Report "Destructive Analysis of 10 Steel Coupons Removed from Red Hill Fuel Storage Tank #14 dated December 17, 2018, October 7, 2019

Enclosure 1 – Regulatory Agencies' Interpretation of Destructive Testing Data

Based on our technical review of the *Destructive Testing Results Report* ("Results Report"), the Regulatory Agencies are requiring further evaluation and improvements to the Tank Inspection, Repair, and Maintenance ("TIRM") process. Given the concerns described in sections one though four (below) over the lack of NDE correlation and increasing corrosion rates, the Regulatory Agencies suggest that the Navy proceed with the following in evaluating current TIRM procedures and come prepared to discuss these and other actions to improve TIRM at the next scoping meeting with the Regulatory Agencies.

ADDITIONAL EVALUATION AND ASSOCIATED IMPACTS ON TIRM

a. Evaluate technology and develop processes to improve the Navy's NDE procedures. This new process should then be assessed for its effectiveness, which should be done with another destructive test.
b. Conduct additional analyses on the condition of the concrete structure and imbedded reinforcing steel.
c. Evaluate potential causes for corrosion and possible actions to reduce corrosion rates, if possible.
d. Immediately reevaluate the repair threshold and associated factor of safety to account for inaccuracies in NDE, corrosion rates, and possible delays in repair cycles. The Regulatory Agencies have noted that the CIR cycle of 20 years has slipped. Based on our calculations, the current CIR is averaging 30 years, with the longest duration being 59 years for Tank 18. We also note that while the next set of inspections are currently scheduled within 20 years, the schedule has already been pushed back from the time the TIRM report that was published in 2017.

The following describes in more detail the basis for the agencies' recommended actions:

1. INTERPRETATION OF COUPON RESULTS

Coupon 1 – False Positive

According to nondestructive examination ("NDE") data provided to the Regulatory Agencies, the site for Coupon 1 was initially indicated as needing a repair since phased array ultrasonic testing (PAUT) indicated a minimum remaining wall thickness of 0.112 inch. However, the laboratory analysis performed after the destructive testing indicated the remaining wall thickness was actually 0.208 inch and therefore a repair was not actually needed. The Regulatory Agencies regard this coupon as a false positive, meaning that a repair action was assigned, but a repair was not actually needed. The Results Report states on

p. 44 that a repair was specified, but the discussion on p. 61, seems to ignore the laboratory analysis and state that the need for repair was confirmed.

Although the Regulatory Agencies have greater concern with of false negatives, the presence of a false positive is still important. The Summary and Recommendations section of the Results Report also seems to misinterpret the accuracy of the NDE for this coupon.

Coupon 3- False Negative

The initial screening of Coupon 3 with low frequency electromagnetic testing (LFET) indicated a thickness of only 0.033". The prove up with PAUT over the region, however, indicated no metal loss, but instead identified non-actionable lamination (p. 46). Based on the NDE, Coupon 3 was not recommended for repair (p.46): "Prove-up thickness (PAUT): No indication noted, so no repair recommended." The destructive testing determined that the minimum remaining wall thickness was 0.132 inch, indicating that repair should have been specified. The Results Report claims that a nearby area was indicated for repair and that for this reason, the site of Coupon 3 has been selected for a repair. The Regulatory Agencies are unable to verify that this would be the case and cannot corroborate that a patch plate finding the first piece of suitable metal would cover the site for Coupon 3. Both the drawing that the Navy provided, and the PAUT indicate that no repair would have been conducted.

It is difficult to reconcile the basis for stating that a repair would be found at Coupon 3 when comparing what occurred at Coupon 8, for example. At Coupon 8, LFET indicated the need for a repair, but PAUT suggested that no repair was needed. In the Coupon 8 instance, a repair was not pursued, and the destructive testing corroborated that no repair was needed. Regarding Coupon 3, LFET identified a thickness of 0.033", but the technician could not find the defect using PAUT in the region (or had not proved up the region); hence, no action was recommended. The destructive testing, however, identified a pit with remaining thickness of 0.132" within Coupon 3, which is actionable. Hence, this should be a false negative.

Coupon 6- False Negative

A pit of concern was found through laboratory analysis at Coupon 6. This pit was deep, but of small volume. The Results Report claiming that this miss was caused by an instrumentation miss and not a technician error. The Results Report does not provide sufficient information to allow the Regulatory Agencies to validate the cause of this error. The Regulatory Agencies were assured that all areas of metal thickness below 200 mils would have been recorded during a first pass low frequency electromagnetic scan. The Regulatory Agencies also note that at 0.158 inches that this site should have been repaired. Page 61 of the Results Report also states that a repair was not needed which is not consistent with the repair criteria.

Coupon 7- False Positive

The Regulatory Agencies regard this coupon as a potential false positive, meaning that a repair action was assigned, but a repair was not actually needed. The *Destructive Testing Results Report* ("Results Report") states on p. 52, *"The LFET minimum screening thickness was 0.157 inch. The prove-up thickness was 0.135 inch. Therefore, a repair was specified in* *this area. Destructive testing found pitting and a minimum wall thickness of 0.164 inch. The remaining wall thickness was within the 20-mil range for pitting but thicker than expected for the prove-up testing (164 mils vs. 135mils)."* The actual vs NDE PAUT measurement exceeded the +/- 5% lab measured goal.

As previously stated, the Regulatory Agencies have greater concern with of false negatives, the presence of a false positive is still important. Both highlight the current inaccuracy of the NDE process.

2. DEFICIENCIES IN DATA COLLECTED / DEVIATIONS FROM WORKPLAN

The Navy's laboratory analysis did not or was not able to identify the thinnest portions of each plate which made a good portion of this destructive testing exercise and analysis incomplete. The thinnest portion was not found due to insufficient coupon cleaning and failure to complete profilometry of the entirety of each coupon.

The Regulatory Agencies disagree with Navy's statement on page 61 of the Report. *"The Navy holds that the analysis of coupons in this study is an effective means of validating nondestructive examination findings. ...Every coupon area at which the contractor did not recommend repair (Coupons 6, 8, 10, and A2) was found through destructive testing ("DT") and through additional analysis not to require repair after all. Every coupon area at which the contractor did recommend repair (Coupons 1, 2, 5, 7, 9, and A1), as well as the one coupon area near which the contractor found an indication of excessive backside corrosion (Indication B near Coupon 3) that warranted repair, was indeed found by DT to be thin enough to require repair. Therefore, the NDE results are validated, both by DT and thorough, case- by- case analysis."*

3. UNCERTAINTY REGARDING NON-DESTRUCTIVE EXAMINATION (NDE) ACCURACY

The Regulatory Agencies believe that there lacks sufficient correlation between NDE and the laboratory measurements, therefore further evaluation of NDE procedures should be pursued.

a. The Destructive Plan, section 3.1.1 *Screening Criteria* on pages 3-4, outlines the current TIRM procedures to be validated by the destructive test. For example, the expected accuracy for the NDE measurements is as follows:

- "Backside Pitting. Prove-up measurement (pit depth) within 20 mils of actual laboratory results.
- Wall Thinning. Prove-up measurements within 5% of actual laboratory results."

In the Results Report, five of the ten coupons had Phased Array Ultrasonic Testing (PAUT) or prove-up measurements provided. Only two out of five (40%) coupons had PAUT-measured pit depths within the 20 mils and/or +/- 5% of the laboratory-measured value. Table 1 below shows the difference between PAUT-measured values and actual laboratory-measured pit depths.

Table 1. Phased Array Ultrasonic Testing (PAUT) Comparison							
Coupon #	EEI (PAUT) NDE Remaining Thickness (mil)	Thinnest Laboratory Measured Value (mil)	5% of Laboratory Measured Value (mil)	-5% (mil)	+5% (mil)	Test Tolerance (In/Out)	Difference between PAUT and Laboratory Measured Values(mil)
1	112	207.9	10.4	197.5	218.3	Out	-95.9
2	150	152.4	7.6	144.8	160.0	In	-2.4
7	135	163.8	8.2	155.6	172.0	Out	-28.8
8	200	205.9	10.3	195.6	216.2	In	-5.9
10	200	241.7	12.1	229.6	253.8	Out	-41.7

b. Based on laboratory measurements, four out of ten coupons reversed their repair status as intended based on NDE measurements. Coupons 1 and 7 changed from a Fix to No Fix status ("False Positive"); whereas, Coupons 3 and 6 changed from a No Fix to Fix status ("False Negative"), which indicates a 40% error rate. In general, false negatives are of greater concern because the unidentified pit or corrosion areas will remain unrepaired and depending on its size, could potentially develop into a through-hole leak prior to the next Clean, Inspect, and Repair ("CIR") cycle. Coupon 6 is a concern since the Low Frequency Electromagnetic Testing ("LFET") did not require further evaluation. While the actual pit was a few mils under the 160-mil repair threshold established for Tank 14 CIR, the fact that the LFET scan was not able to identify this pit did not allow for the PAUT, the Navy's identified "prove-up" process, to further evaluate the need for repairs.

c. The Navy contends that the false negative of Coupon 3 was a result of an incomplete NDE process and that the NDE process worked. However, based on the information provided, the Regulatory Agencies disagree with this assertion.

i. First, the report states, "During the PAUT prove-up, the 33-mil thickness was identified not to be metal loss but instead was a non-actionable lamination. Therefore, a repair was not initially specified in this area. Backside corrosion was not expected." Figure 4-5 description mentions that "PAUT prove-up determined no repair."

ii. Second, the report further notes that the PAUT technician could not find the 33-mil measurement in Indication A, which is consistent that a repair was not identified in this area and only in Indication B.

iii. Third, the report states that the repair for Indication B was incorrectly inputted as the repair for Indication A (noted as repair of 15 inches wide and 8 inches high, at x= 7 inches and y=5 inches).

We agree that the repair appears intended for Indication B based on the handwriting on the tank wall and on the listed coordinates. With this understanding, the intended repair would not have covered the corrosion found behind Coupon 3. Note that the Computed Tomography ("CT") scan version (Figure 4-6 on page 47) of the coupon should be rotated 90 degrees clockwise and flipped 180 degrees on horizontal center axis to bring the drill hole of the Coupon 3 in alignment with Figure 8 on page 31 of Results Report Appendix A and Figure 4-7 on page 48 of the Results Report. The proper orientation of the CT scan photo indicates that the corrosion area requiring repair is further away (left-hand side of Coupon 3) from Indication B as depicted on page 48. Therefore, the report's statement, *"Laboratory results from Coupon 3 showed an area of remaining thickness of 131 mils, which is actionable. This thickness is within the layout area of Indication B."* is incorrect.

d. The Regulatory Agencies are concerned that the thinnest metal location for Coupons 2, 7, and A1 may not have been located, further questioning the Navy's conclusions on NDE accuracy. As specified in The Destructive Plan, section 4.2e., the Results Report does not contain three-dimensional ("3D") profilometry data after proper cleaning of the coupon. 3D profilometry data would have provided a more detailed surface characterization of the exterior and interior surfaces of the steel coupon. Further discussion on this issue is provided in enclosure, Hihara Corrosion Consulting (HCC), LLC, "*Corrosion Report on Red Hill Bulk Fuel Storage Facility" ("HCC Corrosion Report")*, February 5, 2020.

4. POTENTIAL FOR INCREASING CORROSION RATES

The Regulatory Agencies believe the Navy is underestimating corrosion rates for Tank 14 and should reassess corrosion rates as used in calculating repair thresholds under TIRM. In addition, the potential cause for increasing corrosion rates creates concern for potential corrosion of imbedded steel in the concrete.

a. In calculating corrosion rate for Tank 14, the Navy used the thinnest metal thickness identified by the laboratory in Coupon 3, 131.5 mils, subtracted from the initial metal thickness of 250 mils and divided by the number of years that tank was in service. The Regulatory Agencies have multiple concerns in the way this corrosion rate was calculated.
   i. Although Coupon A2 had the thinnest laboratory-measured thickness at 122.4 mil instead of 131.5 mil for Coupon 3, this thinnest measurement is only representative of the 10 coupons. These coupons did not represent the most corroded areas of Tank 14, so a thinner wall thickness may exist.
   ii. Navy should look at their past tank repair records and use the first reported tank through-hole to establish a worst-case corrosion rate. As an example, *Red Hill Facility Tank Inspection, Repair, and Maintenance Report (AOC/SOW), Section 2.2 of 11 October 2016*, page 18-1, mentioned tank through-hole found during Tank 16 repair in May 2006 with a corrosion

rate of 3.72 mil/yr. While we recognize that corrosion rates among tanks may not be consistent as explained in HCC Corrosion Report, a worst-case corrosion rate should be established by Navy in assessing repair thresholds that would be most protective of the environment.

iii. The Navy assumed that corrosion would occur at a linear rate over the life of the tank. Environmental and chemical conditions may increase corrosion and need to be taken into consideration in estimating corrosion rates. The basis for consideration is further discussed in the paragraphs below.

b. Results Report, page 61, states, "On-site testing and laboratory testing of concrete powder samples indicated that the concrete behind the steel tank liner is alkaline and in sound condition. Alkaline concrete is necessary to avoid corrosion." The Regulatory Agencies believe that there is greater concern for corrosion and the potential for increasing corrosion than the Results Report implies. The enclosed HCC Corrosion Report (Enclosure 2) provides detailed analysis of the current state of corrosion as related to the ten coupons removed from Tank 14. A summary is presented below.

   i. Tables 15 and 16 of the Results Report Appendix A show measured pH is less than (<) 11 for concrete samples behind seven out of ten coupons, whereas pH for fresh concrete is around 13 or 14. When pH < 11, the concrete's ability to protect steel from corrosion decreases and corrosion rates start to increase and accelerates as the pH levels drops.

   ii. Table 3-11 of the Results Report lists the structure-to-electrolyte corrosion potential and shows that only one of ten coupons have a low probability for corrosion, while four of the ten coupons indicate active corrosion. When compared with remaining plate thickness, a strong correlation between remaining plate thickness and corrosion potentials was observed. The remaining plate thickness decreased as the corrosion potential decreased, indicating various degrees of active corrosion.

   iii. Corrosion rates of steel can increase by 1) decreasing pH of concrete caused by carbonation (the production of calcium carbonate when carbonic acid from carbon dioxide reacts with calcium hydroxide) and 2) by elevated concentration of chloride ions. Corrosion product samples from seven of ten coupons had concentrations of chloride ions >0.3 wt %.

c. Understanding the potential causes for corrosion (i.e., high carbonation, presence of chlorides), may also help recognize the potential for increasing corrosion rates. One theory is rainfall infiltration.

   i. Energy dispersive X-ray analyses (Tables 6, 7, 8, 9, 10, 12, and 13) in Appendix A of the Results Report indicate the presence of chlorides in the corrosion products of the steel plates. The levels of chlorides in the corrosion products were significantly higher than those in the concrete (Tables 15 and 16) suggesting that the source of chlorides may be elsewhere, such as rainwater percolating through the soils and concrete above the tanks and then selected regions of the structure. This could also explain the relatively high levels of nitrite and nitrate in the concrete (Tables 15 and 16) and the carbonation of the concrete. Water percolating through soils can pick up nitrite and nitrate from decaying vegetation and animal residue. Dissolved carbon dioxide is also a byproduct of decaying organic matter.

ii. The Results Report described voids between the concrete and steel liner in nine of ten coupon areas, ranging from 1/16-inch to ½-inch, providing the possibility of rainfall to more readily move along the tank liner. As mentioned in the *Historic American Engineering Record, no. HI-123, 2015, National Park Service, U.S. Department of the Interior,* report, the "removal of the tell-tales eliminated a way to drain off any rainwater that percolates down through the lava rock and finds its way into the space between the back side of the steel shell plates and the inner side of the concrete wall. The standing water could cause accelerated corrosion of the back side of the steel shell plate."

Enclosure 2

Corrosion Report on Red Hill Bulk Fuel Storage Facility

Submitted by
Hihara Corrosion Consulting (HCC), LLC

To
State of Hawaii, Department of Health, Solid & Hazardous Waste Branch

5 February 2020

Lloyd H. Hihara
Lloyd H. Hihara
Member Manager HCC LLC

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1 Introduction

An assessment was made on the corrosion of Tank 14 of the Red Hill Fuel Storage Facility based on the analyses of data from the Red Hill Bulk Fuel Storage Facility Destructive Testing Results Report, AOC/SOW Section 5.3.3 (Report Number: SSR-NAVFAC EXWC-CI-1941) [1], and the Red Hill Bulk Fuel Storage Facility, Scope of Work for Destructive Testing Supplement, Destructive Testing Plan [2]. The main objective of the destructive testing was to validate the non-destructive evaluation (NDE) results, and not to specifically determine the condition of the tank [1]:

> Due to the large surface area of the steel tank liner, acquiring sufficient number of samples for meaningful statistical analysis is infeasible. Therefore, coupons were selected strategically not to characterize the condition of the tank but to verify the NDE findings in areas throughout the tank. With input from Regulators and their Subject Matter Experts (SMEs), coupons with isolated pitting, general corrosion, pitting with general corrosion, and no identified corrosion were selected. The expected results were compared with the destructive test results to validate the NDE process.

