**Contract No:**

This document was prepared in conjunction with work accomplished under Contract No. 89303321CEM000080 with the U.S. Department of Energy (DOE) Office of Environmental Management (EM).

**Proceedings of the ASME 2023**
**Pressure Vessels & Piping Division Conference**
**PVP2023**
**July 16-21, 2023, Atlanta, GA, USA**

# PVP2023-101366

# STATISTICAL ANALYSIS OF WASTE TANK PIT DEPTH MEASUREMENTS FOR CORROSION RATE PROJECTIONS

**Stephen Harris[1], Bruce Wiersma[1], Jim Elder[2], Alan Plummer[3], Ruel Waltz[4]**

[1] Savannah River National Laboratory, Aiken, SC
[2] ITIVS, N. Augusta, SC
[3]Savannah River Mission Completion, Aiken, SC
[4]Pinnacle Specialty Group, Aiken, SC

## ABSTRACT

*Liquid radioactive waste is stored in large, underground carbon steel tanks at the United States Department of Energy's Savannah River Site in Aiken, South Carolina. As a component of the site's Structural Integrity Program, in-service inspection of these tanks is conducted to ensure tank integrity and to verify the effectiveness of waste chemistry requirements for mitigation of corrosion degradation. The inspections are performed using a projection image scanning (P-scan) automated ultrasonic testing device, which is remotely operated on a magnetic wall crawler. The inspections focus on gathering data related to the primary corrosion mechanisms of concern: general corrosion, pitting corrosion, and stress corrosion cracking. The inspections provide a real-time assessment of actual conditions to confirm that the corrosion control program is effectively mitigating corrosion.*

*A horizontal band of incipient pits was identified on one of these tanks over 25 years ago. As a precaution, the site has monitored this band of pits to determine if they were actively growing (i.e., pit depth increasing). In 2012, the location of nearly 100 of these pits were referenced. In 2022, the inspection plan for this tank required that these same pits be measured. A statistical analysis was performed to determine if a difference between the pit distributions measured in 2012 and 2022 exists. Statistical tolerance limits for pit depth were also calculated assuming the Largest Extreme Value (LEV), negative Weibull and log-Normal probability distributions for comparisons. The analysis confirmed that there was no significant difference between the two distributions and hence pit growth is not occurring. The analysis provided the basis for discontinuing future inspection of the horizontal band on this tank.*

*Keywords: Ultrasonic Testing, Corrosion, Statistical*

## NOMENCLATURE

| | |
|---|---|
| CCP | Corrosion Control Program |
| HorzScan | UT Horizontal Scan |
| ISI | In-Service Inspection |
| ITIVS | Independent Tank Integrity Verification Specialist LLC |
| LEV | Largest Extreme Value Distribution |
| LN | Log-Normal Distribution |
| LW | Liquid Waste |
| SRNL | Savannah River National Laboratory |
| SRS | Savannah River Site |
| UT | Ultrasonic Testing |
| VertScan | UT Vertical Strip Scan |

## 1. INTRODUCTION

Liquid waste (LW) has been stored in underground carbon steel tanks at the United States Department of Energy's Savannah River Site (SRS) in Aiken, South Carolina since the 1950s. To ensure the safe storage of LW, the tank structures must provide confinement via a leak-tight barrier to the environment. Additionally, the tanks must maintain acceptable structural stability during design basis events, including loads from both normal service and abnormal (e.g., seismic) conditions. Buried underground in concrete vaults, individual tanks are enormous in size (Figure 1), with diameters of approximately 25 meters and heights of approximately 10 meters (Figure 2). The storage capacity for individual tanks is approximately 4.9 million liters. During service life, the tanks

This work was produced by Battelle Savannah River Alliance, LLC under Contract No. 89303321CEM000080 with the U.S. Department of Energy. Publisher acknowledges the U.S. Government license to provide public access under the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

contain varying volumes and compositions of LW. In the process of remediation and disposition of LW, tanks will be emptied, cleaned, grouted, and permanently closed. The inspection of structural integrity of the tanks providing a real-time assessment of actual conditions while in service is imperative but bears logistical challenges intrinsic to underground tanks. Risers provide limited access and structural supports interfere at times with surface area and directionality of instrumental inspections.

