FURY: A REMOTE UNDERGROUND STORAGE TANK INSPECTION/ASSESSMENT SYSTEM

USACERL
Champaign, IL 61826 USA
1-800/USA-CERL

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1. Introduction

1.1 Background Information

The necessity for developing non-invasive procedures for tank condition assessment is currently predicated on the initial removal of tank hazardous wastes followed by the complete removal of the tank from the ground. This is an expensive effort because current EPA requirements dictate that regular procedures be implemented to ensure the usefulness of tank walls and the prevention of seepage of tank contents in groundwater. Continued reliance on this method has resulted in increased maintenance fees and new methods for cheaper and safer inspection of UST's is needed.

Ultrasonic thickness inspection methods are widely used in a number of industries. There are ASTM standards for measurement procedures [26, 27] as well as existing certification programs for technicians. Currently approved in NLPA 631, "Entry, Cleaning, Interior Inspection, Repair and Lining of Underground Storage Tanks", are hand held ultrasonic thickness measurement techniques for the assessment of UST condition. The robotic tank inspection system combines two existing technologies to produce a cost-effective tool for underground storage tank inspection. Mobile robots have been used to move inspection devices over structures. Ultrasonic transducers have been extensively used to inspect metallic structures. These technologies are combined and extended to provide a robotic inspection system that enters the tank through an existing fill pipe, moves over the interior surfaces of the tank and can operate in tanks containing combustible liquids or vapors.

The U.S. Army Construction Engineering Research Laboratories (USACERL) in conjunction with RedZone Robots has developed an automatic in-situ tank assessment system which eliminates the problems of safety and expense often associated with tank inspection. The robot is currently under development through an SBIR Phase II contract and is designed for implementation by DoD customers with UST's containing hazardous wastes as well as in a dual use mode in the commercial sector. In order to achieve this The FURY robot moves by means of magnetic wheels and has a central pivot to allow for full motion of the steering head. FURY also utilizes ultrasonic transducers to measure the thickness of the tank wall at all locations and includes 90-degree transition arms for robot positioning on endcaps. Control of the FURY is accomplished through a tether attached to the rear of the robot. The robot is designed to fit through a small diameter pipe, which mitigates invasive tank entry during assessment and allows for non-destructive evaluation.

Leaking underground storage tanks (USTs) containing petroleum products are a source of soil and ground water pollution. As a result, the Environmental Protection Agency (EPA) and others developed requirements adopted into the Code of Federal Regulations. As required by 40 CFR 280 and 281, all existing UST systems must be, or upgraded to be, in compliance with one of the allowed alternatives not later than December 22, 1998 [1]. In addition to closure, total UST replacement, and internal lining (banned by AR 200-1), these alternatives include the option of upgrading with cathodic protection. For USTs which are 10 years old or more it is required that the UST's integrity be ensured prior to upgrade. A comprehensive study performed by the United States Environmental Protection Agency (EPA) estimates there are 796,000 motor fuel storage tanks within the United States with a mean age of 12 years [2]. The U.S. Army owns and operates some 20,000 USTs that must meet the compliance requirements of 40 CFT 280-281.

It has been established that the predominant mode of UST failure is from external pitting corrosion [3-5]. Pitting is a localized form of corrosion, which is dependent on a number of factors (e.g., soil resistivity, moisture, pH, temperature, chloride/sulfide levels) and can lead to UST perforations. One study, [4], closely examined 500 steel USTs immediately after excavation and another, [3], analyzed test data from 1,636 steel USTs. Taken together it was determined that perforation was caused by external, pitting corrosion some 70-80% of the time. Failures were found to occur less then 3% of the time [3-5].

The nature of pitting corrosion has been extensively studied [6-11]. For USTs some causes of external pitting are: non-select backfill (which could include rocks, twigs, beverage cans, shells etc.), scratches, adjacent areas with differential oxygen or water content, local inhomogeneities in the steel alloy composition, stray subsurface DC currents, and differing types of soils. The study of corrosion of metals buried in soils goes back a number of years. One study begun in 1922 by the National Bureau of Standards [12] ran for over 30 years and compiled data on 37,000 specimens. Some work has been done on the natural rate of pit growth [3, 13, 14] in a variety of environments but these are not inclusive of all environments typically encountered by USTs. UST perforation is directly correlated to pit depth. When sufficient metal ions have migrated away from a localized pitting area in the presence of an electrolyte, such as water, the remaining tank wall thickness decreases to zero and a perforation results. A typical UST will in time experience a distribution of pitting areas over the external soil side surface and, as well, a distribution of growing pit depths.

It should be noted that virtually every standard or federal regulation relating to the upgrade of existing UST systems refers to soil side corrosion. In accordance with both ASTM ES 40-94 [24] and NLPA 631[1] a tank is acceptable for upgrade with cathodic protection when no pitting is greater than 50% of the original wall thickness and the average wall thickness remaining is greater than 85% of the original wall thickness. With the addition of cathodic protection and required follow up system maintenance, all external UST corrosion is stopped.

Some areas where corrosion occurs more frequently have been suggested but documentation is scarce. These areas include the bottom external third of the UST, as well as occasionally the internal "water" line and at the inside top from moisture condensation. The existing inspection standards do not address these areas specifically and instead call for a randomly distributed sampling.

Owing to the nature of pitting corrosion 100% inspection is not needed to assess a buried structure's condition. In 1963 after 3,000 pit depth measurements, a relationship predicting the maximum pit depth from the average pit depth was determined [15]. For soil side corrosion of gas piping [3, 13] this relationship of the average pit depth to the maximum pit depth was empirically found to be,

$$P(\text{max}) = 1.41\ P(\text{avg.}).$$

In a more rigorous manner the so-called Hazard Function (used for in-service component failures and actuarial tables), or extreme-value statistics also applies. The theory behind extreme-value statistics is well established [17] and, has been applied to soil side, external pitting corrosion [19-22]. The sample size that is required for ultrasonic wall thickness measurements according to an EPA report on inspection procedures and equipment [23] (which references UL58, API 1631 and NLPA 631) has been estimated as 7% of the total wall area. In ASTM ES 40-94 [24] this has been essentially doubled to 15%. One of the main benefits of the Fury robotic assessment system will be the ability to cost effectively and accurately determine a tank's current condition.

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[1] National Leak Prevention Association (NLPA) 631, Entry, Cleaning, Interior Inspection, Repair and Lining of Underground Storage Tanks

1.2 Official DoD Requirement Statement(s)

N 2.III.2.a Environmentally Safe Storage Capability

1.3 Objectives of the Demonstration

One cost-effective compliance option for USTs over 10 years old is condition assessment followed by upgrading with cathodic protection. In support of this option Army wide, an improved inspection and assessment robotic technology was developed under the Small Business Investment Research (SBIR) program, and is being demonstrated under support from the Environmental Security Technology Certification Program (ESTCP). A previous demonstration at Ft. Lee, VA served to validate the capabilities of this inspection system in part through result comparison with third party inspection of an excavated UST [29]. The objectives of the demonstration at the Hunter Army Air Field (a sub-installation of Ft. Stewart, GA) include the remote assessment of the condition of three, 50,000 gal. USTs from a total of thirty-one 50,000 gal. USTs. To accomplish this, the applicability of the new robotic inspection and assessment technology for determining the condition of USTs will be demonstrated and validated. The data collected by this technology will be used to help determine how suitable these tanks may be for upgrading with cathodic protection, thus avoiding the significant expense of replacement.
The Ft. Lee tank, being scheduled for removal, was used mainly for validation purposes. In addition to an inspection in accordance with ASTM ES40-94 [32], a number of performance capabilities were documented on videotape. This included a real time video feed from inside the tank to an outside monitor. The capabilities documented included: entry/exit through a riser pipe, adherence to the inner tank wall in all orientations, movement in the forward and reverse directions, obstacle sensing and avoidance, traversal of lap joints, transitions to and from endcap walls, navigational accuracy, surface cleaning and ultrasonic thickness measurements. After the tank was removed MRI, INC. performed a third party inspection in accordance with procedures developed by the EPA [33].
At Hunter Army Air Field a demonstration of the Fury robotic system was performed. Three USTs of 50,000 gal. capacity were assessed according to ASTM ES40-94. This information will be used to make better informed management decisions concerning upgrade versus replacement. The full replacement of 30 tanks at Hunter has been estimated at $10M. If some or all of these tanks are found to be suitable for upgrade then a significant cost will be avoided.

1.4 Regulatory Issues

United States Environmental Protection Agency regulations contained in CFR 280-281 require that underground storage tanks be protected from the effects of perforation due to corrosion. In particular, tanks installed on or before Dec. 22, 1988, the effective date of the regulations, must be upgraded or replaced by Dec. 22, 1998. Two upgrade measures are allowed: cathodic protection and/or tank lining. Under federal law, states have enforcement responsibility and may impose more stringent requirements. Determining tank condition is necessary in order to decide if a tank should be upgraded or replaced.

Risk-based corrective action (RBCA), a formalized, decision-making process that takes risk into account when determining site remediation strategies, is being used increasingly at contaminated UST sites. For example, if a site is contaminating groundwater but there are no drinking wells in the area and the plume does not appear to be expanding, then indefinite monitoring of the site may be sufficient. If the groundwater is being used for drinking or if the plume is migrating, however, then a full scale groundwater cleanup may be required. Clearly, RBCA can have a major impact on determining what the eventual cleanup costs will be. To perform RBCA correctly extensive site assessment information, which requires additional soil borings and monitoring wells, is necessary. The EPA is not officially promoting RBCA, but it is providing the information to states to allow them to make their own decisions on how to incorporate risk-based decision-making into their UST programs [28]. Prior to the initiation of any remediation strategies, identification of leaking USTs has to occur first.

The majority of Department of Defense (DoD) USTs are steel. A cost effective robotic inspection system for assessing the condition of underground storage tanks would allow DoD to more cost effectively achieve regulatory compliance.

1.5 Previous Testing of the Technology

Previous testing of the Fury robotic system has consisted of operation in a partial tank at the RedZone facility for development purposes and also in a local tank as a test deployment prior to validation efforts at Ft. Lee, VA.

