Red Hill Administrative Order on Consent, Attachment A Scope of Work Deliverable

Section: 5.2 Corrosion and Metal Fatigue Practices Report

In accordance with the Red Hill Administrative Order on Consent, paragraph 9, DOCUMENT CERTIFICATION

I certify under penalty of law that this document and all attachments were prepared under my direction or supervision in accordance with a system designed to assure that qualified personnel properly gather and evaluate the information submitted. Based on my inquiry of the person or persons who manage the system or those persons directly responsible for gathering the information, the information submitted is, to the best of my knowledge and belief, true, accurate, and complete. I am aware that there are significant penalties for submitting false information including the possibility of fines and imprisonment for knowing violation.

Signature: ______________________

CAPT Dean Tufts, CEC, USN
Regional Engineer, Navy Region Hawaii

Date: 4/4/16

RED HILL FACILITY

CORROSION AND METAL FATIGUE PRACTICES REPORT

Administrative Order on Consent (AOC) and Statement of Work (SOW) Section 5.2

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CHAPTER 1 INTRODUCTION

1-1 BACKGROUND.

On December 9, 2013, the Navy placed one of the tanks (Tank No. 5) at the Red Hill Bulk Fuel Storage Facility back into service after it had undergone routine scheduled maintenance. The maintenance work consisted of cleaning, inspecting, and repairing multiple sites within the tank. Upon placing Tank No. 5 back into service, the Navy commenced filling the tank with petroleum. On January 13, 2014, Navy discovered a loss of fuel from Tank No. 5 and immediately notified the State of Hawaii Department of Health (DOH) and the United States Environmental Protection Agency (EPA).

In response to the fuel release reported by the Navy, an Administrative Order on Consent (AOC) between the Navy, EPA, and the DOH [1] provides for the performance by the Navy and DLA of a release assessment, response(s) to release(s), and actions to minimize the threat of future releases in connection with the field-constructed bulk fuel underground storage tanks (USTs), surge tanks, pumps, and associated piping at the Red Hill Bulk Fuel Storage Facility located near Pearl Harbor, on the island of Oahu in the State of Hawaii.

1-2 PURPOSE AND SCOPE.

The purpose of this Corrosion and Metal Fatigue Practices Report is to describe current practices to control corrosion of the Red Hill tanks and evaluate the possibility and extent of metal fatigue at the Facility in accordance with the AOC and its Statement of Work (SOW). The report includes an explanation of the current practices for assessing the condition of the tanks and associated fuel containment infrastructure. Additionally, the report describes any recordkeeping relating to corrosion and metal fatigue practices at the Facility.

1-3 TANK CONSTRUCTION FEATURES IMPACTING CORROSION.

The Red Hill complex was constructed during August 1940 to September 1943 and consists of twenty underground vertical cylindrical reinforced concrete fuel storage tanks (Tanks 1 - 20) with a domed top and bottom and internal steel liner, fuel piping, upper and lower tunnel, and associated infrastructure. The tanks and related components at the facility are unique, because they are constructed of steel, encased by concrete. The reinforced concrete around the outside of the upper dome is eight (8) feet thick at the base (springline) gradually narrowing to four (4) feet thick at the crown (top). The reinforced concrete surrounding the lower dome is a minimum of four (4) feet thick except for the 20 feet diameter flat bottom plate at the center of the lower dome which sits on top of a plug of concrete approximately 20 feet thick. The reinforced concrete surrounding the cylindrical “barrel” of the tank is an estimated minimum of 2.5 to 4 feet of concrete. The entire tank is surrounded and supported by basalt bedrock.

Tanks 1 through 4 are 100’-0” in diameter and 238’-6” in overall height and have a nominal storage capacity of 285,851 barrels (BBL) each. Tanks 5 through 20 are 100’-0” in diameter and 250’-6” in height and have a nominal storage capacity of 302,637 BBL each. The top of the tank upper domes are located 110 feet to 175 feet below ground.

The upper tunnel provides access to the tank manholes and gauging platforms. The lower tunnel provides access to the tank piping and valves. The only access into the tanks is through an 8-feet diameter manhole at the upper tunnel level.

The primary structure of the tanks consists of an upper dome, barrel, and lower dome. The tanks were constructed by excavating the lava rock formation of Red Hill to create a vault for each tank which was then lined with concrete and a 0.250 inch thick steel liner and a 0.500 inch thick by 20 feet diameter steel plate at the center of the lower dome of the tank. The upper dome was constructed first. Rock was excavated to create a cavity for the upper dome. Steel framing and liner plates were then installed, followed by filling the cavity with four (4) to eight (8) feet thick reinforced concrete. After the upper dome was constructed and grouted to consolidate it with the surrounding rock, the barrel and lower dome were excavated and the rock face was sealed with gunite. The wall of the barrel was constructed of reinforced concrete (minimum of 2'-6" thick at the top, and minimum 4'-0" thick at the bottom) and lined with 0.250 inch thick steel plates. After the barrel and lower dome were constructed, they were pre-stressed and consolidated with the surrounding rock by injecting grout under pressure into the joint between the reinforced concrete and the gunite layer covering the lava rock. The lower dome was constructed of reinforced concrete and lined with 0.250 inch thick steel plates. The floor of the lower dome is flat and consists of 0.500 inch thick steel plates.

Each tank has a seven (7) by seven (7) feet steel framed tower in the center of the tank extending from the floor of the lower dome to the top of the upper dome and a walkway from the manhole at the upper tunnel level to the tower. The center tower was used during original construction to construct the tanks.

CHAPTER 2 CURRENT CORROSION ASSESSMENT PRACTICES

2-1 INTRODUCTION

This section of the report provides technical content describing various corrosion prevention and control practices considered and implemented, as well as limitations based upon construction features of the storage tanks at the Red Hill Facility, including discussions on:

- Cathodic protection (CP) technology and the impracticality of applying CP to the Red Hill storage tanks.
- Protective coatings technology and current practices of applying protective coatings to the Red Hill storage tanks.
- Current integrity/corrosion assessment practices for the Red Hill fuel storage tanks.

2-2 TANK CONSTRUCTION FEATURES – EFFECTS ON CORROSION CONTROL AND ASSESSMENT PRACTICES

The Red Hill storage tanks were constructed by excavating the lava rock formation of Red Hill to create a vault for each tank which was then lined with concrete and a 0.25 inch thick steel liner as described in paragraph 1-3. Steel in contact with highly alkaline (pH>~13), contaminant-free, concrete pore water soon develops a stable oxide/ hydroxide passive film. This film lowers the rate of the anodic reaction (corrosion) to an extremely low value, on the order of a small fraction of 1 μm/year when expressed as a corrosion rate [2]. At that rate, penetration of a 0.25 inch thick liner wall would not be an engineering concern.

Disruption of the passive film can, and does take place if the pore water pH drops and becomes appreciably lower (e.g., pH<~10), or if the concrete concentration of chloride ions at the steel-concrete interface exceeds a threshold level (e.g. several hundred parts per million of the concrete density). Contaminants including other halides and sulfate ions could have a similar effect. Contaminants and a decrease in pH could act synergistically as well, so disruption could occur with lesser extents of either factor if they are present simultaneously.

Foreign materials embedded in the concrete that are in contact with the steel walls can also result in accelerated corrosion, e.g. a piece of the wood in forms prior to concrete placement. Wood naturally has an acidic pH that can alter the local chemistry and disrupt the passivity of the carbon steel. The corrosion macro-cell created in the low resistivity concrete by a relatively small anodic area that is coupled to a large cathodic surface drives localized corrosion at enhanced rates on the steel in contact with the piece of wood.

Construction features that impact common corrosion prevention methods for the Red Hill storage tanks include the following:

- Historical construction records [3, 4] do not indicate that protective coating systems were applied to the exterior surfaces of the steel plate during construction. A protective coating cannot be applied now as there is no access to the external walls of the tank.
- If pre-coated plates (external side) were retrofitted into the tank, welding and mechanical damage would render the coating ineffective. In addition, corrosion would be concentrated at coating defects (holidays) and increase the likelihood of pitting, full penetration, and releases of fuel into the environment.
- The external rock/concrete vault prohibits practical application of cathodic protection (CP) to the external side of the steel plates. Reinforcing steel in the concrete, if electrically continuous, will shield CP current from reaching the tank walls. If the reinforcing steel is not electrically continuous, CP currents passing through the reinforcing will cause unintended corrosion of the reinforcing and degrade the integrity of the concrete encasement around the steel tank.

2-3 CATHODIC PROTECTION.

2-3.1 Applicable Standards.

National Association of Corrosion Engineers (NACE)

- NACE Standard Practice, SP0169, Control of External Corrosion on Underground or Submerged Metallic Piping Systems.
- NACE Standard Practice, SP0285, External Corrosion Control of Underground Storage Tank Systems by Cathodic Protection.

Unified Facilities Criteria (UFC)

- UFC 3-460-01, Petroleum Fuel Facilities.
- UFC 3-570-02N, Electrical Engineering Cathodic Protection.

2-3.2 Technical Discussion.

The mechanism of corrosion, by nature, is an electrochemical process. Buried metals corrode because of the formation of numerous micro anode and cathode points on the surface of the metals when buried in an electrically conducting environment. The anode sites corrode preferentially, but result in protection of the cathode sites on the surface. This natural process is referred to as a corrosion cell. In a poor electrically conductive environment, the corrosion process would be minimal or non-existent. CP is actually the beneficial application of a corrosion cell in which an external anode is provided to preferentially corrode, resulting in the protection of the cathode (tank or pipeline surface); hence the term, “cathodic protection.”

Provision of a functioning CP system on a buried structure, when practical, will extend the life of a buried structure indefinitely as long as the system is properly operated and maintained, and the consumable components, i.e. the anode system, are periodically replaced. It is very important to note that retrofit CP installation **will not** remediate any corrosion damage that may have already occurred on a structure prior to the installation of the CP system.

Historical construction records do not indicate that protective coating systems were applied to the exterior surfaces of the steel plate during construction. Even if a protective coating was provided, it is likely deteriorated to the point where the exterior of the tanks would be considered to be bare steel from a CP standpoint. Based on the size of the tanks, the estimated CP current that would be required for each tank would be in excess of 200 amperes, or more than 4,000 amperes total for the entire Red Hill Facility.

The biggest hindrance to applying CP to the Red Hill storage tanks would be the ability to distribute the protective current to the entirety of the exterior steel liner surfaces (the cathodes in a CP system). CP systems are electrical systems and require the ability to conduct electrical current from a current source, i.e. one or more power sources and an anode system installed around the tanks, to the exterior tank surfaces. However, the basalt rock and concrete environment surrounding the tanks are very poor electrically conductive media rendering it very highly impractical to provide functional retrofit CP systems. Additionally, any reinforcing steel in the concrete surrounding the tanks would also block or drain away protective current intended for the tank surfaces. Even if one were to assume that there are fissures and cracks in the rock and concrete to permit electrical current flow through water infiltrating down through the varying electrically conductive layers of rock surrounding the tanks, there would be no practical way of assuring that the electrical current is being evenly distributed to the entire exterior surface of each of the tanks.

2-3.3 Historical Third Party Assessments.

The Navy has been continually concerned about corrosion prevention of its fuel storage and distribution assets including the Red Hill Facility and periodically conducts surveys of its facilities to evaluate and re-evaluate assessment, repair and improvement techniques for its fuel storage and distribution assets including the application of protective coating and CP. Except for a 1998 Functional Analysis and Concept Design study for Tank No. 19 described in paragraph 2-3.3.4, the application of cathodic protection has not been considered to be practicable for the Red Hill tanks.

2-3.3.1 1949 Assessment Survey Report.

In 1948, just a few years after construction of the Red Hill storage tank facility, the Bureau of Yards and Docks contracted the Bechtel Corporation to conduct an Engineering Survey of all of the petroleum facilities in and around the Pearl Harbor Navy Base including the Red Hill storage tanks, and including investigations into corrosion (referred to as electrolysis in the study). The objectives of the survey were to determine condition and recommend improvements to be accomplished by:

- Better operation and maintenance.

- Rehabilitation including the installation of protective measures to guard against corrosion.
- New construction to improve integration or capacity

The findings of the survey report [5] specific to Red Hill are summarized as follows:

- Generally, the tankage is in good condition.
- The workmanship on Tank 16 is good and construction conforms to the design drawings.
- However, Tank 16 is subject to leakage which is attributed to defective welds. A careful test of the welds was made, and no major defects were found. However, several minute leaks were noted. Six seepages of water were observed during the leak test, which were due to pinholes in the welding. Accurate measurements of loss were difficult. The rate of loss was established over a significant period of time, and the order of magnitude was so small that such factors as minor differences in temperature or liner plate movement were probable significant impacts on the loss measurements. A total hole area of one fiftieth of a square inch could have accounted for the leakage indicated in the test, whereas the steel wall area is about two acres in extent.
- The tell-tale system is not reliable for either testing the welds or denoting leakage.

The recommendations of the survey report specific to Red Hill are summarized as follows:

- Tanks 14 and 16. Wash down the tank interior sides to remove grout. Repair points of seepage in Tank 16 by re-welding. Apply a protective coating to the interior bottom plate only.
- Improve operation of the level and temperature indicating equipment.
- Modify the design for construction of any future tanks to make possible testing of the welds and also provide a positive drainage system which would, in case of a weld rupture, convey the oil to a central point of drainage and thus prevent leakage into the surrounding earth. (This was the intent of the original tell-tale pipe design if installed properly).
- No specific recommendations for the application of CP to the exterior surfaces of the steel liners were made.
- The tanks should be visually inspected at intervals tentatively established at five years. Findings of these inspections will determine the long range maintenance program and minimum interval of inspection. All weld and plate areas should be visually inspected for corrosion.