The various types of data collected during the removal of the steel-plate coupons, however, enabled preliminary characterization of the condition of some regions of Tank 14.

The type of tank-wall steel, concrete pH readings, presence of contaminants (such as chlorides), corrosion-potential readings, corrosion rates, nondestructive testing results, and destructive testing results are analyzed and discussed.

2 Data and Procedures

The data analyzed in this report related to Tank 14 of the Red Hill Fuel Storage Facility were provided to Hihara Corrosion Consulting, LLC by the State of Hawaii, Department of Health, Solid & Hazardous Waste Branch:

1) Red Hill Bulk Fuel Storage Facility Destructive Testing Results Report, AOC/SOW Section 5.3.3 (Report Number: SSR-NAVFAC EXWC-CI-1941) [1] - hereafter referred to as the DT Results Report. Note that the third-party Destructive Testing Laboratory Report by IMR Test Labs is in the appendix of the DT Results Report [1].

2) Red Hill Bulk Fuel Storage Facility, Scope of Work for Destructive Testing Supplement, Destructive Testing Plan [2].

Other sources in the literature were cited and are listed in the References section.

3 Results and Discussion

The chemical analyses of the steel plate coupons that were removed from Tank 14 indicated that the alloy was similar to that of ASTM A36 [1], which is a plain-carbon structural steel. Plain-carbon steels generally corrode actively in neutral and acidic solutions, but passivate with marked reduced corrosion rates in most alkaline environments [3]; such as, in alkaline, non-carbonated concrete [4]. Plain-carbon steel can remain passive in concrete until the pH drops by a process called carbonation or by the presence of chlorides, both which breakdown passivity and cause corrosion rates to increase [4].

3.1 Concrete pH

Bulk pH measurements (Table 1) [1] from the concrete powder samples taken from behind the steel-plate coupons showed an average pH of 10.62 with a standard deviation of 0.56. Seven of the ten concrete samples had bulk pH values ranging from 9.86 – 10.65, and only three plates had bulk pH values above 11. Values of pH were also measured from the surface of the concrete (Table 1) [1] behind the steel plate coupons. The surface pH ranged from 7 – 12.5 (Table 1) [1]. The very low pH levels (i.e., pH 7) could be due to the presence of the steel corrosion products. Variation and precision between the bulk pH and surface pH (Figure 1) was likely due to the location of where the pH was sampled and the method of measurement. The bulk pH was measured using the concrete powder samples; whereas, the surface pH was measured on localized regions of the concrete surface [2]. Due to the importance of pH and its effect on steel corrosion, a more in-depth study on concrete pH is recommended to avoid the possibility of corrosion products affecting pH readings.

Table 1: Concrete Data: Bulk pH, Surface pH, and Structure-to-Electrolyte Corrosion Potentials [1]

Property	Notes	Corresponding Coupon Number													
		P1	P2	P3	P5	P6	P7	P8	P10	PA1	PA2	Min	Max	Avg	SD
pH of Bulk Concrete Powder	pH measurement per ASTM D1293-12	9.86	11.79	11.03	11.13	10.27	10.65	10.55	10.37	10.45	10.10	9.86	11.79	10.62	0.56
pH of Concrete Surface	pH measurement per NACE SP0308-2008	9 to 9.5	11-12 10-11 (CP)	11-12 7-8 (CP)	11-12	12.5	9- 10	11-12	12-12.5	11-12 7-8 (CP)	11-12				
Structure to Electrolyte Potential (V_{CSE})		-0.252	-0.380	-0.488	-0.220	-0.387	-0.276	-0.248	-0.181	- 0.448 - 0.432 (CP)	-0.226 (middle) -0.230 (right side)				

CP = corrosion product present

Table 2: Concrete Composition based on X-ray Diffraction [1]

Phase	Composition (wt%)													
	Concrete P1	Concrete P2	Concrete P3	Concrete P5	Concrete P6	Concrete P7	Concrete P8	Concrete P10	Concrete PA1	Concrete PA2	Min	Max	Avg	SD
Calcium Oxide (CaO) (Lime)	4	0	4	2	11	13	3	2	2	12	0	13	5.3	4.8
Calcium Carbonate ($CaCO_3$) (Calcite)	37	5	12	53	49	49	32	55	69	39	5	69	40.0	19.7
Silicon Dioxide (SiO_2) (Coesite)	22	8	41	10	37	30	60	32	12	4	4	60	25.6	17.7
Calcium Sulfate ($CaSO_4$)	36	0	0	0	0	0	0	0	7	38	0	38	8.1	15.4
Calcium Sulfate Hydrated ($CaSO_4$•$2H_2O$) (Gypsum)	1	0	16	27	3	8	3	10	10	7	0	27	8.5	8.1
Calcium Hydroxide ($Ca(HO)_2$) (Portlandite)	0	87	27	8	0	0	2	0	0	0	0	87	12.4	27.5

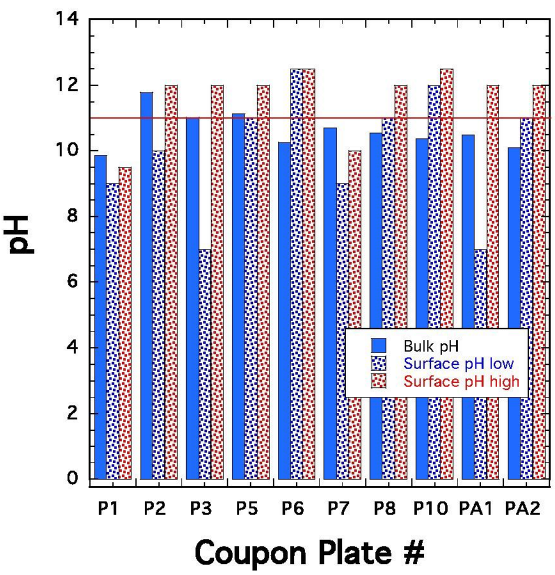


Figure 1: Bulk and surface pH of concrete corresponding to the removed steel coupon plates. Bulk pH data and surface pH from DT Results Report [1].

X-ray diffraction results (Table 2) [1] of the concrete powdered samples showed an average calcium carbonate content of 40.0 wt% with a standard deviation of 19.7%. The large variation in concrete composition (Table 2) could be accentuated by the small sample size. The general trend of increasing calcium carbonate with decreasing calcium hydroxide (Figure 2) was also observed. The origin of the high levels of calcium carbonate is not exactly known, but could be the result of carbonation, where carbonic acid from dissolved CO_2 gas in water reacts with calcium hydroxide in the concrete to form calcium carbonate [5]. This reaction can generally increase the strength of concrete [4, 6], but decrease its alkalinity and adversely affect the corrosion resistance of imbedded steel [4]. The pH measurements coupled with the X-ray diffraction results [1] showed 1) decreasing concrete bulk pH with increasing calcium carbonate (Figure 3) and 2) decreasing concrete bulk pH with decreasing calcium hydroxide content (Figure 4).

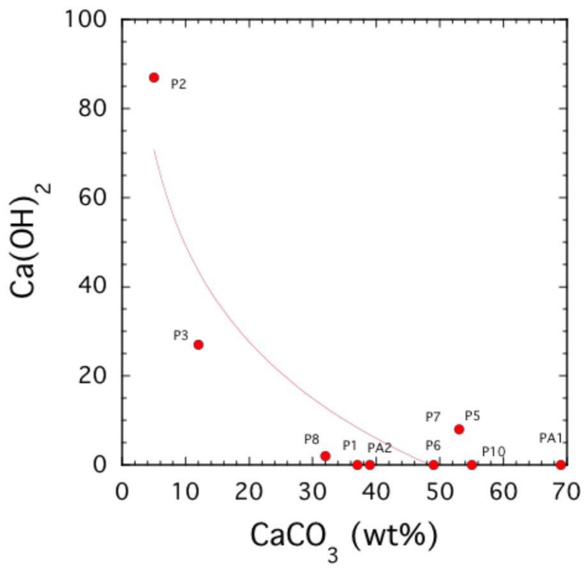


Figure 2: $Ca(OH)_2$ vs $CaCO_3$ content in concrete behind the removed steel coupon plates. $Ca(OH)_2$ and $CaCO_3$ data from the DT Results Report [1].

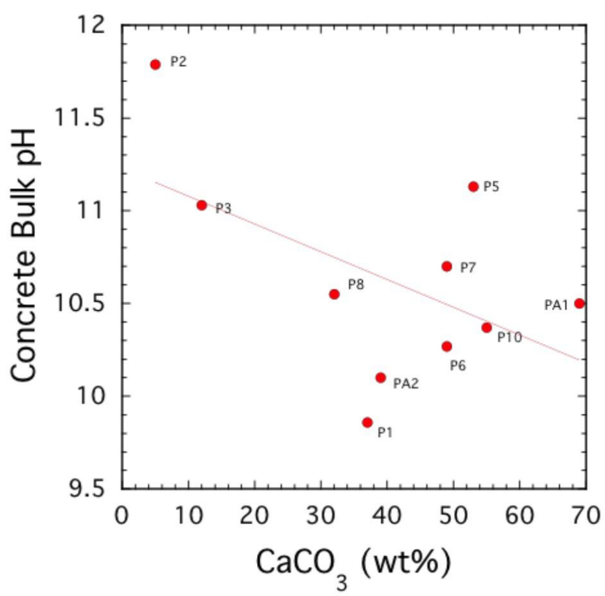


Figure 3: Concrete bulk pH vs $CaCO_3$ content in concrete behind removed steel coupon plates. Bulk pH and $CaCO_3$ data from the DT Results Report [1].

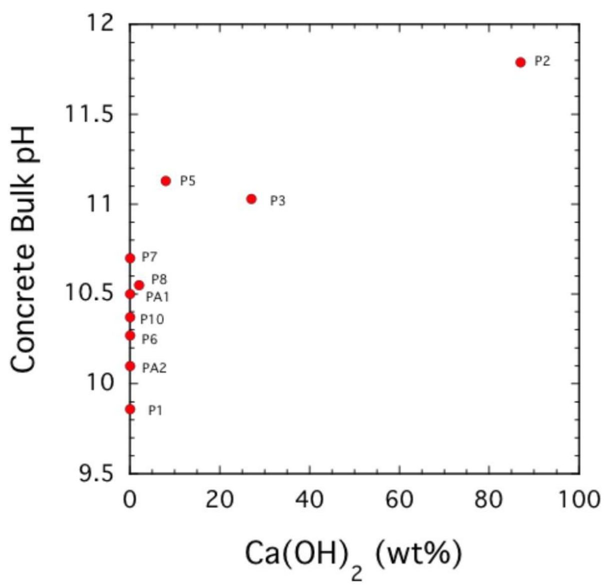


Figure 4: Concrete bulk pH vs $Ca(OH)_2$ content in concrete behind removed steel coupon plates. Bulk pH and $CaCO_3$ data from the DT Results Report [1].

The alkalinity of pore solution in fresh cement and concrete is approximately pH 13 – pH 14 [4]. As the concrete ages, the alkalinity is maintained at the pH 12 - pH 13 level [5] until the calcium hydroxide is consumed by the carbonation reaction. Once the calcium hydroxide is consumed and calcium carbonate precipitates, the pH drops further to levels where imbedded steel can corrode [4, 5]. In non-carbonated, highly alkaline concrete, the corrosion rate of steel is extremely low [4]. When the pH of the concrete falls below approximately pH 11, however, such as by carbonation, corrosion rates begin to increase [7] and passivation is lost at approximately pH 10 [3, 5]. The plot of pH values (Figure 1) shows that many values dropped below pH 11, where plain-carbon steel begins to lose passivity and its corrosion rate begins to increase [3, 5, 7].

3.2 Structure to Electrolyte Potential

The structure-to-electrolyte potential (corrosion potential) measurements also corroborate the possible loss of passivity behind some regions of the tank wall. Based on corrosion potential measurements in concrete, ASTM Standard C876 [8] gives guidelines relating corrosion potential readings of uncoated reinforcing steel rebar and corrosion tendency. The tank plates and uncoated reinforcing steel rebar (referred to in ASTM C876) are carbon steel, although the exact compositions could be different. Hence, the following is only a guideline, but should be applicable. Based on ASTM C876, if the corrosion potential falls within specific ranges, the tendency of corrosion can be determined [8]:

> "If potentials over an area are more positive than −0.20 V CSE, there is a greater than 90 % probability that no reinforcing steel corrosion is occurring in that area at the time of measurement.
>
> If potentials over an area are in the range of −0.20 to −0.35 V CSE, corrosion activity of the reinforcing steel in that area is uncertain.
>
> If potentials over an area are more negative than −0.35 V CSE, there is a greater than 90 % probability that reinforcing steel corrosion is occurring in that area at the time of measurement."

Of the potential measurements corresponding to the back side of the tank wall, only one potential was more positive than -0.2 V_{CSE}, indicating low probability of corrosion; five potentials were in the potential range of -0.20 to -0.35 V_{CSE}, indicating uncertainty of corrosion; and four potentials were more negative than -0.35 V_{CSE}, indicating high likelihood of corrosion. The reported minimum remaining plate thickness values for each plate was plotted vs the corrosion potentials (Figure 5), showing strong correlation. The more negative the corrosion potential (indicating a higher tendency to corrode), the lower the measured remaining plate thickness. Plates P5, P10, and PA2 corresponding to the three most positive corrosion potentials (> -0.23 V_{CSE}) showed no or only very light surface rust (Figure 6) [1]. Plates P1 and P8 (with potentials ≈ -0.25 V_{CSE}) showed mostly mild surface rust (Figure 6) [1]; whereas, the remaining plates PA1, P2, P3, P6, and P7 (with potentials < -0.27 V_{CSE}) showed significantly more severe rusting (Figure 6) [1].

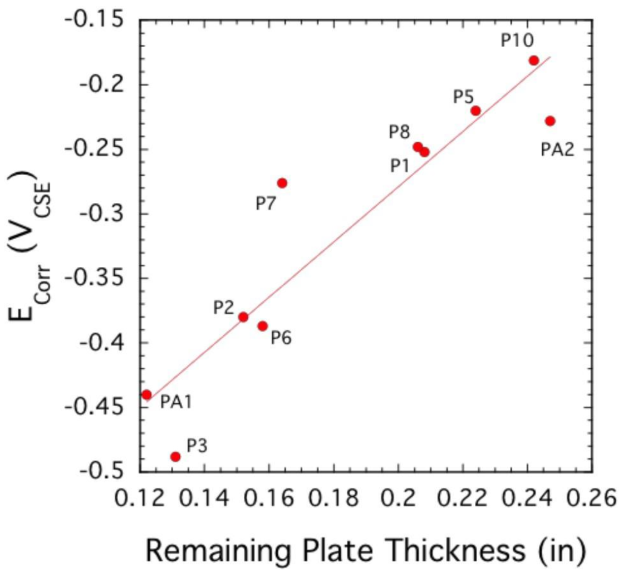


Figure 5: Corrosion potential vs minimum remaining plate thickness. Data summarized from the DT Results Report [1]. Since two corrosion potential values were given for plates A1 (-0.448 V_{CSE} and -0.432 V_{CSE}) and A2 (-0.226 V_{CSE} and -0.230 V_{CSE}), the average value for each plate was plotted.

3.3 <u>Chlorides</u>

Generally, the formation of the visible red-brown rust (Figure 6) on plain-carbon steel indicates that the passivation in that local region has been lost. The gray regions of the plates (excluding the adhering concrete or grout) are regions where the steel is in the passive state (Figure 6). Passivation can be lost when the pH of the concrete drops below approximately pH 11 [7], or chloride (Cl) ions are present in sufficient concentration [4, 7]. The NACE Standard Practice SP0308-2008 [9] indicates that acid-soluble chlorides in excess of approximately 0.2 % (by weight of cement) can initiate corrosion of steel in concrete. The ion chromatography analyses of the concrete powder samples showed that the chloride concentration in the concrete ranged from 50 ppm (0.005 % by weight of cement) to 171 ppm (0.017 wt%), which is much lower than the threshold. The concentration of chlorides detected in the corrosion products using energy dispersive X-ray analyses (EDXA), however, was significantly higher: The maximum value of 1.7 wt% (17,000 ppm by weight of corrosion product) was detected in the corrosion product of plate PA1; 0.6 wt% (6,000 ppm) in plates P2 and P7; 0.3 wt% (3,000 ppm) in plates P3, P5, P6, and P10; and none in plates P1, P8, and PA2. The detection limit of EDXA is on the order of 0.1 wt% (1,000 ppm). The maximum concentration of the chlorides in the corrosion products were up to approximately 100 times higher than the maximum concentration in the concrete. Chlorides at these levels as well as the drop in concrete alkalinity below approximately pH 11 are likely to breakdown passivation and cause increasing corrosion rates of the steel.