2. Technology Description

2.1 Description

The robotic tank inspection system consists of four assemblies: the robot assembly, the inspection assembly, the tether management assembly and the operator console (Figure 1).
The robot assembly supports and moves the inspection assembly over the tank interior surfaces. Permanent magnet wheels are used to attach the system to the tank walls allowing the system to move over the tank endcaps and overhead portions of the tank wall. Electric motors to power the robot components are contained in the purged and pressurized lightweight aluminum robot housing. Steering and transition mechanisms are provided for robot mobility.
The inspection assembly contains the ultrasonic transducer for wall thickness measurement and the tank wall cleaning components. Tank wall cleaning is needed to assure ultrasonic wall thickness measurement performance. Cleaning is done by powered cleaning wheels and brushes. Cleaning system drive is supplied from the robot assembly. The ultrasonic transducer is mounted in a guide shoe that protects the transducer and holds it perpendicular to and against the tank wall. The guide shoe directs couplant flow to the transducer - wall interface. Tank contents are used for couplant to avoid contamination.
The tether management assembly drives tether into or out of the tank and stores unused tether. A guide is provided to minimize tether damage. The tether management assembly is controlled from the operator console allowing one person operation. A couplant supply and purge gas supply are contained in the tether management assembly.
The operator console consists of an intelligent controller, an ultrasonic data acquisition system and power distribution unit. The operator console displays numeric and graphical information showing the position of the robot in the tank and robot status. The inspection system is controlled using mouse click selections. The ultrasonic data acquisition system is also controlled from the operator console. The power distribution unit supplies electrical power to the intelligent controller, ultrasonic data acquisition system, robot assembly and the tether management assembly.

2.2 Strengths, Advantages and Weaknesses

The robot assembly, inspection assembly and tether are small enough to enter the underground storage tank through the four inch diameter pipe used to fill the tank. This eliminates the need to dig through pavement and earth to reach the tank and cut an access opening in the tank. This avoids damage to the tank or piping during digging and reduces disruption at the tank site.

FURY

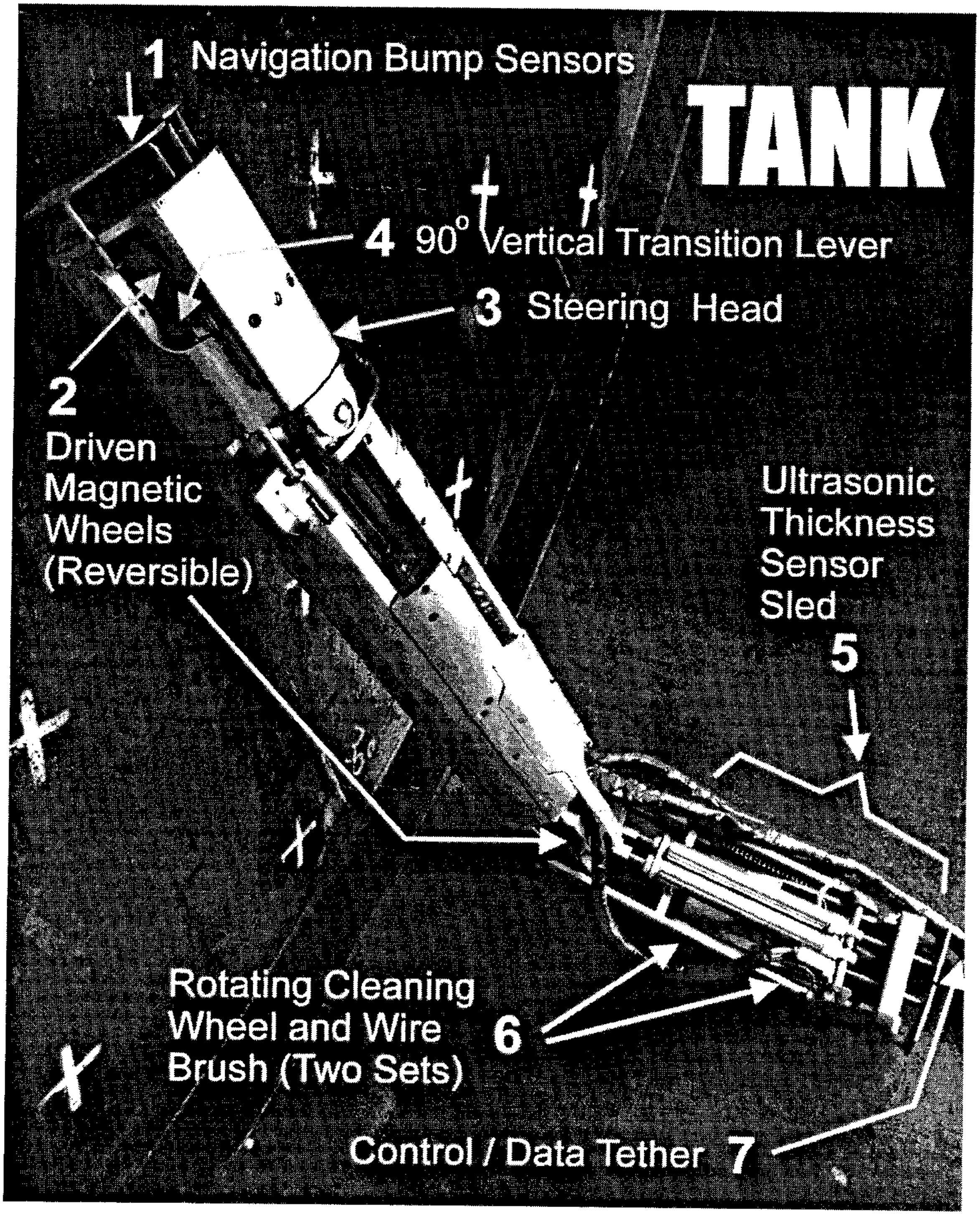

Figure 1: Photograph of Fury Robot

Safety approval or certification is being sought for the robotic system. For the current demonstrations safety certification is not needed. The lessons learned from the demonstration field experience will be incorporated into a redesigned system which can obtain safety approval. The considerable advantage of certification is to allow for use in tanks containing fuel. Tanks do not have to be emptied, cleaned, purged, or made inert prior to inspection. This eliminates the risk of spillage during emptying and cleaning steps, and the disposal of tank residuals and cleaning materials. Disruption of tank operation is also eliminated and the tank can remain in service during the inspection.

A single operator is required for the inspection system. That technician needs specific training in the operation of the inspection system and will need to be qualified as a level II ultrasonic inspection technician.

A typical tank inspection can be completed in less than one day. Both NLPA 631 and an EPA report [23] recommend sampling of approximately 7% of the UST wall area when using ultrasonic thickness techniques. For increased environmental safety this sampling requirement has been doubled in the ASTM ES 40-94 standard. Currently a random sampling of the tank walls with no overlap is required. There are some indications that a more directed survey might be beneficial but thus far this has not been well established nor verified.

The ultrasonic system directly measures the remaining wall thickness of the tank, the measurement of interest. As specified in ASTM ES 40-94, wall thickness is measured to an accuracy of +/- 0.010 in. over the tank wall surface as well as under 0.125 in. diameter flat bottom pits. The nature of UST failure, predominantly exterior pitting corrosion, allows for accurate measurement using ultrasonic techniques. For very small pits there will necessarily be some averaging of measured depth owing to the variation in profile encountered by the input pulses. However, as these pits grow (and hence become more of a concern) a more accurate value is easily obtained.

Seam or weld leaks typically occur early in a tank's life and so are removed from older UST populations. Seam leaks have been shown to rarely be the cause of failure [3-5]. In addition, recent unpublished work strongly suggests that seam leaks very seldom occur without pitting corrosion being present. General corrosion over large areas also occurs on the soil side of USTs but is less of a concern because of its spatial distribution. For the rare cases of interior UST corrosion the decrease in remaining wall thickness will be measured with equal effectiveness. Differentiation between interior and exterior corrosion is not readily obtained by the robotic system. However, the specific ability to identify between the two has very little bearing on UST integrity.

The robot assembly can also move the inspection assembly over 95% of the accessible interior of the tank.

Since the robotic inspection system is operated remotely and does not require workers to enter the tank, confined space exposure is eliminated and chemical exposure is reduced.

Human invasive inspection has been used for many years to determine tank condition. More recently, video inspection and mean time to corrosion failure methods have been developed.

2.2.1 Human Invasive Inspection.

Human invasive inspection consists of emptying, purging/inerting, unearthing, cutting, entering, desludging, grit blasting, vacuuming, visually and manually inspecting (including probing, hammer testing, etc.), and restoring the site after inspection. Personnel enter the tank to prepare it for inspection and to perform the inspection.

Internal manual inspection is required before tank lining, but is not necessary before installing cathodic protection. This inspection method is described in API 1631 and included in 40 CFR §280.21 (b)(2)(I).

2.2.2 Mean Time to Corrosion Failure.

Mean time to corrosion failure is a predictive method, based upon soil characteristics and tank age, that has been approved by many states for testing prior to cathodic upgrade. Tank site soil samples are laboratory tested for parameters known to promote tank corrosion. Parameter values are input into a mathematical model which calculates likelihood of corrosion failure for tanks of a given age at the site. Parameters measured include soil pH, resistivity, sulfides, moisture, and tank size.

The advantages of mean time to corrosion failure inspection include no disruption of tank operations. To date, the accuracy and value of the method to owner/operators remains unclear, and if soil samples reveal evidence of past spills or leaks expensive environmental cleanup may be mandated. Mean time to corrosion failure inspection is described in ASTM ES 40-94 .

2.2.3 Video Invasive Inspection

Video invasive inspection methods insert specialized cameras and lighting into the fill tube of a UST. The camera, on the end of a long stick, is rotated, raised, and lowered to provide a full view of the tank interior. High-magnification lenses and explosion-proof lights are used. The tank must be emptied prior to inspection. Sludge removal and cleaning may be required to expose the tank wall for inspection.

The advantages of video inspection include creation of a visual record of the tank interior. Disadvantages include separate sludge removal costs, no surface cleaning, and surface-only characterization. Video is somewhat disruptive in that the equipment, truck, and personnel are over the tank pad.

One disadvantage is that it is a proprietary service available from a private company. Any report fully detailing a validation procedure was unable to be located. In conversation with company representatives a data base containing 50,000 USTs is often mentioned but is unavailable for inspection.

2.3 Factors Influencing Costs and Performance

For those methods where human entry is needed, tank accessibility can be a factor in cost. The occasional need to cut a manway will add expense. The methods that require extensive soil sampling will have added expense if pavement or concrete is present.

3. Demonstration Approach and Cost Assessment

3.1 Performance Objectives

The main performance objectives are to quantify and document:

1. Main system components and associated equipment lists.
2. Set up time, procedures, and any unexpected impediments to inspection/assessment.
3. Actual inspection rate and all procedures associated with UST integrity assessment including duration of each procedure.
4. Exit procedures (including data storage) and site clean up.

3.2 Physical Setup and Operation

The tank filler pipe must be accessible by a vehicle towing a trailer. A source of 110 VAC 20 amp power must be available. The drop tube must be removed from the tank filler pipe if a drop tube is installed. A single operator is required for the robotic inspection system.