2-3.3.2 1959 Preliminary Engineering Report of Conversion of Fuel Storage.

During the 1960 - 1963 timeframe, four of the Red Hill storage tanks were modified in order to store volatile fuels. The preliminary engineering report [6] stated that the tanks must be cleaned, tested, and rendered leak-proof before they could be used to store volatile fuels. It also stated that every precaution must be taken to prevent leakage of volatile fuels into the surrounding rock and contaminating the water supply. The 1942 vintage 0.750 inch diameter standard wall tell-tale leak detection system was upgraded (replaced) with 1.500-inch diameter schedule 80 pipe. The increased diameter was intended to preclude plugging and the increased wall thickness to provide more corrosion allowance. The report indicated that there was no indication of leakage from the tanks but specifies that the entire interior of the tanks should be coated with an inert coating to ensure the tightness of the weld seams of the steel tank. The report recommended the use of the special coating being developed and tested by the Naval Research Laboratory (NRL). The polyurethane coating developed by the NRL was the actual coating selected and applied during the tank modifications. The report does not indicate any concern for exterior corrosion of the tanks and does not cite any requirements for application of CP for corrosion protection of the tank exteriors.

2-3.3.3 Repair of the Non-Volatile Section of the Red Hill Fuel Storage Facility

A few years after completion of the modifications of the four tanks to store volatile fuel, the Navy turned its attention to the tanks storing non-volatile fuel.

In 1970, Project No. R1-67 entitled, “Repair of the Non-Volatile Section of the Red Hill Fuel Storage Facility,” cleaned and repaired Tanks 5, 6, and 12. Facility study reports were conducted in 1969 [7, 8]. Based on the studies, the 1942 vintage tell-tale pipes were removed and upgraded similarly to those tanks converted in the 1960-1963 project, plus additional improvements that extended the pipes up to the gauging gallery at the top of the tank to provide access for cleanout, and routed the pipes out of the tank from part way up the wall of the lower dome to the lower access tunnel to preclude exposure to corrosive tank bottom water. No interior coating was applied to these tanks.

In 1978, Military Construction Program Project P-060 entitled, “Modernization of Red Hill Fuel Storage Facility,” cleaned, repaired, and coated Tanks 1 through 16. A conceptual design was prepared in 1977 [9], and was based primarily on the results of an inspection of Tank No. 10 and observations in a few other tanks summarized as follows:

- Tanks 1, 12 and 14 have a leak in the upper dome area. There was very little corrosion or pitting on the interior tank walls.
- The welds on the tank walls were quite good
- The tell-tale system appeared to be the major source of reported leaks and should be removed.

The conceptual design recommended/specified the following actions during the tank repairs:

- Cleaning and inspection of the tanks.

- Conducting a very thorough inspection of the bottom up to the spring line. A Magnaflux weld inspection was not recommended based upon weld inspection results for Tank No. 16 in the 1975-1976 timeframe that detected no defects.
- Cutting coupons from the bottom plate and first course of wall plates to see if any corrosion has occurred on the back side of the plates, and measuring actual plate thickness. As an alternative, conduct ultrasonic testing that would indicate any broad surface corrosion on the back side of the plates.
- Repair of any leaks typically along the weld seams. Grind smooth all burrs, sharp edges, corners and rough welds. Abrasively blast all surfaces prior to application of the protective coating system
- Aluminum metalizing of a 30-ft diameter area of the tank bottom domes, (except for Tanks 3 and 4) to avoid blistering problems with the polyurethane coating.
- Application of coating on the entire interior surfaces with the polyurethane coating developed by NRL.

It was anticipated that the tank side walls would not have any major corrosion problems, no external cathodic protection system was recommended, and coupon cutting and ultrasonic testing would probably not be required. Actual work was accomplished on Tanks 1 through 16 between 1978 and 1984. Tank history records for Tanks 5, 6, and 12 after the upgraded tell-tale pipes were installed in 1970 indicated there were no tell-tale leak problems. Unfortunately, because of a lack of information due to the untimely death of the Fuel Department Superintendent, all of the tell-tale pipes including those in Tanks 5, 6, and 12 were removed.

2-3.3.4 1998 Functional Analysis Concept Design (FACD) study for Tank 19.

In 1998, the firm, Enterprise Engineering Inc. was contracted to complete a Functional Analysis Concept Design (FACD) study to develop possible repair options for Tank 19 [10]. The study was performed due to tank integrity issues, environmental concerns, lack of leak detection capability, and lack of secondary containment. Several concepts were brainstormed by the team.

FACD studies are cooperative efforts by the design team, user/customer representatives, facility engineering command personnel, and other interested parties for development of a conceptual design in response to functional, aesthetic, environmental, base planning, site, budgetary, and other requirements. The objective of an FACD study is to take a comprehensive look at project requirements to define and organize program elements and design features before beginning a schematic design. The intent is to enhance communications among team members analyze and address all facts, concepts, issues, and priorities pertaining to the project; and understand the goals, objectives, processes, and relationships of the users being served. As a minimum, the following is addressed in the project analysis conference and documentation:

- Project goals and objectives;
- Graphic analysis of project site, existing facilities, and other pertinent factual data;
- Interviews, focus groups, and work sessions with user groups and key decision makers;
- Conceptual information (graphically organized and diagrammed);
- Refined quantitative information including project scope, budgetary cost estimate (primary and supporting facilities), etc.;
- Summary project statements that reflect the unique qualitative aspects of the project;
- Outstanding issues to be resolved with indication of responsibility. Total team consensus on project description (all of the above).

The study selected three concepts for cost estimating, two of which conceptually required application of CP to the existing tank exterior steel surfaces. Since the CP design was only conceptual, it was not based on design survey field investigations or measurement of actual field test data. Rather, it was based on notional ideas of how CP could possibly be applied based on past experiences on projects on DoD installations worldwide. Due to the high resistivity rock/concrete formations in which the tanks were constructed, the concept was focused on how it may be possible to provide a low resistance CP anode well system. However, the concept did not address the adequacy of CP current distribution to all exterior tank surfaces, nor did it address the possible issue of shielding by reinforcing steel in the concrete encasement around the steel tank that would block current from reaching the tank surfaces. It also did not address potential stray current interference on the concrete reinforcing steel that could cause corrosion damage of the reinforcing steel.

The concept also included provision of a few reference electrodes at anticipated spots of lowest protection levels to monitor CP system effectiveness. The few spots that were identified may be sufficient for a small gas station tank in a uniform soil environment, but would be inadequate for properly monitoring the large sized tanks of Red Hill.

The report also recommended complete ultrasonic scanning of the tank surfaces to improve corrosion assessment of the exterior surfaces in order to better, more reliably, assess the condition of the exterior surfaces. Current tank assessment procedures now include complete scanning of the tank surfaces as described in paragraph 2-5 of this report.

2-3.3.5 Use of Electrical Resistance Sensors to Monitor External Corrosion.

During the late nineties timeframe, the Pearl Harbor Fuel Office researched the possibility of utilizing recently developed electrical resistance (ER) probes for use as corrosion sensors. However, the use of such sensors was not deemed practicable, as very large numbers of sensors would need to be installed to provide an accurate assessment of the general condition of the exterior surfaces. Also, as there is no access to the exterior surfaces of the tanks, a large number of holes would have needed to be cut in the tank walls to install the sensors and route the sensor wires to a point at where they could be periodically measured. The large number of tank wall penetrations would have presented a significantly increased risk of release of fuel into the environment.

2-3.3.6 2008 CP Assessment.

In 2008, the firm, Enterprise Engineering Inc. (EEI), was contracted by the Naval Facilities Engineering Services Center to develop concept alternatives and associated planning level cost estimates to repair the 20 underground tanks at Red Hill. The purpose of this study was to develop tank repair concepts that would provide a long term life extension renewal of the Red Hill tanks. The repair alternatives were required to meet the following primary objectives:

- Provide a tank life expectancy of 40 years, with reliable inspection intervals of 20 years.
- Minimize risk of a fuel leak.
- Contain leaks that may potentially occur.
- Have the capability to detect and locate potential leaks and repair leaks.

The following paragraphs summarize the conclusions of the study final report [11] regarding the application of CP to the tanks, including a critique of the 1998 FACD Study CP conceptual design:

The 1998 Repair Tank 19 FACD study considered the installation of a CP system to reduce exterior corrosion of the existing liner. The 1998 study concluded that the application of CP for the existing steel liner could be accomplished by installing deep impressed current anodes. For such a CP system to prove effective, a continuous media must exist between the anodes and the steel liner. There also cannot be any other structures that would block the protective current. The media on the exterior of the tanks, however, is not continuous. Gaps and voids have been found between the steel liner and concrete when the Red Hill tanks have been taken out of service for inspection. Additionally it is likely that gaps and cracks have formed between the concrete and pre-stressing grout, between the grout and gunite, and between the gunite and rock due to thermal expansion and shrinkage.

Documentation from original construction also noted that large voids were encountered in the lava rock when the tanks were excavated. The voids in the rock are vent holes that were formed when the lava solidified. More than likely, the corrosion observed on the existing steel liner follows the gaps and cracks, giving the impression of “worm lines”. The voids and gaps pose a problem to installing any deep anodes as current from the anodes would be hindered by voids in the rock, and gaps between the rock/gunite interface, gunite/pre-stressing grout interface, grout/concrete interface, and concrete/steel liner interface, leaving areas of the steel liner without effective protection.

Another concern with providing CP is the effect of the reinforcing steel in the concrete surrounding the lower dome, barrel, and upper dome. Record drawings show the concrete around the barrel ranges from 2 to 4 feet thick and contains two layers of reinforcing steel. The concrete on the outside of the lower dome is a minimum of 4 feet thick and reinforced. The reinforcing steel would intercept a significant amount of the protective current. If the reinforcing steel is electrically grounded to the steel liner, it will benefit from the current, but will shield the existing steel liner from protection. If the reinforcing steel is not electrically grounded to the steel liner, it will be subject to stray current corrosion. This occurs when the current picked-up by the reinforcing steel jumps through the concrete to the steel liner. Where the current jumps off, the reinforcing steel will be subject to severe corrosion and metal loss.

There is little confidence that the application of CP could effectively control corrosion of the existing steel liner, and its application could damage the reinforcing steel in the supporting concrete. The application of CP to control corrosion is therefore not viable.

2-4 INTERNAL PROTECTIVE COATING.

2-4.1 Applicable Standards.

American Petroleum Institute (API)

- API Recommended Practice 652, *Lining of Aboveground Petroleum Storage Tanks*, Latest Edition.

National Association of Corrosion Engineers (NACE)

- NACE Recommended Practice, SP0288, *Inspection of Lining Application on Steel and Concrete Equipment*.

Unified Facilities Criteria (UFC)

- UFC 3-460-01, Petroleum Fuel Facilities.

Unified Facilities Guide Specification (UFGS)

- UFGS 09 97 13.15 (February 2010), Epoxy/Fluoropolyurethane Interior Coating Of Welded Steel Petroleum Fuel Tank
- UFGS 09 97 13.15 (February 2015), Low VOC Polysulfide Interior Coating of Welded Steel Petroleum Fuel Tanks
- UFGS 09 97 13.17, Three Coat Epoxy Interior Coating of Welded Steel Petroleum Storage Tanks

2-4.2 Technical Discussion.

The interiors of fuel storage tanks are provided protective coatings to:

- Protect the stored product from the tank substrate, and maintain the integrity of the fuel and prevent contamination.
- Protect substrate from product and maintain the integrity of the tank structure. Water and oxygen in the fuel will result in the development of corrosion cells on the tank surfaces and slowly corrode the steel if left unprotected.

The choice and extent of interior coating depends on the size and use of the tank. Economics may dictate a trade-off between the need for protection and the additional cost for that protection. For Navy bulk fuel storage tanks in which fuel storage levels may be static for months at a time, interior protective coatings are generally provided on the following areas:

- Tank bottom
- Three feet up the side walls
- Tank roof down to the operational fuel storage line.

The risk of corrosion is greater as water in the fuel settles at the bottom of the tank resulting in corrosion of the tank bottom and side walls near the bottom of the tank. Also, the air above the operating fuel storage line is laden with moisture that results in corrosion of the steel exposed to the airspace above the fuel storage line. Conversely, since fuel is not an electrically conductive medium, damaging corrosion cells do not develop on the side wall surfaces constantly submerged in fuel.

For distribution and operational issue tanks in which fuel storage levels are dynamic, much like a small gas station storage tank, the entire tank interior is fully coated. All of the surfaces in such tanks are at risk of corrosion as the frequent changes in fuel levels expose more of the steel surfaces, including the side walls to moisture laden air.