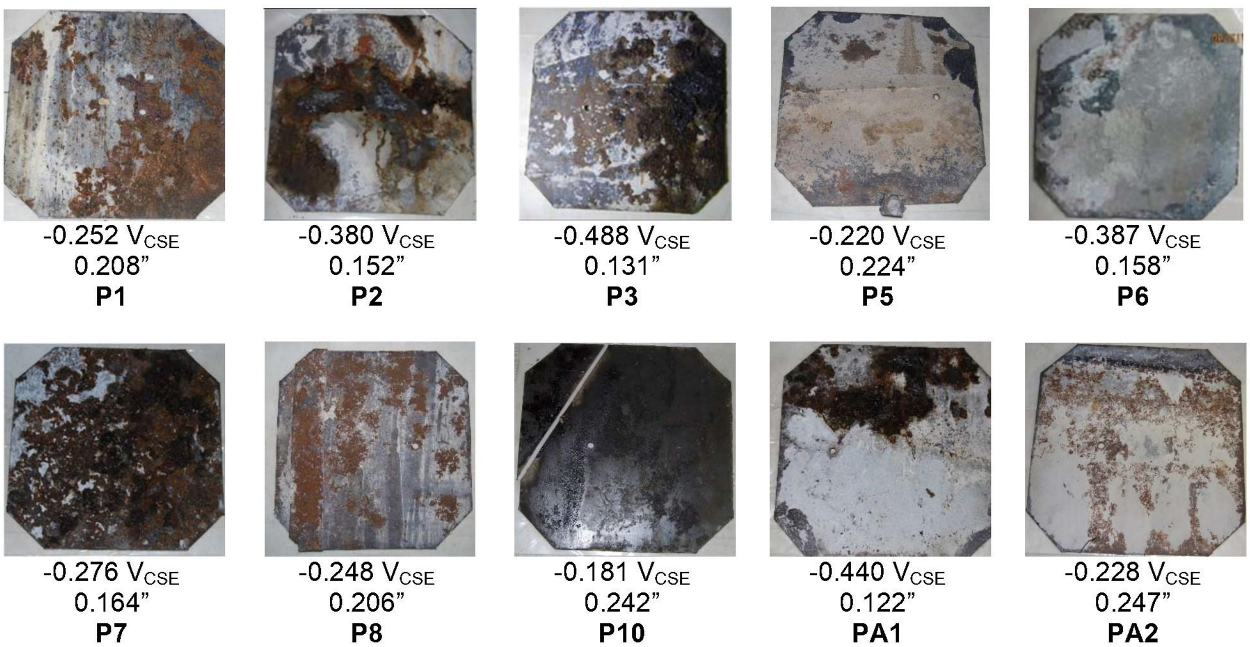


Figure 6: The back side of the steel coupons, structure-to-electrolyte corrosion potentials (in V_{CSE}), and the minimum remaining thickness (in inches) that was measured for each plate. From DT Results Report [1]

3.4 Corrosion Rate

When steel corrodes in concrete, there is an initiation phase and a propagation phase (Figure 7) [4]. During the initiation phase, the steel is passive and corrodes at a very low rate. When the concrete becomes carbonated or contaminated with chlorides, the steel loses passivity and corrosion rates begin to increase in the propagation phase (Figure 7). In Figure 6, regions of the coupons that were bonded to the concrete or grout and not corroded (e.g., gray regions) were still in the initiation phase (Figure 7) and have a very low passive corrosion rate. Regions that show rust (e.g., red or brown corrosion products) are in the propagation phase and have higher active corrosion rates. Unfortunately, knowledge of the active corrosion rate cannot be used to determine the total service life or time before penetration as the initiation phase can dominate the service life (Figure 7 and 8a) [10]. However, if the remaining wall thickness and the active corrosion rate are known, the remaining time before wall penetration can be estimated (Figure 8b).

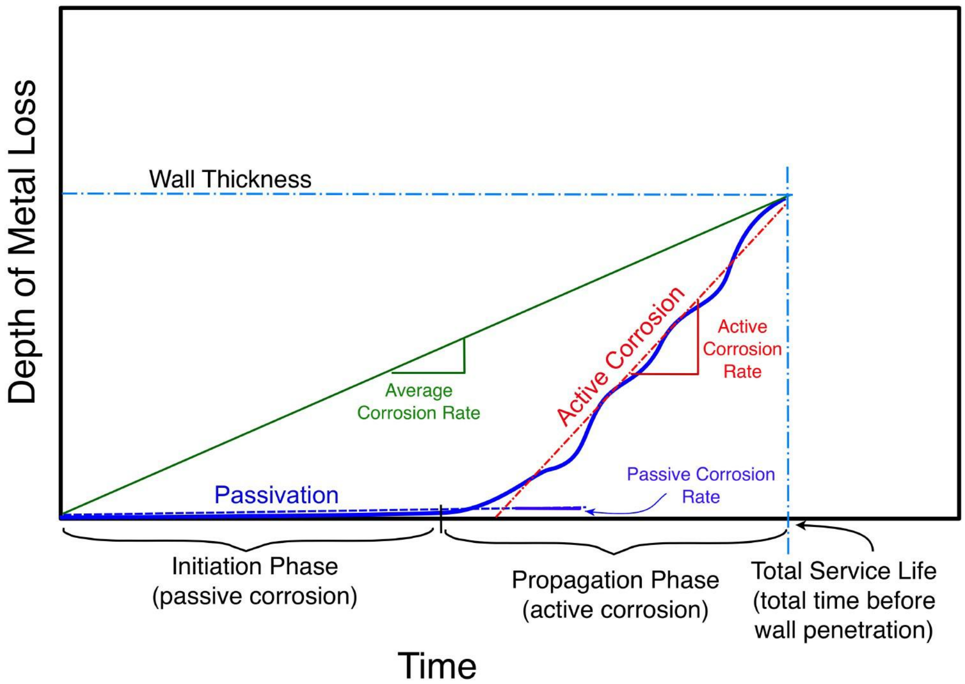
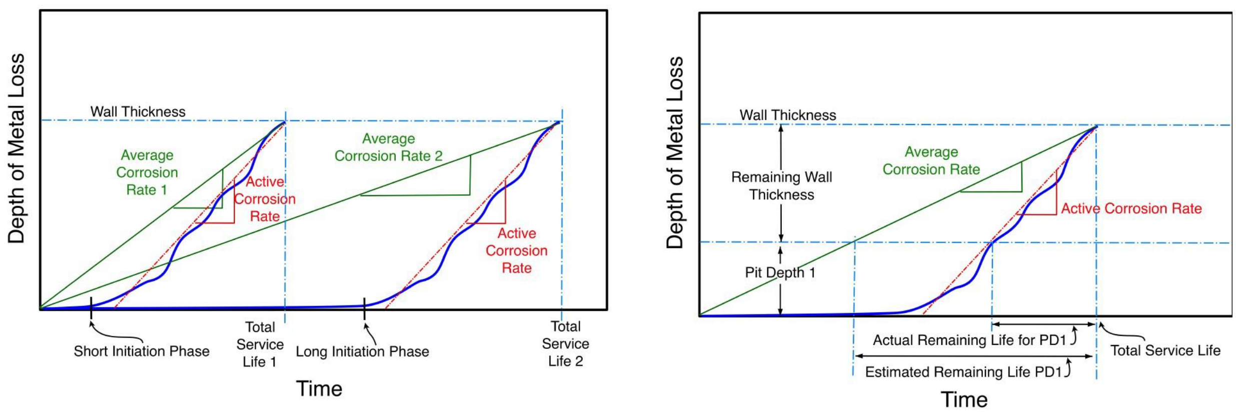


Figure 7: Initiation and propagation phases of steel corrosion in concrete. Modeled after Tuutti [10] in [4].



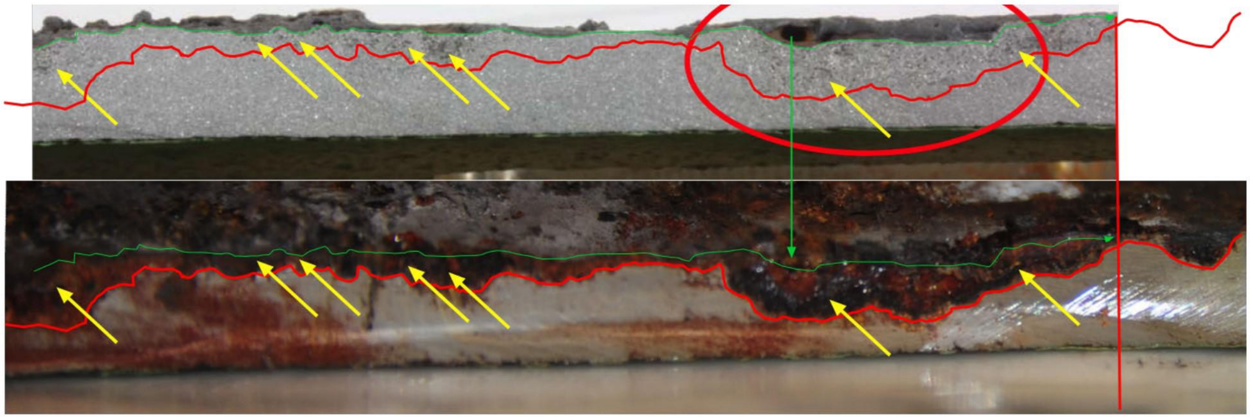
(a)

(b)

Figure 8: Effect of initiation phase on average corrosion rates (a). Remaining life (b) based on active and average corrosion rates and pit depth 1 (PD1).

The electrolyte in the corrosion product at the corrosion front can become very corrosive due to acidification and accumulation of chlorides. This may have been observed on the cut edge of coupon plate P7 [11]. A photograph of the cut edge of plate P7 was taken on June 25, 2018 (bottom photo in Fig. 9a), approximately one week after coupon plate P7 was cut and removed from Tank 14. The image showed what was initially thought to be significant corrosion (dark brown rust) penetration into the thickness of the plate. To verify if the corrosion had actually penetrated into the plate, the edge of the specimen was cleaned by sandblasting [11] (approximately in March 2019, or six months after the coupon was extracted). The photo of the cleaned edge of coupon plate P7 was compared (Figure 9) to the photo of the un-cleaned edge. The demarcation between the cleaned steel plate and the free surface was highlighted with a thin green line (Figure 9a top), and the demarcation between the shiny cut edge of the corroded un-cleaned plate and the apparent corroded regions were highlighted with a thicker red line (Figure 9a bottom). Both lines were superposed on the cleaned and uncleaned plates (Figure 9a). The darker corroded regions on the edge of the uncleaned plate (Figure 9a bottom) corresponded to the areas that appeared to be porous (yellow arrows) on the cleaned plate (Figure 9a top and Figure 9b). The apparent porosity (Figure 9a top and Figure 9b) could be due to corrosion caused by corrosive electrolyte that leached out of the corrosion products onto the cut edge. Some of the pores appeared to be on the order of 5 to 10 mils in width (Figure 9b). If it is assumed that the pits are as deep as they are wide, the rate of corrosion would be on the order of (5 to 10 mils)/6 months or 10 to 20 mils/yr, which is much higher than passive corrosion rates. It is also recommended that the surface porosity be further investigated to verify whether the region is only superficially pitted or is actually porous.

For moist concrete that is carbonated or contaminated by chlorides, the literature suggests that the corrosion rate can be of the order of 100 μm/yr (4 mils/yr) [4]. The corrosion rate can be less if the moisture level decreases, but can also increase by an order of magnitude with heavy chloride contamination [4]. Since the corrosion rates are difficult to predict, historical corrosion data from all of the Red Hill tanks should be analyzed to help bracket realistic values. Additionally, if possible, active corrosion rates should be determined by measuring changes in the remaining wall thicknesses of known pit sites while tanks are out of service. This could be accomplished using, for example, ultrasonic testing.



(a)

(b)

Figure 9: Optical images (a) of cleaned (top) and uncleaned (bottom) edge of coupon plate P7. Magnified view (b) of the cleaned edge of coupon plate P7 showing pitted surface. Wavy red and green lines, yellow arrows, and 10 and 20 mils scale bars were superposed on original photos of the cleaned edge [11].

The higher historical corrosion rates could be associated with short initiation phases (Figure 8a) from regions where steel lost passivation in the early stages. Regions where the steel remain passivated and have long initiation phases (Figure 8a) will result in low average corrosion rates. Currently, any region of the tank that has back-side corrosion (i.e., rusting and remaining thickness less than the original plate thickness of 0.25") is likely not passivated, and in the propagation stage (Figure 7). To obtain an accurate remaining life before wall penetration, realistic corrosion rates are needed. Therefore, in regions of the tank that are no longer passivated, actual measured active corrosion rates or historical corrosion rate data with a short initiation phases (Figure 8a) are needed to more accurately estimate the remaining life

(Figure 8b). If corrosion rates based on long initiation phases are used, the actual remaining life could be grossly over estimated (Figure 8b).

3.5 Other Ions, Source of Moisture, and Delamination

Although chlorides can become concentrated in anodic regions that are actively corroding, the high chlorides levels in the corrosion products may not have only originated from the concrete. The ion chromatography analyses of the concrete also showed relatively high levels of nitrite and nitrates in the concrete behind plates P1 (nitrite 282 ppm; 273 nitrate ppm) and P2 (nitrite 595 ppm; 535 nitrate ppm); whereas, the maximum corresponding to the remaining plates are 26 ppm for nitrite and only 15 ppm for the nitrates. Nitrites and nitrates can originate from fertilizer or decaying vegetation and animal residue [12]. Dissolved carbon dioxide in water is also a byproduct of bacterial oxidation of organic matter and often found in water percolating through soils [12]. The concentration of dissolved CO_2 in ground water can be relatively high since it cannot escape to the atmosphere. Dissolved CO_2 can result in carbonic acid formation which could induce carbonation of the concrete. There is a possibility that rainwater maybe percolating through the soil above the tanks, carrying nitrites and nitrates as well as chlorides. The following is an excerpt from "U.S. Naval Base, Pearl Harbor, Red Hill Underground Fuel Storage System (Red Hill Pumphouse, Tanks, Tunnels, Adits, and Ventilation Structures), HAER No. HI-123" [13]:

> "….removal of the tell-tales eliminated a way to drain off any rainwater that percolates down through the lava rock and finds its way into the space between the back side of the steel shell plates and the inner side of the concrete wall. The standing water could cause accelerated corrosion of the back side of the steel shell plate." [13]

Concrete and loose grout were found at the steel interface behind coupon plate P6 (Figure 10). The description of the initial tank construction, however, describes that grout was injected between the outer Gunite layer and reinforced concrete (p. 2 of reference [14]), but not between the reinforced concrete and tank steel wall:

> "If no gross leaks were identified, the barrel was prestressed by injecting grout between the reinforced concrete and Gunite layer. Grout was injected via tubes that penetrated the steel liner and extended through the concrete to the Gunite layer." [14]

Apparently [15], however, pressurized grout may have also been injected into crevices that formed between the steel plates and the reinforced concrete that shrank during hardening causing the concrete to pull away from the tank walls:

> "- Finally, you had the vault complete - a steel shell as tall as a twenty-five-story building, as large around as a house lot - backed by many feet of solid concrete butting tight against the rock. As the concrete hardened, it shrank slightly away from the steel. Into this space grout under heavy pressure was forced through pipes welded into the plates. This filled in every remaining crevice and pushed inward against the steel with a pressure equal to the outward thrust expected from the oil." [15]

Since the grout was pressurized to 350 psi, it could have likely found its way to the steel-concrete interface from the concrete-Gunite interface through any crevice or crack that may have formed. In one case, grout was found as far as 200 ft away from the tanks in an upper access tunnel [13]. The description of the tell-tale system, also indicates that crevices could exist between the tank wall and concrete layer [13]:

> "In this way, the tell-tales pipes were designed to collect any fuel that leaked through a hole in a shell plate (or through a hole in a shell-plate weld) into the tiny space between the back side of the steel shell plates and the inner side of the reinforced concrete wall." [13]

Figure 10: Loose grout behind coupon plate P6. From DT Results Report [1].

Also, when steel corrodes, the volume of rust that forms occupies much more space than the volume of steel corroded [5]; hence, the expanding rust can also de-bond the steel plate from the concrete and grout. This can create a wedging effect that can propagate the de-bonding between the steel plate and concrete, and initiate corrosion down the sides of the tank if moisture is present. The results of the field analyses [1] showed that voids between the steel plates and the concrete/grout structure ranged in gap size from $^{1}/_{16}$" to ½" for nine of the ten steel coupon sites. The presence of moisture [1] was also noted on the back side of the steel coupons or the concrete structure for six of the ten coupon locations. The results from the DT Results Report [1] show that the steel was rusting and had lost passivation on 7 of the 10 coupons removed.