SRS implemented a corrosion control program (CCP) for the LW tanks in 1977 to mitigate general corrosion, pitting corrosion, and stress corrosion cracking of the carbon steel structures [1]. The program requires that minimum levels of corrosion inhibitors (e.g., sodium hydroxide and sodium nitrite) be maintained in the liquid portion of the waste and that maximum allowable interior temperatures are not exceeded. If these requirements are met, general corrosion rates and the risk of pit initiation are expected to be low. However, deviations from ideal chemistries may occur, for example, when waste is transferred between tanks. The carbon steel thinning due to degradation (e.g., pitting or corrosion) would reduce the original confinement capacity of the LW tanks. The majority of the tanks have been in compliance with the CCP since being placed in service.

**FIGURE 1: (a) Type III LW Tank under Construction during the 1960s**

**FIGURE 1: ( (b)Top View of an Underground Type III LW Tank.**

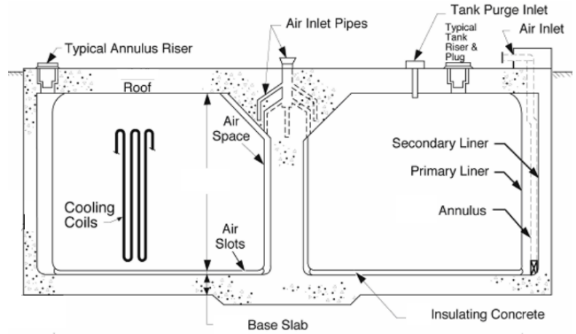


**FIGURE 2: Cut-Away Drawing of an Underground Type III LW Tank.**

An in-service inspection (ISI) program, begun in 1971 at SRS, is used to assess and demonstrate the structural integrity of the tanks and to confirm that the CCP is effectively mitigating corrosion. The ISI program focuses on ultrasonic inspection of the LW tanks. All ultrasonic inspections are performed using the projection image scanning (P-Scan) automated UT device, which is remotely operated on a magnetic wall crawler (see Figure 3.1, 3.2). The inspection frequency for each tank, ranging between seven to ten years, was based on the severity of its service history and the severity of the projected service. The inspections focus on gathering data related to the primary corrosion mechanisms of concern: general corrosion, pitting corrosion, and stress corrosion cracking. No cracking has been found in Type III/IIIA LW tanks.

## 2. BACKGROUND

However, evidence of “incipient pitting” (i.e., pit depths less than 1.6 mm) has been observed in several of the tanks. These pits are not presently a threat to either structural stability or leak integrity as they represent a less than 10% reduction in wall thickness. They are monitored, however, to ensure that there is no further growth between inspection intervals, which range between 7-10 years. These incipient pits are generally broad and shallow and for the most part are isolated (i.e., less than 5 pits per tank measured). On the other hand, one tank exhibited approximately 100 such pits. These incipient pits were identified after a 2005 inspection to reside in a horizontal band approximately 30 cm in width and approximately 175 cm above the tank bottom (Fig. 4.1). The location of the pits also coincided with the location of a stagnant liquid-air interface. This condition has been associated with the potential for accelerated pitting corrosion. Therefore, the facility decided to monitor these pits to determine if they were propagating pits. This area of the tank was re-inspected in 2012 and 2022. A vertical scan of a fixed strip within the tank was also conducted in 2012 and 2023 for monitoring 23 pits (Fig. 4.2). This paper is a follow-up to the 2012 paper published in the Journal of Pressure Vessel Technology [1] and presents a statistical analysis of the pit measurements from these inspections. The results of this analysis will determine whether pit propagation is continuing or not.