Historically, coatings for the interiors of Navy fuel tanks has changed and improved with time:

- Prior to storage tank regulations: no coatings - bare steel
- After storage tank regulations: 3 coats of epoxy or 2 coats of epoxy and 1 coat of fluoropolyurethane (FPU)
- Recent Improvement: Polysulfide Modified Novolac Epoxy (PMNE)

In contrast to the above general history and requirements, the interiors of the Red Hill storage tanks have been coated in their entirety starting in 1960, with the FPU specially developed by the Naval Research Laboratory. Since 2008, improved surface preparation methods, and coating application processes include

- Cleaning of the tank plates to remove oil and salt contamination.
- Abrasively blasting of the steel surfaces to near white metal in accordance with SSPC SP-10.
- Coating application with a MIL-DTL-24441 epoxy polyamide primer and intermediate coat and a FPU topcoat in accordance with UFGS 09 97 13.15 (February 2010) “Epoxy/Fluoropolyurethane Interior Coating of Welded Steel Petroleum Fuel Tanks”.
- Provision of dehumidification during surface preparation and coating application processes.

- Surface preparation and coating of the steel liner in sections due to the amount of surface area involved.
- Inspection of the entire coating process by an SSPC QP-5 certified inspector.
- Maintenance of records of the entire coating application process, including post application dry film thickness, adhesion tests, and results of holiday testing.

In 2015, the general Navy coating system specification was revised to specify the application of PMNE as detailed in UFGS 09 97 13.15 (February 2015) "Low VOC Polysulfide Interior Coating of Welded Steel Petroleum Fuel Tanks." Test results on Navy fuel tanks in various locations indicate the coating to be a better life-cycle alternative to the FPU coating.

2-4.3 Current Tank Interior Coating Assessment Practices.

The tank internal protective coatings condition is assessed during routine tank integrity inspection assessments as described in paragraph 2-5. Assessment results dictate the need and scope of repairs for the protective coating system.

During recent Red Hill tank assessment inspections, the FPU coating was observed to have several major areas of deterioration and concern. The majority of the bottom dome and several of the lower shell courses exhibited major flaking, disbonding and large uncoated areas. The shells and upper domes were in fair condition with scattered random areas of deterioration, flaking, disbonding and uncoated areas.

The coatings continued to dry out during the integrity inspection process and additional disbonding and flaking were observed. This continued during the inspection and non-destructive evaluation (NDE) testing activities. Where the coating was hindering the inspection process, loose and disbonded coatings were blasted off, which revealed that in some tanks, approximately 70 - 80 percent of the interior coating was deteriorated and in poor condition, and would need to be properly removed and repaired.

This is a typical problem that occurs on equipment where coating is in an immersed service application. When the equipment is brought out of service and left out of service for an extended period of time, the evaporative /moisture rate of the coating as it dries out can induce tension in the coating if the rate varies (areas where coating thickness varies dramatically), rough surface conditions or there is deterioration which may not be visible (disbonding behind the coating) during an internal inspection. As the coating dries out the tension between the thickness interfaces are greater than the coating limits or strength; causing separation, tearing or disbonding. The areas where improper coating applications, rough surfaces, contamination, voids or bubbles were observed on the original coating application are more likely to fail as they dry out due to coating discontinuities which weaken the overall coating strength.

2-5 TANK INTEGRITY ASSESSMENT.

There is currently a program to clean, inspect and repair all of the tanks with goal of returning the tanks to service for another 20-year cycle. The inspections of the Red Hill tanks are performed in accordance with the requirements of API Standard 653, Tank Inspection, Repair, Alteration and Reconstruction; and as supplemented by the NAVFAC EXWC Contract Statement of Work. The inspection, preliminary and final field reports; tank evaluation and integrity analysis are completed in accordance with applicable general industry practices, codes, standards; federal and local regulations.

Past inspections and repairs of the Red Hill storage tanks indicated that external failures due to corrosion are rare. In general, external corrosion defects were more prevalent in the upper dome areas of the tank. Most observed corrosion defects were due to interior corrosion where the protective coatings failed. Many of the past “leaks” found during leak testing were due to porous and defective welds which were repaired prior to placing the tanks back in service. Although the tanks are repaired and leak tested for their full storage capacity, because of past issues with welds and corrosion in the upper dome, as a standard normal operating procedure, the fuel tanks are not filled to full capacity, but are kept about 25 feet below the full capacity of the tank.

The discovery for the first time of external corrosion on the steel shell plates took place around 1998 during work being done on Tanks 7,8, and 10. The inspectors first noticed a liquid filled blister in the coating of one of the tanks, and they cut open the blister and found that it contained water. The blistered coating was removed which revealed a pinhole on the surface of the shell plate. A vacuum box test confirmed that the pinhole was a "wormhole" that extended completely through the steel plate. A circular coupon containing the wormhole was removed which revealed a small block of wood embedded in the concrete resting against the back of the plate. Paragraph 2-2 provides a brief technical explanation for the occurrence of corrosion at the wood-steel interface in concrete.

2-5.1 Applicable Standards.

American Petroleum Institute (API)

- API Recommended Practice 575, Inspection of Atmospheric and Low-Pressure Storage Tanks, Latest Edition.
- API Standard 650, Welded Steel Tanks for Oil Storage, Latest Edition.
- API Standard 653, Tank Inspection, Repair, Alteration and Reconstruction, Latest Edition.
- API Standard 2550, Measurement and Calibration of Upright Cylindrical Tanks

American Society of Mechanical Engineers (ASME)

- ASME VII Non-Destructive Examination, Latest Edition.
- ASME IX Welding and Brazing, Latest Edition.

National Association of Corrosion Engineers (NACE)

- NACE Recommended Practice, RP0193, External Cathodic Protection of On-Grade Carbon Steel Storage Tank Bottoms.
- NACE Standard Practice, SP0288, *Inspection of Lining Application on Steel and Concrete Equipment*.

National Fire Protection Association (NFPA)

- NFPA-30, Flammable and Combustible Liquids Code.

Steel Tank Institute (STI)

- STI SP001, Standard for the Inspection of Aboveground Storage Tanks.

Unified Facilities Criteria (UFC)

- UFC 3-460-01, Petroleum Fuel Facilities.

Unified Facilities Guide Specification (UFGS)

- UFGS 09 97 13.15 (February 2010), Epoxy/Fluoropolyurethane Interior Coating Of Welded Steel Petroleum Fuel Tank
- UFGS 09 97 13.17, Three Coat Epoxy Interior Coating of Welded Steel Petroleum Storage Tanks
- UFGS 09 97 13.15 (February 2015), Low VOC Polysulfide Interior Coating of Welded Steel Petroleum Fuel Tanks
- UFGS 09 97 13.27, Exterior Coating of Steel Structures
- UFGS 33 56 13.13, Steel Tanks with Fixed Roofs

2-5.2 Technical Discussion.

Current and previous inspections and tank repairs and modifications have been provided over the years that include:

- Removal of leak detection piping inside some of the tanks.
- Repair of defective welds in the upper dome.
- Repair of defective welds in the barrel and lower dome.
- Repair of pitting, holes, and thin areas in the steel liner.
- Removal of grout tube couplings in the steel liner. The couplings were removed during original construction and the openings in the liner repaired with welded patch plates.
- Full coating of all of the Tanks with NRL FPU coating systems as described in previous paragraphs 2-3.3.2 and 2-3.3.3.

The round of inspections that included Tanks 2, 6, 15, 16 and 20 was the first time the tanks received 100 percent scanning of the steel liner plates and welds, a recommendation of the 1998 FACD study for Tank 19.

2-5.2.1 Ultrasonic Testing

Non-destructive examination (NDE) and testing for the tank shell, upper and lower domes, welds and appurtenances is conducted by NDE testing which examine the walls and components for remaining wall thickness measurements. The testing utilizes three different NDE methods:

- Low Frequency Electromagnetic Technique (LFET)
- Balanced Field Electromagnetic Technique (BFET)
- Traditional ultrasonic longitudinal and shear wave inspection for proofing areas. In areas where LFET examination indicates loss of material, Ultrasonic Technique (UT) measurement back up is completed to verify extent of underside corrosion. In areas where BFET examination indicated a discontinuity, UT shear wave or Magnetic Particle Testing (MT) examination was performed to verify extent of the discontinuity and limits for acceptability.

2-5.2.2 **Low Frequency Electromagnetic Technique**

The LFET was developed out of further research of the Remote Field Electromagnetic Technique. The main difference of LFET is the placement of the sensors between the two poles of an electromagnetic driver. With a low frequency AC driver signal of 3 to 40 Hz for carbon steel, the driver signal fully penetrates the material being tested (see Figure 1). When the scanner passes over an area with no defects, the magnetic fields are not distorted.

When the material being scanned has a defect and the sensors are located above that defect, distortions in the magnetic field indicate presence of the flaw. LFET instruments measure this distortion as changes in phase and amplitude. Depth of the flaw is proportional to these phase and amplitude changes. The diameter of the defect is related to the number of sensors affected.

The LFET System consists of a one sixteenth inch modular swath containing 32 probe heads. This configuration allows for 100% coverage of the tank plate. The probe emits a very low frequency electromagnetic field which penetrates the tank plate. Any variation in the tank plate thickness will cause the electromagnetic field to change. These changes are very small, which necessitates the use of digital signal processing to enhance the resulting signal. The resulting processed signal is in the form of phase and amplitude readings. Calibration tables are used to convert these signals into percentage wall loss values.

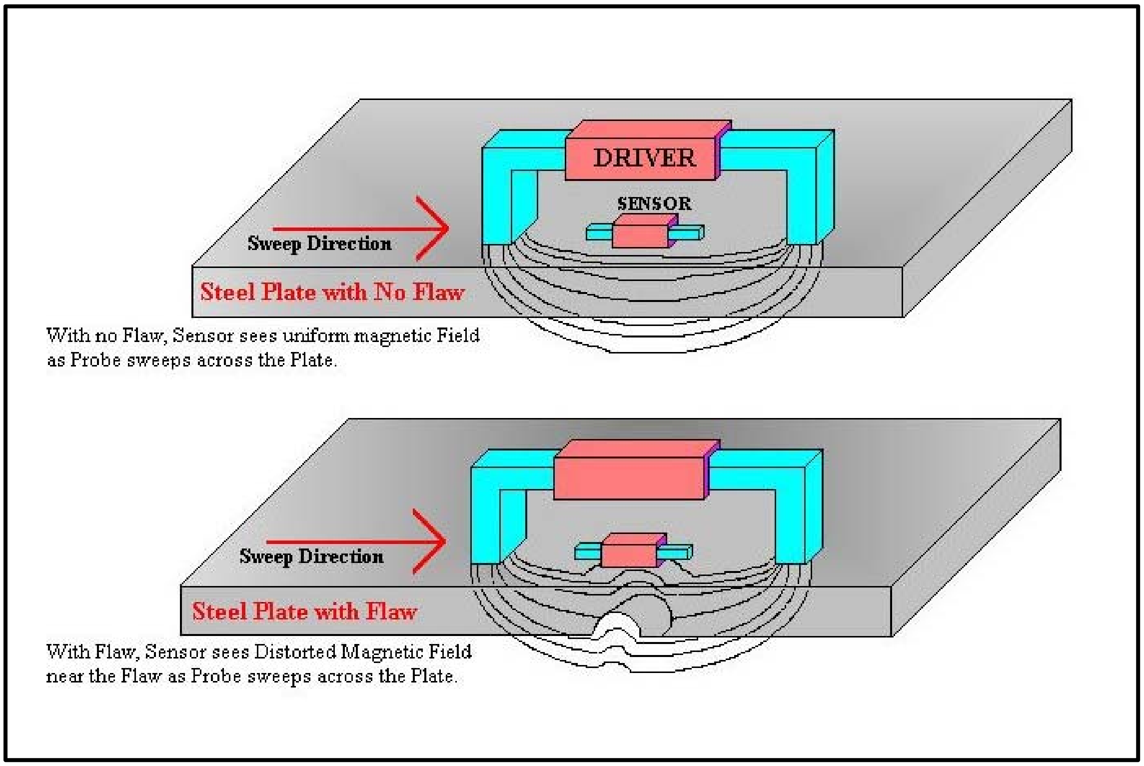

Figure 2-1. Principles of LFET

The data analysis and display module software contains the calibration curves for plate thinning, volume losses, pits, vibration/fret wear, and correlates the calibration standard information with the actual data for flaw sizing and evaluation. It has routines for digital filtering, averaging techniques, background evaluation, curve fitting, and other useful signal processing techniques. Up to three waveforms can be displayed simultaneously on the screen and the "zooming" algorithm enables the user to easily examine small segments of the waveform.

The lock-in amplifier is capable of measuring very low-level signals in the microvolt range and can measure small phase angle changes of a fraction of a degree, even in the presence of a considerable amount of noise. This system, when used in conjunction with the calibration standards for partial and through-wall pitting, gradual wall thinning, hydrogen damage, etc. and their respective calibration curves, allows measurement of small gradual wall losses on the order of 10 percent, pits of diameter 0.062 inch (1.57mm), and vibration/fret wear of five volume percent. Figures 2-2 through 2-5 are examples of scan waveforms.

2-5.2.3 Balanced Field Electromagnetic Technique

A special electromagnetic probe is based on the principle of achieving a “balanced field” for the probe. A single element probe of this type was used to detect “surface and subsurface cracking.” This probe is very sensitive to small changes in electromagnetic field, and the noise is significantly reduced by appropriate phase rotation of the horizontal and vertical component of the signal. This is accomplished through a special algorithm in which the liftoff/probe wobble noise elements are rotated away from the main signal. Processing is used to reduce gradual changes in the waveform to make detection easier.