3.6 Correlation between Nondestructive Evaluation (NDE) and DT Results

The DT Results Report (p. 61 in DT Results Report) [1] also clarified that the location of the maximum corrosion pit depth was not necessarily recorded with high accuracy:

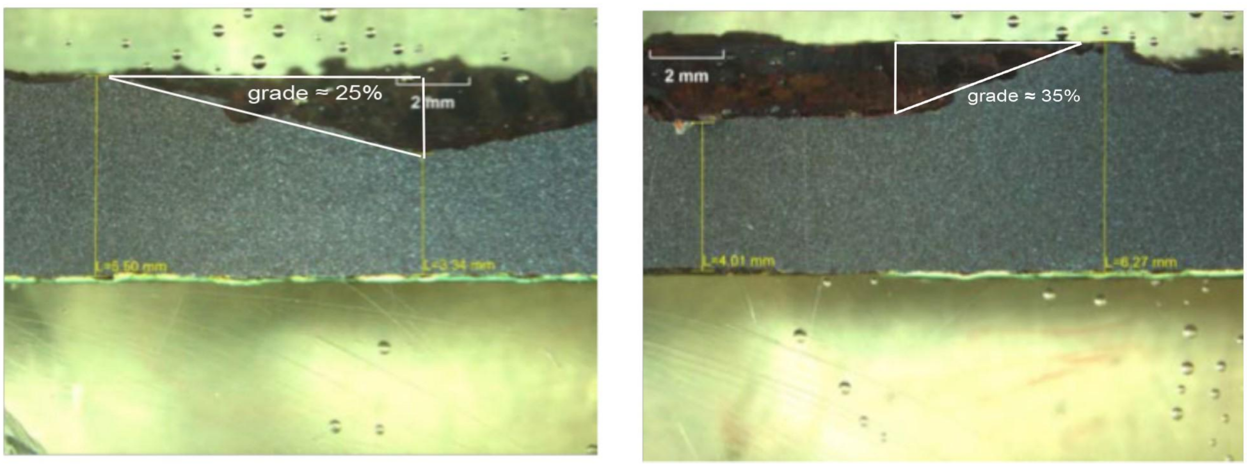
> "This objective does not require or justify the need to record the exact location and depth of every pit or thinned area so long as the damage is properly repaired. As a result, no attempt was made to assess the minute accuracy of the locational coordinates of pits or areas of wall thinning. For this reason, it should not be expected that the maximum pit depth was recorded for any given area." [1]

Hence, this may have contributed to the less than definitive agreement between NDE results and the destructive testing results. Of the 10 coupons taken from Tank 14, four coupons measured minimum thicknesses that triggered differing repair actions than recommended based on the NDE data. Two of the four coupons (i.e., coupon plates P3 and P6) were not recommended for repairs based on the NDE data, but based on laboratory measurements, repairs should have been required.

For coupon plates P3 and P6, a remaining thickness less than 0.200" was not expected (pp. 46 and 51 of DT Results Report [1]); however, the destructive testing showed minimum remaining thicknesses of 0.131" and 0.158", respectively, for coupon plates P3 and P6. The pit size and grade (Figure 11) were well within the detectable limits of the low frequency electromagnetic technique (LFET) [16], but these pits were not recorded. The DT Results Report [1] also showed that the there were high levels of magnetite in the corrosion products ranging from 17 % to 84 wt% (Table 3). It has been reported in the literature [17] that when magnetite deposits are encountered in Type 304 stainless steel tubes, the LFET signal decreases indicating additional metal. When tube wall loss is encountered, the LFET signal increases. Hence, it should be further investigated if the high content of magnetite in the corrosion products behind the steel plates could also affect the LFET signals and interpretation of remaining plate thickness.

Table 3: Corrosion Product Composition based on X-ray Diffraction [1]

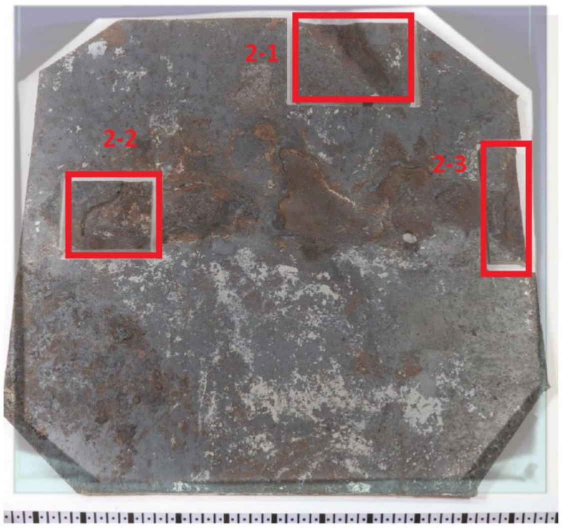
Phase	Coupon Plate #					
	P1	P2	P3	P6	P7	P8
Iron Oxide (Fe_3O_4) [Magnetite]*	60 (±0.3)	57 (±0.4)	48 (±1.1)	50 (±4.6)	84(±1.5)	17 (±0.3)
Iron Hydroxide ($FeHO_2$)	40 (±1.2)	34 (±0.6)	46 (±1.2)	33 (±1.3)	16(±0.7)	71 (±1.0)
Calcium Carbonate ($CaCO_3$)	ND	6 (±0.5)	6 (±0.6)	ND	ND	ND
Silicon Dioxide (SiO_2)	ND	3 (±0.3)	ND	4 (±0.9)	ND	12 (±1.1)
Hydrous Calcium Aluminum Sulfate ($Ca_6Al_2(SO_4)_3(OH)_{12}$ 26 H_2O)	ND	ND	ND	13 (±1.7)	ND	ND
Values in relative weight percent						
ND=Not Detected						
* - In the original Table 19 and Table 20 of the DT Results Report [2], the Iron Oxide was labeled as Fe_3O_2, which is likely in error as the XRD spectra in Figures 123 - 128 correctly labeled the iron oxide as Magnetite Fe_3O_4.						



(a) (b)

Figure 11: Cross section of coupon plate P3 (a) at the area of maximum wall loss (p. 18 of DT Results Report [1]) out of four sections examined, and cross section of coupon plate P6 (b) at area of maximum wall loss out of three sections examined (p. 24 of DT Results Report [1])

There are also concerns of whether or not the sites with the deepest pits were sampled during the destructive testing. The steel coupons were specified to be cleaned and subjected to three-dimensional profilometry (as specified on p. 8 of the DT Results Report, [1]) to document the surface profile of the remaining steel substrate. The steel coupons were cleaned with a CO_2 dry ice blast, but all of the corrosion products were not removed; hence, the regions of the deepest pits would be difficult to determine. The three-dimensional profilometry data was not provided in the DT Results Report [1], but the results would likely not have characterized the bare steel substrate since the corrosion products were not thoroughly removed. X-ray computed tomography (CT) was used to aid in selecting the regions with the deepest pits, but in some cases, regions with potential deep pits were apparently not sampled (e.g., Figures 12, 13, and 14). The DT Results Report [1] did not describe if other methods were used to confirm the location of the deepest pits.



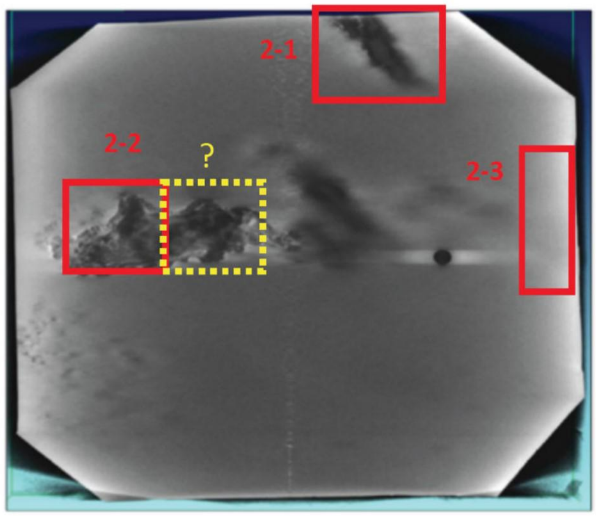
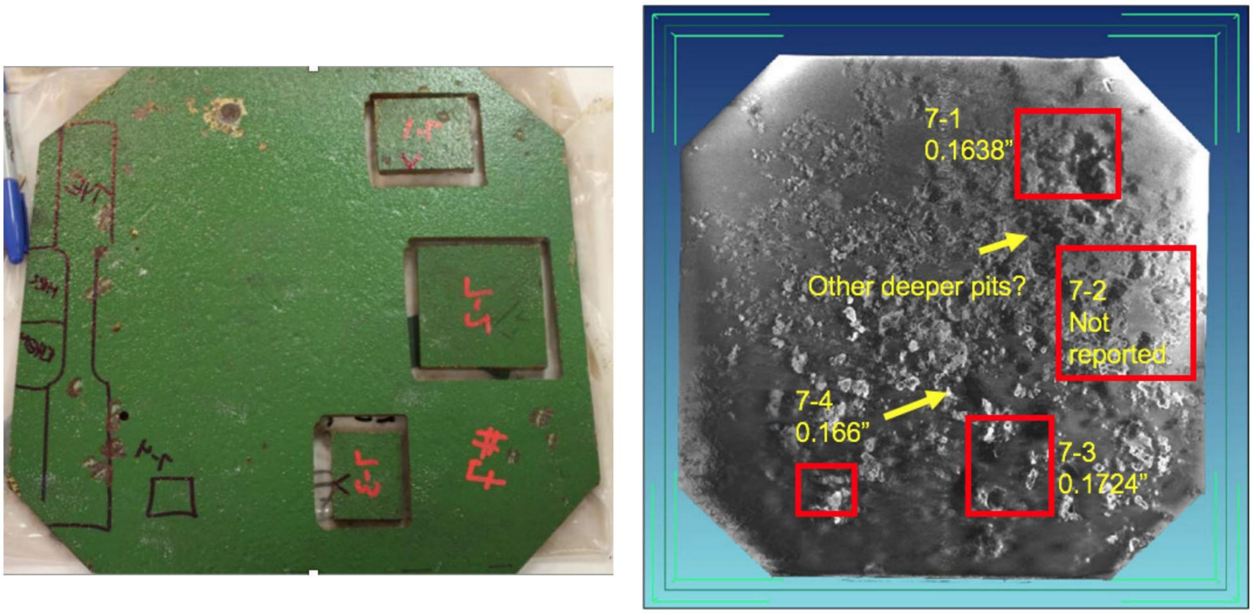
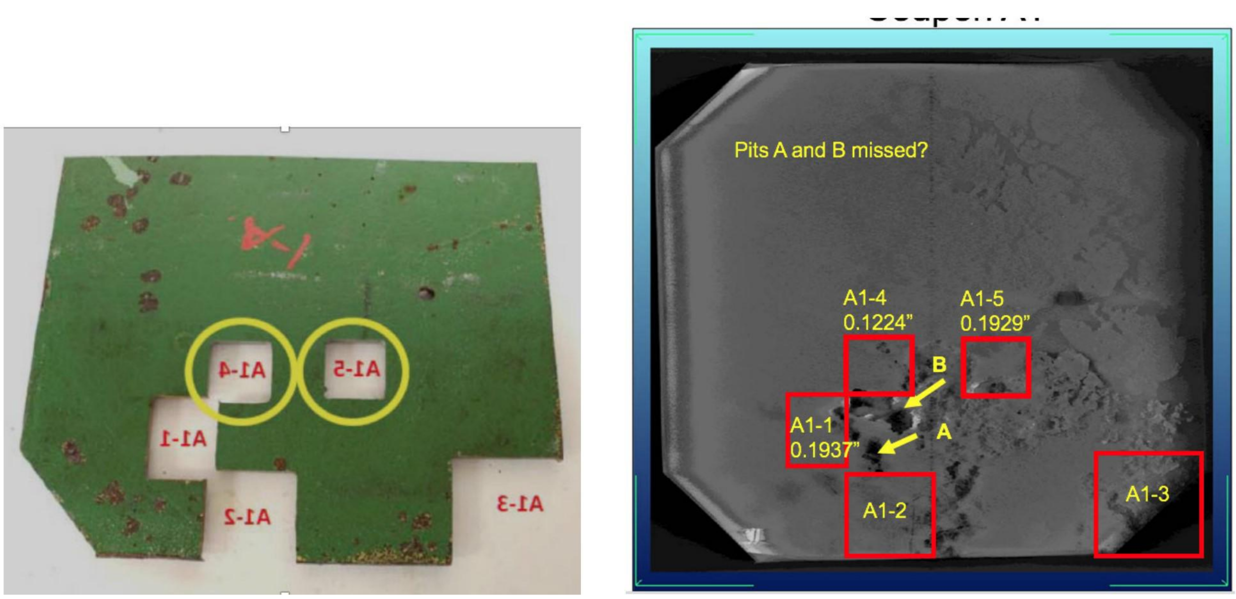


Figure 12: Coupon plate P2. Possible deep pit in yellow box region not sampled. Original images from DT Results Report [1].



(a) (b)

Figure 13: Coupon plate P7. Possible deep pits in region of yellow arrows not sampled. Original images from DT Results Report [1].



(a) (b)

Figure 14: Coupon plate PA1. Possible deep pits in region of yellow arrows not sampled. Original images from DT Results Report [1].

4 Conclusions

The presence of carbonation was indicated by increasing calcium carbonate and decreasing calcium hydroxide levels in the concrete with concomitant decreasing concrete pH levels. In seven of the ten concrete samples, the bulk pH values ranged from 9.86 – 10.65, and only three plates had bulk pH values above 11. The DT Results Report [1] indicated that the pH values of some of the concrete samples could have been affected by corrosion products; hence, due to the importance of accurate pH readings, it is recommended to perform a thorough concrete pH study to eliminate the possibility of contamination. The pH levels of fresh cement and concrete reside between ≈13 and ≈14. The corrosion rates of plain-carbon steel begin to increase when the pH drops below ≈11, and passivity is lost when the pH drops below ≈10. The presence of chlorides was detected in the corrosion pits of the steel coupons. Both carbonation and the presence of chlorides can depassivate steel in concrete, causing steel to corrode actively. The loss of passivation of the steel was corroborated visually and with the measurement of corrosion potentials. Seven of the 10 plates clearly showed significant corrosion products or metal loss indicating active corrosion. Of the ten corrosion potential measurements corresponding to the back side of the tank wall, only one potential was more positive than -0.2 V_{CSE}, indicating low probability of corrosion; five potentials were in the potential range of -0.20 to -0.35 V_{CSE}, indicating uncertainty of corrosion; and four potentials were more negative than -0.35 V_{CSE}, indicating high likelihood of corrosion. The nitrate and nitrite contamination in the concrete, chlorides in the concrete and corrosion products, and moisture (behind seven of the ten plates) indicate that water (e.g., possibly rainwater) may be percolating through the soils above the tank. It is recommended that the possibility of rainwater percolation above the tanks and the composition of such water be further studied.

To obtain an accurate estimate of remaining tank life, both reliable active corrosion rate and remaining wall thickness are needed. The actual active corrosion rates of the steel plates are very difficult to estimate from historical corrosion rate data due to the initiation phase when the steel is passive. The average corrosion rate based on historical corrosion rates calculated by dividing the time to penetration by the age of the tank will only accurately estimate the active corrosion rate if the initiation phase was very short. Hence, historical corrosion rate data for the earliest of failures should tend to be more accurate in estimating the active corrosion rate. If possible, the remaining wall thickness of known pits sites should be monitored in out-of-service tanks to determine actual active corrosion rates. The corrosion (having the appearance of porosity) on the cut edge of coupon plate P7 by corrosive electrolyte that leached out of the corrosion product gave an indication that the corrosion rate could have been on the order of

10-to-20 mils/year over the six-month period after the coupon was extracted from the tank. However, it is not proven whether this rate is applicable to corrosion of undisturbed plate in the tank structure. For moist concrete that is carbonated or contaminated by chlorides, the literature suggests that the corrosion rate can be of the order of 4 mils/yr. The corrosion rate can be less if the moisture level decreases, but can also increase by an order of magnitude with heavy chloride contamination. Further study is needed to bracket realistic active corrosion rates. Coupon plate P7 should also be re-examined to clarify whether the porosity was superficial or through the thickness.

The accuracy of the remaining wall thickness by the NDE was not adequately corroborated with the destructive test results. First, the DT Results Report [1] stated that the deepest pit within the sample regions was not necessarily measured or recorded. In some cases, pits that should have been detected by the LFET were not reported. It is not clear if this was due to procedure, human error, or deficiency of the technique. The DT Results report [1] indicated that a large fraction of the corrosion products were comprised of magnetite, which has been reported in the literature to affect LFET signals in stainless steel tubes. The corrosion products from the extracted coupons were also not completely removed, preventing the identification of the deepest pits using three-dimensional profilometery. The location of the deepest pits were estimated visually and using CT imaging. However, based on the CT images, some regions that appeared to have deep pits were not sampled. It is recommended that 1) the effect of magnetite on the interpretation of the LFET signal be further studied to determine if its presence can attenuate metal loss readings, and 2) the corroded coupons be thoroughly cleaning to verify whether or not the deepest pits were measured.

In short, the evidence of carbonation of the concrete, presence of chlorides in the corrosion products, and structure-to-electrolyte corrosion potential readings all corroborate that regions of the tank were actively corroding. The comparison of the NDE and DT results did not definitively show the expected correlations, which may have been due to procedure, human error, or deficiency of technique. Better estimate of the corrosion rate and remaining wall thickness are needed to be able to determine the appropriate extent of repair and inspection intervals to reduce the risk of leakage.

