In-service Inspection of Radioactive Waste Tanks at the Savannah River Site – 15410

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ABSTRACT

Liquid radioactive wastes from the Savannah River Site (SRS) separation process are stored in large underground carbon steel tanks. The high level wastes are processed in several of the tanks and then transferred by piping to other site facilities for further processing before they are stabilized in a vitrified or grout waste form. Based on waste removal and processing schedules, many of the tanks, will be required to be in service for times exceeding the initial intended life. Until the waste is removed from storage, transferred, and processed, the materials and structures of the tanks must maintain a confinement function by providing a barrier to the environment and by maintaining acceptable structural stability during design basis events, which include loadings from both normal service and abnormal (e.g., earthquake) conditions. A structural integrity program is in place to maintain the structural and leak integrity functions of these waste tanks throughout their intended service life.

In-service inspection (ISI) is an essential element of a comprehensive structural integrity program for the waste tanks at the Savannah River Site (SRS). The ISI program was developed to determine the degree of degradation the waste tanks have experienced due to service conditions. As a result of the inspections, an assessment can be made of the effectiveness of corrosion controls for the waste chemistry, which precludes accelerated localized and general corrosion of the waste tanks. Ultrasonic inspections (UT) are performed to detect and quantify the degree of general wall thinning, pitting and cracking as a measure of tank degradation. The results from these inspections through 2013, for the 27 Type III/IIIA tanks, indicate no reportable in-service corrosion degradation in the primary tank (i.e., general, pitting, or cracking). The average wall thickness for all tanks remains above the manufactured nominal thickness minus 0.25 millimeter and the largest pit identified is approximately 1.70 millimeter deep (i.e., less than 10% through-wall).

Improvements to the inspection program were recently instituted to provide additional confidence in the degradation rates. Thickness measurements from a single vertical strip along the accessible height of the primary tank have been used as a baseline to compare historical measurements. Changes in wall thickness and pit depths along this vertical strip are utilized to estimate the rate of corrosion degradation. An independent review of the ISI program methodology, results, and path forward was held in August 2009. The review recommended statistical sampling of the tanks to improve the confidence of the single strip inspection program. The statistical sampling plan required that SRS increase the amount of area scanned per tank. Therefore, in addition to the baseline vertical strip that is obtained for historical comparisons, four additional randomly selected vertical strips are inspected. To date, a total of 104 independent vertical strips along the height of the primary tank have been completed. A statistical analysis of the data indicates that at this coverage level there is a 99.5% confidence level that one of the

worst 5% of all the vertical strips was inspected. That is, there is a relatively high likelihood that the SRS inspection program has covered one of the most corroded areas of any of the Type III/IIIA waste tanks. These data further support the conclusion that there are no significant indications of wall thinning or pitting. Random sampling will continue to increase the confidence that one of the worst 5% has been inspected.

In order to obtain the additional vertical strips, and minimize budget and schedule impacts, data collection speed for the UT system was optimized. Prior to 2009, the system collected data at a rate of 32 square centimeters per minute. The scan rate was increased to 129 - 160 square centimeters per minute by increasing the scanner step and pixel sizes in the data acquisition set-up. Laboratory testing was utilized to optimize the scan index/pixel size such that the requirements for wall thinning and pit detection were still maintained. SRS continues to evaluate improvements to ultrasonic equipment.

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 1960s. 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 25.9 meter and heights of approximately 10 meter (Figure 2). The storage capacity for individual tanks is approximately 4.9 million liters. During service life, the tanks contain varying volumes and constitutions of LW. In the process of remediation and disposition of LW, tanks will be emptied, cleaned, grouted, and permanently sealed. A real-time assessment of actual conditions while in service is imperative to ensure the structural integrity of the tanks, but such and inspection 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.[2]

(a) **(b)**

Figure 1: (a) Type III LW Tank under Construction during the 1960s; (b)Top View of an Underground Type III LW Tank.