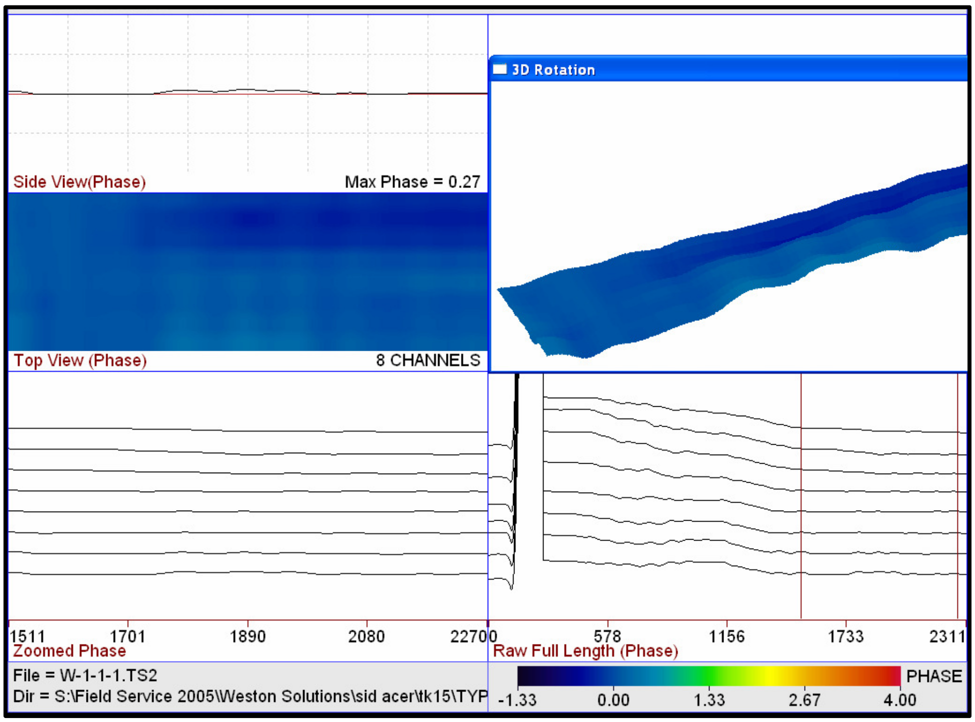

Figure 2-2. Example of an LFET scan indicating nominal plate thickness of 0.250 inch.

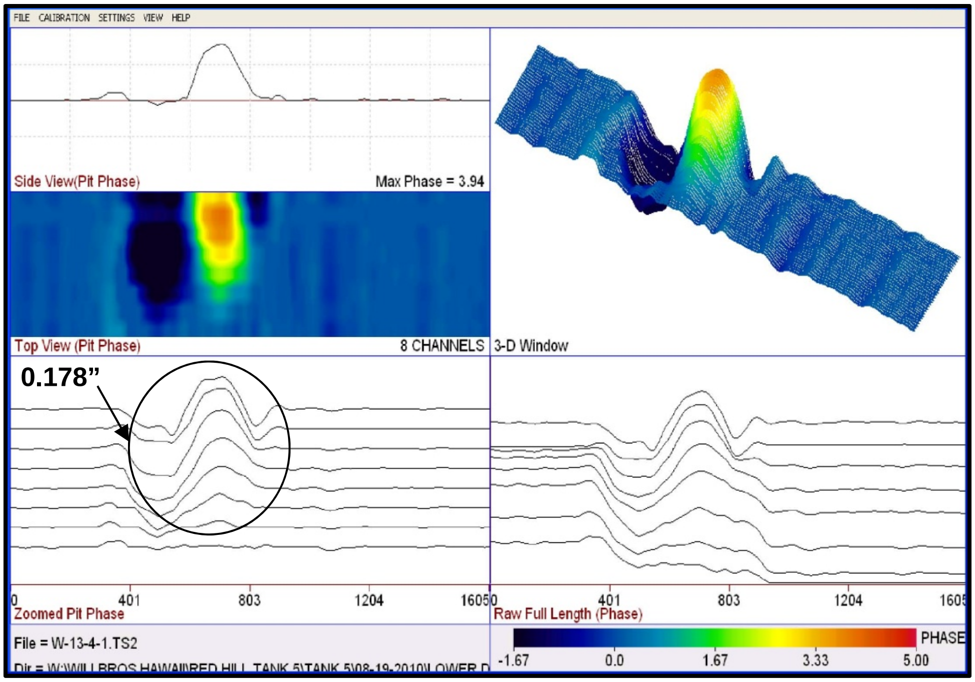

Figure 2-3. Example of an LFET scan indicating underside corrosion exhibiting 0.178 inch remaining wall thickness.

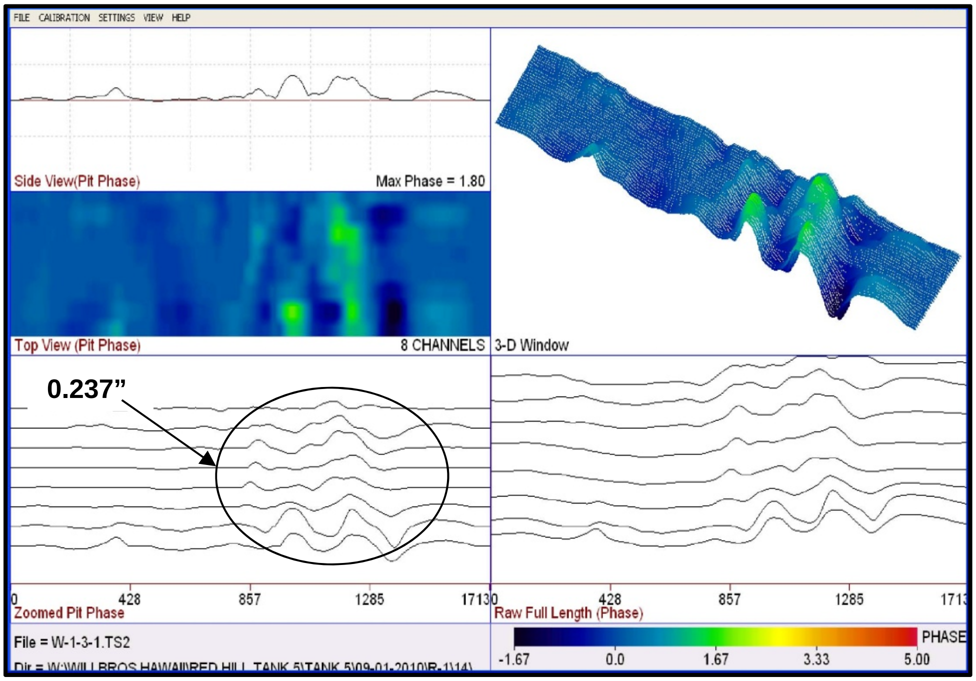

Figure 2-4. Example of an LFET scan indicating underside corrosion exhibiting 0.237 inch remaining wall thickness.

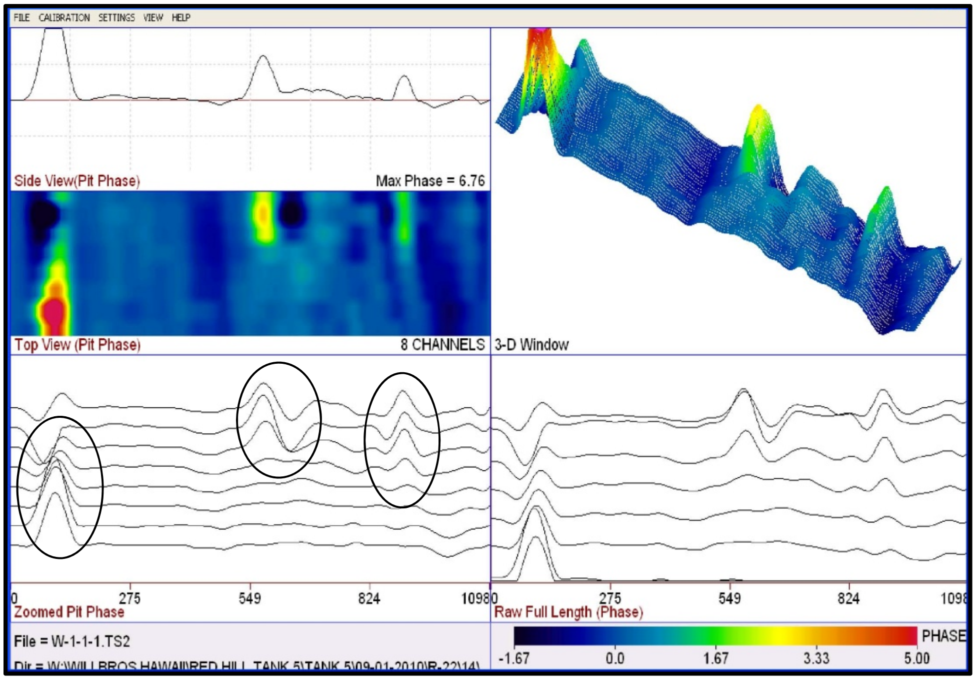

Figure 2-5. LFET scan indicating three dents between 0.200 and 0.240 inch deep.

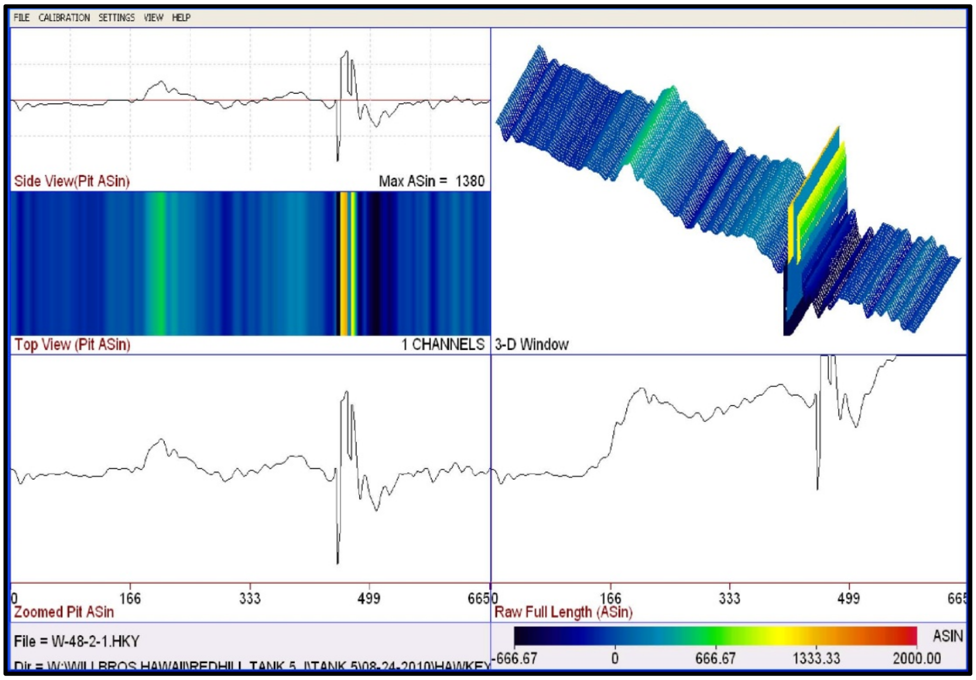

Figure 2-6. Waveform indicating undercutting of a weld 0.125 inch deep and 5.0 inches long.

2-5.2.4 Ultrasonic Shear Wave (Angle Beam) Testing

The instrument used for Shear Wave or Angle Beam Testing is a simple pulse-echo flaw detector with A-Scan, receiving, and transmitting capabilities in which the user can size the length, depth, and distance of the flaw. The primary reason for using shear waves is for the detection of discontinuities with geometries and orientations non-parallel to the testing surface. The Angle Beam technique is extensively used for weld testing at ½ step and full step distances. The frequency range specifically for weld testing with angle beam transducers is 1MHz to 5MHz. The most common Angle Beam contact transducers are designed to produce shear waves of 45, 60, and 70° in steel.

2-5.3 Current Assessment Procedures.

2-5.3.1 Historical Record Review

The API 653 inspector first reviews the available historical records for the entire tank detailing as much information as possible, including the following as accessible:

- Nameplate Information - tank dimensions, capacity, operating and design pressure.
- Tank Data - original manufacturer, construction contractor, and year of construction.
- All applicable construction standards used.
- A general plan drawing, showing the general arrangement of the major components, and the location and size of all penetrations. Product presently stored.
- Design specific gravity, maximum permissible liquid level and maximum operating temperature.
- Shell material and allowable stress of each shell course to be used in calculations.
- Previous inspection reports, as available.
- List and description of any significant environmental (earthquake, hurricane, etc.) or operational (over-pressure, vacuum, foundation settlement, etc.) events.
- Description of any repairs or alterations completed (drawings, material test reports/certifications, radiographs attached, etc.)
- All other pertinent information and details.

2-5.3.2 General Tank Overview

The API 653 inspector conducts a general overview of the tank for compliance with applicable requirements of the latest editions of API 653, *Tank Inspection, Repair, Alteration and Reconstruction,* and modified as appropriate for Red Hill; applicable codes and standards; good tank construction, industry standards and operating practices. This includes as applicable, but is not limited to:

- General assessment of the tank site, soil structures, soil conditions and surrounding areas.
- Description of nearby tanks that could possibly affect the tank undergoing inspection.
- Description of any signs of over-pressure or vacuum such as shell buckling, distortions, dimpling not accounted for in the historical review.
- Description of any signs of significant natural attack or event not accounted for in the historical review.