5 References

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BOARD OF WATER SUPPLY

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October 7, 2019

Mr. Omer Shalev
EPA Red Hill Project Coordinator
United States Environmental Protection Agency
Region IX
75 Hawthorne Street
San Francisco, California 94105

and

Ms. Roxanne Kwan
Solid and Hazardous Waste Branch
State of Hawaii
Department of Health
2827 Waimano Home Road
Pearl City, Hawaii 96782

Dear Mr. Shalev and Ms. Kwan:

Subject: Honolulu Board of Water Supply Comments on Navy's "AOC SOW Section 5 Corrosion and Metal Fatigue Practices, Destructive Testing Results Report" dated July 7, 2019 and IMR's Report "Destructive Analysis of 10 Steel Coupons Removed from Red Hill Fuel Storage Tank #14" dated December 17, 2018

The Honolulu Board of Water Supply (BWS) offers the following comments on above-referenced reports. In accordance with the requirements of the Administrative Order on Consent (AOC) Statement of Work (SOW), the Navy commissioned destructive testing (DT) on Red Hill Bulk Fuel Storage Facility (RHBFSF) Tank 14. The testing included removal of ten steel liner samples (commonly referred to as "coupons") with "the primary aim of validating" non-destructive examination (NDE) results through third party laboratory testing (Navy, 2019a). IMR Test Labs (IMR) performed the DT and issued a report on December 17, 2018 (IMR, 2018), which it revised and resubmitted on June 3, 2019 as Revision 2 (IMR, 2019). The Naval Facilities Engineering Command (NAVFAC) issued a summary DT report on July 1, 2019 that included the IMR Report Revision 2 as an appendix. In this letter you will find our general remarks followed by detailed comments addressing these documents.

Please note that BWS has submitted letters to the United States Environmental Protection Agency (EPA) and Hawaii Department of Health (DOH) (collectively, "Regulatory Agencies") in the past that commented on other deliverables submitted by the Navy under RHBFSF AOC Section 5 (Lau, 2017a; Lau, 2017b; Lau, 2017c; Lau, 2017d; Lau, 2017e; Lau, 2017f; Lau, 2017g; Lau, 2017h; Lau, 2018a; Lau, 2018b; Lau, 2019a; and Lau 2019b). We are referencing these past letters as they provide context and historical perspective to our comments contained herein.

General Comments on NDE and DT

The BWS has reviewed the IMR reports (IMR, 2018; and IMR, 2019) and the Navy's DT report (Navy, 2019a) describing IMR's laboratory testing, and has itself evaluated how the DT findings compare with results of *in situ* NDE testing prior to coupon removal. This comparison is critical because backside corrosion represents a significant leak hazard in single-walled underground storage tanks with steel liners. Inspection methods to detect backside corrosion must be accurate and reliable to ensure that all locations of deep corrosion that could progress to through-wall are identified and repaired. In larger tanks such as those at the RHBFSF, more area must be checked for corrosion and, therefore, higher inspection accuracy and reliability is required to achieve the same assurance that no areas of significant corrosion will be missed. The Navy's current inspection and repair process depends on its ability to reliably detect backside corrosion-thinned areas using NDE from the inside face of the liner. The BWS has expressed, and continues to express, concerns about the Navy's ability to accurately and reliably find and repair these locations. Nothing in the IMR reports or the Navy's DT report alleviates the BWS' concerns regarding the accuracy and reliability of the Navy's NDE practices.

Moisture trapped between the outside face of the RHBFSF underground storage tanks' steel liner and concrete shell causes corrosion to form on the backside of the liner, and that corrosion progresses inward with time. Because this concealed corrosion can be neither directly observed nor prevented, the Navy's maintenance of the RHBFSF tanks is instead reliant upon being able to detect this corrosion damage indirectly using NDE methods and weld new plates over the compromised portions of the liner before the corrosion can grow through the tank wall. The nature of the RHBFSF tanks' construction and the fact that these single walled, underground tanks have already suffered and will continue to be subjected to ongoing corrosion damage amplify the importance of reliable NDE in light of the following:

- Corrosion is progressing from the backside of the steel liners, which cannot be visually inspected;
- RHBFSF tanks' 75-year-old steel liners have no corrosion protection on the backside surface; in certain locations the steel is adhered to the surrounding concrete and in other locations there are documented gaps where water can collect;
- RHBFSF tanks' ¼-inch steel liners have previously experienced through-wall penetration by corrosion; and,
- RHBFSF tanks' steel liners are the sole barriers against fuel escaping into the environment, as it has been demonstrated during previous leak events that the surrounding concrete cannot provide reliable secondary containment.

The Navy's NDE and DT direct comparison work has confirmed the BWS' concern that the Navy cannot reliably and accurately find all areas of tank wall thinning that need repair. Not only has the Navy failed to establish that its NDE techniques are sufficiently reliable, its own laboratory testing proves that the scanning is inaccurate. For instance, four of the ten coupons were determined by DT to have been thinned by corrosion to the point that repair is required (i.e., a remaining wall thickness of less than 0.160 inches) but the Navy's NDE prior to coupon removal only identified two of these locations as needing repair. In addition, the Navy's NDE identified three areas for repair which, in fact, did not need repair based on the DT results. These misidentified areas demonstrate the inaccuracy of the Navy's NDE process. Statistical analysis of the NDE versus DT results further demonstrates the extent to which the Navy is likely to miss locations in the RHBFSF tanks that should be repaired. The increased risk of fuel release associated with not properly identifying locations of significant backside corrosion has not been acknowledged by the Navy and, consequently, is not being adequately addressed.

A brief summary of BWS' more detailed findings regarding the Navy's NDE and DT efforts as part of Section 5 of the AOC process are as follows:

- Data and analysis indicate that both NDE techniques used to find areas of the RHBFSF tanks in need of repair are highly unreliable;
- The Navy has not sufficiently evaluated the Balanced-Field Electromagnetic Testing (BFET) technique specifically used for weld inspection;
- Data and analysis did not provide adequate information regarding the condition of the surrounding concrete, the condition of the reinforcing steel in the concrete, or the ability of the surrounding concrete to contain fuel leaked through the liner; and
- Data and analysis did not provide any reliable information regarding the corrosion rate that is used to determine the threshold minimum thickness for steel liner repair.

The Navy's DT work under AOC Section 5 reinforces the BWS' belief that the only reliable way to prevent fuel from entering the environment at the RHBFSF is to adopt a tank upgrade alternative (TUA) that either moves the RHBFSF tanks to a location not over our sole-source aquifer or upgrades them with secondary containment.

<u>Background on The Navy's NDE Validation Plan</u>

The Navy uses multiple NDE techniques that are designed to inspect 100% of the ¼-inch thick steel liners in the tanks. The Navy relies on the techniques to identify flaws or deterioration (corrosion-induced plate thinning, weld defects, cracks, gouges, etc.) that could grow into through-wall defects within 20 years, which would be the next scheduled inspection. The first technique used is Low Frequency Electromagnetic Technique (LFET), which is the initial step to determine the presence of backside corrosion (both general wall-thinning and pitting corrosion). LFET is used to scan the entire inside surface of each tank (the Navy's designated "screening" step). The second technique used is Phased Array Ultrasonic Testing (PAUT), which provides spot-checks to the areas identified during the screening step (the Navy's designated "prove-up" step).The Navy has set the action limit for corrosion repair at 0.09-inch corrosion or defect depth, corresponding to 0.160 inches of remaining steel liner thickness of the original (nominal) 0.25-inch thickness. If the prove-up step does not agree with the screening step, the Navy relies on the prove-up data since it is allegedly more accurate. In contrast and more concerning is that areas that are not identified as problematic during the screening step are not subject to any further evaluation. Therefore, if the screening step misses an area, the prove-up step is never performed.

In order to validate the accuracy and reliability of the various NDE techniques, and in accordance with AOC SOW Section 5.3, the Navy needed to perform destructive testing in at least one of the RHBFSF tanks:

> ***"5.3 Destructive Testing***
> *The purpose of the deliverables to be developed and work to be performed under this Section is to verify the findings of the Corrosion and Metal Fatigue Practices Report through the use of destructive testing on at least one tank at the Facility."* (AOC SOW, 2015)

The Navy ultimately performed the DT on Tank 14 by removing ten approximately one-square-foot areas (coupons) cut from the ¼-inch tank liner. These coupons were then sent to IMR, the laboratory the Navy used to characterize the depth of corrosion and flaws found by the Navy's NDE inspectors. This analysis is described as DT because the coupons need to be cut up in order to expose the minimum remaining wall in the plate.

Because the validity of the NDE verification process is dependent upon the methods used to select the specific tank and the portions thereof tested, it is critical to understand how the Navy approached this process. The following is a summary of the Navy's statements and discussions leading up to the selection of these ten coupons.

<u>**The Navy's 2016 DT SOW Drafts**</u>

In 2016, the Navy prepared at least two drafts of its DT SOW for discussion purposes, one on September 9, 2016 (Navy, 2016a) and another on December 23, 2016 (Navy, 2016c). The final DT SOW was issued on May 30, 2017 (Navy, 2017a).

In the September 9, 2016 DT SOW draft for discussion, it was stated that:

> *"Removal of 5 coupons is planned. Locations for selection of coupons for testing will be based on data from previous visual and NDE inspections of the tanks for selection of target areas based on reported reductions in wall thickness, corrosion, and cracking."* (Navy, 2016a)

The locations for the five proposed coupons were generally as follows: (a) one from the upper dome; (b) two from the barrel (i.e., the tank vertical walls); (c) one from the lower dome sloped area; and (d) one from the lower dome bottom plate. Further, at this time in 2016, Tank 17 was the Navy's proposed tank.

In the December 23, 2016 DT SOW draft for discussion, more details were provided regarding the Navy's plan. The Navy specifically started defining the goals and desired outcomes:

- ***Validate the results of Non-destructive examination (NDE) inspection technologies***
- *Characterize steel material*
- *Record observations/chemical characteristics of the concrete behind the liner*
- *Analyze corrosion rate calculation procedures and recommend improvements as warranted*
- *Evaluate results against current corrosion mitigation practices and recommendations for modifications/improvements to tank inspection, repair, and maintenance (TIRM) procedures and tank upgrade alternatives (TUA).* (Navy, 2016c) (emphasis added).

However, later in the document, it was stated that:

> *"As previously indicated, the **Navy desires to minimize the amount of destructive testing** on operational fuel storage tanks required to meet the requirements of the AOC."* (Navy, 2016c) (emphasis added).

To be consistent with both the letter and spirit of the AOC, the goal of the DT work should not have been to minimize the amount of testing, but rather to definitively determine whether the Navy's NDE methods are accurate and reliable for the damage mechanisms that it is assessing. If the Navy did not feel confident that it could achieve that with an operational tank, it should have pursued other options. Nevertheless, at this point the Navy was willing to increase the number of coupons to twelve from the originally proposed limited number of five:

> *"Removal of at least five but no more than 12 coupons is planned. The size of the coupons will be 2 feet by 2 feet and will include a variety of characteristics **(i.e. steel plate with internal/backside flaws, steel plate without flaws, and welded areas)**."* (Navy, 2016c) (emphasis added).

These proposed coupons were four times larger than the ones ultimately removed from the tanks. Even if the larger coupons were used, it would be extremely difficult to provide enough data from twelve coupons for a full statistical analysis given the range of techniques and damage mechanisms that the Navy was trying to assess. The Navy knew this as evident from its statement:

> *"Due to the huge surface area presented by the steel tank liner, acquiring sufficient number of samples for worthwhile statistical analysis of a particular tank's status and behavior with respect to corrosion (and fatigue) would be an inordinate task.*
>
> *...*
>
> *Clearly for the Red Hill Tanks, determination of the number and size of coupons must include good engineering judgement in combination with statistical methods to provide sufficient data for the planned statistical analysis."* (Navy, 2016c)

Given the limited number of coupons for DT, *any* discrepancies or misidentifications found must be considered significant. As discussed below, the Navy's attempt to dismiss the misidentifications on a case-by-case basis is not justified. Such discrepancies and misidentifications demonstrate that the NDE methods are not reliable.

It appears that the Navy also initially recognized the significance of such discrepancies and anticipated more coupon sampling would be required if the DT work did not validate the NDE. In the December 2016 draft DT SOW for discussion, the Navy stated:

> *"If more than five samples exhibit significant difference to the findings of the NDE, take five additional coupons from another tank (either Red Hill or a similar AST of approximately the same vintage) scheduled for inspection and repair."* (Navy, 2016c)

It is highly noteworthy that that DT did not support the NDE conclusions for five of the ten coupons tested. While the BWS believes that more samples would be required to fully and accurately quantify the inaccuracy of the Navy's NDE process, the high failure rate with this small number of coupons clearly establishes that the Navy's NDE process is not accurate and reliable. Clearly the Navy's DT results cannot be used as a basis for validating its NDE process or supporting a position that the single-walled RHBFSF tanks should remain above our sole-source aquifer.

The Navy's 2017 Final DT SOW

The Navy submitted its formal DT SOW on May 30, 2017 which reiterated the Navy's goal to validate the results of NDE using minimum testing on operational tanks (Navy, 2017a).

As of the Navy's 2017 DT SOW, the tank to be sampled had not been decided. Several tanks were proposed, one of which was Tank 14 and it was ultimately selected. The Navy stated:

> *"The two tanks are proposed based upon operational schedule and AOC-SOW Section 5.3 timeline, not on representative condition. The AOC-SOW Section 5.3 scope of work is to validate the non-destructive evaluation (NDE) technology, not the representative condition of the tank."* (Navy, 2017a)

While the Navy's desire to minimize disruption of operations is understandable, this desire should not be allowed to prevail over the need to characterize the accuracy of the various NDE techniques the Navy uses in its inspection and repair procedures. The BWS does not agree with the concept that the validity of the NDE technology can be assessed without consideration of the condition of the tank selected. This is an important issue as Tank 14 may not be representative of the nature and extent of defects in the steel liner of other RHBFSF tanks. The Navy has not provided any basis to establish that Tank 14 is representative of the other tanks with respect to defect type, distribution, and/or depth. Factors such as differences in the order of tank construction, local geology (lava tubes, drainage, etc.), previous inspection and repairs, welder qualifications and training, and other factors may make Tank 14 non-representative and, therefore, extrapolating the NDE-DT comparisons to other RHBFSF tanks may underestimate the potential for corrosion in other locations if those tanks have issues not present at Tank 14. Further, and as an example, if Tank 14 did not have any weld defects then there would be no validation for the ability of the Navy's NDE method to detect weld defects even though the defects might be present in other tanks.

The Navy's 2017 DT SOW refined the number of coupons and size of the coupons:

> *"Removal of at least five (5) but no more than 12 coupons is planned. The size of the coupons may be as large as 12 inches by 12 inches and will be selected* ***to include****, as much as practicable,* ***multiple indications of backside thinning, back side pitting, and linear indication flaws****."* (Navy, 2017a) (emphasis added).

The final coupons extracted from Tank 14 were indeed 12-inches by 12-inches, representing just a quarter of the area proposed in the earlier draft DT SOW documents, which indicated 24-inches by 24-inches (2-feet by 2-feet). Presumably to ensure a broad range of conditions were tested, the coupons were to include instances of backside thinning, backside pitting, and linear indication flaws. Linear indication flaws are likely associated with weld defects and should be detected with the Navy's BFET NDE technique. However, the December 2016 DT DOW draft for discussion indicated that "*steel plate with internal/backside flaws, steel plate without flaws, and welded areas*" would be included in the coupons. As evident from the final coupon selection that occurred in June 2018, no linear indication flaws were extracted. In fact, only one coupon contained an actual plate weld and it does not appear to have been selected because of the weld, the presence of the weld appears to have been by sheer coincidence. Further, that weld did in-fact contain a linear indication (as shown by the destructive testing) and thus the only weld extracted demonstrated another NDE miss.

The Navy DT SOW describes generally the different NDE methods in use at RHBFSF and the general intent as shown below (Navy, 2017a):

Table 2. Red Hill Tank NDE Process

NDE Inspection Type	Primary NDE Testing	Secondary NDE Testing
Pitting	Low Frequency Electromagnetic Technique	Traditional Ultrasonic Testing Methods
Wall Thinning	Low Frequency Electromagnetic Technique	Traditional Ultrasonic Testing Methods
Welds	Balanced Field Electromagnetic Technique	Shear Wave Ultrasonic Testing or Magnetic Particle Testing

The Navy is using LFET and the PAUT NDE methods to find areas that need repair as a result of either pitting or general corrosion. There is nothing inherently wrong in using these methods to check for wall loss; however, the Navy's DT testing has shown these techniques to be inaccurate and unreliable.