**FIGURE 3.1: In-Use UT Wall Crawler with P-Scan Device.**

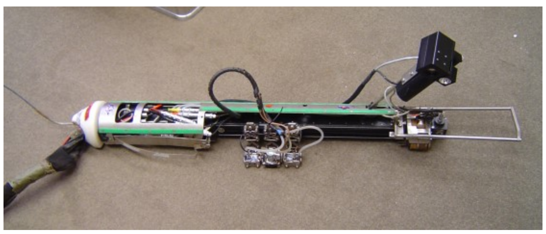

**FIGURE 3.2: Top View of the Wall Crawler with P-Scan Device.**

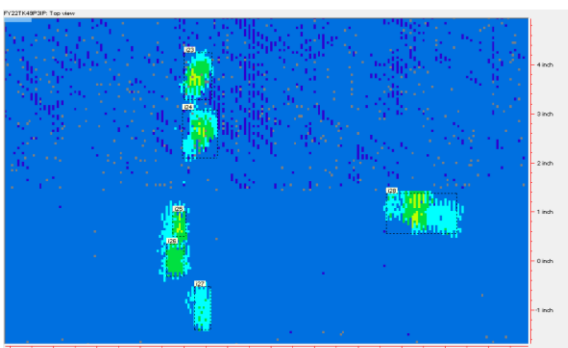

**FIGURE 4.1: 2022 Horizontal UT Scan (97 Pits)**

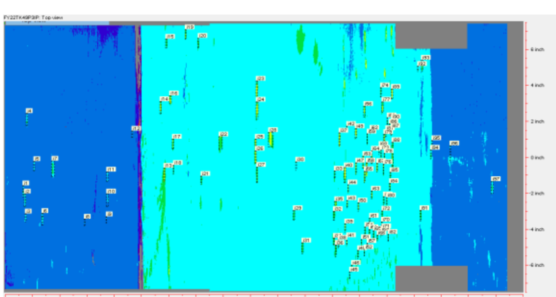

**FIGURE 4.2: 2022 Vertical Scan (23 Pits)**

## 3. DATA AND SUMMARY STATISTICS

The pit depths were measured by UT in the lower section by SRNL in 2012 and then the same pits were measured ten years later in 2022 by ITIVS. Random areas were also UT inspected within the tank and statistically analyzed but not presented in this paper.

There were 120 pits measured, 97 were from a horizontal scan(HorzScan), and 23 measurements were from a scan of a vertical strip(VertScan).

Histograms of pit depth measurements are displayed in Figures 5.1 and 5.2 for the 2022 and 2012 for the horizontal scan measurements and in Figures 5.3 and 5.4 for the vertical strip measurements. A smooth distribution that is skewed to the right is also super-imposed on the histograms.

The horizontal scan pit depth histograms indicate that the distribution is skewed to the right for both years indicating a propensity toward extreme values. The vertical scan pit distribution for 2012 is also skewed to the right but the skewness is not as notable for the 2022 vertical scan measurements.

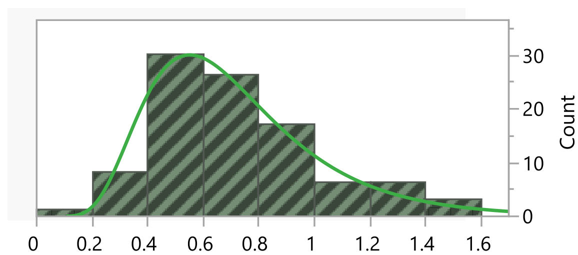


**FIGURE 5.1: 2022 HorzScan Pit Depth (mm)**

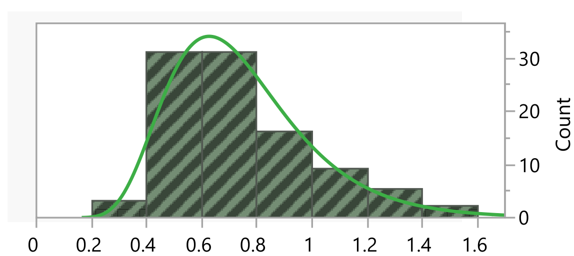


**FIGURE 5.2: 2012 HorzScan Pit Depth (mm)**

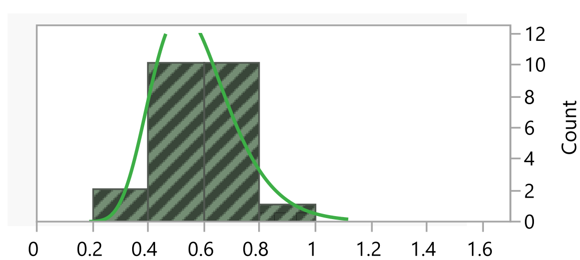


**FIGURE 5.3: 2022 VertScan Pit Depth (mm)**

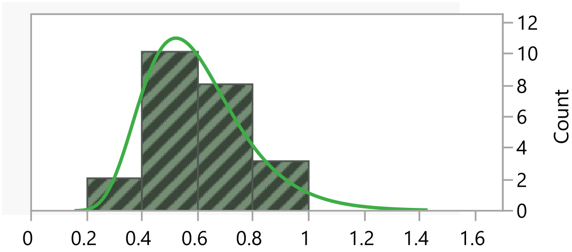


**FIGURE 5.4: 2012 VertScan Pit Depth (mm)**

Summary statistics were obtained using the JMP [2] statistical software and displayed in Table 1. The pit depths overall 120 measurements and years ranged between 0.127 mm to 1.575 mm.