3.3 Sampling Procedures

The sampling plan for the three, 50,000 gal. USTs at the Hunter Army Air Field is to collect ultrasonic thickness measurements on a minimum of 15% of the internal area from each tank. The sampling will be randomly distributed over the tank walls and end caps. Various measurements of soil parameters will also be taken.

3.3.1 Selection of Analytical Laboratory.

An analytical laboratory is not required to perform the demonstration.

3.3.2 Selection of Reference Method.

Three reference methods have been selected for the Ft. Lee validation demonstration. The reference methods to be used will depend on whether or not the tank will be removed from service after completion of the robotic inspection. Mechanical thickness measurements will require destruction of the tank since the tank will have to be cut into sections to provide access for the measurement tools. Manual ultrasonic wall thickness measurements will not require tank destruction. The various media in contact with the outside of an UST should have no effect on ultrasonic thickness measurements. The boundary of differing density causing a reflection and the known time of flight associated with the original wall thickness both serve to eliminate this concern.

Mechanical wall thickness measurements provide an explicit and direct measurement of the tank wall thickness. Micrometer based thickness measurement tools will provide sufficient accuracy.

3.3.3 Sample Collection.

The robotic inspection system produces data files of position locations and corresponding wall thicknesses. A scanning pattern that measures the wall thickness of 15% of the accessible surface area of the tank, including wall and endcaps, will be used. The 15% inspection area figure was arrived at by the ASTM committee of corrosion and UST experts. This figure was based in part on an EPA study on UST assessment techniques which effectively suggested that approximately 7% of the area was sufficient to determine a tanks condition. Following a standard conservative engineering practice this figure was doubled by the ASTM committee for safety. The measurements will be distributed in bands of thickness measurements over the tank surfaces. A band of continuous ultrasonic thickness data will be taken during each traverse of the tank wall from endcap to endcap. So as not to overlap, each traverse will be separated by a minimum of one band width. On the end caps the traverses will be from outer edge to outer edge which will necessarily result in some overlap near the center of the endcaps. To account for this, 20% (typically; modified according to tank size) over sampling will be employed. In total, a minimum of 15% of the inner tank surface will be inspected with no overlap. A quantitative sense of position sensing/representation capabilities will be obtained.

3.3.4 Experimental Controls.

Good ultrasonic inspection practice calls for calibrating the equipment on a calibration plate of known thicknesses before inspection measurements are taken. Good practice also calls for a check of calibration at the completion of the daily measurement activities or when a different ultrasonic operator is used. All periodic calibrations shall be either performed or supervised by a Level II ultrasonic technician.

3.3.5 Sample Analysis.

Post inspection, the data analysis will include the determination of an overall mean value (typically with endcaps and tank wall treated separately) as well as the distribution of the thinnest measurements. In addition, two published life prediction algorithms will be applied using soil data collected in accordance with ASTM ES40-94.

3.4 Analytical Procedures / Performance Criteria

To validate and demonstrate the capabilities of the robotic system, older USTs at both Ft. Lee, VA and Hunter Army Air Field, GA were assessed for their current condition and suitability for upgrade with cathodic protection. The Ft. Lee tank, being scheduled for removal, was used mainly for validation purposes. In addition to an inspection in accordance with ASTM ES40-94 [4], a number of performance capabilities were documented on videotape. This included a real time video feed from inside the tank to an outside monitor. The capabilities documented included: entry/exit through a riser pipe, adherence to the inner tank wall in all orientations, movement in the forward and reverse directions, obstacle sensing and avoidance, traversal of lap joints, transitions to and from endcap walls, navigational accuracy, surface cleaning and ultrasonic thickness measurements. After the tank was removed a third party inspection was performed by MRI, Inc. in accordance with procedures developed by the EPA [5].

3.4.1 Contaminants.

Not applicable.

3.4.2 Process Waste.

For these validation and demonstration efforts the USTs will be empty and so no process waste will be present. In future inspections, once safety certification has been obtained, the system will include a tether handling system which prevents any loss or product.

3.4.3 Factors Affecting Technology Performance.

Three factors may affect robotic inspection system performance. Robot mobility may be reduced by the presence of obstacles in the tank. The obstacles include tank reinforcements, particularly of tank endcaps, and loose objects in the tank. Robot mobility and ultrasonic performance may be affected by very firm sludge that cannot be displaced by the robotic system. Internal corrosion is not expected to affect performance. The amount of oxygen necessary for corrosion in contact with the internal tank walls is limited by the presence of fuel. An existing internal coating could affect the thickness measurement, and hence the analysis. This possibility is discussed in Appendix A.

3.4.4 Reliability.

No reliability problems are expected. A check list is completed prior to robot insertion into the tank. In the event of robot assembly failure, the robot can be retrieved by pulling on the tether. The geometry of standard cylindrical USTs are such that no tether binding nor 90 degree bends are expected. Ultrasonic performance is controlled by calibrating the ultrasonic system before robot insertion and by repeating the ultrasonic calibration after the robot is removed from the tank. Ultrasonic signals are displayed during inspection for review by the operator.

3.4.5 Ease of Use.

The robotic inspection system can be operated by a single trained technician. In addition to specific training to operate the robotic system, certification as a level IIR NDT technician is required to operate the ultrasonic system.

It is expected that a tank inspection covering 15%[2] of the internal surface area of a tank can be completed in less than eight hours from arrival to departure.

The robotic inspection system equipment can be positioned at the tank site by the same operator assuming the tank site is vehicle accessible. Removal of fill connectors and drop tubes can also be accomplished by the operator.

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[2] As required by ASTM ES 40-94

3.4.6 Versatility.

The robotic inspection system can be used to obtain wall thickness information on a variety of steel structures including ships, barges and process vessels. The approval of the system to operate in Class 1, Division 1, Group D areas will allow the system to be used where non-approved robots cannot be used. Once safety certification has been obtained, the robotic inspection system can also operate within fuel, thus providing additional flexibility. Currently the robot is able to operate while immersed in water and other non-flammable liquids.

Other inspection sensors could be installed in place of the ultrasonic transducer to allow other types of inspections to be performed. The design of the robot assembly with a separate inspection assembly allows other inspection sensors to be installed with a minimum of modification. Possible sensors include magnetic flux, far field eddy current, EMAT and corrosion rate measurement. Re-approval would be required to operate the robotic inspection system with a new sensor in classified areas.

3.4.7 Off-the-Shelf Procurement.

No proprietary technologies are used in the robotic inspection system. The robotic inspection system is assembled from a combination of off the shelf and custom components. Those custom components, such as robot housings, magnetic wheels and ultrasonic transducers, can be produced by a variety of sources. No exotic materials or manufacturing processes are used in the robotic inspection system.

3.4.8 Maintenance.

Internal inspection system components are designed to last the life of the product. Non-moving components are projected to last a minimum of 10 years while moving parts will likely require yearly inspection and possible replacement. Periodic replacement of the tether will be required due to abrasion and wear of the tether jacket affecting jacket integrity. The tether is expected to last six months to one year depending on usage and test conditions. The high pressure purge gas supply cylinder will require more frequent replacement. Generally, as the system is fielded incremental improvements in durability will be made.

The tether can be easily disconnected from the operator console so that inspection operations can continue by swapping assemblies.

Normal vehicular maintenance will be required for the tow vehicle (i.e. oil changes, tire pressure checks, etc.) and trailer used to transport the robotic inspection system. The trailer maintenance will be minimal but will include periodic checks of turning and brake lights for safety.

3.4.9 Scale-up Issues.

No scale up issues exist. The system will be tested in the production intent configuration. Continuing design improvements in the robotic inspection system are anticipated as part of normal system evolution.

3.5 Cost Performance

It is expected that tank owners will either purchase a robotic system, or alternatively, procure inspection services under contract. UST inspections are typically of short duration. However, if a particular site or geographic area has a large number of tanks which require periodic inspection it may be more economical to purchase a system. All expenses, man-hour logs and associated tracking of economic data will be recorded on separate cost performance data sheets. The responsibility of accurately recording this information on site will be the responsibility of RedZone Inc. with USACERL personnel serving as oversight.

3.5.1 Start-up Costs

Site preparation costs incurred prior to inspection will be collected from the installations. These could include things like drop tube removal, providing power, providing installation assistance, and providing secure storage. It should be noted that many expenses will be reduced or eliminated once safety certification has been obtained.

For these demonstrations all pertinent expenses associated with start-up (prior to commencing actual inspection activities) will be recorded and will include: travel time, gas, set-up/calibration time, labor, any weather delays, any delays (possibly involving permitting, regulatory, safety, coordination/notification), any replacement parts and other.

3.5.2 Operations and Maintenance Costs

Ongoing O&M costs have thus far been minimal. After each day's use, cleaning degreasers followed by WD-40 were used. It is expected that over time drive chains will need adjustment and other minor repairs on a monthly and quarterly basis will be needed. In continuous and daily use, a yearly overhaul may be needed, but thus far, that sort of representative experience has not occurred.

3.5.3 Demobilization

Demobilization costs are expected to be minimal. The expenses associated with storage or disposal of system components should be negligible. After a thorough cleaning, the POL hazardous waste aspects will not apply. If anything, various components will still have a positive worth. For example, the computer and ultrasonic thickness measuring sub-system could both be used elsewhere.

3.5.4 Life-Cycle Costs

A production model system is estimated to have a first cost of $35,000. A rough figure for monthly maintenance is perhaps $300 including materials. A yearly overhaul may cost from $1,000 to $2,000. At the end of a 20 year life, major sub-assemblies may still be orth $1,000. Without accounting for inflation or a discount factor, the total life cycle cost, less travel and salaries, is approximately $136,000 (over 20 years). In contrast, a service provider might perform three tank inspections a week, for 10 months out of the year, at $1,400 per inspection. This comes to a gross revenue of $168,000 (or cost to installations) in the first year alone, or $3.3M over a 20 year span.

3.6 Cost Comparisons to Conventional and Other Technologies

Other technologies, such as those detailed in NLPA 631, require a minimum of $3,000 to defuel, clean, and inspect a typical 10,000 gal. Tank. In our example above, with the same rate of inspection, first year costs to installations would be $360,000. A detailed breakdown of true costs for other inspection technologies appears to be unavailable for competitive commercial reasons.

4. Site Description and Performance Assessment

4.1 Background

Demonstration site selection of USTs should be based on the following factors:

1. The USTs to be inspected shall be empty and cleaned and have been in service for at least 10 years. This will allow for some corrosion to have taken place and also be representative of the older population of USTs that 40 CFR 280-281 refers to specifically
2. The USTs to be inspected shall be representative of typical DoD applications. This would involve characteristics of capacity, content, use, soil side environment and other aspects. For this demonstration both highly refined fuels such as gasoline and less refined product such as diesel fuel will be sought.
3. The USTs to be inspected shall have filler pipes which are accessible by a vehicle towing a trailer.
4. The USTs to be inspected shall have a source of 110 VAC 20 amp power available, or less preferred, a comparable portable generator present.