As of the Navy DT SOW, the following coupons were intended to be extracted:

- ***One coupon from the upper dome*** *just above spring line.*
- *Cut-out* ***two to four coupons from the barrel****. Coupons will be from opposite sides of the Barrel, with at least one taken from the upper part of the Barrel and one from the lower part. The lower coupon shall be taken from just above a horizontal butt welded joint between the 19.6' x 5.0' shell plates.*
- *Cut-out* ***one or two coupons from the lower dome****. Coupons are to be taken from the sloping plate in the second course up from the flat bottom plate just above a horizontal butt welded joint.*
- *Cut-out* ***one coupon from the lower dome (½" bottom plate.)***
- *Cut-out* ***up to four additional coupons at random locations based on the LFET or BFET scans.***

The Navy, however, did not follow its commitment in the DT SOW and instead selected a much less diverse range of coupons that are unlikely to be representative of the potential conditions within Tank 14 much less the conditions of all the tanks at the RHBFSF. Ultimately, the Navy extracted eight coupons from the tank barrel (i.e., the vertical walls), one from just inside the upper dome, and one from sloped section of the lower dome; shown below for the locations marked in green. The locations marked in red were identified as possible coupon locations but were not extracted. The BWS is not aware of any random locations selected based on the BFET scans specifically to assess the welds. The Navy's description of the NDE result at these coupon locations do not discuss the BFET result at all. Further, the BWS is not aware of any coupons extracted from the lower dome bottom plate.

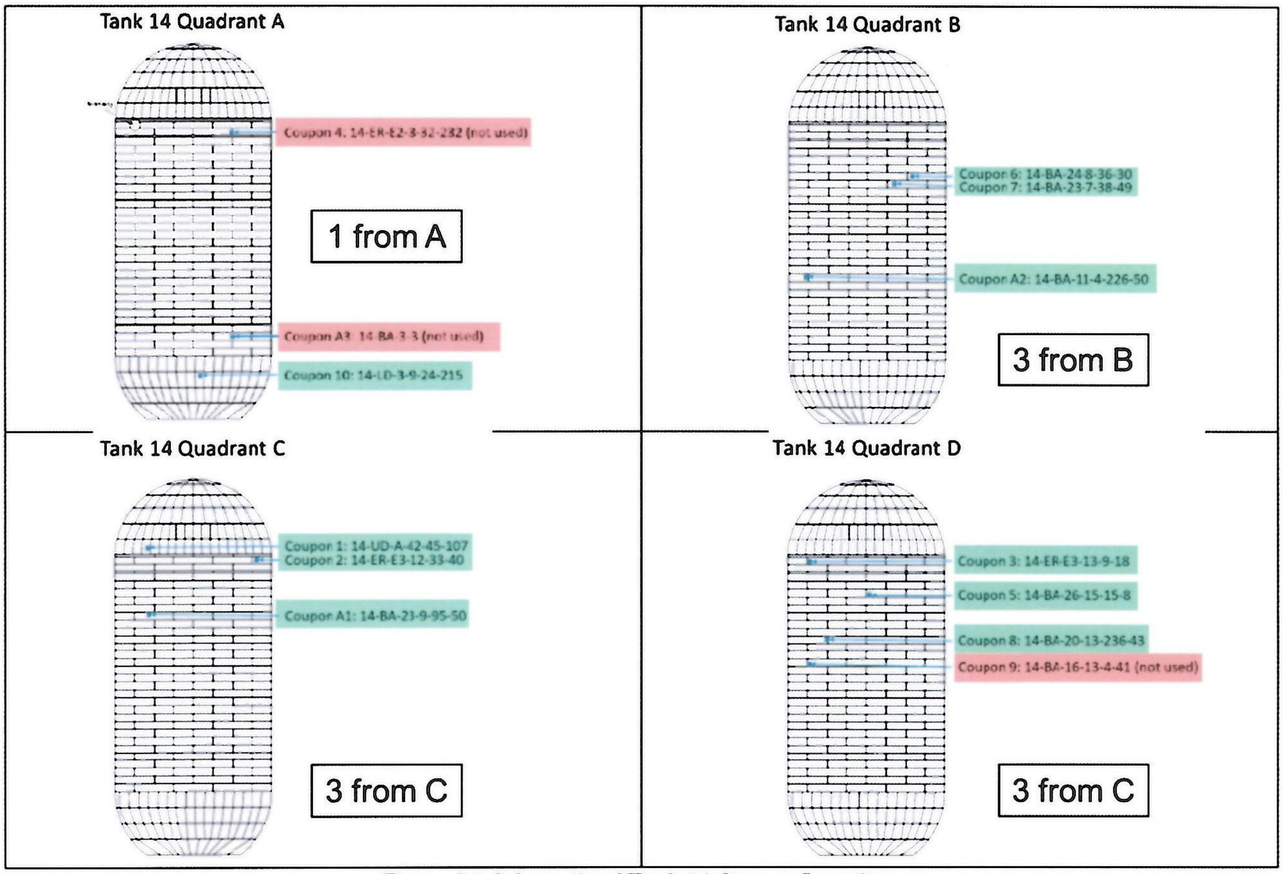

Figure 2-1 Schematic of Tank 14 Coupon Locations

Regulators' 2017 Conditional Approval of the Navy's DT SOW

On July 7, 2017, the Navy was granted conditional approval of its DT SOW. As part of the preamble to the conditions of approval, the Regulatory Agencies stated:

> *"To maximize the effectiveness of this validation, the Regulatory Agencies **seek full transparency in its testing, planning, design and implementation**, and suggest **the Navy and DLA provide transparency to external subject matter experts** as well."* (EPA and DOH, 2017) (emphasis added).

The approval required:

> *"2. … The Regulatory Agencies and external subject matter experts shall be given an opportunity to participate in the review of the NDE strategy, plans, data acquisition and the selection of locations and configuration for coupon sampling."* (EPA and DOH, 2017)

The BWS notes that it still has not had the opportunity to review the past NDE data for the tank that was ultimately used for selecting the coupons to comprise the DT work. For example, the associated American Petroleum Institute (API) inspection report for Tank 14 still has not been made available. However, we understand that the Navy chose the coupon sample areas such that some coupons would exhibit flaws or deterioration, and some would not.

<u>The Navy's NDE Plan</u>

In October 2017, the Navy drafted a NDE plan outline for the RHBFSF tanks being inspected. In the heavily redacted plan made available to external subject matter experts such as BWS, the Navy elaborated on several of the NDE methods that would be utilized. Details for the TesTex devices and methods used in the past for the RHBFSF tanks were expanded upon because the plan was to use them again. Specifically, the Navy proposed to use the TesTex TS-2000 and Falcon Mark II 2000 LFET along with the Hawkeye 2000 system BFET device. The Navy made several claims about these devices.

The LFET devices were purported to be capable of:

> [Falcom Mark II 2000] *"detect[ing] metal plate surface crack, back-side corrosion, and as little as 5% wall thinning. …100% POD at 25% wall loss on defects such as isolated pitting at a 3:1 aspect ratio."*
>
> [TS-2000] *"…sensors have diameters of only a few millimeters, tiny defects like pits can be detected, and scanning in general is in high resolution. … measure small gradual wall losses on the order of 10%, pits of diameter 0.062" (1.57mm), and vibration/fret wear of five volume percent" (Navy, 2017b)*

The BFET method was purported to be capable of:

> [Hawkeye 2000] *"…detect[ing] flaws on and immediately below the surfaces of welds. … In one pass, it can assess both sides of a butt weld… Features it can detect include porosity, slag, undercuts, and cracks. As for cracks in particular, they can be found up to 3 mm or 0.125 inch deep from the surface of carbon steel."* (Navy, 2017b)

The BWS understands that these devices were to be used for the NDE of Tank 14 prior to the DT work but the BWS has never seen any test results or documentation regarding the specific NDE instruments used.

<u>The Navy's DT Plan</u>

On June 1, 2018, the Navy issued its DT Plan. The plan detailed all of the steps that were going to be taken for the DT work and identified the areas from which the coupons were going to be extracted. The Navy re-iterated that a goal and desired outcome was to:

> *"Validate the results of Non-destructive examination (NDE) inspection technologies, specifically the NDE process used at Red Hill."* (Navy, 2018a).

However, the Navy at this point began to start qualifying the extent to which the equipment was going to be validated. Specifically, the Navy claimed that:

> *"Accuracy of detecting defects below the established screening criteria is less of a concern, as they are not expected to cause integrity issues before the next tank inspection based upon current, conservative corrosion rate calculation methodology."* (Navy, 2018a).

The screening criteria was 160 mils (0.160-inches) because that was the actionable wall thickness set by the Navy. Meaning, any area thinner than 160 mils needed to be repaired and any area thicker than that could be left in service. Significantly, the DT work ultimately showed that the Navy's NDE missed two of the four areas that required repair. The Navy's screening step (LFET) identified these two areas as possibly needing repair, but the Navy's prove-up step (PAUT) cleared them as being satisfactory. The DT work showed that the two areas needed repair.

The coupons for DT were selected as a result of discussion with Regulators' and certain subject matter experts:

> *"The Navy provided EPA and DOH a spreadsheet documenting the scan results from the clean, inspect and repair contract for Red Hill tank 14. These scan results provide the basis for coupon selection.* ***The final EPA/DOH approved coupon selection locations are provided in Table 1****."* (Navy, 2018a) (emphasis added).

Further, the BWS understands that:

> *"Selection of coupon locations was* ***based on scanning data from LFET, PAUT and BFET inspections of the tank. Target areas based on*** *reported* ***reductions in wall thickness, pitting****, and* ***weld defects*** *were chosen to provide a representative sampling."*
>
> ...
>
> *"Therefore coupons were selected strategically to characterize the tank and the various NDE findings. With input from Regulators and SMEs,* ***coupons with isolated pitting, general corrosion, pitting with general corrosion, and no identified corrosion were selected****."*
>
> ...
>
> ***"In addition coupons were selected to include areas of where no defect was indicated****."* (Navy, 2018a) (emphasis added).

Although BFET results were purportedly part of the consideration for coupon selection, the BWS is not aware of any coupons having been intentionally selected due to a weld indication. Only one coupon actually contained a plate-to-plate weld and it showed a clear linear weld defect of the shape and size that BFET should have identified. The Navy did not address this in its final report, but, rather downplayed how it validated the BFET results when the only weld extracted contained a missed linear indication. Further, the IMR lab that performed the DT analysis was specifically not analyzing the welds when the Navy's DT Plan indicated that it should have been:

> [Navy DT Plan] *"Analyzing coupons quantitatively to validate NDE process for detecting areas without indications of: … Non-full-penetration welds, welding discontinuities, and welding defects, including corrosion on welds."*
>
> [IMR] *"A full weld evaluation is outside the scope of this effort. The results are thus provided for information only."* (Navy, 2018a)

Finally, the Navy's DT Plan indicated that:

> *"4.3.1 NDE Validation Meets Criteria*
> *If the validation meets the accepted criteria, then the Navy will produce the Destructive Testing Results Report with no further action required.*
>
> *4.3.2 NDE Validation Does Not Meet Criteria*
> ***If the NDE validation criteria are not met, possible causes will be evaluated with input from regulators and SMEs.*** *Requirements for additional testing and the path forward will be evaluated. Possible actions could include obtaining additional coupons from representative plate material. The Destructive Testing Results Report will document any further actions as deemed necessary."* (Navy, 2018a) (emphasis added).

As will be discussed in the remainder of this letter, the DT work did not validate the NDE methods. The DT clearly showed that BWS concerns expressed since the beginning of the AOC process are valid and that the current NDE methods are insufficient for ensuring the tank integrity. The Regulatory Agencies should reject the Navy's attempt to justify the NDE inaccuracies on a case-by-case basis and require the Navy to redo the DT testing in accordance with its original SOW given that:

- The LFET screening method did not find all instances of corrosion.
- The PAUT prove-up method did not confirm the instances of corrosion and did not have an accuracy within 20 mils.
- The BFET method for weld assessment did not accurately identify linear indications and surface breaking flaws, as shown by the one coupon with a weld.
- The DT work demonstrates that the NDE methods are neither highly accurate nor highly reliable as described in the Navy's DT Plan.

The Navy's DT Coupon Removal from Tank 14

In June 2018, the ten steel coupons were removed from Tank 14, so that a metallurgical and corrosion analysis of the coupons could be undertaken, with the primary aim of validating NDE results (Navy, 2018a). As part of this, the Navy stated that a quantitative validation was to be performed based on the following:

- Backside Pitting. Prove-up measurement (pit depth) within 20 mils of actual laboratory results.

- Wall Thinning. Prove-up measurement within 5% of actual laboratory results.
- Welds. (If any identified) Detecting a surface-breaking crack with minimum width dimension of 0.025 inch. (Navy, 2018a)

Although these were the Navy's stated goals, the BWS believes that both PAUT (prove-up) and LFET (screening) should be able to demonstrate accuracy within 20 mils of actual flaw depth (as proposed by the Navy for PAUT validation) since LFET is the technique used to locate corrosion and defects, while PAUT is only intended to verify the LFET results once the defects are identified.

Furthermore, the Navy preformed CT scans (computed tomography x-ray scanning) on the 10 coupons presumably to determine the precise location of the thinnest portions on each coupon such that the metallography specimens could be cut from these locations to validate the NDE results. Neither the Navy nor the IMR reports discuss or describe how the CT scans were used to determine where the metallographic coupons should be taken. Nevertheless, BWS analysis of these scans indicate less than optimal conditions were used for the CT scanning. This could be due to a variety of factors such as a shifting coupon during the scanning. Since the Navy states "*obtaining additional data through more destructive testing does not justify the added investment in terms of time and funding*" the BWS asks that the Regulatory Agencies direct the Navy to provide the metallography specimens and coupon plate remnants such that an independent CT and metallographic analysis can be made.

Finally, although the BWS has previously expressed concern that this sample size (ten coupons) is too small to accurately quantify the reliability and accuracy of the various NDE techniques, the discrepancy between NDE and DT on this small sample clearly indicate the Navy's NDE technique is not accurate and are not reliable.

<u>Summary Statements in the Navy's DT Report</u>

The BWS does not agree with certain conclusions expressed in the DT report. The Navy's DT summary includes what appear to be misleading, incorrect, and/or imprecise statements regarding the comparison between the NDE and DT results. For instance, the Navy states the metallurgical analysis:

> *"[V]alidated NDE results in terms of presence or absence of indications for repair"*
>
> and
>
> *"Sufficient confidence can be placed in the NDE processes which could result in metal loss below the minimum threshold before the next inspection interval"* (Navy, 2019a).

These statements are incorrect. As discussed in this letter, the Navy's NDE:

- Did not find every area that needed repair;
- Did not identify all areas with backside corrosion occurring;
- Did not reliably establish whether an area needed repair or not;
- Did not achieve the intended thickness measurement accuracy of 20 mils for either the LFET screening step or the PAUT prove-up step; and,

- Did not sufficiently evaluate the NDE techniques used for weld flaws.

Given these results, the BWS disagrees with the Navy's conclusion that there is no need to obtain additional data and believes that without such additional data, the Regulatory Agencies must conclude that NDE is not reliable. The Navy's NDE and DT work establish that the current NDE inspection techniques do not have the required accuracy and reliability to find all (or even a reasonable percentage of) areas of the tank that need repair. Additional DT is not required to further demonstrate that the Navy's current NDE techniques are inaccurate and unreliable, nor could additional DT improve the accuracy or reliability of these methods. Improving the accuracy and reliability of the Navy's NDE process would require investment in other equipment or techniques, including additional DT to validate the accuracy of any new methods. If the Navy cannot demonstrate sufficient accuracy and reliability, then the RHBFSF tanks should be moved to a location not over our sole-source aquifer or upgraded with secondary containment.

NDE Qualitative Assessment

The summary table (Table 1) shows the DT report findings for each coupon regarding the NDE qualitative assessment and the BWS assessment of whether the DT work validates the NDE results. As is evident, on four of the ten coupons (3, 5, 6, and 8), backside corrosion was mischaracterized by NDE and thus the areas were incorrectly assessed, but the Navy did not directly address this unreliability in its report.

Table 1 – Summary of the NDE Qualitative Assessment

Coupon #	Expected Features from NDE[1]	Actual Features from Visual Inspection[1]	Qualitative NDE Validation Achieved?[2]
1	One or more backside-corrosion (BC) pits in central part of coupon	Corrosion on many parts of coupon, mostly on right half. Pitting present	**Yes**.
2	One or more BC pits in most of top half of coupon	Corrosion mostly concentrated in a 2" horizontal band. Pitting present. Portions adhered to concrete.	**Yes**; but more corrosion expected
3	Horizontal plate manufacturing flaw† running through middle of coupon, but no backside corrosion	Visible backside corrosion scattered throughout coupon. Pitting present.	**No**; missed backside corrosion of actionable depth (< 0.160-in remaining wall thickness) likely extends to beyond coupon, no manufacturing flaw

5	Horizontal laminar-type manufacturing flaw† all over coupon, but no BC pits expected	Slight corrosion on several isolated parts of coupon surface. Most of coupon was adhered to concrete.	**No**; missed backside corrosion, no manufacturing flaw
6	No indications, including BC pits thinner than 200 mils, expected	Slight corrosion on several isolated parts of coupon surface. Most of coupon was adhered to concrete. Pitting present.	**No**; missed backside corrosion and a pit of actionable depth (< 0.160-in remaining wall thickness)
7	One or more BC pits expected throughout coupon	Thick corrosion product on about 90% of coupon. Pitting present	**Yes**.
8	At center, an inclusion, or an original manufacturing flaw†, expected, with a minimum thickness of 69 mils	Slight corrosion on about 40% of coupon surface. Pitting present	**No**; missed backside corrosion, no manufacturing flaw.
10	No indications, including BC pits thinner than 200 mils, expected. If any BC is present, it would be general metal loss	No significant metal loss found. Black surface throughout coupon area.	**Yes**.
A1	One or more BC pits expected throughout whole coupon, except for left-most 1"	Concrete adhesion on top 2/3 of coupon; concrete on about 60% of bottom 1/3 of coupon. Pitting present	**Maybe**; corrosion on half of the coupon, not throughout the whole coupon, LFET over-predicted the amount of corrosion.
A2	At center, a thickness greater than 160 mils expected, otherwise, no indications. If any BC is present, it would be general metal loss	On most of coupon, from 1" from the top all the way down, slight corrosion scattered throughout surface, with concrete adhesion as well.	**Yes**.