The averages and standard deviations are higher for the horizontal scan measurements in comparison to the vertical scan pit depth measurements (e.g.: 2022 0.719mm HorzScan mean vs. 0.574 mm VertScan mean). The statistics between years for the horizontal scan appear to be similar (HorzScan 2012 vs. 2022 mean 0.747 mm vs. 0.719 mm; VertScan 0.597 mm vs. 0.574 mm mean). A visual display of the data using mean diamonds is presented in Figure 6 for both the horizontal scan and vertical scan measurements. The top and bottom of each diamond represent a 95% confidence interval for the mean. The middle of the diamond is the average. The mean diamonds suggest that there is no difference in means between 2012 and 2022 horizontal scan and between 2012 and 2022 vertical scan measurements.

| Year/Scan | N Rows | Mean(mm) | Std Dev(mm) | Min(mm) | Max(mm) |
|---|---|---|---|---|---|
| 2022 HorzScan | 97 | 0.719 | 0.292 | 0.127 | 1.575 |
| 2012 HorzScan | 97 | 0.747 | 0.269 | 0.305 | 1.549 |
| 2022 VertScan | 23 | 0.574 | 0.144 | 0.356 | 0.813 |
| 2012 VertScan | 23 | 0.597 | 0.167 | 0.229 | 0.965 |

**TABLE 1: Summary Statistics of Pit Depth by Scan and Year**

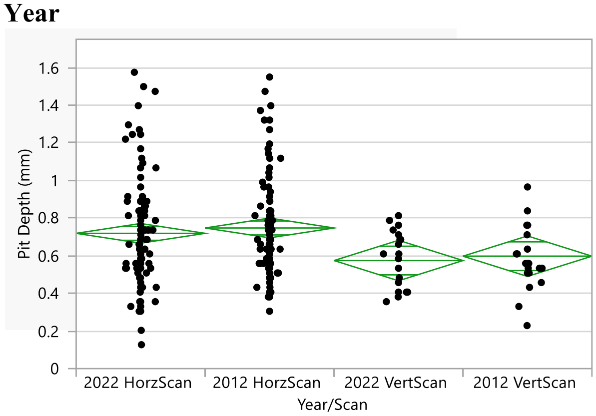


**FIGURE 6: Mean Diamonds for the Horizontal Scan and Vertical Scan Measurements by Year**

No tank elevation (in. from bottom) trend was observed for the vertical strip measurements (Fig. 7).

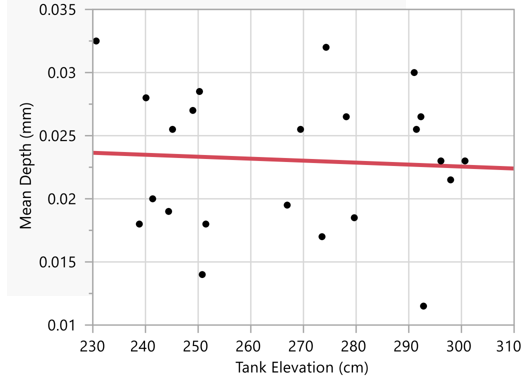


**FIGURE 7: Vertical Scan Pit Mean Depth (mm) vs. Tank Elevation (cm)**

A slight impact within the horizontal band was within measurement error and non-consequential because of its narrow elevation range.

For a more precise comparison, the pairwise differences between 2012 and 2022 pit depth scans are displayed in Table 2 for the horizontal scan and vertical scan measurements. Corresponding histograms are presented in Figures 8.1 and 8.2. The overall pit depth difference between the 2012 and 2022 measurement ranged between -0.307 mm and 0.330 mm for the 120 measurements. There appears to be negligible differences in averages between 2012 and 2022 pit depth measurements. Formal statistical testing of the paired pit depth differences is presented in the next section.

| Scan | N | Mean (mm) | Std Dev (mm) | Min (mm) | Max (mm) |
|---|---|---|---|---|---|
| HorzScan | 97 | -0.029 | 0.115 | -0.305 | 0.330 |
| VertScan | 23 | -0.023 | 0.124 | -0.305 | 0.178 |