2-5.3.3 Bottom, Upper & Lower Dome, Shell and Extension Section Inspections

Non-destructive examination (NDE) and testing inspection is conducted on 100% of the tank's welds, shell, upper and lower dome steel plate surfaces to determine the remaining wall thickness and condition of each section or component. The NDE technicians and API 653 inspector conduct examinations and inspections according to Section 5.0 of API 653 and the Navy contract Statement of Work (SOW) requirements [12]. The API 653 inspector performs a comprehensive visual inspection on all tank components, records all relevant observations, and photographs areas as necessary to document the condition of each relevant indication in the tank. LFET or UT readings and visual inspections are conducted as follows:

- Are conducted by certified ASNT Level II NDE Inspection Technicians
- Includes inspection of the upper and lower domes, extension, and shell.
- Any relevant indications or defects are mapped in the Tank Inspection Report and marked on the tank surface.
- Any relevant corrosion areas are mapped in the Tank Inspection Report and marked on the tank surface.
- In areas where LFET examination indicates loss of material, UT back up measurements are taken to verify extent of underside corrosion.

BFET/UT or MT inspections are conducted as follows:

- Are conducted by a certified API 653 Tank Inspector and ASNT Level II NDE Inspection Technician.
- Includes inspection of all welds.
- Any relevant indications or defects are mapped in the Tank Inspection Report and marked on the tank surface.
- In areas where BFET examination indicates a discontinuity, UT shear wave or MT examination is performed to verify extent of the discontinuity and limits for acceptability.

The tank shell is measured in accordance with API 653 for dimensional tolerances. All measurements, including peaking, banding, plumbness and roundness, are performed in accordance to API 653 and recorded in the inspection report and engineering data.

2-5.3.4 Ultrasonic Testing

Non-destructive examination and testing for the tank shell, upper and lower domes, welds and appurtenances is conducted by two (2) non-destructive examination and testing crews that examine the walls and components for remaining wall thickness readings. The NDE testing and evaluation is performed on 100 percent of courses A, B, C, D, E and F of the upper dome; the extension (including the manway); the tank's shell barrel (including under the cat walk); courses 1, 2, 3, 4 of the lower dome; and the floor. The LFET is used for component scanning for wall thickness and back side corrosion, with UT prove up as needed for actual wall condition or weld quality. The BFET is used to evaluate the accessible tank welds for surface and toe cracks. Ultrasonic (UT) shear wave and magnetic particle (MT) color contrast dry particle testing are used for prove up of the BFET scans as needed.

2-5.3.5 Methodology for Determining Repairs

Current and previous inspections have found defects in the tank liner (weld quality and corrosion) that required repair before returning the tanks to service. The current tank assessment program intent is to clean, inspect and repair all of the tanks with the goal of returning the tanks to service for another 20-year service interval. The current approach consists of performing an out-of service inspection of the tank interior (including scanning the steel liner plates and welds for corrosion and other defects) and repairing defects found during the inspection. Under this approach, select defects such as holes and cracks and only those areas having a remaining thickness below a predetermined minimum thickness of 0.170 inch are repaired. Areas having a remaining thickness less than 0.170 inches and holes are repaired by welding patch plates over the area in accordance with API 653.

The assessment consists of calculating an external corrosion rate and a minimum required thickness of the 0.250-inch thick steel liner plates. This minimum thickness serves as the screening criteria for determining whether to repair thin areas and pits in the steel liner plates for another 20-year interval until the next inspection. For example an external corrosion rate of 0.001744 inches/year for Tanks 2 and 20 was calculated using the linear method of API 653, a remaining thickness of 0.100 inch at the end of a 20-year service interval in 2028, and other parameters as follows [13]:

Original thickness of plates: 0.250”
Remaining thickness at next inspection: 0.100”
Interval until next inspection: 20 years maximum
Year tank constructed: 1942

Maximum permissible metal loss = 0.250” – 0.100” = 0.150”
Age of tank in 2028: 2028 – 1942 = 86 years

A 0.100 inch remaining minimum thickness is an assumption used as the steel liner plates are a hydraulic barrier and are not relied upon as a structural element to resist hoop and tensile stresses in the barrel and lower dome, or compressive stress in the upper dome. The 0.100 inch criterion is similar to API 653 Section 4.4.5 criteria for tank floors that requires the bottom thickness to be calculated no less than 0.100 at the end of the in-service period.

Considering that the 0.150 inch of maximum metal loss occurs over the life of the tank, the external corrosion rate is calculated as follows:

External corrosion rate = 0.150”/86 years = 0.001744 inch/year

Recognizing that the external corrosion is a theoretical rate, twice the corrosion rate (i.e. 0.003488 inch/year) was used as a conservative engineering assumption made following a similar practice in API 570 to calculate a minimum thickness for repair screening criteria. At two times the corrosion rate, the metal loss expected to occur during the next 20 years is

Metal loss during next 20 years = 0.003488 inch/year X 20 years
= 0.070 inch/year

The minimum thickness (t_{min}) at the present time required to have at least 0.100 inch at the 20 year maximum inspection interval at twice the corrosion rate of 0.003488 inch/year) is

t_{min} = 0.070” + 0.100” = 0.170 inch

The calculated minimum thickness of 0.170 inch was used as the screening criteria for several tanks in determining whether thin and pitted areas in the 1/4-inch thick steel liner plates require repair. At twice the calculated corrosion rate of 0.003488 inch/year, the steel liner will reach a minimum thickness of 0.100” in 20 years and is predicted to penetrate through in 48.7 years. Data and lessons learned from future tank inspections may result in revising the screening t_{min} criteria

2-5.3.6 Example of Determined Repairs (Tank No. 5)

Over 800 various indications and flaws were found during the API 653 inspection including 404 found by NDE examination of Tank 5 surfaces and components in the following locations of the tank and classification type [14]:

Area

Upper Dome	110
Extension	30
Barrel	205
Lower Dome	57
Floor	2

Type

Underside corrosion (WL)	153
Underside corrosion around patch plates/anchors [WL (APP)]	50
Underside corrosion on patch plates/anchors [WL (OPP)]	46
Through holes	0
Topside (pits (SP), gouges (G), tack welds (TW))	36
Dents (D)/bulges	20
Weld (WD): LOF/IP/Porosity/Undercutting	40
Weld: Cracking	1
Grout Nozzles (GN)	48
No Reportable Indication (NRI)	10

Most of these indications or flaws are relatively small in overall size and repair(s) that will be required. Due to the types of indication or flaw sizes, depths and conditions found in Tank 5; it was found not suitable to return to service until all of the items identified were repaired as appropriate for the intended service and operational interval. Tables in the inspection report describe the repairs by type, size, classification and action to be taken. The following is a summary of repairs required and classification for mandatory, short term and long term intervals:

Mandatory Repairs are immediate repairs required before returning tank to service.

- Repair areas where pits, gouges or corrosion are less than the minimum thickness (t_{min}) required.

Short Term Repairs are repair indications or flaws found that have the criteria which exceeds the intended (10-year) service and operational interval.

- Repair areas where pits, gouges or corrosion are less than the minimum thickness (t_{min}) required for this interval.
- Repair coating in areas required to eliminate corrosion cells on internal surfaces, extend component service life and inspection intervals.

Long Term Repairs are repair indications or flaws found that have the criteria which exceeds the intended (20-year) service and operational interval.

- Repair areas where pits, gouges or corrosion are less than the minimum thickness (t_{min}) required for this interval.
- Repair coating in areas required to eliminate corrosion cells on internal surfaces, extend component service life and inspection intervals.

CHAPTER 3 METAL FATIGUE DESIGN CONSIDERATIONS

3-1 INTRODUCTION

Fatigue is the process of progressive localized permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point or points and that may culminate in cracks or complete fracture after a sufficient number of fluctuations. Fluctuations may occur both in load and with time (frequency) as in the case of random vibration [15]. The following concepts are important perspectives related to the phenomenon of fatigue:

- Process
- Progressive
- Localized
- Permanent structural change
- Fluctuating stresses and strains
- Point or points
- Cracks or complete fracture

Fluctuating stresses and strains are important elements. The need to have fluctuating (repeated or cyclic) stresses acting under either constant amplitude or variable amplitude is critical to fatigue. When a failure is analyzed and attributed to fatigue, the only thing known at that point is that the loads (the stresses/strains) were fluctuating.

In simplest terms, failure occurring under conditions of dynamic loading is called fatigue failure. In metals these failures can occur at much lower repetitive or fluctuating stress than that required to cause fracture on a single application of load. It occurs with no gross deformation at the fracture, which usually initiates at a point of stress concentration, and produces a brittle-appearing fracture surface.

3-1.1 Stages of Fatigue.

Studies of fatigue divide the process into stages:

- Crack initiation – plastic stresses in localized areas, usually at stress concentrations on the surface or at pre-existing defects.
- Stage I and II crack growth – crack propagation that can be expressed in terms of the stress intensity factor K defined by fracture mechanics.
- Final fracture – ultimate ductile failure when the crack reaches sufficient length that the remaining cross section can no longer carry the load.

In the case of fuel storage tanks, final fracture is not necessary; just sufficient propagation of a crack completely through the metal is necessary to cause a leak.

3-1.2 Necessary Factors.

Three basic factors are necessary for a fatigue crack initiation and propagation.

- A minimum tensile stress of sufficiently high value.
- A large enough variation in the stress.
- A sufficient number of cycles of stress.

Numerous other factors including stress concentrations, corrosion, temperature, residual stress, and metallurgical structure, affect the conditions required for failure.

3-1.3 Endurance Limit.

The basic method of presenting engineering fatigue data is by means of the S-N curve, a plot of the stress, S, verses the number of cycles to failure, N. Normal practice is presentation of the results for complete reverse bending, where the mean stress is zero. The number of cycles of a given stress a metal can endure before failure increases with decreasing stress. At a certain limiting stress for steel, the S-N curve becomes horizontal. Presumably below this limit, the material can endure an infinite number of cycles without failure. However, it must be recognized that fatigue life and endurance limit are statistical quantities. Every test specimen will have its own fatigue limit, and the critical stress will vary from specimen to specimen for subtle reasons.

3-1.4 Stress Cycles.

While S-N curves based on complete reverse bending provide valuable information, real world loading is normally more complex. Figure 3-1 presents three loading scenarios. The blue curve represents completely reversed cycles of stress of sinusoidal form used for generating S-N curves. In this case the stress alternates between equal tension and compressive stresses. However, commonly, the stress experienced is much more complex. The yellow curve represents a repeated stress cycle while remaining in tension. The red curve represents a irregular or random stress cycle.

A fluctuating stress cycle can be thought of consisting of two components, a mean stress, and an alternating stress. The range of stress is the difference between the maximum and minimum stress in a cycle. The alternating stress is considered one-half the range of stress. The mean stress is considered the algebraic mean of the maximum and minimum stress in the cycle. Studies have shown that non-zero mean stress significantly affects fatigue life, with crack propagation rates increasing with higher mean stress.

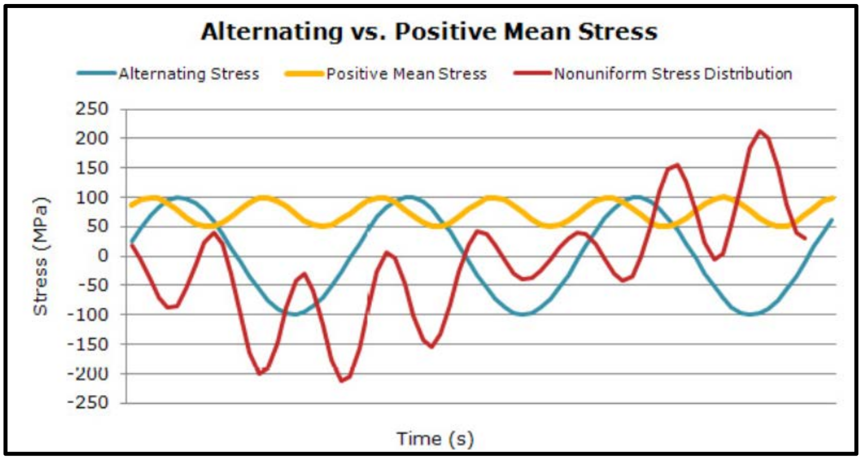

Figure 3-1. Stress Loading Scenarios

3-2 SPECIFIC CONSIDERATIONS

3-2.1 Stress Concentrations.

Fatigue strength is reduced considerably by the introduction of stress risers (locations of increased stress due to some irregularity in the metal) such as those created by surface irregularities. In part this explains why practically all fatigue failures start at the surface. Additionally, for common types of loading, like bending and torsion, the maximum stress occurs at the surface. However, failures with axial loading normally initiate at the surface as well.

Irregularities created by scrapes, deformations, plate attachments and penetrations, and corrosion, as well as the inherent plate surface roughness itself, all affect fatigue strength. In lieu of major anomalies, the greatest concentration of these stress risers may be considered to be at shell plate welds.

3-2.2 Residual Stress.