† Manufacturing or lamination flaw not be expected to be observed on the surface of the metal
[1] Navy Destructive Testing Report (Table 4-1, p. 43, Navy, 2019a)
[2] BWS comment

Source: Site Specific Report. SSR-NAVFAC EXWC-CI-1941. "Red Hill Bulk Fuel Storage Facility Destructive Testing

Results Report, AOC/SOW 5.3.3." July 7, 2019 (Navy, 2019a).

Case-by-Case Justifications

The DT report states:

> *"Therefore, the NDE results are validated, both by DT and thorough, case-by-case analysis" (p. 61, Navy, 2019a).*

This statement is incorrect. The DT work did not confirm all the NDE results on a case-by-case basis. The two NDE methods performed by the Navy in Tank 14, LFET and PAUT, produced estimates that were not significantly correlated with the actual thickness of the coupons. In fact, at times the two NDE methods contradicted each other. For example, LFET screening identified actionable wall loss to Coupon 3 but then PAUT prove-up cleared it, meaning no repair was required. The DT work showed definitively that corrosion was present and that the area did need repair. In this case, LFET screening was correct but the supposedly more accurate PAUT failed to confirm the corrosion. Furthermore, the NDE technique reportedly used for weld inspections, BFET, does not appear to even have been evaluated in this NDE versus DT study.

The DT report also states:

> *"Every coupon area at which the contractor did not recommend repair (Coupons 6, 8, 10, and A2) was found through DT and through additional analysis not to require repair after all" (p. 61, Navy, 2019a).*

Again, this claim is incorrect. Most notably, this statement does not mention that the Navy's NDE was inaccurate with respect to Coupon 3. The Navy tries to minimize missing this repairable location:

> *"Coupon 3 destructive testing showed actionable metal loss whereas the NDE did not identify any in this exact location. ...An actionable indication was found adjacent to where Coupon 3 was cut out. During the follow-on repair process, however, the metal loss at the Coupon 3 location would have been detected" (p. 61, Navy, 2019a).*

This statement is misleading. The location of Coupon 3 needed repair and PAUT was clearly in error. The fact that an adjacent area required repair and that the corrosion under Coupon 3 might have been found through those repair efforts, is irrelevant as the goal of the NDE/DT efforts was to evaluate the accuracy and reliability of the NDE methods for specific coupon areas. The PAUT prove-up step was not only being evaluated against the qualitative findings but also against its quantitative findings. PAUT should have been accurate to within ±20 mils (0.020 inches) of the actual minimum thickness. However, for Coupon 3, PAUT reported a minimum thickness greater than 0.200 inches and the actual minimum thickness was 0.132 inches, an error more than three times larger than the Navy's stated accuracy objective.

In addition, Coupon 6 required repair but its thinned condition was missed by both LFET and PAUT. The DT report attempts to downplay this missed corrosion location as follows:

> *"Coupon 6 showed more metal loss than was predicted by the NDE and was just below the repair threshold. The destructive testing identified this to be a pit of very small volume. The NDE method used (LFET) does not always detect metal losses of very small volume" (p. 61, Navy, 2019a).*

However, the BWS disagrees with both the DT report's characterization of the corrosion pit identified at Coupon 6 and the significance of the inability of the LFET method to identify such a pit. First, both LFET methods as described in the Tank Inspection and Repair, and Maintenance (TIRM) Report (Navy, 2016b) should have detected the pitting found in Coupon 6. From the October 2016 TIRM Report, there were two LFET methods being considered:

1. The larger, TesTex Falcon Mark II 2000 device should have been able to detect the pit in Coupon 6. According to the Navy this device has a probability of detection (POD) of 100% at 25% wall loss on pits with an aspect ratio of 3:1. The deepest pit in Coupon 6 amounted to ~37% wall loss and aspect ratio of greater than 3:1 (width to depth ratio). Figure 1 shows the cross-section through the deepest pit in Coupon 6 where the size and depth of the pit is obvious.
2. The smaller, TesTex TS-2000 device should have been able to detect the pit in Coupon 6 as the Navy stated this device can detect pits with a diameter of 1.57 mm. The width of the corrosion pit in Coupon 6 was much, much wider than 1.57 mm as is shown in Figure 1.

Second, the BWS believes Figure 1 clearly demonstrates this pit cannot be described as a "*pit of very small volume.*" This figure clearly shows a broad pit of considerable volume.

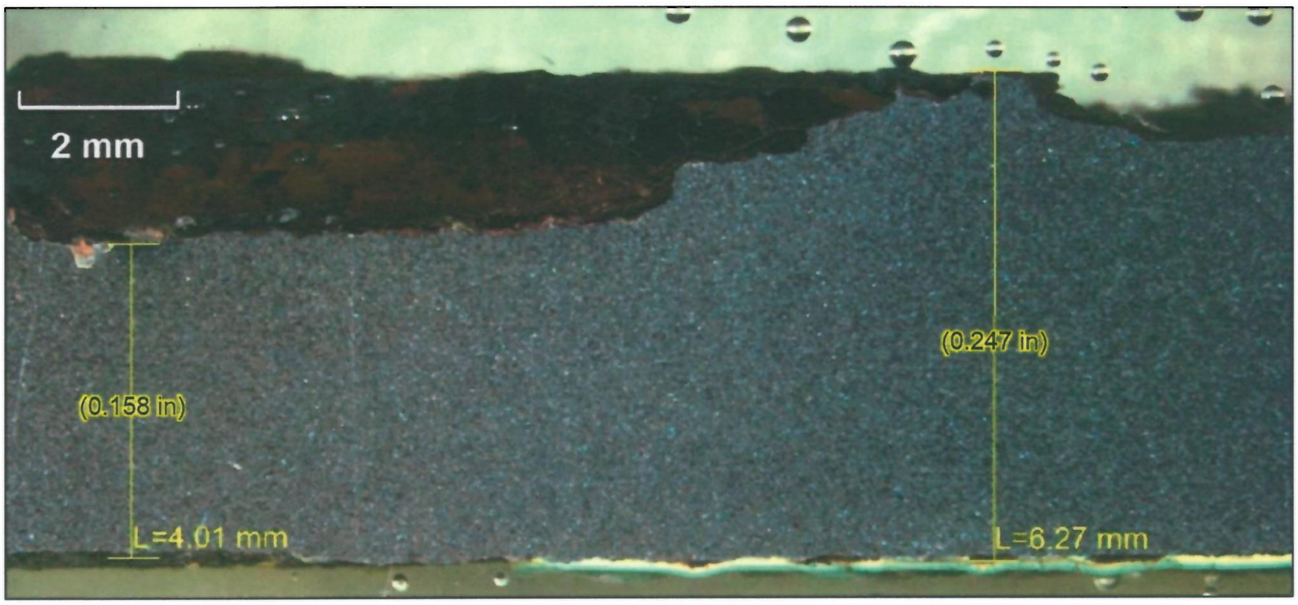

Figure 1 – Destructive Testing Cross-section from Sample 6-1

Source: Site Specific Report. SSR-NAVFAC EXWC-CI-1941. "Red Hill Bulk Fuel Storage Facility Destructive Testing Results Report, AOC/SOW 5.3.3." July 7, 2019 (Navy, 2019a).

Weld Quality

The DT report states:

> *"The NDE results did not find linear indications on any of the welds on the coupons. … The laboratory findings are consistent with weld examination results for the entirety of Tank 14 in that linear indications were not found" (p. 60, Navy, 2019a).*

The BWS does not believe that there is a reasonable basis for such conclusions. Specifically:

1. The NDE and DT AOC/SOW Section 5 selection process did not have a sufficient number of coupons with welds to allow any meaningful conclusions regarding the ability to detect weld flaws. Only one coupon out of the ten coupons taken, Coupon 8, contained an actual plate-to-plate butt weld. Coupon 10 had an anomalous errant weld deposit, and thus should not be used for the purpose of weld evaluation.
2. The DT lab report from IMR explicitly states that it was not investigating weld quality.
3. The DT report incorrectly asserts that because no weld indications were identified in Tank 14, the welds must be good. This is a false equivalency since if BFET is inaccurate and unreliable, then no weld defects would be found even if they are present. Furthermore, BWS notes again that we do not have either the API inspection report for Tank 14 or the NDE scan data spreadsheet provided to the DOH and EPA regulators over a year ago (Navy, 2018a).
4. The DT inspection did find weld defects. The one coupon that actually had a weld contained a linear defect that was found by destructive testing. This lack of fusion linear weld defect is shown below.

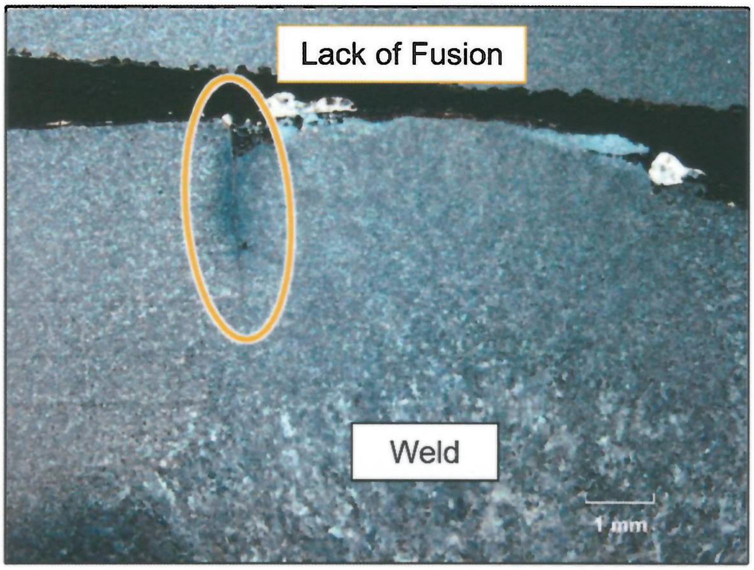

Figure 2 -- (Image from: IMR Test Labs. 2018)

Source: Site Specific Report. SSR-NAVFAC EXWC-CI-1941. "Red Hill Bulk Fuel Storage Facility Destructive Testing Results Report, AOC/SOW 5.3.3." July 7, 2019 (Navy, 2019a).

Corrosion Rates

The DT report states:

> *"The results of the destructive testing validate that the method is conservative. No changes to the corrosion rate assessment are recommended" (p. vi, Navy, 2019a).*

This claim does not appear to be supported by technical analysis and, moreover, it is contradicted by other statements in the report (*see* Navy, 2019a, pp. 52, 59, 60 and 62). For instance, the Navy implies that since corrosion has been occurring over 75 years a low corrosion rate is warranted but, on the other hand, the Navy states that "corrosion cells observed on the Tank 14 coupons could have remained dormant for many years." A shorter time span of active corrosion would significantly increase the corrosion rate over the values the Navy reported. As previously discussed by the BWS, the corrosion rates that occur to the tanks' steel liners are uncertain and the BWS does not believe there is justification to use any corrosion rate lower than about 0.004 inch/year, 4 mils/year, (Lau, 2016).

Further, the Navy has found pitting corrosion in certain areas and knows that pitting corrosion can have higher corrosion rates compared to the bulk uniform corrosion rate. Pitting corrosion is generally faster and less predictable compared to uniform corrosion. The Navy is aware of these aspects as they have previously described pitting as:

> *"Pitting, **a localized form of corrosion**, presents **a higher risk to the integrity of a Red Hill tank** steel liner than wall thinning or metal fatigue. While general external corrosion rates of the liner are low due to the passivating nature of*

> *concrete,* ***a pit caused by corrosion can occur at an accelerated rate.***" (Navy, 2017a) (emphasis added).

Despite this recognition, the Navy seems to minimize pitting corrosion as being a serious mechanism for fuel release. For example, the Navy attempts to minimize the significance of this error since the pit was "*of very small volume.*" Based on the reported LFET accuracy, the pit in question should have been found regardless of the volume. Furthermore, its miss is significant given that pitting corrosion rates can be higher and more variable than uniform corrosion rates and as such represent a risk to the tank integrity.

The DT report further states:

> *"Water moving through the subsurface .... does not affect the reinforced concrete structures because the concrete is high above the groundwater table and the surrounding geology contains many vertical passages for water drainage" (p. 59, Navy, 2019a).*

Nothing in the DT report can be reasonably construed to inform the condition of the concrete shell, the shell reinforcement, or the water/moisture environment at the shell-to-liner interface. The BWS recommended that coring or other destructive examination of the concrete shell be performed at the time the coupons were removed, but the Navy chose not to do such testing.

<u>Prove-Up Data</u>

The DT report provides a table that purports to represent a summary of the NDE and DT findings. This table, reproduced here as Figure 3 with red highlights, misconstrues the findings from PAUT prove-up. For instance, on several coupons the prove-up measurement is listed as "No prove-up" when, in fact, PAUT prove-up did occur. The column in this table is supposed to provide the minimum thickness found by PAUT, but the PAUT prove-up step cannot report a thickness when the value is greater than 0.200 inches. Therefore, just because a precise value was not reported, that does not mean that information about the coupon thickness predicted by the prove-up measurement is not available. For example, Coupon 3 has no prove-up thickness listed when it was reported from the DT plan that:

> *"Prove-up thickness (PAUT): No indication noted, so no repair recommended Horizontal indication at y = 18" believed to be a plate manufacturing flaw; PAUT prove-up determined no repair"* (p. B-4, Navy, 2018a).

PAUT prove-up cleared Coupon 3 when in fact DT indicated that this coupon had a deep defect that should have been found and repaired. Further, for Coupon 3, the Fuel Tank Advisory Committee (FTAC) November 2018 update presentation stated:

> "*Initial Indication:*
>
> - *Screening scan indicates repair is <u>necessary</u>*
> - *Prove-up scan indicates repair is <u>unnecessary</u>*
> - ***Expect lab measurements to validate NDE measurements***"
>   (Slide 23, Navy, 2018b) (emphasis added).

The Navy's expectation was not confirmed by the DT laboratory measurements. The BWS does not believe that DT report Table 2-1 is an accurate depiction of available information, nor does it provide any reasonable basis upon which to consider the Navy's NDE techniques reliable.

Table 2-1 Tank 14 Coupon Locations

#	Row in Master Table	Overall ID	Contractor Repair No.	Region	Course	Plate	X-Coord	Y-Coord	Ind Type	Screening Measurement (in)	Prove-up Measurement (in)	Actual Minimum Thickness (in)
1	2282	14-UD-A-42-45-107	14-UD-A-42-45-107-3	UD	A	42	45	107	BC	0.147	0.112	0.208
2	2892	14-ER-E3-12-33-40	14-ER-E3-12-34-44-5	ER	E3	12	33	40	BC	0.157	0.150	0.152
3	2903	14-ER-E3-13-9-18	14-ER-E3-13-7-5-2	ER	E3	13	0-18	18	BC	0.033	No prove-up	0.131
4	2959	14-ER-E2-3-32-232	14-ER-E2-3-32-232-5	ER	E2	3	32	232	BC	0.110	No prove-up	Not used
5	3706	14-BA-26-15-15-8	14-BA-26-15-28-3-1	BA	26	15	27	8	BC	0.047	No prove-up	0.224
6	N/A	N/A	N/A	BA	24	8	N/A	N/A	N/A	N/A	No prove-up	0.158
7	3944	14-BA-23-7-38-49	14-BA-23-7-32-36-1	BA	23	7	38	49	BC	0.157	0.135	0.164
8	4300	14-BA-20-13-236-43	(No Repair)	BA	20	13	236	43	BC	0.069	0.200	0.208
9	4625	14-BA-17-13-4-41	14-BA-17-13-4-41-1	BA	17	13	4	41	BC	0.037	No prove-up	Not used
10	6492	14-LD-3-9-24-215	(No Repair)	LD	3	9	24	215	BC	0.198	0.200	0.242
A1	3962	14-BA-23-9-95-50	14-BA-23-9-94-53-2	BA	23	9	87-103	45-55	BC	0.134	No prove-up. Weld repair	0.122
A2	5176	14-BA-11-4-226-50	(No Repair)	BA	11	4	226	50	BC	0.161	No prove-up	0.248
A3	N/A	N/A	N/A	BA	3	3	N/A	N/A	N/A	N/A	No prove-up	Not used

Note: Coupons 4 and 9 were not used due to anticipated difficulties in removing them, as explained in the text of Section 2.0, so Coupons A1 and A2 were substituted for them. Coupon A3 was an alternate coupon that was not used.