**TABLE 2: Summary Statistics for Pit Depth Difference by Scan Type (Pit Depth 2022-Pit Depth 2012 by Pit)**

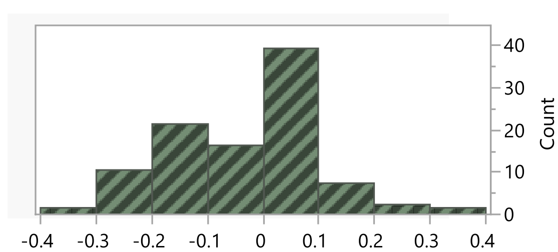


**FIGURE 8.1: Histogram for HorzScan Pit Depth Difference (mm)**

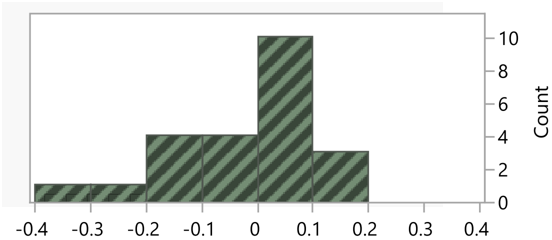


**FIGURE 8.2: Histogram for Vertical Scan Pit Dept Difference (mm)**

A dot plot and mean diamonds for the pit depth differences is presented in Figure 9 for both the horizontal scan and vertical scan measurements. The Horizontal Scan Mean Diamonds shows that the mean is slightly below zero (2022 pit depth mean is less than the mean 2012 pit depth) and significant.

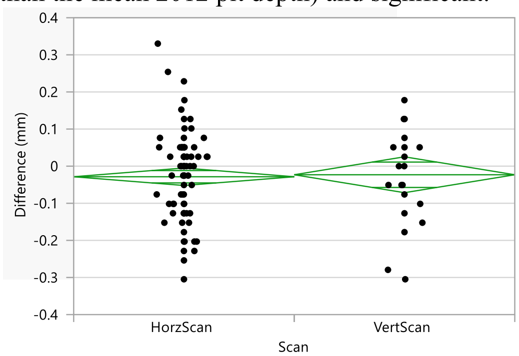


**FIGURE 9: Dot Plot for Pit Depth Difference (mm) by Scan**

## 4. STATISTICAL ANALYSIS

The Fréchet, negative Weibull, and largest extreme value distribution are within the largest extreme value (LEV) family of distributions. These extreme value distributions are the limiting distributions for the maximum of a very large collection of random observations. The LEV family covers any specified average, standard deviation and high skewness. The LEV family of distributions was fit to the pit depth data from UT scans. In addition, the lognormal (LN) family of distributions was also fit to the pit depth data. The log-normal family includes the lognormal, negative lognormal, and the normal distributions. Both the LEV and LN family of distributions have been used as a model for modeling extreme observations. Within each family of distributions, the one most consistent with the measurements was selected (Table 3) as determined by the goodness-of-fit p-values. Either distribution fits the data equally well for each scan and year combinations. Therefore, the more extreme prediction is used to be conservative. The parameters were estimated using the Distribution Analyzer [3] software. The Goodness-of-fit p-values indicate that the distributions are reasonable for the pit depth measurements (p<0.05 indicated lack of fit).

| Scan | Year | Dist Family | Distribution | p-value | Parameter Estimates |
|---|---|---|---|---|---|
| HorzScan | 2012 | LEV | Largest Extreme Value | 0.53 | $\mu = 0.63,\ \sigma = 0.20$ |
| HorzScan | 2012 | LN | LogNormal | 0.97 | $\varepsilon = 0.14,\ \mu = -0.59,\ \sigma = 0.43$ |
| VertScan | 2012 | LEV | Negative Weibull | 0.57 | $\varepsilon = 1.17,\ \sigma = 0.63,\ \eta = 3.92$ |
| VertScan | 2012 | LN | LogNormal | 0.70 | $\varepsilon = -5.26,\ \mu = 1.77,\ \sigma = 0.02$ |
| HorzScan | 2022 | LEV | Negative Weibull | 0.88 | $\varepsilon = 4.75,\ \sigma = 4.16,\ \eta = 17.25$ |
| HorzScan | 2022 | LN | LogNormal | 0.83 | $\varepsilon = -0.33,\ \mu = 0.01,\ \sigma = 0.27$ |
| VertScan | 2022 | LEV | Negative Weibull | 0.11 | $\varepsilon = 0.95,\ \sigma = 0.43,\ \eta = 3.08$ |
| VertScan | 2022 | LN | LogNormal | 0.07 | $\varepsilon = -23.77,\ \mu = 3.19,\ \sigma = 0.01$ |

**TABLE 3: Distribution for Pit Depth by Scan and Year**

The location and scale parameters for the largest extreme value distribution are $\mu$ and $\sigma$, respectively. The location, scale and shape parameters are $\varepsilon$, $\mu$ and $\sigma$, for the lognormal distribution, respectively. The location, scale and shape parameters are $\varepsilon$, $\sigma$ and $\eta$ for the negative Weibull distribution, respectively.