4.1.1 Pre-Demonstration Sampling and Analysis

Some pre-demonstration analysis and choice of USTs will be required. First, a steel tank older than 10 years is required. A site willing to actively participate and assist in a demonstration is also necessary. For validation purposes a site with a number of USTs marked for removal is practical in the event that an alternative UST is needed. USTs with excessive structural degradation or that have been exposed internally to rain or ground water should be excluded for not being representative of the intended use of the robotic system. As well, lacking safety certification, for these demonstrations a clean, defueled, non-explosive environment will be required.

4.2 Site/Facility Characteristics

The demonstration site will be the Hunter Army Air Field associated with Ft. Stewart, GA.
Demonstration Site: Ft. Stewart, GA
Sub-Installation: Hunter Army Air Field
Location: 10 miles W of Savannah, GA (and NNE from Ft. Stewart)
Dates: 16-20 SEP 96
POC: Mr. John Baker (912-767-7876), Mr. Vic Muldon (912-767-5220)
The Hunter Army Air Field has thirty-one 50,000 gal. USTs which they suspect may be in perfectly good condition based on some previously removed tanks. An A/E contractor performed a study which concluded that complete replacement was needed and would cost approximately $12M. The Ft. Stewart Director of Public Works (DPW) is very interested in

reliable information regarding the in-situ condition of these USTs. In discussions with Mr. Baker, who has been dealing with this problem for some time, the opinion was expressed that Fury is the "only device I know of that can give you that information".

4.2.1 Site/Facility Photograph

Figure 2 shows the Ft. Stewart, GA. site.

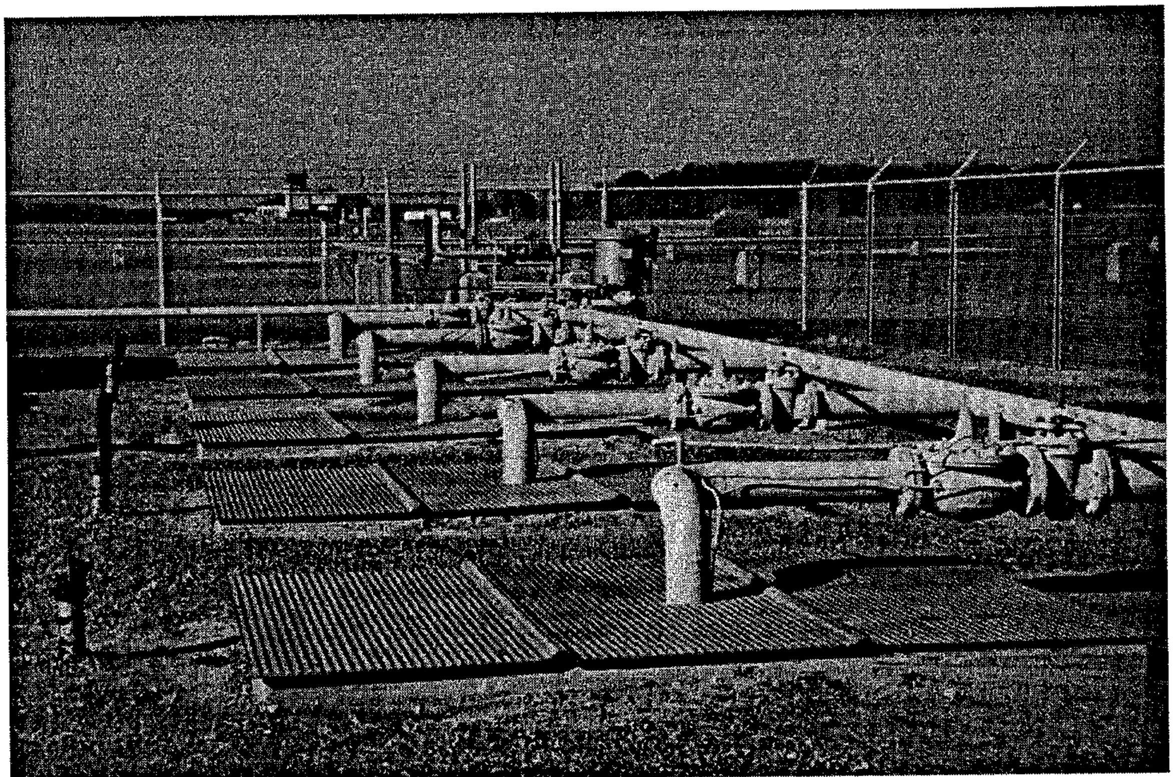

Figure 2: Photograph of Hunter Army Airfield Underground Storage Tanks

4.3 Performance Data

This paper discusses the application of statistical theory for the determination of probability of failure from perforations from maximum pit depths from the Ft. Stewart (Hunter Air Force) tank site. Large data sets containing the thickness of Underground Storage Tank (UST) walls were procured using the FURY robotic in situ device. Three separate tanks were processed and descriptive and inferential statistics are considered. Leak prediction models are developed from this analysis. In the case of inferential analysis extreme value statistics are utilized on the maximum pit depths obtained from the data and the probability of failure is determined through statistical methods. The methods employed characterize a logical approach for determining the best parameter estimates and confidence intervals through current statistical techniques. The application of extreme value statistics is first conducted via Least-Squares Estimation to obtain initial parameter estimation. Two approaches are employed. First, graphical estimates are made by plotting the maximum pit depths on probability paper—the resulting plots gave estimates for the slope and shape parameter which are then used to calculate the probability of survival P_s of maximum pit depths. The graphical estimates are also used as initial estimates for the Maximum Likelihood Estimates (MLE). Second, a statistical program used its own least-squares analysis as initial estimates to obtain convergence for methods based upon the Newton-Rhapson method for function minimization. The latter method allows us to obtain parameter estimates and confidence intervals for an MLE on the probabilities of occurrence of pit depths greater than the ones observed and compared with the graphical estimates for the probability of survival. This inferential approach is based upon the assumption that the distribution of maximum pit depths follows a Gumbel Type I distribution. This assumption is not without precedence; similar analysis in the field of failure analysis shows that the Gumbel or extreme distribution is an appropriate technique for fitting maximum pit depth data. The probability of survival for any pit depth is also based upon a Gumbel Type III distribution. The criteria for perforations is established in accordance with specified ASTM requirements.

A descriptive analysis was conducted on the available data and the distribution of thicknesses is presented through histograms over several different thickness regions. Exploratory analysis in this manner allows us to characterize each tank's condition by defining areas where wall thickness is thinnest. Typically useful descriptive statistics are performed on the data sets. This includes the sample means, medians, variance, standard deviations, and ranges. Statistical analysis for the parameters include the intercept and scale parameters for the response variable (in this case the pit depth), the variance-covariance matrix or information matrix for determination of confidence intervals, the standard errors, and statistical tests such as χ^2 for comparison to our initial distribution assumption.

4.3.1 Descriptive Analysis of UST

The FURY robot compiled thickness data from three UST's at the Army Installation. Data acquisition was completed in 10 ft. tank sections. Approximately 460,000 measurements were acquired for tank 3, 340,000 for tank 4, and 160,000 for tank 5. Only the bottom one-third of each tank was considered. Histograms are plotted for each tank which show the distribution of thicknesses obtained from the analysis. Tables are given for the number of data points over the range of thickness values observed for each tank. Tank 5 contains the largest percentage of thickness values at the lower thickness ranges. These are shown in region A, B, and C in the attached tank 5 histograms. The histograms also show the thickness ranges greater than 0.375 in. Tests for outliers are used to exclude spurious data. Reference is made to the tables for the exact number of thickness values collected by the robot and the number of thickness values observed over a particular range. Most of the thicknesses fall within 0.375 in. The nominal wall thickness for tanks having a 50,000 gallon capacity is 0.375 in. An average of 76% of the data for all three tanks is comprised of thickness values greater than expected nominal wall thickness. Determining the error associated with the acoustic measurement is dependent upon several variables.

4.3.2 Analysis of Error

First is error associated with instrument accuracy. Accuracy is defined as the difference between the ideal input value and the value converted by the sensor, and without any additional error, converted back. Second is the type of error introduced through calibration.

$$\Delta = s' - s$$

With respect to the acoustics, this systematic inaccuracy shifts the transducer stimulus by a constant. The shift is not necessarily uniform over the range of stimulus points and depends on the type of calibration error introduced. Hysteresis error is defined as a deviation of the sensor's output at a specific point of input when it is approached from opposite directions. Finally, non-linearity is defined as the deviation of a real transfer function from the approximation straight line. The above are examples of systematic distortions. Other relevant errors are associated with random distortions. Measurement errors not documented or known for the sensors and data acquisition system are then analyzed via statistical methods. Considerations for the distortion effect of the epoxy on the measuring device are analyzed in this manner. The absolute deviation of a value from the mean is defined by:

$$Abs.Dev = \frac{\sum_{i=1}^{n} |s_i - \bar{s}|}{n}$$

the average of the deviation or the variance is defined as:

$$v^2 = \frac{\sum_{i=1}^{n} (s_i - \bar{s})^2}{n-1}$$

Here, $\bar{s}$ is the sample mean. The square root of the variance is equal to the sample standard deviation and measures the dispersion in the sample data. With a large n, v is considered to be equal to the true standard deviation. With increasing n the thickness distribution approaches Gaussian. This means that approximately 68, 95, and 99% of the thickness values fall within 1, 2, and 3 standard deviations, respectively.

Tank 3 has approximately 30% of the thickness values greater than 0.380 in., tank 4 has approximately 25% of the thickness values greater than 0.380 in., and tank 5 has approximately 40% of the thickness values greater than 0.380 in. Outliers are computed through methods like the Chauvenet's criterion and also through normal probability plots.

4.3.3 Descriptive Statistical Analysis

Data acquired from the three tanks is analyzed and quantified using the following methodology. Thickness distributions and pit depth values are analyzed by fitting distributions from failure life analysis models. The application of extreme value statistics is considered for the present purpose and its advantages are defined. Parameter estimation is done via least-squares and maximum likelihood estimation. For the latter, results given include the confidence intervals associated with each estimate and the resulting probability of finding a pit depth greater than the maximum observation is found to be within a reasonable limit. Extrapolation of pit depths to predictions of probability of survival are based upon graphical estimation of the extreme distribution, i.e., the Gumbel Type III distribution. Assumptions for the type of distribution best fitting the pit depths are confirmed by the χ^2 test for significance.