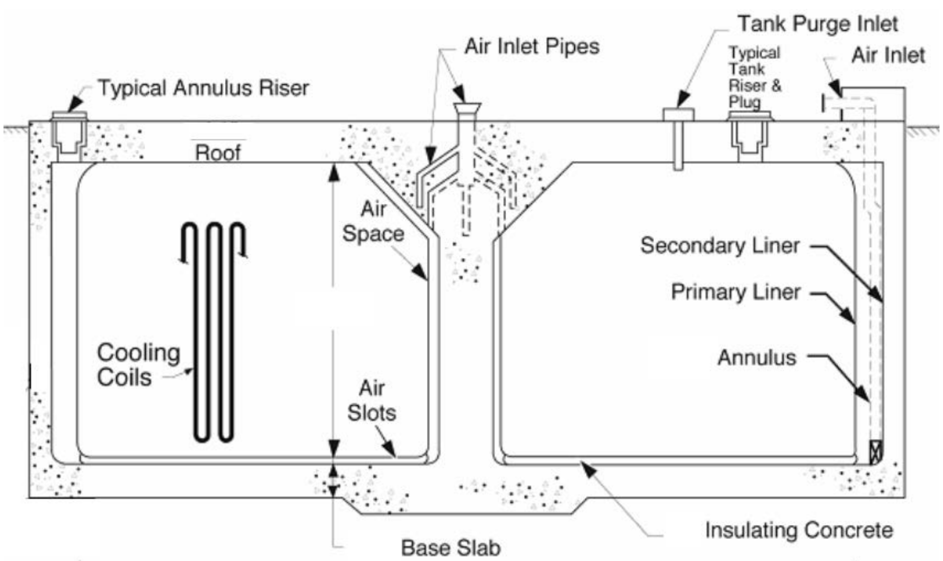


Figure 2: Cut-Away Drawing of an Underground Type III LW Tank.

An in-service inspection (ISI) program, begun in 1971 at SRS, is used to assess 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). 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.

In 2009, an independent panel was tasked with reviewing the adequacy of the ISI program.[2] The two primary recommendations from the panel were: 1) Develop a technology that collects the UT data at a faster rate, while still maintaining the necessary resolution to make accurate assessments, and 2) Develop a statistical basis for determining the adequacy of the extent of the tank inspections. The remainder of this document will discuss the improvements that have been made to the ISI program as a result of responses to these recommendations.

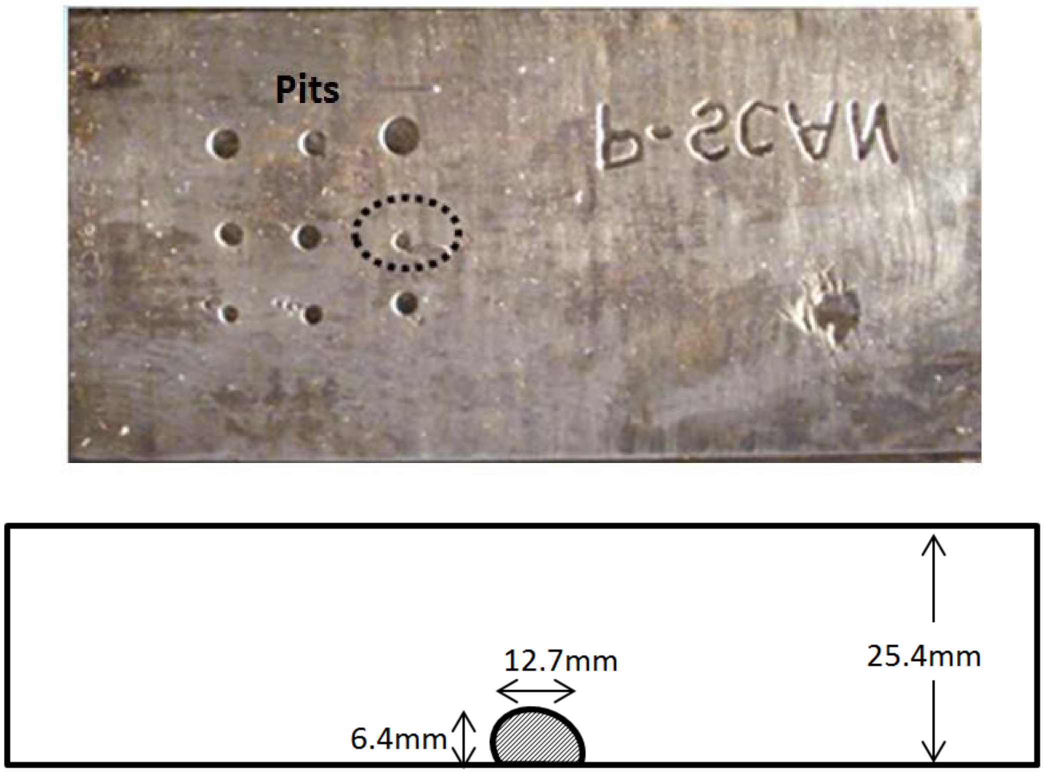
Figure 3. (a) In-Use P-scan Wall Crawler (b) Top View of the P-san Wall Crawler.