Statistical analysis of matched pairs was conducted to compare the mean pit depth between 2012 and 2022 to assesses their differences. The paired t-test takes the correlation between the 2012 and 2022 pit depth measurements into account. The matched pairs analysis compares row-by-row differences between two years using a paired t-test. The x-axis in Fig. 10 is the average of the pit depth measurements on a pit-by-pit basis for the horizontal scan pit depths. The y-axis is the difference between the 2022 and 2012 measurements. The horizontal solid lines near zero is the average pit depth difference. The dotted lines are a 95% confidence interval fot the mean pit depth. They indicate that the average pit depth in 2012 is slightly larger than that in 2022 for the horizontal scan. In formal statistical testing (Table 4), the mean difference is -0.0285 mm and the p-value for the one-sided test for 2012 being larger than 2022 is 0.0083 (<0.05).

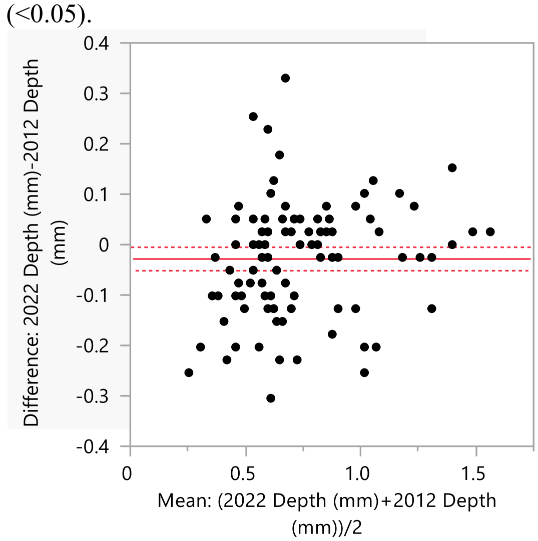


**FIGURE 10: HorzScan Pit Depth Difference: 2022 Depth**

**(mm)-2012 Depth (mm)**

| | | | |
|---|---|---|---|
| 2022 Depth (mm) | 0.71879 | t-Ratio | -2.43662 |
| 2012 Depth (mm) | 0.74734 | DF | 96 |
| Mean Difference | -0.0285 | Prob > \|t\| | 0.0167* |
| Std Error | 0.01171 | Prob > t | 0.9917 |
| Upper 95% | -0.0053 | Prob < t | 0.0083* |
| Lower 95% | -0.0518 | | |
| N | 97 | | |
| Correlation | 0.9187 | | |

**TABLE 4: HorzScan Pit Depth Difference: 2022 Depth (mm)-2012 Depth (mm)**

The paired-comparison t-test for the vertical scan pit depth measurements is displayed in Figure 11 with corresponding statistics in Table 5. There is no statistical difference in means between the 2012 and 2022 pit depth measurements (p=0.38).

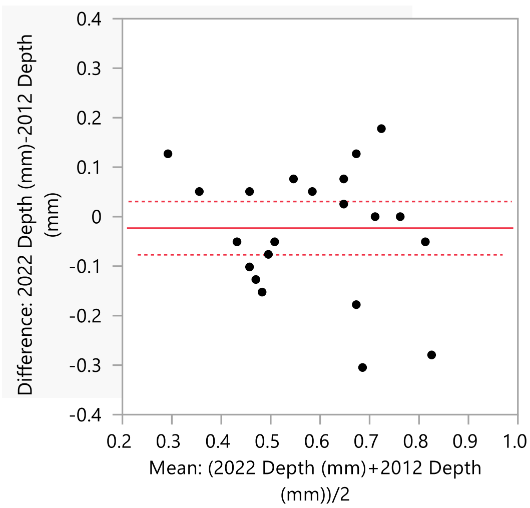


**FIGURE 11: Vertical Pit Depth Difference: 2022 Depth (mm)-2012 Depth (mm)**

| | | | |
|---|---|---|---|
| 2022 Depth (mm) | 0.57426 | t-Ratio | -0.89397 |
| 2012 Depth (mm) | 0.59745 | DF | 22 |
| Mean Difference | -0.0232 | Prob > \|t\| | 0.3810 |
| Std Error | 0.02594 | Prob > t | 0.8095 |
| Upper 95% | 0.03061 | Prob < t | 0.1905 |
| Lower 95% | -0.077 | | |
| N | 23 | | |
| Correlation | 0.68766 | | |