For practical purposes of analysis, residual stress can be considered to be the same as stresses produced by an external force. The most significant cause of residual stress may be the steep temperature gradient introduced by welding. Proper welding procedures can minimize the introduction of this stress. This is particularly important where residual stress is added to high service loading which may be experienced at shell girth seams.

3-2.3 Sources of Fatigue.

There are numerous sources of cyclic loading. These may be considered high cycle as in the case of mechanical equipment vibrations, or low cycle ($N<10^4$ cycles), which more typically would include stress due temperature variations, or fuel level fluctuations.

3-2.4 Approach to Engineering Analysis of Fatigue Strength.

Upon material verification, if in the unlikely event applicable data already exists, S-N curves could be generated through testing a series of specimens to establish endurance limits. Notched specimens as well as un-notched specimens would be desirable, to evaluate the effect of stress risers.

The difficulty in application of this data lies in establishment of the load history of the tank plates and components. As discussed in paragraph 3-1 numerous factors can influence fatigue behavior. While the tanks might be instrumented in some manner to acquire real time data, extrapolation over the tanks lifetime would prove difficult. However, this analysis may validate assumptions that the cyclic stresses are sufficiently low or of insufficient numbers to be an issue.

As discussed in paragraph 3-2.1, greatest stresses would be expected at welds between steel plates. If it can be shown that the inspection techniques that have been employed in the tanks are sufficiently sensitive to fatigue crack detection, these inspections may serve as an indication that fatigue is not an issue.

3-3 TANK DESIGN FEATURES

3-3.1 Applicable Standards.

American Petroleum Institute (API)

- API Standard 650, Welded Steel Tanks for Oil Storage, Latest Edition.
- API Standard 653, Tank Inspection, Repair, Alteration and Reconstruction, Latest Edition.

American Society for Testing and Materials (ASTM)

- ASTM E 1150-1987, Standard Definitions of Fatigue

American Society for Materials (ASM)

- ASM Handbook, Volume 19, Fatigue and Fracture

Unified Facilities Criteria (UFC)

- UFC 3-460-01, Petroleum Fuel Facilities.

3-3.2 Tank Construction Features/Operational Procedures Impacting Metal Fatigue.

3-3.2.1 Material.

Although not confirmed, the most likely material used for shell plates was ASTM A283, “Low and Intermediate Tensile Strength Carbon Steel Plates of Structural Quality”, Grade C. This material has a tensile requirement of 55,000 to 65,000 psi, and a minimum yield point requirement of 30,000 psi (per 1974 revision). The material also has specific elongation, bend test, and chemical requirements. Metallurgical analysis of the tank shell plate is the only method of verification the shell plate chemical composition, and its physical and mechanical properties.

3-3.2.2 Operational Procedures

The Red Hill storage tanks are bulk fuel storage tanks in which under normal operation, fuel storage levels are static for months at a time, and may sit in storage for up to two years, unlike operational issue tanks or small gas station storage tanks in which fuel storage levels are dynamic with frequent changes in fuel levels (dispensing and refilling). Static fuel levels in the Red Hill tanks limit susceptibility to fatigue issues that may be experienced by smaller tanks with fluctuating fuel levels.

To date, there has been no inspection data that suggest any metal fatigue issues in the tanks. If under certain rare operational circumstances where the steel plates experience cyclic loads or stresses, fatigue would be expected to culminate in cracks in the tank steel plate welds. However, the welds undergo 100% NDE during the API 653 tank assessments, and any defective welds are repaired.

CHAPTER 4 HISTORICAL RECORDS

4-1 GENERAL

This report section provides a brief description of the recordkeeping practices and procedures for corrosion prevention and control of the Red Hill Storage tanks.

4-2 HISTORICAL RECORDS PRACTICES

The subsections of this paragraph will identify recordkeeping practices and procedures at each of the different known entities responsible for keeping records. The paragraphs describe available data such as as-built tank drawings, project construction report excerpts, historical corrosion assessment reports, and other site-specific data that constitute Navy recordkeeping practices and analyses for the Red Hill fuel storage tanks using historical records.

4-2.1 Fleet Logistics Center Pearl Harbor

The Fleet Logistics Center (FLC) Pearl Harbor, as the operators of the Red Hill Facility, maintains the official records of the facility. Most of the printed copies of records including studies, reports, and contract correspondence, are maintained on designated shelving in a Technical Library at the FLC Pearl Harbor Fuel Office. The files are catalogued and arranged in chronological order on the shelves, and include available historical records from construction of the facility up through the latest tank integrity assessments and repair efforts.

Besides the inspection and NDE scan data, the recent tank inspection reports done since 2005 include

- Tabular lists of all defects found. Figure 4-1 is an example.
- Identification of the location of the defects on a schematic drawing of the tank. Figure 4-2 is an example.
- Photo documentation of the defect(s) where possible and necessary to document the defect(s). Figure 4-3 is an example.
- An explanation of the methodology used to calculate the steel tank corrosion rates as well as the minimum wall thickness used to generate actionable repair requirements (Refer to paragraph 2-3.5.3).
- Tabulated list of repair requirements. Figure 4-4 is an example.

FLC Pearl Harbor also maintains drawings of all of their facility assets including the Red Hill Storage Facility. The drawing files are also located at the FLC Pearl Harbor Fuel Office, adjacent to the Technical Library. FLC Pearl is currently undertaking a process of creating electronic copies of their drawings, and some of the Red Hill Facility drawings have already been scanned and are stored electronically on a central computer.

4-2.2 Naval Facilities Engineering Command (Expeditionary Warfare Center/ Pacific/ Hawaii)

NAVFAC is the execution agent for much of the work requiring engineering, repairs and modification to the facilities. NAVFAC execution offices retain records for contract file purposes and as background information/lessons learned for subsequent efforts. Most, if not all of the technical reports generated are duplicates of copies available in the FLC Pearl Harbor technical library. Project engineers will retain printed copies of the reports for a period of time, and electronic copies are retained on desktop computers as well as central computers.

As the primary execution agent and subject matter expertise for POL facilities, the Naval Facilities Engineering and Expeditionary Warfare Center (NAVFAC EXWC) analyzes the tank inspection results and historical data and modifies the tank inspection statement of work based upon lessons learned.

4-2.3 Other Known Repositories

Work has also been managed by execution agents other than NAVFAC. These execution agents are also known to have retained records for contract file purposes. The availability of these records is dependent upon those that are retained by the project management, and some have been made available to the Navy upon request.

Contractors who have performed work on the Red Hill facility are also known to retain records of their work for their contract file purposes. On occasion, they have provided copies of available specific historical records upon request.

WILLBROS

Tank Inspection Data – Lower Dome **Table 6-1** Date: 11/16/2010 Rev B

Row No.	Plate No.	Description of Condition / Inspection Findings	Picture / Sketch	Repair Type	Repairs Required
C3	18	**Plate: Condition** – Good **Distortions** – Up to 1" within the radius. **Corrosion** - Light scattered corrosion and pitting up to 0.030" in depth, with size(s) from 1/8" to 1/4" diameter. Isolated corrosion and pitting up to 0.030" in depth, with size(s) from 3/16" to 3/4" in length. No relevant areas of corrosion were found. **Welds:** Overall fair condition. **Corrosion** - Light scattered corrosion and pitting, no relevant areas were found. **Discontinuities** – Scattered undercutting within code; scattered areas of excess reinforcement. **Paint / Coating:** Overall poor; with areas disbonded, flaking or missing.			
C3	19	**Plate: Condition** – Good **Distortions** – Up to 1" within the radius. **Corrosion** - Light scattered corrosion and pitting up to 0.030" in depth, with size(s) from 1/8" to 1/4" diameter. Isolated gouge up to 0.080" in depth, with size(s) from 3/16" to 1 1/2" in length and 0.095" in depth by 1/2" diameter. No relevant areas of corrosion were found. **Welds:** Overall fair condition. **Corrosion** - Light scattered corrosion and pitting, no relevant areas were found. **Discontinuities** – Scattered undercutting within code; scattered areas of excess reinforcement. **Paint / Coating:** Overall poor; with areas disbonded, flaking or missing.	#43 #43A (P)C3-19-1 (P)C3-19-2	S S L	Gouge Repair- 0.080" 3/16" x 1 1/2" L Gouge Repair- 0.095" x 1/2" dia Gouge Repair- 0.060" x 1/2" dia
C3	20	**Plate: Condition** – Good **Distortions** – Up to 1" within the radius. **Corrosion** - Light scattered corrosion and pitting up to 0.030" in depth, with size(s) from 1/8" to 1/4" diameter. No relevant areas of corrosion were found. **Welds:** Overall fair condition. **Corrosion** - Light scattered corrosion and pitting, no relevant areas were found. **Discontinuities** – Scattered undercutting within code; scattered areas of excess reinforcement. **Paint / Coating:** Overall poor; with areas disbonded, flaking or missing.			
C3	21	**Plate: Condition** – Good **Distortions** – Up to 1" within the radius. **Corrosion** - Light scattered corrosion and pitting up to 0.030" in depth, with size(s) from 1/8" to 1/4" diameter. Isolated gouge up to 0.080" in depth, with size(s) from 3/16" to 2" in length. No relevant areas of corrosion were found. **Welds:** Overall fair condition. **Corrosion** - Light scattered corrosion and pitting, no relevant areas were found. **Discontinuities** – Scattered undercutting within code; scattered areas of excess reinforcement. **Paint / Coating:** Overall poor; with areas disbonded, flaking or missing.	#41 #41B	M S	Plate Repair- Tack Weld 2" L Gouge Repair- 0.080" 3/16" x 2"L
C3	22	**Plate: Condition** – Good **Distortions** – Up to 1" within the radius. **Corrosion** - Light scattered corrosion and pitting up to 0.030" in depth, with size(s) from 1/8" to 1/4" diameter. Isolated corrosion and pitting up to 0.030" in depth, with size(s) from 1/8" to 16" in length. Isolated gouge up to 0.080" in depth, with size(s) from 3/16" to 2" in length. No relevant areas of corrosion were found. **Welds:** Overall fair condition. **Corrosion** - Light scattered corrosion and pitting, no relevant areas were found. **Discontinuities** – Scattered undercutting within code; scattered areas of excess reinforcement. **Paint / Coating:** Overall poor; with areas disbonded, flaking or missing.	#41A (P)C3-22-1	S	Gouge Repair- 0.080" 3/16" x 1 3/4" L
C3	23	**Plate: Condition** – Good **Distortions** – Up to 1" within the radius. **Corrosion** - Light scattered corrosion and pitting up to 0.030" in depth, with size(s) from 1/8" to 1/4" diameter. Isolated corrosion and pitting up to 0.045" in depth, with size(s) up to3/8" diameter. No relevant areas of corrosion were found. **Welds:** Overall fair condition. **Corrosion** - Light scattered corrosion and pitting, no relevant areas were found. **Discontinuities** – Scattered undercutting within code; scattered areas of excess reinforcement. **Paint / Coating:** Overall poor; with areas disbonded, flaking or missing.			
C3	24	**Plate: Condition** – Good **Distortions** – Up to 1" within the radius. **Corrosion** - Light scattered corrosion and pitting up to 0.030" in depth, with size(s) from 1/8" to 1/4" diameter. Isolated corrosion and pitting up to 0.045" in depth, with size(s) up to 3/8" diameter. No relevant areas of corrosion were found. **Welds:** Overall fair condition. **Corrosion** - Light scattered corrosion and pitting, no relevant areas were found. **Discontinuities** – Scattered undercutting within code; scattered areas of excess reinforcement. **Paint / Coating:** Overall poor; with areas disbonded, flaking or missing.	(P)C3-24-1	L	Pit Repair- 0.045" x 3/8" dia.
C3	25	**Plate: Condition** – Good **Distortions** – Up to 1" within the radius **Corrosion** - Light scattered corrosion and pitting up to 0.030" in depth, with size(s) from 1/8" to 1/4" diameter. Isolated corrosion and pitting up to 0.040" in depth, with size(s) from 1/8" to 1/2" in length. No relevant areas of corrosion were found. **Welds:** Overall fair condition. **Corrosion** - Light scattered corrosion and pitting, no relevant areas were found. **Discontinuities** – Scattered undercutting within code; scattered areas of excess reinforcement. **Paint / Coating:** Overall poor; with areas disbonded, flaking or missing.			
C3	26	**Plate: Condition** – Good **Distortions** – Up to 1" within the radius. **Corrosion** - Light scattered corrosion and pitting up to 0.030" in depth, with size(s) from 1/8" to 1/4" diameter. No relevant areas of corrosion were found. **Welds:** Overall fair condition. **Corrosion** - Light scattered corrosion and pitting, no relevant areas were found. **Discontinuities** – Scattered undercutting within code; scattered areas of excess reinforcement. **Paint / Coating:** Overall poor; with areas disbonded, flaking or missing.			
C3	27	**Plate: Condition** – Good **Distortions** – Up to 1" within the radius. **Corrosion** - Light scattered corrosion and pitting up to 0.030" in depth, with size(s) from 1/8" to 1/4" diameter. No relevant areas of corrosion were found. **Welds:** Overall fair condition. **Corrosion** - Light scattered corrosion and pitting, no relevant areas were found. **Discontinuities** – Scattered undercutting within code; scattered areas of excess reinforcement. **Paint / Coating:** Overall poor; with areas disbonded, flaking or missing.			

Figure 4-1. Example excerpt from list of flaws.