4.3.3.1 Distributions

No a priori assumptions were made regarding the distribution of thicknesses in each tank. In order to arrive at stable estimates for the parameters, a null hypothesis was postulated regarding the distribution of maximum pit depths. That is, a Gumbel distribution is assumed and the probability of rejecting this null hypothesis is determined. The Gumbel distribution was chosen based upon past work in the field of analysis of pit depth. Statistical tests are done for such inferential statistics via χ^2 tests which allow us to accept or reject the significance of a calculation based upon the Gumbel distribution. Thus, the probability of perforation by pitting is calculated via extreme value statistics (non-parametric methods) and statistical tests are used to judge the merits of the initial assumptions as well as the resulting probabilities. Normal probability plots and the frequency distributions are included as part of the descriptive statistical.

4.3.3.2 Histograms and Distribution of Thicknesses

Histograms are constructed for all thickness data measured for each tank and plotted against the expected normal. Three sets of graphs are included together with their frequency tables. Each tank has a graph which shows the overall distribution of thicknesses followed by three smaller regions labeled A, B, and C to show the data values at each end of the distribution. Tank 3 has approximately 71% of all data points between 0.345 and 0.395 in. For the thinnest values approximately 0.04% of all data is between 0.070 and 0.100 in. Tank 4 has approximately 82% of all data points between 0.340 and 0.395 in. The thinnest values for tank 4 ranging between 0.070 and 0.100 in. contain approximately 0.01% of all data points. Tank 5 data values fall mainly between 0.350 and 0.395 in. and comprise 74% of all data points. The thinnest values for this tank comprise approximately 1% of the data between 0.070 and 0.100 in. Tank 5 has the most thinnest values of all tanks with 0.35% of the total thicknesses residing at 0.070 in. The histograms for Region C for tank 5 shows graphically the distributions at the lower end of the tank. The exact number of data points and the percent and cumulative percent for each thickness region is given.

4.3.4 Theory and Application of Extreme Value Statistics

The Gumbel distribution is considered asymptotically efficient. This means it is conducive to stable parameter estimates of the data for right tail data for maximum values for the pit depths. Properties of the Gumbel distribution are termed regularity properties: the maximum log-likelihood estimates of the Gumbel distribution are also asymptotically unbiased and asymptotically normal. Most of the work in extreme value distributions was done by Gumbel so the extreme value distribution is often referred to by his name. The probability density function for the Gumbel Type I distribution is:

$$f(w) = \frac{e^{\frac{w-\mu}{\sigma}} e^{-e^{\frac{w-\mu}{\sigma}}}}{\sigma} \quad (1)$$

and the associated cumulative distribution function or survival function is:

$$F(x) = \Pr(X \le x) = e^{-e^{\frac{-(x-\mu)}{\sigma}}} \quad (2)$$

Here, e is Euler's constant. The cumulative distribution function (c.d.f.) relates the distribution of smallest extremes. This c.d.f. is used for obtaining parameter estimates for observations which follow an extreme distribution. The extreme distribution is also equivalent to the 2 parameter log-Weibull distribution. All extreme distribution are related through a log transformation. The c.d.f. for the extreme distribution is a two parameter distribution and for (2), μ and α are the shape and scale parameters, respectively. These parameter estimates are obtained by maximizing the likelihood function formed from the sample observations. Several sample sizes are considered from each tank. A function minimizing algorithm (Newton-Rhapson) is used to estimate the parameters and calculate the Fisher information matrix (also called the Hessian). This matrix allows us to determine the variance, covariance, standard errors, and the confidence intervals associated with the parameter estimations. Initial parameter estimates are obtained through least-squares estimation. MLE is a better method than least-squares estimation because it tends to eliminate bias and gives better standard deviations. Estimation procedures for the scale and shape parameter are done in an iterative manner.

4.3.5 Graphical Estimation of Parameters of Extreme Distribution

Several different sample numbers of maximum pit depths were used in this and subsequent analysis. The general rule of thumb is that $2\sqrt{n}$ values be considered for statistical significance. Our large data size allowed us to vary this number for the most stable estimates achievable. Therefore, sample sizes range from the top 7 to top 100 points in each tank are considered. A methodology is given to show how the probability plots were used to find initial estimates for the scale and shape parameter of the Gumbel Type I distribution. Initial estimates for the parameters are obtained via graphical estimates. This is done in the following manner: the n observed extremes are ordered in increasing value and plotted at their relative cumulative frequency, referred to here as the plotting position:

$$x_m;\ \mathrm{m} = 1,\ 2,\ 3,\ \ldots,\ \mathrm{n} \quad (3)$$

$$\varphi(x_m) = \frac{m}{n+1} \quad (4)$$

For a probability plot, the upper axis gives the probability of occurrence and is defined by the following equation:

$$P_W = e^{-e^{-a(w-W)}} \qquad (5)$$

Here, a is the shape factor in cumulative maximum pit depth distribution. w is the pit depth in mils and W is the characteristic deepest pit depth. The reduced variate Y, defined as A(x-U), is plotted on the lower x-axis on a linear scale and P_w is plotted on the upper x-axis on a non-linear scale. The N extreme pit depths at their relative cumulative frequencies are plotted on the Y-axis on a linear scale. The resulting data are scattered around a straight line according to the following formula:

$$X = U + \frac{1}{A} Y \qquad (6)$$

Therefore, we can determine U and A by fitting a straight line via the method of least squares. Note that the data represent maximum pit depths and not perforations. A perforation is defined as the time when pit depth reaches the thickness of the tank. The data was taken at one time and therefore only one graph is shown for the distribution of these pit depths. The probability of survival P_s is calculated by extrapolating of the fitted straight line which allows us to determine the probability of occurrence of any given value of variate. The Gumbel Type III extreme distribution is:

$$P_S = e^{-\left(\frac{t}{V}\right)^k} \qquad (7)$$

Here, t is the exposure time in years, k is a constant and V is the characteristic age of the tank in years.

Explanation of the graphs:

Graphs 1-4: Distribution of maximum pit depths

The lower x-axis gives the reduced variate or theoretical quantile. A Y value of 1, for instance, shows that approximately 75% of the data have maximum pit depths less than approximately 110 mils. Plots of the top 7, 14, 28, and 56 data points for tank 3 are included.

4.4 Data Assessment / Upgrade Suitability

The robotic inspection system produces an electronic data file consisting of tank wall thickness measurements and the corresponding tank position co-ordinates. The electronic data file has a header containing tank and inspection identification information.

Data from the analytical methods will be recorded on a form that documents: tank site, tank identification, date of measurement, analytical method used, analytical equipment description including serial numbers, operator name, tank surface position co-ordinates and corresponding wall thickness.

4.4.1 UST Upgrade Suitability

As part of the test, demonstration, and validation of the FURY robot, , Russell Corrosion Consultants, Inc. (RCC) in association with Bushman & Associates, Inc. were tasked to determine the suitability of upgrading the USTs by the addition of cathodic protection. To do this, RCC and Bushman were requested to perform the following tasks:

1) Provide expert corrosion consultation on the USTs being evaluated at Hunter Army Airfield (Ft. Stewart, Savannah, GA) in conjunction with the robotic inspection.
2) Perform external corrosion assessment tests on the USTs being robotically evaluated at Hunter AAF in accordance with a protocol developed in ASTM Emergency Standard Practice ES-40 entitled "Standard Practice for Alternative Procedures for the Assessment of Buried Steel Tanks Prior to the Addition of Cathodic Protection" including:
   a) Soil Resistivity Measurements[3]
   b) Soil Type Analysis
   c) Moisture Content
   d) Presence of Sulfides and Chlorides
   e) Soil pH
   f) Tank to Electrolyte Potentials
3) Determine if the USTs at Hunter AAF are suitable for upgrading using the ES-40 protocol given that the robotic inspection will provide the wall thickness deterministic value.
4) Prepare a report detailing the findings of the external corrosion assessments on the USTs together with preliminary design recommendations for cathodic protection of the USTs if considered appropriate.

The external corrosion field testing at Hunter AAF was performed during the week of March 3, 1997, and the report on this work was completed on April 20, 1997. The following conclusions were made in the report:

1) Given that the USTs at Hunter AAF were reported to have been installed in 1953 and are therefore 43 years old and have had supplementary cathodic protection, these USTs are suitable for upgrading based on the external corrosion data gathered and the data evaluation formulae provided by CERL. Ordinarily, even if they had not been provided with cathodic protection, they would still also have to pass the maximum robotically measured pit depth of 50% of the tank original wall thickness. This requirement does not hold for these tanks, however, since they had been upgraded by installing cathodic protection before the regulation enactment date of December 22, 1988.

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[3] RCC and Bushman's study reverified the high soil resistivity at Hunter Army Airfield which was documented in a 1978 Corrosion Survey Report by the U.S. Army Facilities Engineering Support Agency [31].

2) In order to maintain the upgraded status of the Hunter AAF USTs, it is critical that the protection levels be restored as soon as possible (and absolutely not later than one year from the date of this inspection). This will require a more detailed system evaluation, repair and redesign corrosion engineering design study that was outside the scope of this project.
3) Two equations, "MicroGPiper" Equation No. 6 and "Leakage Potential of USTs" Equation No. 6 were provided by CERL for use in this study. In testing the sensitivity of the equations to deal with wide variations in soil characteristics, while conforming to well established modes of impact on corrosion rates by these variables, it became quite evident that the second equation ("Leakage Potential of USTs") more realistically modeled the probability of corrosion pitting penetration of USTs over the broadest potential range of variables.
4) The on site testing necessary to conform to the requirements of the currently recognized (by the U. S. EPA's Office of Underground Storage Tanks) ASTM ES-40 Standard using the Robotic Ultrasonic Invasive Procedure would require less than 4 to 8 man-hours on site time to acquire the necessary data.
5) Evaluation of the data under this study required considerable time to develop computer analysis tools using Microsoft's Office Pro/Excel 97 spreadsheet program to facilitate the analysis. CERL should consider having these computer models refined and protected for use by their contractors such that the data could be easily inputted into the program while providing a uniform and rapid means for assessment of the data. This would not eliminate the need for the Corrosion Expert but would greatly reduce the amount of time he or she would require to reach a valid conclusion using a clearly defined consistent approach as to the upgradeability of the UST system being evaluated.

The full text of this study is included as an attachment to this report [30].