**TABLE 5: Vertical Pit Depth Difference: 2022 Depth (in)-2012 Depth (mm)**

Based on the distributions in Table 3, the upper tolerance limit for 99% of the pit depth distribution is less than 1.801 mm with 95% confidence for the LEV distribution and 1.919 mm for the lognormal distribution (Table 6).

| Scan | Year | LEV Prob | LN Prob | LEV UTL (mm) | LN UTL (mm) |
|---|---|---|---|---|---|
| HorzScan | 2012 | 0.53 | 0.97 | 1.801 | 1.919 |
| VertScan | 2012 | 0.57 | 0.70 | 1.298 | 1.154 |
| HorzScan | 2022 | 0.88 | 0.83 | 1.767 | 1.775 |
| VertScan | 2022 | 0.11 | 0.07 | 1.194 | 1.067 |

**TABLE 6: LEV Upper Tolerance Limits with 95% Conf and 99% Coverage** *(LEV & LN Prob: Skewness-Kurtosis Test for Goodness-of-Fit)*

Then the estimated percentage of pit depth measurements greater than 1.78 mm, 2.03 mm and 2.29 mm was estimated using the LEV distribution and also the lognormal distribution (Table 7). The percentages for the log-normal distribution are in parentheses in Table 7. Less than 0.333% of pit depths are estimated to be above 2.29 mm with 95% confidence over all scans (HorzScan and VertScan) and years (2012 and 2022).

| Scan | Year | Pit Depth % > 1.78 mm | Pit Depth % > 2.03 mm | Pit Depth % > 2.29 mm |
|---|---|---|---|---|
| HorzScan | 2012 | 1.084 (1.542) | 0.422 (0.712) | 0.160 (0.330) |
| VertScan | 2012 | 0.001 (0.001) | n/a | n/a |
| HorzScan | 2022 | 0.942 (0.979) | 0.292 (0.346) | 0.079 (0.117) |
| VertScan | 2022 | 0.001 (0.001) | n/a | n/a |

**TABLE 7: Lower Plate Pit Depth Distribution Exceeding 0.07 in, 0.08 in and 0.09 in with 95% Confidence**

The percentage pit depths exceeding 1.78 mm, 2.03 mm and 2.29 mm is 1.553%, 0.707% and 0.333%, respectively, from fitting the lognormal distribution to the 2012 horizontal scan data. These pit depths are less than 10% of the plate wall thickness.

## 5. CONCLUSIONS

There is no statistical evidence of pit depth growth over the years 2012 to 2022. The percentage of all pit depths exceeding 2.29 mm is less than 0.33% regardless of the year of UT inspection. There is negligible difference between year inspected for the horizontal scan measurements. Moreover, the 2022 mean measured pit depth is less than that from the 2012 UT scan measurements. There is no statistical difference between year inspected for the vertical scan measurements. Therefore, since these pits are not continuing to propagate, future inspections of the horizontal band of incipient pits are unnecessary. It is likely that these pits existed prior to the tank being placed in-service. In addition, the size of the pits measured are typically less than or equal to the depth that would have been acceptable during the final inspection of the tank wall before it was placed in service.

Therefore, the facility may discontinue inspection of this band of pits without an increase in risk to the tank leak integrity. It was also noted that it is unlikely that the maximum pit depth is approaching the plate wall thickness.

## 6. REFERENCES

[1] Baxter, L.R. and Harris, S.P. (2012). Statistical Sampling for In-Service Inspection of Underground Storage Tanks, Journal of Pressure Vessel Technology, October 2012, Vol. 134.

[2] JMP Pro, Version 11.2.1, SAS Institute, Cary, NC.

[3] Distribution Analyzer, Ver. 1.2, Taylor Enterprises, Inc., Libertyville, IL, http://www.variation.co