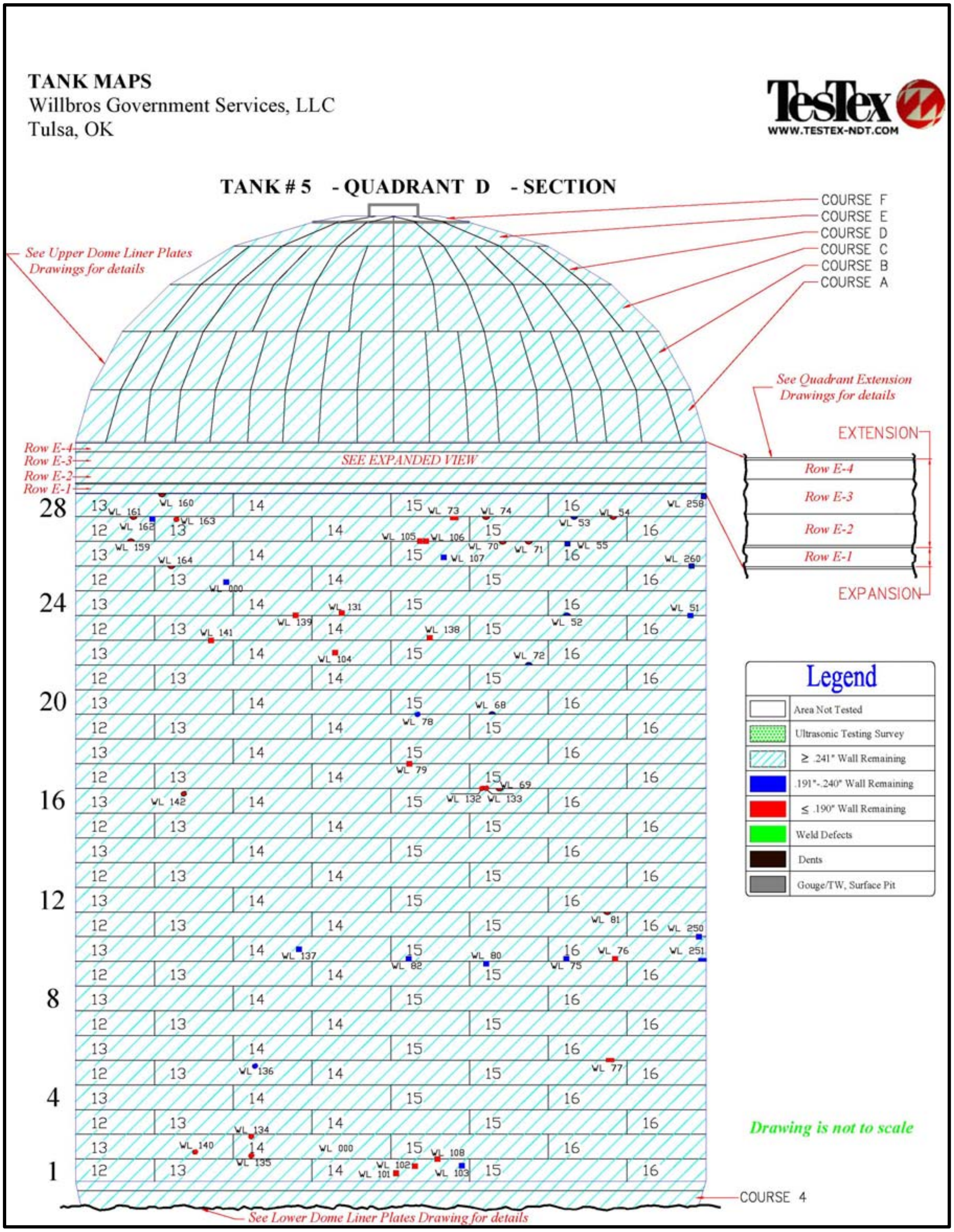

Figure 4-2. Example schematic drawing showing locations of flaws.

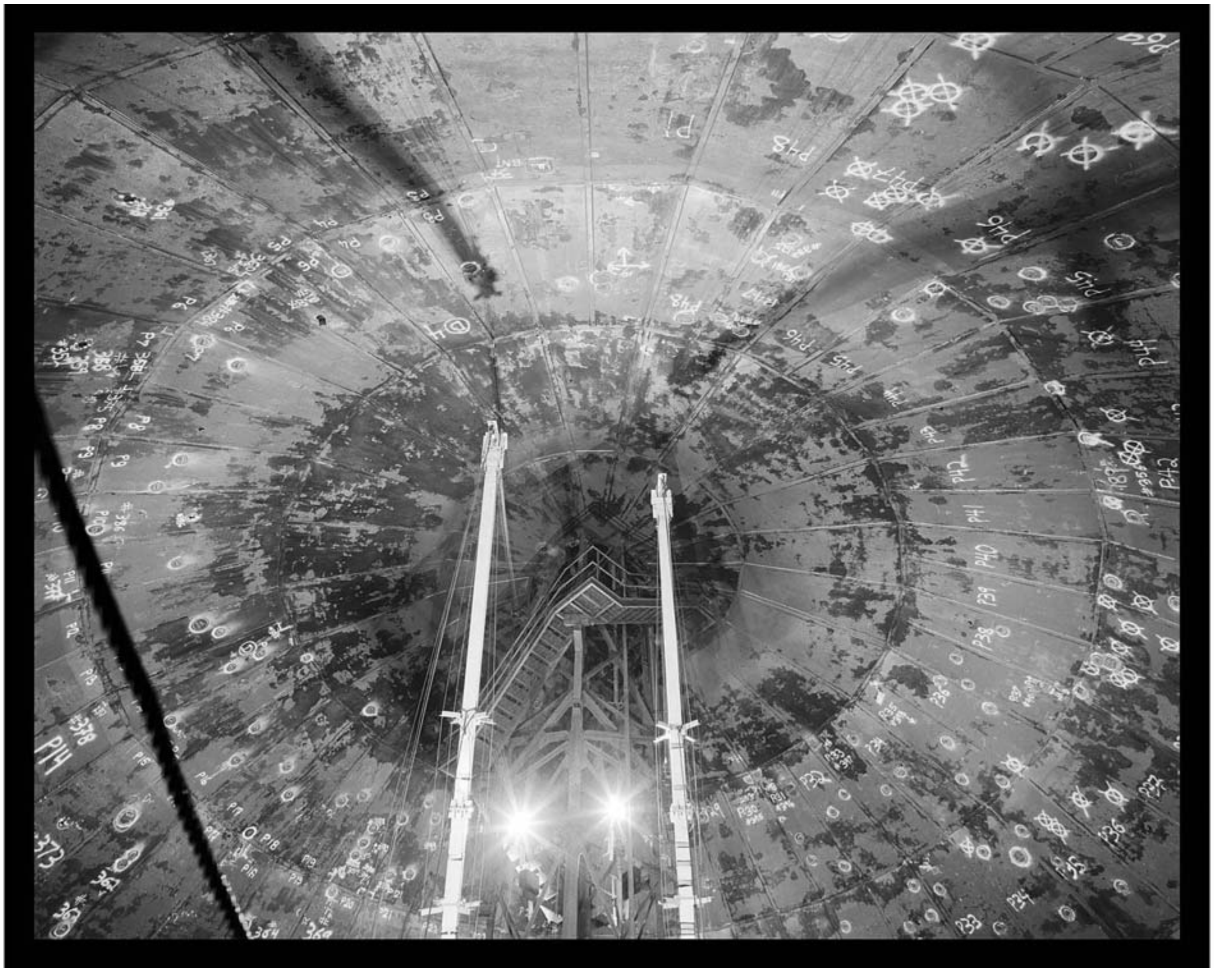

Figure 4-3. Example photo (black and white copy) of noted defects in tank upper dome

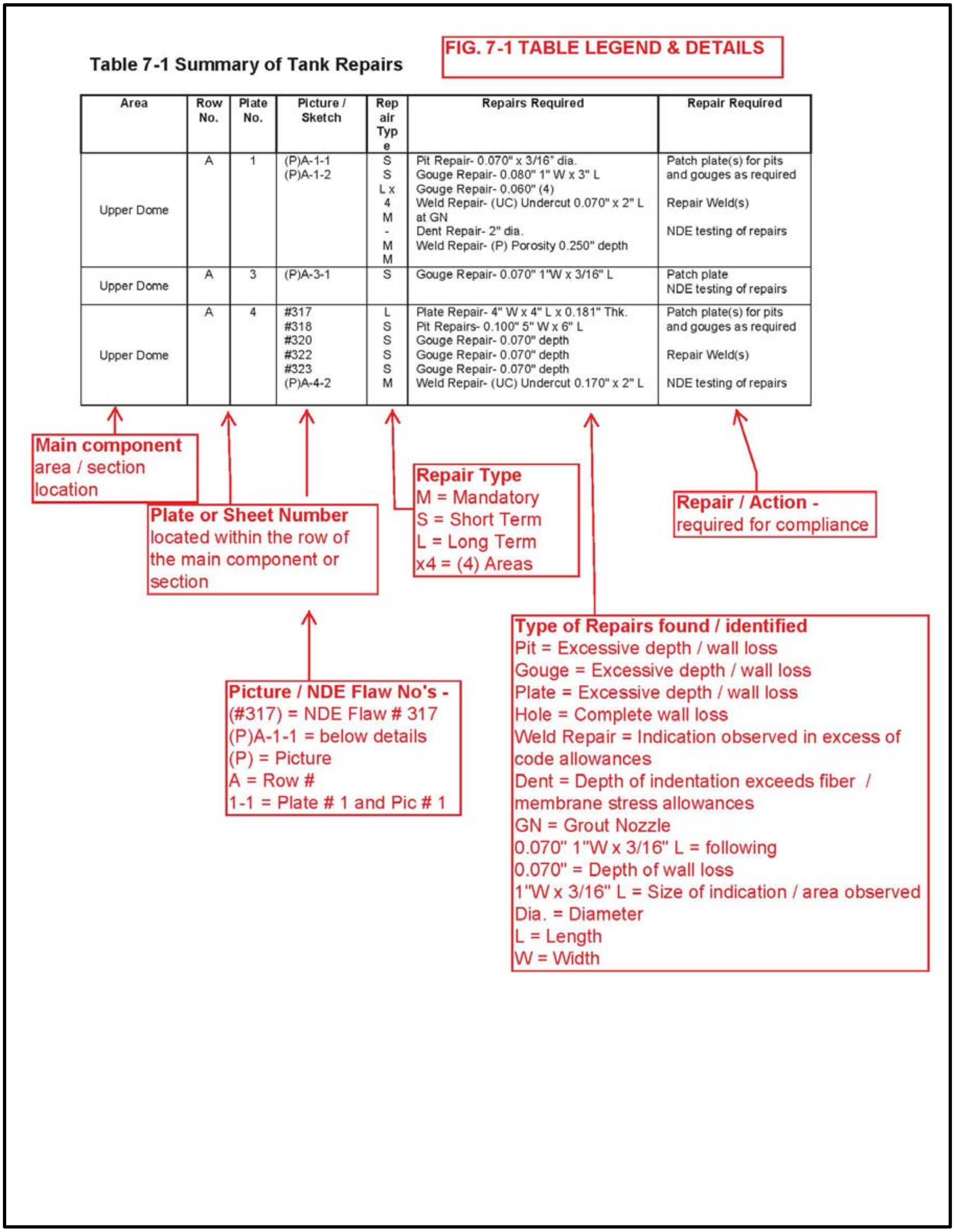

Table 7-1 Summary of Tank Repairs

Area	Row No.	Plate No.	Picture / Sketch	Repair Type	Repairs Required	Repair Required
Upper Dome	A	1	(P)A-1-1 (P)A-1-2	S S L x 4 M - M M	Pit Repair- 0.070" x 3/16" dia. Gouge Repair- 0.080" 1" W x 3" L Gouge Repair- 0.060" (4) Weld Repair- (UC) Undercut 0.070" x 2" L at GN Dent Repair- 2" dia. Weld Repair- (P) Porosity 0.250" depth	Patch plate(s) for pits and gouges as required Repair Weld(s) NDE testing of repairs
Upper Dome	A	3	(P)A-3-1	S	Gouge Repair- 0.070" 1"W x 3/16" L	Patch plate NDE testing of repairs
Upper Dome	A	4	#317 #318 #320 #322 #323 (P)A-4-2	L S S S S M	Plate Repair- 4" W x 4" L x 0.181" Thk. Pit Repairs- 0.100" 5" W x 6" L Gouge Repair- 0.070" depth Gouge Repair- 0.070" depth Gouge Repair- 0.070" depth Weld Repair- (UC) Undercut 0.170" x 2" L	Patch plate(s) for pits and gouges as required Repair Weld(s) NDE testing of repairs

Figure 4-4. Example excerpt of repair requirements list with table legend

CHAPTER 5 SUMMARY

5-1 GENERAL

In response to a fuel release reported by the Navy, An Agreement on Consent between the Navy, EPA, and DOH provides for the performance by Navy and DLA of a release assessment, response(s) to release(s), and actions to minimize the threat of future releases in connection with the field-constructed bulk fuel USTs, surge tanks, pumps, and associated piping at the Red Hill Bulk Fuel Storage Facility located near Pearl Harbor, on the island of Oahu in the State of Hawaii.