Figure 3 – Table 2-1 from the DT Report (p. 4, Navy, 2019a).

Source: Site Specific Report. SSR-NAVFAC EXWC-CI-1941. "Red Hill Bulk Fuel Storage Facility Destructive Testing Results Report, AOC/SOW 5.3.3." July 7, 2019 (Navy, 2019a).

BWS Summary Comparison of NDE and DT Results

BWS has taken the information from the Navy's NDE and DT reports and summarized it in the following table. This table shows that of the ten coupons the DT showed that four coupons actually needed repair (Coupons 2, 3, 6, and A1), i.e., 40% of the coupons were in need of repair. However, the Navy's NDE only predicted that two of the four actually needed repair. That is the Navy missed 50% of the coupons in need of repair.

Table 2 – NDE and DT Summary

Coupon #	LFET Min Thickness (in)	PAUT Min Thickness (in)	Would Navy Repair?	Best Est. NDE Min Thickness[a]	DT Actual Min Thickness (in)	Does DT Support Decision?	LFET Error	PAUT Error	LFET Within 20 mils?	PAUT Within 20 mils?
1	0.147	0.112	Yes	0.112	0.208	No	-29%	-46%	No	No
2	0.157	0.150	Yes	0.150	0.152	Yes	3%	-2%	Yes	Yes
3	0.033	NR, >0.200	No	**>0.200**	0.132	No	-75%	**≥ 52%**	No	**No**
5	0.047	NR, <0.160	Yes	**<0.160**	0.224	No	-79%	**≤ -29%**	No	**No**
6	NR, >0.200	NR, >0.200	No	**>0.200**	0.158	No	**58%[b]**	**≥ 27%**	**No**	**No**
7	0.157	0.135	Yes	0.135	0.164	No[c]	-4%	-18%	Yes	No
8	0.069	NR, >0.200	No	**>0.200**	0.206	Yes	-66%	--	No	Maybe
10	0.198	NR, >0.200	No	**>0.200**	0.242	Yes	-18%	--	No	Maybe
A1	0.134	NR, <0.160	Yes	0.134	0.122	Yes	9%	--	Yes	Maybe
A2	0.161	NR, >0.160	No	**>0.160**	0.248	Yes	-35%	--	No	Maybe

NR: not recorded (per 6/1/18 DT Plan)

[a] Where thickness values are given for both screening (LFET) and prove-up (PAUT) we use the prove-up value as presumably it is more accurate. Since PAUT cannot detect plate thickness greater than 0.200-inch plate thickness could be anywhere between 0.200 and 0.250. Where PAUT is only reported as being above or below the repair threshold (i.e., 0.160) we use the LFET value if available, consistent with PAUT, and is not unrealistically small (i.e. Coupon 5).

[b] No indication noted, and no thickness reported, assumed thickness of 0.250 in.

[c] DT showed a minimum wall thickness only 0.004-in larger than the threshold.

Data Source: Site Specific Report. SSR-NAVFAC EXWC-CI-1941. "Red Hill Bulk Fuel Storage Facility Destructive Testing Results Report, AOC/SOW 5.3.3." July 7, 2019 (Navy, 2019a).

We have also plotted the actual minimum plate thickness determined from the DT against the best estimate of the coupon minimum thickness determined prior to the DT, Figure 4. To simplify, we conservatively assume the NDE-measured thickness in censored cases (i.e., the coupons for which thickness is reported as known only to be either greater or less than a specified value) were the specified bounding values. Similar analyses were also done for each NDE method treating those cases as interval-censored, and the results did not change significantly.

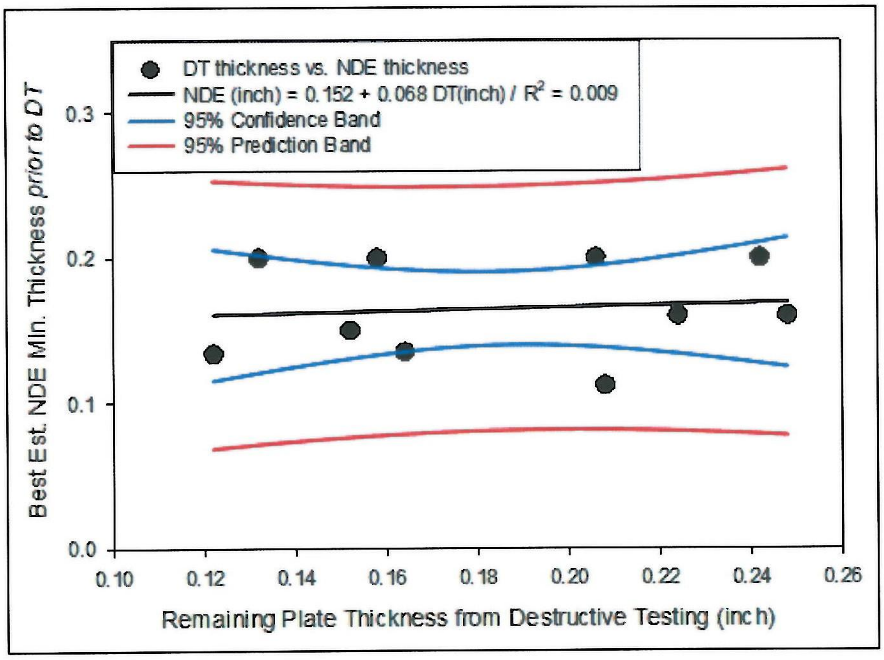

Figure 4 – Relationship between NDE thickness estimate prior to DT and the actual remaining thickness determined from DT.

Figure 4 clearly indicates the NDE techniques are neither accurate nor reliable. First, the slope (0.068) of the line drawn through the DT vs NDE data is very flat (close to zero), indicating the NDE results are essentially insensitive to actual corrosion depth. For comparison, if NDE was perfectly accurate, then the DT thickness would be equal to the NDE thickness and the slope of the line drawn through the data would be 1.0. Instead, the calculated slope is consistent with what one would expect if the NDE results were simply chosen at random without regard to the actual coupon thickness. Another indication is the coefficient of determination (R^2), which measures NDE accuracy by comparing the variation in NDE results to the residual variation after accounting for the actual coupon thickness (using the regression line). As noted in Figure 4, the R^2 value is effectively zero (0.009), indicating none of the observed variation in NDE-measured thickness is attributable to corresponding variation in the actual thickness of the test coupons.

Finally, the figure includes plots of the 95% lower and upper prediction bands, which are very broad. For example, for a coupon with an actual remaining wall thickness of 0.12 inch, with 95% probability the corresponding NDE-measured thickness will fall between 0.070 and 0.25 inch (the values at which the lower and upper bands, respectively, intersect the vertical line at 0.12 inch). The bands vary little over the range of coupon thickness studied. Thus, for any actual tank wall thickness, the NDE-measured thickness can be reasonably expected to range from effectively no damage to severe damage.

A more graphic illustration of the error in the NDE methodology is shown in Figure 5. The image on the left-hand side of Figure 5 shows the extensive backside corrosion on Coupon 3. The right-hand side of Figure 5 shows the plate's reported thinnest area in cross-section after destructively testing. While it is unclear from the DT and IMR reports, this thinned region

(0.131-inch-thick) was presumably located by CT scanning of the entire coupon. The Navy NDE predicted that this area had little to no backside corrosion.

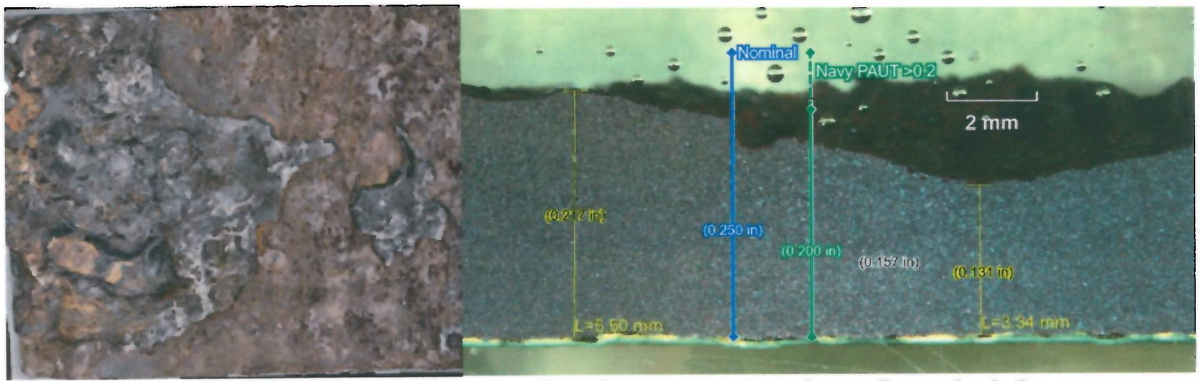

Figure 5 – Destructive Testing Cross-section from Sample 3-3.

Source: Site Specific Report. SSR-NAVFAC EXWC-CI-1941. "Red Hill Bulk Fuel Storage Facility Destructive Testing Results Report, AOC/SOW 5.3.3." July 7, 2019 (Navy, 2019a).

The thin blue-green layer on the bottom of the plate on the right-hand side of Figure 5 is the paint on the fuel wetted side of the steel liner. The blue line shows the full plate thickness of 0.250 inches. The yellow line on the left side is the actual maximum plate thickness which shows 0.217 inches thickness indicating general corrosion thinning and deeper corrosion over the back side of this steel coupon. The green line shows the thickness the PAUT found, i.e., > 0.200 inches (LFET found a remaining wall of 0.033 inches but the supposedly more accurate PAUT indicated the plate was much thicker). The actual minimum thickness found by DT was 0.131-inches as shown by the yellow line on the right side. This variation in the lengths of the colored lines illustrates how large the difference can be between the various NDE inspection techniques and the actual depth of corrosion. In this case, LFET indicated the plate was very thin, the PAUT prove-up indicated little-to-no corrosion, and the DT indicated that this location was sufficiently thinned that repair should have been triggered.

A similar figure was provided for Coupon 6 in Figure 1. The Navy's LFET and PAUT entirely missed the backside corrosion on Coupon 6, but the DT showed the minimum wall to be 0.158 inches thick. That is, DT demonstrated that this location should have been repaired, whereas both the LFET and PAUT NDE techniques indicated that the liner in this area was thicker than 0.200 inches.

The accuracy and reliability of the NDE techniques used to inspect the steel liner of the RHBFSF tanks is of critical importance as the steel liner is the only fuel-tight barrier protecting the environment. The surface area of steel liner and length of the welds to be inspected in each tank are enormous–over 1.3 acres of steel plate and several miles of welds per tank. These expanses of material to be inspected demand a much more accurate process of finding backside corrosion, otherwise many locations requiring repair will be missed. In recent testimony, the Navy reported up to 2% of the tank liners required repair (Navy, 2018c), which translates to about 1,600 square feet (tank surface is 80,000 square feet or 1.8 acres). Given the demonstrated unreliability of the Navy's NDE process (50% rate of correctly identifying areas in need of corrosion repair), the chance of missing a substantial number of corroded areas that should have been repaired is almost certain. This risk to the aquifer is simply unacceptable.

The Section 5 AOC SOW NDE and DT results reinforces BWS' belief that the only reliable way to prevent fuel from entering the environment is to move the RHBFSF tanks to a location not over our sole-source aquifer or to upgrade them with secondary containment.

Further Work on the Coupons

Following the initial issue of IMR on December 17, 2018, the Navy asked IMR to further investigate the corrosion seen on the edge on the remains of Coupon #7. IMR used CO_2 cleaning of the test sample edge. These results are provided in Appendix A of the IMR revised report. Figures A-4 and A-5 of the IMR revised report are included below to show the area of concern. The revised report Appendix A concludes:

1. No pitting was observed, as shown in Figures A-3 and A-4.
2. The rust-colored feature shown in the photographs provided to IMR on March 13, 2019 was a stain on the surface or some other artifact and not a deep pit.
3. The IMR report hypothesizes atmospheric corrosion, corrosive media attack or sectioning heat effects could have caused the observed damage in the area of concern.

BWS disagrees:

1. There was pitting observed as shown in their Figure A-4
2. It is not surprising that corrosion was not found as this area had been sandblasted.
3. The explanation that the area of concern "had been superficially altered by heat associated with sectioning or some other post-sectioning reaction (atmospheric corrosion or corrosive media attack)" is not credible. Atmospheric corrosion would be uniformly distributed along the cut surface, but the area of concern is localized. Secondly, the porosity is not consistent with heat associated with sectioning. Finally, we are unaware of any corrosive media used during coupon removal that could have locally attacked the edge in the area of concern.

Figure A-4. Detail of the sandblasted edge on 3/20/19 in the same location as shown in the picture below. The sandblasting revealed that the feature was not a corrosion pit, as shiny metal was revealed when the red-colored staining was removed. There was an unusual appearance to the edge in this location, as though the sectioned edge had been superficially altered by heat associated with sectioning or some other post-sectioning reaction (atmospheric corrosion or corrosive media attack). That alteration gave the appearance of a deep corrosion pit.

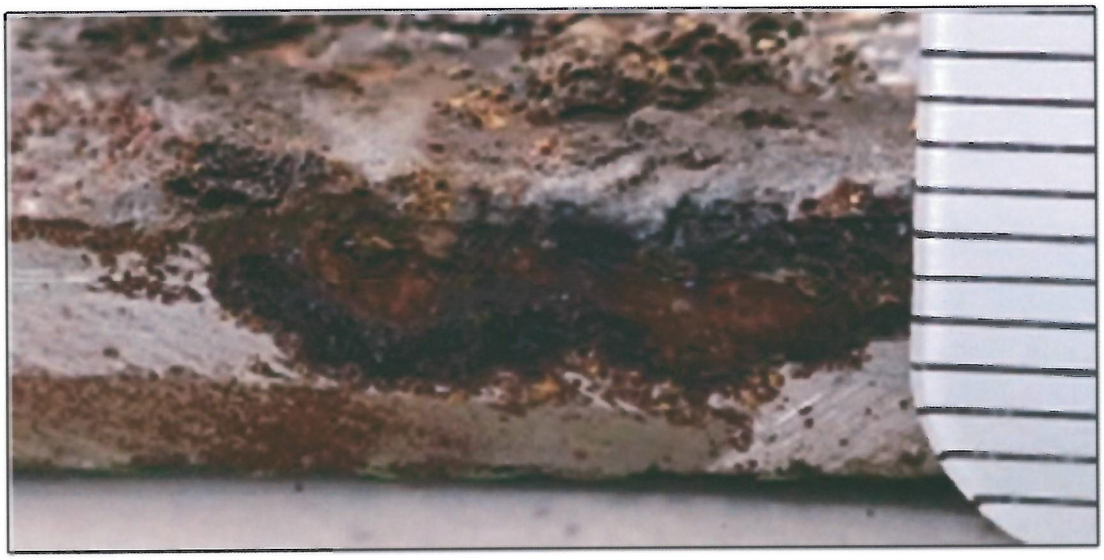

Figure A-5. The same area is shown in an image provided prior to shipping Coupon #7 to IMR (provided to IMR on March 13, 2019). What appeared to be a deep corrosion pit was actually rust-colored staining of the edge surface

Source: Site Specific Report. SSR-NAVFAC EXWC-CI-1941. "Red Hill Bulk Fuel Storage Facility Destructive Testing Results Report, AOC/SOW 5.3.3." July 7, 2019 (Navy, 2019a).

Because the area of concern has not yet been fully investigated, the BWS requests that it (and the other coupons) be made available for independent analyses. At the very least, BWS requests that these coupon remnants and metallographic mounts be preserved for future examination.

Conclusions

In summary, the Navy's NDE and DT efforts, as part of the AOC Section 5 process show:

- NDE techniques used by the Navy to find areas of the RHBFSF tanks in need of repair are highly unreliable;
- NDE techniques used by the Navy qualitatively missed four instances of backside corrosion, two of which required repair;
- PAUT prove-up reported the minimum thickness to be greater 0.200-inch or less than a 0.160-inch threshold value seven times, and three of those assessments were incorrect;
- PAUT prove-up reported precise minimum thickness values three times, and two of those did not achieve the required accuracy of 20 mils;
- Navy does not appear to have sufficiently evaluated the BFET inspection technique required for welds;
- The DT scope was insufficient to inform any of the Navy's statements regarding condition of the concrete shell, the shell reinforcement, or the water/moisture environment at the shell-to-liner interface; and,
- Navy did not provide any reliable information regarding the corrosion rate or justification not to conservatively presume a higher corrosion rate to determine the threshold minimum thickness for steel liner repair.

The Navy's AOC Section 5 SOW efforts reinforce the BWS' belief that the only reliable way to prevent fuel from entering the environment is to relocate the RHBFSF tanks away from our sole-source aquifer or upgrade them with secondary containment.

Thank you for the opportunity to comment. If you have any questions, please contact Mr. Erwin Kawata, Program Administrator of the Water Quality Division, at 808-748- 5080.

Very truly yours,

ERNEST Y.W. LAU, P.E.
Manager and Chief Engineer

CC: Mr. Steve Linder
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