4.4.2 Selected Validation Results from Ft. Lee

One of the most critical comparisons was that of the Fury in situ ultrasonic thickness measurements to other reference methods. Three 5x5 square grids with 10 cm. spacing were located near the center bottom, one approximately one half the distance to the end cap near the bottom, and one on one end cap. These test grids were marked out with wax pencil and stamp markers. Each measurement location was circled using a vibrating engraver and a robot template positioner. The template was used to assure that in-situ comparison measurements with a hand held ultrasonic thickness gauge were taken from exactly the same position. Both the robot sensor and the hand held thickness gauge were calibrated on the same step block before and after each group of measurements. After the tank was pulled the grids were cut out of the tank, sectioned, and the same measurements were performed using a standard mechanical micrometer capable of an accuracy of 1/1000 of an inch. The in situ Fury and laboratory micrometer measurements are shown in Figures 3 through 5.

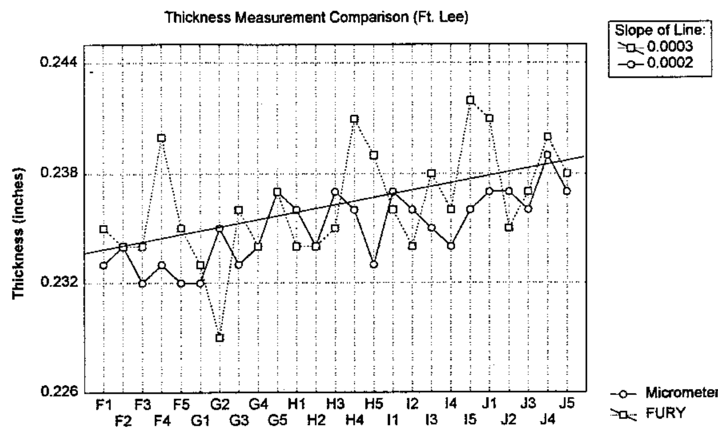

Figure 3. Bottom, Middle Mechanical vs. Fury Thickness Measurement

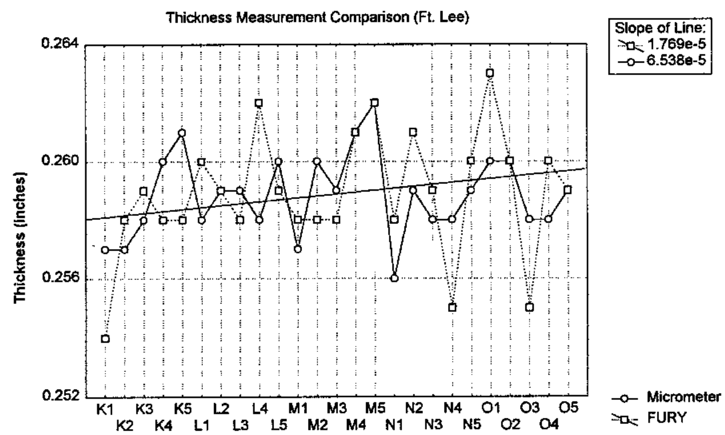

Figure 4. Bottom, Quarter Mechanical vs. Fury Thickness Measurement

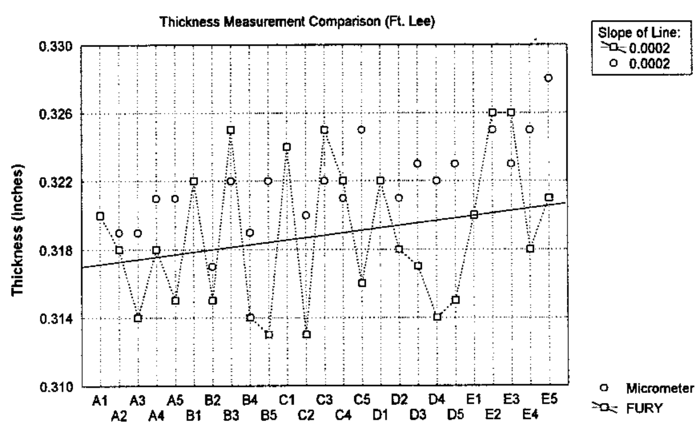

Figure 5. End Cap Mechanical vs. Fury Thickness Measurement

Laboratory analysis of the three 5x5 grid pattern readings were performed in accordance with ASTM G46 [25]. In addition, MRI, Inc. performed independent ultrasonic measurements on a different grid system in accordance with an EPA procedure for the field evaluation of USTs. The comparison of the measurements are given in Table 1. It is worth noting that the external hand held ultrasonic measurements taken by MRI, Inc. are almost identical to those called for by NLPA 631 and, considered alone, were inadequate to determine the tanks condition. In fact, no measurement indicating a remaining wall thickness less than 50% of the original value was found.

TABLE 1. Statistical Comparison of Ft. Lee Thickness Data Sets

Method	Position	valid n	mean(in)	min(in)	max(in)	std dev(in)
Fury Robot	wall	111952	0.255	0.071	0.543	0.033
Micrometer	wall	50	0.247	0.232	0.262	0.012
Ultrasound*	wall	77	0.245	0.222	0.274	0.012
Fury Robot	far end cap	3683	0.324	0.251	0.485	0.0100
Fury Robot	near end cap	18	0.234	0.071	0.441	0.124
Micrometer	end cap	20#	0.322	0.316	0.327	0.003
Ultrasound*	North end cap	9	0.325	0.318	0.331	.005
Ultrasound*	South end cap	9	0.322	0.312	0.328	0.006

*= MRI ultrasonic tank thickness measurements
# = five samples were rendered unusable by the cutting torch
n= number of data points
mean = average thickness of section
min = minimum thickness measured in section
max = maximum thickness measured in section
std. dev = standard deviation from the mean thickness

One of the main advantages of the Fury robotic system is its ability to rapidly take data while in motion. Virtually all of the data taken at Ft. Lee was during the last day of a week long effort after a number of other validation tasks had been completed. Table 2 shows the results of a statistical analysis for the full data set as separated into tank wall and end caps (which typically have a larger initial wall thickness). The Fury data can be displayed in a number of ways. With position coordinates associated with each measurement the positions of the thinnest measurements can be displayed. Figure 4 shows the four thinnest ranges of measurement for the curved tank wall (displayed as if viewed from above and opened to each side from a longitudinal top seam). A feature along a lower circumference approximately eight feet from the southern end cap is evident. This feature was visually confirmed after the tank was removed. One possible explanation is that during installation a lifting strap caused some initial damage which over time lead to differential corrosive attack.

TABLE 2. Statistical Analysis of Complete Ft. Lee Data Set

Position	valid n	mean(in)	min(in)	max(in)	std dev(in)
Wall	111952	0.2549	0.0707	0.5426	0.0333
Far end cap	3683	0.3244	0.2508	0.4845	0.0100
Near end cap	18	0.2336	0.0707	0.4412	0.1243

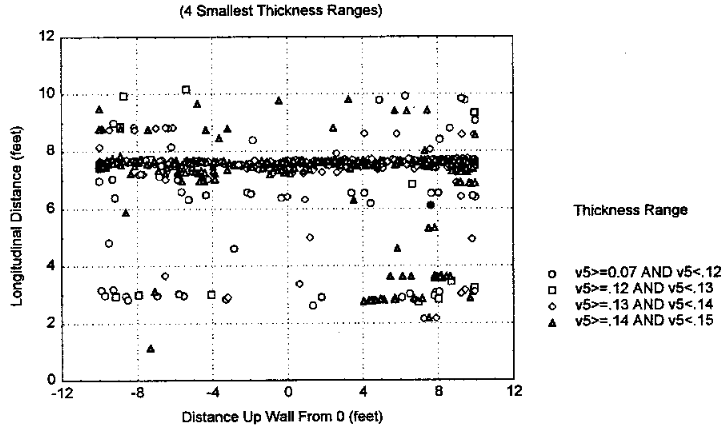

Figure 6. Location Distribution of 1000 Thinnest Wall Thickness Measurements

4.4.3 Validation and Results at Hunter Army Airfield

Fury collected in excess of 940,000 measurements from three USTs at Hunter Army Airfield. Each of the tanks were selected from three separate pump stations each consisting of a bank of 10 tanks. Measurements on the bottom one-third were emphasized in order to provide a conservative assessment. Table 3 summarizes the results obtained after correction for an internal epoxy coating. The data was then sorted according to thickness. Table 4 shows the results of an analysis of the 500 thinnest measurements. Histograms showing the number of measurements within successive ranges of wall thickness are shown in Figures 7 - 12. Tanks 3 and 4 appear to be in pretty good shape while Tank 5 clearly shows a large number of observations at the lower thickness ranges. Taken together with the findings from the other procedures detailed in ASTM ES40-94 tanks 3 and 4 are considered suitable for upgrade while tank 5 is not.

From a corrosion engineering viewpoint the character of the wall thickness histograms is intriguing. It may be that as a tank undergoes the accumulated damage of corrosive degradation the condition represented by Figures 8 and 10 evolves more toward a condition represented by Figure 12. The statistics of these so called "extreme values" (e.g., the thinnest measurements) is currently being examined. The potential benefits include a further improvement in knowing a tanks condition, with either an equal or lesser amount of data, as well as a greater understanding of the degradation process itself.

TABLE 3. Descriptive Analysis of Hunter Airfield Data Set

Tank	Valid n	mean(in)	min(in)	max(in)	std. dev(in)
3	463408	0.38945	0.07096	0.56196	0.03232
4	321919	0.37601	0.07563	0.58053	0.03305
5	157183	0.36974	0.07034	0.57284	0.06551

TABLE 4. 500 Thinnest Data Points at Hunter Army Airfield

Tank	mean(in)	min(in)	max(in)	std. dev(in)
3	0.12664	0.07096	0.14700	0.02270
4	0.13498	0.07563	0.14973	0.01299
5	0.07252	0.07034	0.07614	0.00164