The purpose of this Corrosion and Metal Fatigue Practices Report is to describe current practices to control corrosion of the Red Hill Storage Tanks and evaluate the possibility and extent of and metal fatigue at the Facility in accordance with the AOC-SOW. The report includes an explanation of the current practices for assessing the condition of the Tanks and associated fuel containment infrastructure. Additionally, the report describes any recordkeeping relating to corrosion and metal fatigue practices at the Facility.

5-2 CURRENT CORROSION ASSESSMENT PRACTICES

5.2.1 Tank Construction Features – Effects on Corrosion Control and Assessment Practices

The Red Hill storage tanks were constructed by excavating the lava rock formation of Red Hill to create a vault for each tank which was then lined with concrete and a 0.250 inch thick steel liner. The highly alkaline lowers the rate of the anodic reaction (corrosion) to an extremely low value, and penetration of the 0.25 inch thick liner wall would not be an engineering concern.

5-2.2 Cathodic Protection

Cathodic protection cannot be practicably installed on the Red Hill storage tanks. The biggest hindrance to applying CP to the Red Hill storage tanks would be the ability to distribute the protective current to the entirety of the exterior steel liner surfaces (the cathodes in a CP system). CP systems are electrical systems and will require the ability to conduct electrical current from a current source, i.e. one or more power sources and an anode system installed around the tanks, to the exterior tank surfaces. However, the rock and concrete environment surrounding the tanks are very poor electrically conductive media rendering it very highly impractical to provide functioning retrofit CP systems. Even if one were to assume that there are fissures and cracks in the rock and concrete to permit electrical current flow, there would be no practical way of assuring that the electrical current is being evenly distributed to the entire exterior surface of each of the tanks. Additionally, any reinforcing steel in the concrete surrounding the tanks would also block or drain away protective current intended for the tank surfaces.

5-2.3 Internal Protective Coating

Historical construction records do not indicate that protective coating systems were applied to the exterior surfaces of the steel plate during construction. A protective coating cannot be applied now as there is no access to the external walls of the tank.

The interiors of the Red Hill storage tanks have been coated in their entirety starting in 1960, with the FPU coating specially developed by the Naval Research Laboratory. Since 2008, improved surface preparation methods, and coating application processes have been implemented.

In 2015, the general Navy coating system specification was revised to specify the application of PMNE as detailed in UFGS 09 97 13.15 “Low VOC Polysulfide Interior Coating of Welded Steel Petroleum Fuel Tanks.” Test results on Navy fuel tanks in various locations indicate the coating to be a better life-cycle alternative to the FPU coating.

The tank internal protective coatings condition is assessed during routine tank integrity inspection assessments. Assessment results dictate the need and scope of repairs for the protective coating system.

5-2.4 Tank Integrity Assessment.

There is currently a program to clean, inspect and repair all of the tanks with goal of returning the tanks to service for another 20-year cycle. The inspections of the Red Hill tanks are performed in accordance with the requirements of API Standard 653, Tank Inspection, Repair, Alteration and Reconstruction; and as supplemented by the NAVFAC EXWC Contract Statement of Work. The inspection, preliminary and final field reports; tank evaluation and integrity analysis are completed in accordance with applicable general industry practices, codes, standards; federal and local regulations.

The round of inspections that included Tanks 2, 6, 15, 16 and 20 was the first time the tanks received 100 percent scanning of the steel liner plates and welds, a recommendation of the 1998 Functional Analysis Concept Design (FACD) study for Tank 19.

Non-destructive examination (NDE) and testing for the tank shell, upper and lower domes, welds and appurtenances is conducted by non-destructive examination and NDE testing which examine the walls and components for remaining wall thickness readings. The testing utilized three different NDE methods:

- Low Frequency Electromagnetic Technique (LFET)
- Balanced Field Electromagnetic Technique (BFET)
- Traditional ultrasonic longitudinal and shear wave inspection for proofing areas. In areas where LFET examination indicates loss of material, UT measurement back up is completed to verify extent of underside corrosion. In areas where BFET examination indicated a discontinuity, UT

shear wave or MT examination is performed to verify extent of the discontinuity and limits for acceptability.

The current tank assessment program intent is to clean, inspect and repair all of the tanks with the goal of returning the tanks to service for another 20-year service interval. The current approach consists of performing an out-of service inspection of the tank interior (including scanning the steel liner plates and welds for corrosion and other defects) and repairing defects found during the inspection. Select defects such as holes and cracks and only those areas having a remaining thickness below a predetermined minimum thickness are repaired.

5-3 METAL FATIGUE DESIGN CONSIDERATIONS

Fatigue is the process of progressive localized permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point or points and that may culminate in cracks or complete fracture after a sufficient number of fluctuations. *Fluctuating stresses and strains* are important elements. The need to have fluctuating (repeated or cyclic) stresses acting under either constant amplitude or variable amplitude is critical to fatigue.

Although not confirmed, the most likely material used for shell plates was ASTM A283, “Low and Intermediate Tensile Strength Carbon Steel Plates of Structural Quality”, Grade C. This material has a tensile requirement of 55,000 to 65,000 psi, and a minimum yield point requirement of 30,000 psi.

The Red Hill storage tanks are bulk fuel storage tanks in which fuel storage levels are static for months at a time, unlike operational issue tanks or small gas station storage tanks in which fuel storage levels are dynamic with frequent changes in fuel levels (dispensing and refilling). Static fuel levels in the Red Hill tanks limit susceptibility to fatigue issues that may be experienced by smaller tanks with fluctuating fuel levels.

To date, there has been no inspection data that suggest any metal fatigue issues in the tanks. If under certain rare operational circumstances where the steel plates experience cyclic loads or stresses, fatigue would be expected to culminate in cracks in the tank steel plate welds. However, the welds undergo 100 percent NDE during the API 653 tank assessments, and any defective welds are repaired.

5-4 HISTORICAL RECORDS

The Fleet Logistics Center (FLC) Pearl Harbor, as the operators of the Red Hill Facility, maintains the official records of the facility. Most of the printed copies of records including studies, reports, and contract correspondence, are catalogued and maintained on designated shelving in a Technical Library at the FLC Pearl Harbor Fuel Office.

NAVFAC is the execution agent for much of the work requiring engineering, repairs and modification to the facilities. NAVFAC execution offices retain records for contract file purposes and as background information/lessons learned for subsequent efforts. Most, if not all of the technical reports generated are duplicates of copies available in the FLC Pearl Harbor technical library.

Work has also been managed by execution agents other than NAVFAC. These execution agents are also known to have retained records for contract file purposes. The availability of these records is dependent upon those that are retained by the project management, and some have been made available to the Navy upon request.

Contractors who have performed work on the Red Hill facility are also known to retain records of their work for their contract file purposes. On occasion, they have provided copies of available specific historical records upon request.

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APPENDIX A REFERENCES

[1] United States Environmental Protection Agency Region 9/The Department Of Health State Of Hawaii. Administrative Order on Consent In the Matter of Red Hill Bulk Fuel Storage Facility. EPA DKT NO. RCRA 7003-R9-2015-01/ DOH DKT NO. 15-UST-EA-01. San Francisco, CA/ Honolulu, HI: September 2015.

[2] *Nuclear Containment Steel Liner Corrosion Workshop: Final Summary and Recommendation Report*, Albuquerque, NM and Livermore, CA, Sandia National Laboratories, 2011.

[3] Various construction drawings for the Red Hill Storage Tanks

[4] Red Hill Construction Report, Chapter XV, San Francisco, CA: Earl and Wright Consulting Engineers, report date unknown.

[5] *Engineering Survey of U.S. Navy Petroleum Facilities at Pearl Harbor,* San Francisco, CA: Bechtel Corporation, May 1949.

[6] *Preliminary Report for Conversion of Fuel Storage and Transfer Facilities and Acquisition of Real estate at U.S. Naval Supply Center, Pearl Harbor, Oahu, T.H. Volume Two,* San Francisco, CA: Earl and Wright Consulting Engineers, January 1959.

[7] *Repair of the Non-Volatile Section of the Red Hill Storage Facility, U.S. Naval Supply Center, Pearl Harbor, HI Facility Study*: Publisher unknown.

[8] *Repair of the Non-Volatile Section of the Red Hill Storage Facility, U.S. Naval Supply Center, Pearl Harbor, HI.* San Francisco, CA: Earl and Wright Consulting Engineers, February 1969.

[9] *Conceptual Design for Modernization of Red Hill POL Facility, U.S. Naval Supply Center, Pearl Harbor, HI.*: Hallanger Engineers, Inc., April 1977.

[10] *Repair Tank 19 Red Hill FISC Pearl Harbor, HI DESC Project PRL 98-9*, Anchorage, AK: Enterprise Engineering, Inc., May 1998.

[11] *Red Hill Repair Tanks Options Study, FISC Pearl Harbor, Hawaii, Final Report,* Anchorage, AK: Enterprise Engineering, Inc., September 2008.

[12] U.S. Navy. Naval Facilities Engineering and Expeditionary Warfare Center. *Contract N62583-09-D-0132 Task Order 0003 Clean, Inspect, and Repair Storage Tank 5 and 17 at Red Hill Complex, FISC Pearl Harbor, HI.* Port Hueneme, CA: January 2010

[13] *Tank 2 Engineering Review and Suitability for Service Evaluation, API 653 Out-Of-Service Tank Inspection by Others, FISC Pearl Harbor, Red Hill Complex, Hawaii,* *Final Report,* Honolulu, HI: Shaw Environmental, Inc. and Anchorage, AK: Enterprise Engineering, Inc., October 2008.

[14] *Tank 5 and 17 Cleaning, Inspection and Repairs Project, Tank 5 Inspection Draft Report,* Tulsa, OK: Willbros Government Services, LLC, November 2010.

[15] *Specification and Manual for External Corrosion Protection of Underground Steel Storage Tanks*, American Society for Materials, Lake Zurich, IL, 2014.

APPENDIX B GLOSSARY

ACRONYMS

AOC	Administrative Order on Consent
ASTM	American Society for Testing and Materials
BBL	Barrels
CFR	Code of Federal Regulations
CP	Cathodic Protection
DoD	Department of Defense
DOH	State of Hawaii Department of Health
EPA	Environmental Protection Agency
FACD	Functional Analysis Concept Design
FISC	Fleet Industrial Supply Center (Pearl Harbor)
FLC	Fleet Logistics Center (Pearl Harbor)
GCP	Galvanic (Sacrificial) cathodic protection
ICCP	Impressed current cathodic protection
pH	A measure of hydrogen ion activity
POL	Petroleum, Oil and Lubricants
NACE International	National Association Corrosion Engineers International
NAVFAC	Naval Facilities Engineering Command (NAVFACENGCOM)
NRL	Naval Research Laboratory
SOW	Statement of Work
UFC	Unified Facilities Criteria
UFGS	Unified Facilities Guides Specifications.
U.S.	United States
UST	Underground Storage Tank

DEFINITION OF TERMS

Anode: The electrode of an electrochemical cell at which oxidation occurs. (The anode is usually the electrode where corrosion occurs and metal ions enter the solution).

Cathode: The electrode of an electrochemical cell at which reduction occurs.

Cathodic protection: A technique to prevent the corrosion of a metal surface by making that surface the cathode of an electrochemical cell.

Coating: A dielectric material applied to a structure to separate it from its environment.[1]

Conductivity: The measurement of a material's ability to conduct electrical current.

Corrosion: The deterioration of a material or its properties due to a reaction of that material with its chemical environment.

Corrosion potential: The potential of a corroding metal surface relative to a reference electrode under specific conditions in an electrolyte.

Corrosion rate: The rate at which corrosion proceeds.[1]

Current density: The current per unit area.

Electrode: A conductor used to establish electrical contact with an electrolyte and through which current is transferred to or from an electrolyte.[1]

Electrolyte: A chemical substance or mixture containing ions that migrate in an electric field. Examples are soil and seawater.

Galvanic anode. A metal that, because of its relative position in the galvanic series, provides sacrificial protection to metal or metals that are more noble in the series, when coupled in an electrolyte. These anodes are the current source in one type of cathodic protection.[1]

Galvanic cell: A corrosion cell in which anode and cathode are dissimilar conductors, producing corrosion because of their innate difference in potential.

Galvanic corrosion: Corrosion resulting from the coupling of dissimilar metals in an electrolyte.

Holiday: A discontinuity in a coating that exposes the metal surface to the environment.

Impressed current: Direct current supplied by a power source external to the electrode system. For the purposes of this report, direct current for cathodic protection.

Interference: Any electrical disturbance on a metallic structure as a result of stray current.

pH: A measure of hydrogen ion activity defined by: $pH = \log_{10} (1/aH^+)$ where aH^+ = hydrogen ion activity = molal concentration of hydrogen ions multiplied by the mean ion activity coefficient (= 1 for simplified calculations).

Reference electrode: A reversible electrode with a potential that may be considered constant under similar conditions of measurement.

Resistivity: The measurement of a material's ability to oppose the flow of electric current.

Rust: A reddish-brown corrosion product of iron that is primarily hydrated iron oxide.

Sacrificial anode: See galvanic anode.

Stray current: Current flowing through paths other than the intended circuit.

Stray current corrosion: Corrosion resulting from stray current flow through paths other than the intended circuit.

Uniform corrosion: Corrosion attack of a metal that is essentially the same at all exposed areas of its surface.

Voltage: An electromotive force, or a difference in electrode potentials expressed in volts.

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