UT DATA COLLECTION OPTIMIZATION

Thickness mapping was performed utilizing one 5 MHz, dual element transducer to inspect for thinning and pitting corrosion. Vertical strips along the tank wall were collected in a raster pattern over 216 mm wide strips every 1.27 millimeters in both the "X" and "Y" directions. Several gate evaluation methods, including multiple echo techniques are utilized and recorded at each location. The UT technique that was utilized had an average scan rate of 32 cm^2 of data per minute.

Savannah River Remediation (SRR) requested that the Savannah River National Laboratory (SRNL) investigate optimizing the standard UT system by determining the effects of increasing the scan rate and pixel size on the data resolution. The test configuration utilized was similar to what is recommended for large area scans. To increase the data collection speed, the scanner step and pixel sizes were increased in the data acquisition set-up for the UT equipment. Two thickness mapping transducers are used simultaneously in conjunction with two angle beam probes to evaluate crack detection and sizing. Use of two transducers effectively cut the probe travel distance in half.

The testing was performed on plates that contained pre-existing flaws (i.e., pits or notches) (see Figure 4). Thickness mapping scans were performed on carbon steel plate that was nominally 12.7 mm thick. The plate contained pre-drilled pits with depths that ranged between 0.94 mm to 4.5 mm. Crack detection scans were performed on 25.4mm thick welded plate that contained 12.7 mm long circular, thumbnail notches that were machined on the opposite surface. Scans were performed at the maximum speed of 152 mm/sec for all scans. The scan resolution indexes ranged from the 0.89 mm to 11.4 mm settings and each test scan was replicated. Scans were repeated at varying resolution settings to determine the maximum speed/pixel size that could be employed, yet still reliably detect and measure flaws.



P1 & P2 Parallel Semi-circular Notch

Figure 4. Carbon steel plate with pits and sketch of notches used for optimization of UT technology.

The results of the scans are shown in Table 1. At scan resolution intervals up to 2.54 mm, all pits and notches were detected. Thus, the data collection rate could be increased by a factor of four and still produce reliable data. This technique was employed in revisions to the ISI program since 2010. The data collected is used to assess new areas that are being scanned, but is not used to compare with previous pitting depth/diameter data as the accuracy and uncertainty are not as good.

Table 1. Results of UT Optimization Tests

Thickness						Crack Detection				
File Name / step size (mm)	Ave. Thickness (ME)	Min Thk (Pk-E)	# Pits	Pit C3 Depth (TWDx10)		Notches detected @ (-6dB)	Length P-1 @ (-6dB)	max dB P1	Length P-2 @ (-6dB)	max dB P2
0.889 a	12.09	7.87	9	0.89		8	19.46	22	17.35	15
0.889 b	12.09	7.87	9	0.89		8	19.74	22	17.12	15
1.27 a	12.09	7.87	9	0.84		8	19.46	22	16.71	14
1.27 b	12.09	7.87	9	0.84		8	19.79	22	16.64	14
1.905 a	12.09	8.13	9	0.76		7	18.92	21	17.20	14
1.905 b	12.09	8.10	9	0.74		6	19.56	21	17.60	14
2.54 a	12.09	7.95	9	0.71		7	18.24	22	17.93	15
2.54 b	12.09	8.00	9	0.64		8	17.68	22	18.01	13
3.81 a	12.09	8.13	9	0.66		**3**	15.67	20	15.67	10
3.81 b	12.09	8.36	9	0.53		**3**	22.66	20	15.24	10
5.08 a	12.09	8.31	**6**	0.58		**3**	15.42	21	15.14	12
5.08 b	12.09	8.18	**7**	0.74		**3**	20.62	20	15.14	7
6.35 a	12.09	8.23	**4**	N/D		**3**	19.05	17	12.70	7
6.35 b	12.09	8.26	**3**	N/D		**3**	19.05	16	12.70	7
7.62 a	12.09	8.13	**5**	0.38		**3**	15.24	16	12.70	8
7.62 b	12.09	8.13	**5**	0.64		**3**	15.24	17	12.70	9
8.89 a	12.09	8.15	**4**	N/D		**3**	17.78	22	17.78	4
8.89 b	12.09	8.15	**5**	N/D		**3**	17.78	21	17.78	4
10.16 a	12.09	8.36	**3**	N/D		**3**	20.83	13	10.67	12
10.16 b	12.09	8.31	**3**	N/D		**3**	20.32	14	10.16	12