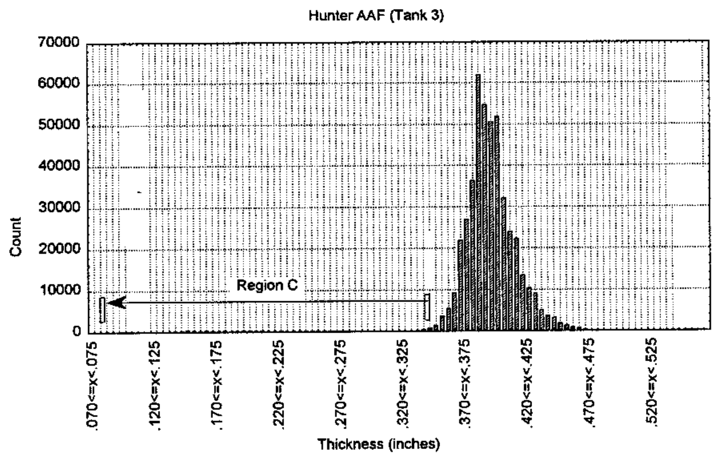

Figure 7. Thickness Distribution in Tank 3

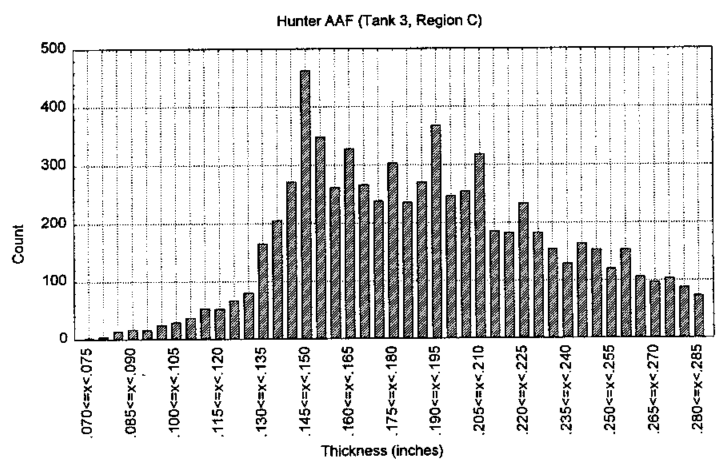

Figure 8. Thickness Distribution Region C in Tank 3 (Figure 5)

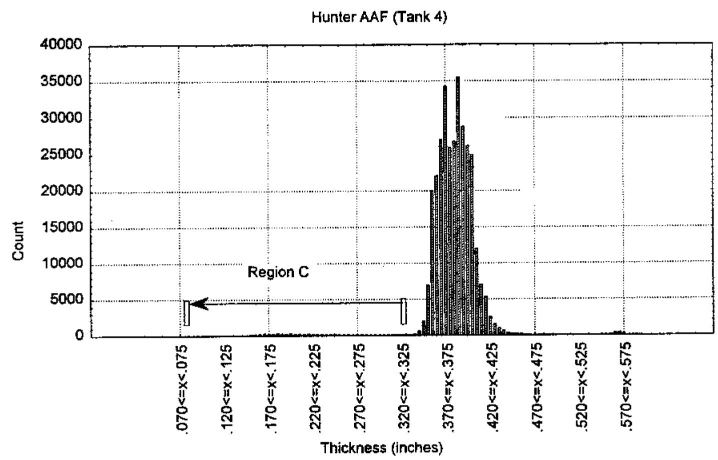

Figure 9. Tank 4 Thickness Distribution

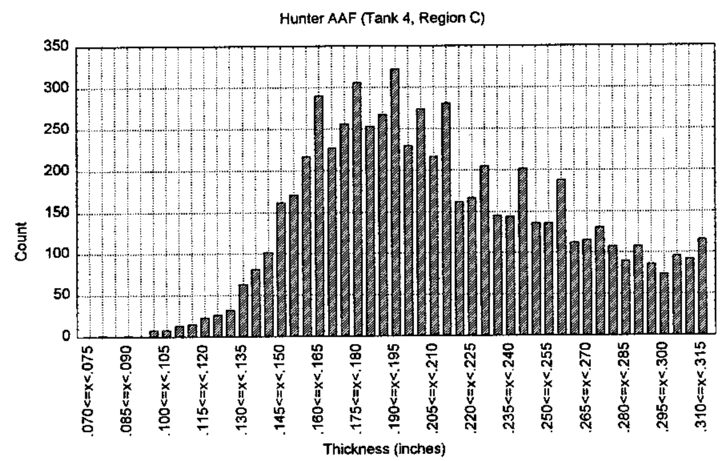

Figure 10. Region C Thickness Distribution in Tank 4 (Figure 7)

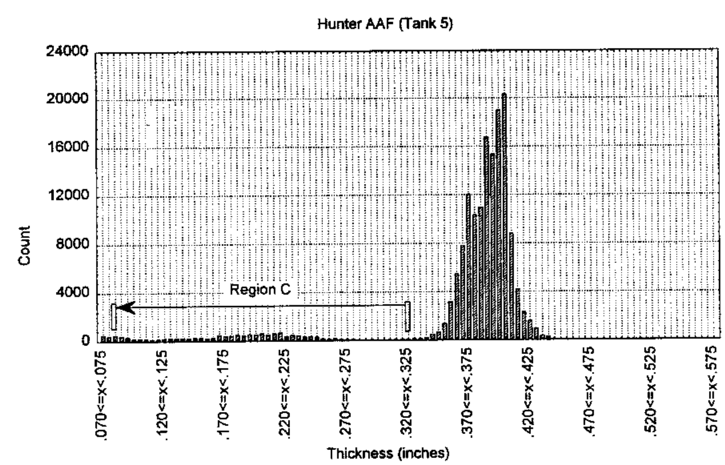

Figure 11. Tank 5 Thickness Distribution

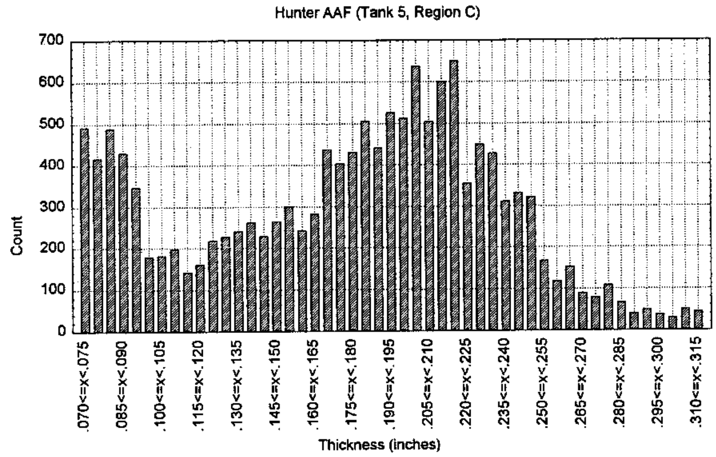

Figure 12. Region C Thickness Distribution Tank 5, (Figure 9)

4.5 Technology Comparison

Prior to this effort and associated work that resulted in the ASTM standard, the only guidance as to procedures used to assess the integrity of an underground storage tank was National Leak Prevention Association (NLPA) standard 631. NLPA 631 allows both hammer testing and hand held ultrasonic thickness testing. Both of these procedures require human entry into an emptied, cleaned and vapor free tank. Combined with the surface preparation requirements contained in NLPA 631, a tank being inspected happens to then be ready to have an internal liner installed. Hammer testing is a non-quantitative method, which historically was first used for boiler inspection. One or more inspectors typically use a ball peen hammer by gently striking the tank from the inside while looking for areas where the wall has become thin. This is indicated by the feel of the rebound. NLPA 631 suggests that inspectors first practice on known 0.125 in. and 0.25 in. thick plates.

Hand held ultrasonic thickness measurements consist of an inspector inside the tank using a standard device, which uses a time-of-flight ultrasound approach. Measurements are taken one per three foot square. Depending on the result, occasionally the nine one foot squares within the area will also be measured at the frequency of one measurement per square foot. A typical hand held ultrasonic thickness measurement can take from two to ten minutes. A typical 10,000 gal. Tank will be assessed on perhaps 80 to 100 measurements. These measurements in total represent [100 * (25/(750*144))]% = 2.3% of the surface area of the tank.

In comparison, Fury does not require human entry. Fury also takes ultrasonic thickness measurements at a rate of 30 per sec. This capability leads to the ability to sample 15% of the surface area and therefore obtains a much more representative sample. In addition, using the procedures detailed in the ASTM standard, external soil chemistry and resistivity data are combined with the direct measurements of wall thickness in order to predict remaining tank life before first leak. This result can be used by tank managers to make well informed decisions.

5. Regulatory Issues

5.1 Approach to Regulatory Compliance and Acceptance

Some regulatory issues associated with these demonstrations have been identified. At Ft. Stewart various health and safety aspects were checked on but did not represent insurmountable hurdles. When human entry was needed for validation purposes, masks, harnesses with retrieval tethers, and oxygen sensors were required. In addition, before each entry, must be certified to be "vapor free" by a certified individual.

Both, volatile organic compound (VOC) release and petroleum, oils and lubricant (POL) spills did not apply to these demonstrations since the tanks were empty and vapor free. In intended future inspections in fully fueled tanks a tether handling system should limit any POL spills associated with tether removal. The non-recurring point source release of volatile organic compounds (VOCs) will be minimal and will also be limited owing to the use of an inert gas in the tank head space.

In addition, safety certification should greatly promote regulatory acceptance (both State and Federal) as well as greatly improving the cost of inspection.

Use in a fueled tan is intended to begin by introducing an inert gas through the vent pipe. At least ten times the volume of either the tank or the head space would be used to initially flow through the head space. A chambered launching device would be added, and the tan would be sealed. Once an over pressure of inert gas is in the tank relative to the atmosphere, the robot would be activated and launched. Alternatively, the unpowered robot could be inserted without a launching device and additional inert gas would be used. If at any time a loss of pressure is detected in the tank then all power to the robot would be automatically cut. Also present will be at least two pressure release valves for the tan itself, separated by no less than five feet. After copleting an inspection the robot would be positioned below the point of entry, the power cut, and the robot would be retrieved. The approach may vary depending on whether the product is #6 fuel oil, or JP4.

5.2 Quality Assurance

The purpose of the Quality Assurance Plan is to specify the means of assuring that the specified procedures are followed, that the specified data is gathered and that the specified documentation is retained. The Quality Assurance Plan applies to the Technical Demonstration Plan activities involving the inspection and evaluation of data for three tanks.

5.2.1 Quality Assurance Responsibilities

A representative of the US Army Construction Engineering Research Laboratories is responsible for quality assurance auditing.

5.2.2 Data Quality Parameters

There are five data quality parameters: representativeness, completeness, comparability, accuracy and precision. Representativeness refers to the degree to which the data accurately and precisely represent the conditions or characteristics of the parameter represented by the data. Completeness refers to the amount of data collected from a measurement process compared to the amount that was expected to be obtained. Comparability refers to the confidence with which one data set can be compared to another. Accuracy refers to the degree of agreement of a measurement to the true value. Precision refers to the reproducibility of measurements of the same characteristic, usually under a given set of conditions.

The periodic representativeness of the Ft. Stewart data (aside from periodic before and after calibrations) will be assumed dependent upon the Ft. Lee validation results. No human entry is scheduled for the Ft. Stewart tanks.

The completeness of the robotic inspection system data is expected to be less than 100% due to variations in ultrasonic coupling to the tank wall. Inadequate ultrasonic coupling will result in signals that cannot be automatically analyzed to determine wall thickness. However, inadequate measurements are easily identified during data analysis. Over sampling is used to easily compensate for this.