- Length, Depth and Thickness (Thk) units in millimeters.
- Scans “a” and “b” represent duplicate scans as each resolution was performed twice.
- Pit C3 is 0.94mm deep x 6.35mm diameter at the surface.
- “N/D = Pit “C3” Not Detected.
- Highlighted yellow indicates that not all 9 pits on the test sample were detected.

STATISTICAL BASIS FOR EXTENT OF INSPECTION

Due to the high cost and time constraint of inspecting even a portion of a single tank, a statistical sampling strategy was implemented to account for variations in the materials of construction, tank chemistry, and measurement uncertainty. The strategy was to employ an inspection criterion for LW tanks similar to that indicated in DOE-STD-3013[3] for packaging and storage of excess plutonium from the United States nuclear weapons program. The standard directed that a surveillance plan be developed and used for monitoring the condition of the 3013 containers during storage. As a result, Los Alamos National Laboratory (LANL) in New Mexico developed the statistical strategies reported in the “Selection of 3013 Containers for Field Surveillance.”[4]

By expanding and modifying the LANL strategy for 3013 containers, the ISI program aims to produce high confidence in the structural integrity and safety of the in-service Type III/IIIA LW tanks.[5] This report outlines the statistical sampling strategy for ISI of these underground tanks at SRS.

Background on Statistical Sampling Strategy

As part of the surveillance program for the 3013 containers, LANL has put forth a statistical sampling strategy for the 3013 containers that have structure and contents that are classifiable by way of laboratory tests on pedigree materials and that have container loading history. The 3013 containers are subjected to a decision tree process for classification based on their risk potential. As per the LANL plan, a container is classified (binned) according to how its safety/integrity may be challenged through pressurization and/or corrosion.

The statistical sampling strategy for evaluating the safety/integrity of the 3013 container population states that a sample should be random and large enough to attain a 99.9% probability (also called "confidence") of observing at least one of the worst 5% of the containers under study, denoted as 99.9%/5%.

UT has been conducted periodically on the external surfaces of the primary tanks mainly near adjacent risers. The UT data include wall thickness and pit depth measurements. Wall thickness was measured with UT starting in 1975, but pit depth was not typically measured prior to 1995. The LANL 3013 statistical sampling strategy was adapted for the ISI program to determine the area to inspect across the ISI tanks, and the new SRS sampling strategy will henceforth be referred to as the "UT Statistical Sampling Plan" (UT-SSP).

The Statistical Sampling Plan

The purpose of the UT-SSP is to improve the credence and spatial application of current inspection results, with the goal of verifying tank integrity throughout service life. The UT-SSP is based on UT inspection of vertically oriented unit areas called "strips." A strip is typically 216 mm wide (0.27% of the tank circumference) and covers the accessible height of the primary tank wall, including areas on the top and bottom knuckles (Figure 5). Within each strip, an inherently random collection of areas from the lower, middle, and upper plates is characterized.

The intent of the strip selection is to develop statistical confidence in the CCP's ability to mitigate pitting and thinning of the inner wall of the LW tanks. Strip selection is stratified by quadrant, with a minimum of four strips randomly selected per tank for each scheduled inspection. In addition, during each scheduled inspection, one static "baseline" strip per tank that has been previously inspected will be inspected again. The baseline strip provides a basis for trending corrosion rates and developing service-life projections.