Comparability, accuracy, and precision are additional measures of data quality and are considered extensively in the validation inspection performed at Ft. Lee. For the Ft. Stewart and subsequent inspections the representative sampling required by ASTM ES40-94 should be sufficiently representative of a tank's condition.

5.2.3 Calibration Procedures, Quality Control Checks and Corrective Action

The operating procedures for the robotic inspection system contain calibration procedures, quality control checks and corrective actions for the robotic inspection system wall thickness measurement system.

5.2.4 Demonstration Procedures

Technology start-up will consist of connecting the tether to the operating system, assuming that each sub-system is functioning properly and performing the initial ultrasonic thickness calibration.

5.2.5 Calculation of Data Quality Indicators

Completeness will be determined by dividing the total number of non zero data entrees in a robotic inspection data set by the total number of entries in that data set.

Precision will be measured by computing the standard deviation of 30 thickness measurements made on a block approximately 0.25 in. thick.

5.2.6 Performance and System Audits

Two on site audits will be conducted. One audit will occur while the robotic inspection system is inspecting a tank. This audit will verify that robotic inspection system calibration and operating procedures are being followed, and that robotic inspection system data is being properly stored. A second audit should occur while the manual tank wall thickness measurements are being made.

This audit will verify that the appropriate calibration and operating procedures are being followed.
A contingency laboratory is not required.

5.2.7 Quality Assurance Reports

A report will be prepared by the auditor at the conclusion of the tank testing documenting the results of the audit activities. Significant problems that would affect the usefulness of the collected data will be reported immediately to the ESTCP project manager and the auditor's supervisor at US Army Construction Engineering Research Laboratories.

6. Technology Implementation

6.1 DoD Need

The DoD need for this technology, in terms of total number of regulated USTs, is currently decreasing. However, it is projected that there will still be a significant number of regulated USTs that will need periodic integrity assessment inspections for some time to come. As an example, the U.S. Army Training and Indoctrination Command (TRADOC) plans to maintain approximately 400 USTs into the foreseeable future. Projected proportionally across DoD, this suggests at least 6,000 to 10,000 ongoing regulated USTs. In addition, for a period of time, a small subset of steel tans will reach 10 years of age and will become prime candidates for integrity assessment with the Fury robotic system.

6.2 Transition

The transition to widespread implementation could occur along two paths, either separately or simultaneously. The first would be to place a Fury inspection system and one to three trained operators in a region. They would then provide inspection services within that region as needed. It is projected that a production model of the Fury system will cost approximately $30-50K. Operator training could be as short as one to two days.

The second implementation path would be for environmental service companies to provide inspections on an as needed basis. A number of articles and presentations have generated commercial interest. Additionally, two-day training sessions sponsored by ASTM and pertaining to the standard expected to be final this August (as opposed to the emergency standard which went into effect in 1994) should also generate commercial interest. An inspection cost of $1,400 for a typical 10,000 gal. Tan is projected. However, the market forces of supply and demand will also have an effect. Data reduction typically takes about two days, and can be performed by any computer literate individual. The development of a dedicated program could cut this down to two hours. Using a standardized report template, a corrosion engineer can produce report in about one hour. An example of a spreadsheet template has been previously supplied to the ESTCP program office.

The timing of implementation appears to be somewhat problematic. The was a concerted and coordinated opposition to the ASTM standard by a determined minority whose exclusive business interest were perceived to be under threat. After much effort and delay ASTM officials stepped in to facilitate the finalization of a consensus based standard in strict accordance with their official procedures. The inability thus far to attract funding for safety certification for immersion in fuel has also had a detrimental effect on implementation. However, there is much interest and implementation is proceeding considering the large number of USTs, as well as above ground storage tanks, that will still be in use after the upcoming deadline. Effectively, the actual "deadline" for USTs will be defined by the enforcement by state regulators. Regulation for above ground storage tanks is expected within the next few years.

Further assisting implementation is the pursuit of a patent on the Fury system. A detailed patent with 14 figures and 50 claims has been submitted to the Corps of Engineers Headquarters. In addition, a Cooperative Research and Development Agreement (CRADA) will soon be finalized with the industry partner. With these documents, multiple robot production companies can be employed in a cost effective manner. In summary, multiple implementation efforts are ongoing which have effectively made up for the six month delay in receipt of initial funding.

7. Lessons Learned

A remote robotic UST inspection and condition assessment system has been both validated and demonstrated at two separate sites on a total of four tanks. Virtually all the capabilities of the system were verified and documented. In terms of wall thickness data acquisition Fury advances the state of the art by three or four orders of magnitude compared to current methods. Another benefit is the ability to inspect a tank without requiring human entry. The results obtained from the Hunter AAF inspections are representative of how Fury can be used as a tool in order for owners to make better informed decisions about UST management. In addition, it will also allow tank owners to more cost effectively comply with federal, state and local requirements prior to the 1998 deadline and beyond.

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Appendix A

Points of Contact

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Appendix B

Data Archiving and Demonstration Plan

Two copies have been made of all electronic files relevant to the demonstration onto diskettes or other permanent storage media.
All electronic files, documents and samples collected will be stored at the US Army Construction Engineering Research Laboratories in Champaign, IL.
Copies of the approved demonstration plan may be obtained from the US Army Construction Engineering Research Laboratories in Champaign, IL.

Appendix C

Sound Velocity in Epoxy

The sound velocity in epoxy is given by the equation for the speed of sound in a solid.[1]

$$\sqrt{(Y/\rho)}=V_{sound}$$

where
Y= Young's modulus or the elastic modulus
ρ= Density of the epoxy

Young's modulus is the ratio of the tension stress to the tension strain and can be computed from the tensile stress/strain data on the epoxy.[1]

$$3k(1-2\sigma)=Y$$

where
k= Compression modulus
σ= Poisson ratio

The compression modulus is the ratio of the compressive stress to the cubical compression. The Poisson ratio is the ratio of the transverse contraction strain to the transverse elongation strain. The sound speed can be rewritten as:

$$\sqrt{(3k(1-2\sigma)/\rho)}=V_{sound}$$

Most manufacturers do not determine the tensile properties of the epoxies. Dow Chemical did provide such data on its DERAKANE 470 epoxy resin used for lining steel tanks used in storing solvents and fuels.[2][3]

$k= 0.95\times10^6$ psi or 6.55×10^9 kgm/sec^2
$\sigma= 0.411$

Dow did not release data on the solid density of the hardened epoxy but typical densities of a solid epoxy were given by Ameron Protective Coatings. The range of densities are: [4]

ρ= 16-22 lbs/gals

A density of 22 lbs/gals has a sound velocity of 0.62×10^5 in/sec and a density of 16 lbs/gals has a sound velocity of 0.73×10^5 in/sec. In the tank analysis a conservative value of 0.6×10^5 in/sec was used for the sound speed in the epoxy.

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Appendix D

ROI for Army Implementation

Problem/Technology: At least 4,000 Army Underground Storage Tanks (USTs) will need to comply with the 22 December 1998 deadline contained in 40 CFR 280[4]. Thereafter a considerable and ongoing need for inspection will also exist. The "Fury" remote robotic condition inspection/assessment system will dramatically decrease inspection/assessment costs, greatly improve accuracy/reliability over existing techniques, help avoid soil and water contamination, help avoid the cost of UST replacement, improve mission readiness by not

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requiring de-fueling, and eliminate the danger and expense of human entry into these confined spaces.

Implementation: Regulatory acceptance by the EPA Office of Underground Storage Tanks (EPA OUST) will be through a nationally recognized standard. ASTM ES40-94, which covers remote UST inspection, was previously recognized by the EPA OUST and has been revised and improved for an upcoming ASTM wide vote. It is expected that installations will purchase inspection services from contractors who have purchased production models of Fury. Currently an advanced prototype has been validated at Ft. Lee, VA and demonstrated at Hunter AAF, GA under ESTCP. Alternatively, selected Area Offices or Districts could purchase Fury robots and periodically supply the service as needed.

Cost to Implement Army Wide:

$600 K Safety Certification
$ 50 K first production model
4,000 USTs x $1,200 = $4,800 K (Fury inspection cost per tank)
4,000 USTs x 0.90 x $800 = $2,880 K (approximate cost to retrofit with cathodic protection)

$8,330 K

Cost Savings to Installations:

4,000 USTs x $3,000 = $12,000 K (current inspection technology cost per tank)
4,000 USTs x 0.10 x $125,000 = $50,000 K (remediation cost using EPA average)
4,000 USTs x 0.10 x $35,000 = $14,000 K (replacement cost)

$76,000 K

ROI = 8.12 (Note: Based on inspection alone the ROI = 1.50)

Qualitative Benefits:
1. Avoid the need for the danger of confined space entry
2. Avoid the need to interrupt operations (increased readiness)
3. Accuracy of each UST assessment drastically improved (e.g., 100,000s of measurements vs. Ballpeen hammer)

Assumptions:
1. The Army currently has and will maintain 4,000 regulated USTs
2. Virtually all of the Army's tanks currently require assessment
3. 10% of Army tanks are leaking (90% can be upgraded)
4. Fury inspections will be available as a service to installations
5. The average cost per tank of cathodic protection retrofit is $800

6. A typical replacement cost for a 12,000 gal. tank is $35,000
   (Source: Southern Cathodic Protection, Atlanta, GA)
7. ROI = simple return on investment = (net savings) / (investment for those savings)

Case Study: Hunter Army Air Field (Savannah, GA)

Hunter AAF currently has 30 USTs, each of 50,000 gal., which were installed around 1956. An A/E contractor recommended complete replacement at a cost of $10M. An assessment of three of these tanks was performed in accordance with ASTM ES40-94. Two of the three were found suitable for upgrade with cathodic protection in order to be brought into compliance with Federal Law (40 CFR 280). The Army Petroleum Center cost of these three inspections totaled $40K ($20K to CERL and $20K to the installation to empty, clean and provide a vapor free environment). It should be noted that these inspections were part of a research effort with an advanced prototype device and that these tanks were considerably larger then average. The cost per typical inspection/assessment should decrease dramatically.

Assuming the same proportion of suitability for upgrade for all 30 tanks the avoided cost for replacement alone would be:

Implement --	10 x ($40K / 3 USTs) = $400K
Avoided replacement –	$10,000 K x 67% = $6,700 K

ROI = 15.8

This calculation ignores the avoided cost of remediation and the cost of retrofit/upgrade with cathodic protection.

Dated Signature of Project Lead

Revision 1:

--- 29 JUN 1998

Charles Marsh, Materials Engineer Date

U.S. Army Construction Engineering Research Laboratories

Champaign, IL