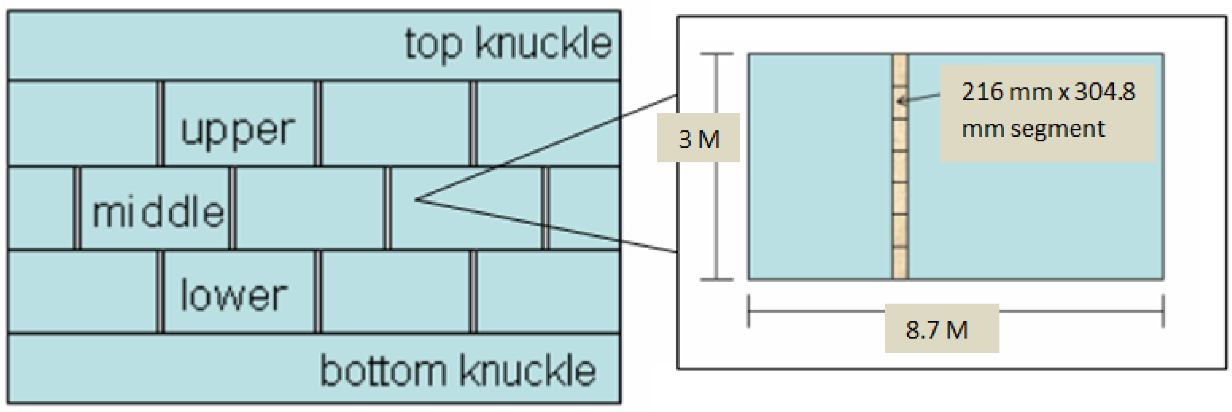


Figure 5: Left: Profile of a LW Tank Wall; Right: Profile of a Typical Plate.

Like the 3013 statistical sampling strategy, the UT-SSP approach requires no assumptions about which specific strips or tanks are the "worst." Assumptions targeting tanks or strips within specific tanks for UT inspection could introduce bias, especially across a population of tanks of this size with variable service-life contents. However, due to the large surface area, it is necessary to define a criterion for determining one of the worst strips within any particular LW tank for efficient utilization of UT resources. The objective of the UT-SSP will be to utilize stratified random sampling to provide an increasing confidence that at least one of the strips from the worst 5% within the entire population of tanks will be observed. In addition, over the service life of any Type III/IIIA LW tank, the increasing number of strips will provide greater confidence that at least one strip will have been amongst the worst 5% of the strips within that tank with the assumption that the worst area within a tank.

Furthermore, the UT-SSP examinations will be used to validate current models that trend general wall thinning and pitting. Data obtained from inspection of the strips include pit depth measurements and wall thickness, the latter of which is determined by averaging thousands of measurements over 305 mm segments of each strip. From previous UT inspections, pit depths greater than 0.38 mm were identified along with their location on the corresponding strips. Averaged wall thickness data was stratified by either lower, middle, or upper plate locations (starting about 0.6 m from the tank floor) and statistically analyzed for trending and tank lifetime projections.

Statistical Methodology

There are three aspects to the statistical methodology in the UT-SSP:

1) Select random strips for UT inspection to assure unbiased statistical results,
2) Determine the number of strips to inspect when considering all Type III/IIIA ISI tanks to have high confidence that at least one of the "worst" (i.e., pit depth or wall thickness) 5% will be examined,
3) Determine the confidence gained by increased inspection within any single tank,

This multifaceted approach to evaluating the integrity of the ISI LW tanks will ensure their safe and continued reliable use throughout their in-service lifetimes.

Random Sampling

From the perspective of corrosion behavior, general corrosion rates should be low, and pitting should be mitigated in all the CCP tanks.[1] Confirmation of the effectiveness of the CCP is achieved through a random sampling plan. In particular, stratified random sampling is conducted for each tank to complement UT data from past inspections, providing an increasing confidence in the integrity of the LW tanks over time. Implemented in 2010, the sampling plan includes one strip randomly selected within each non-overlapping 90 degree quadrant of each tank. In addition, a fixed strip has been selected for UT inspection that will be used to model corrosion and/or pit depth growth with respect to time. The fixed strip selected for continued inspection in most cases was first inspected thirty to forty years ago and correlates with the beginning of the tank service history.

The majority of pre-2010 data was obtained from strips located near one of the outer tank wall access areas referred to as “risers.” Because of the distribution of pit and wall thickness data points across various plate areas, sheets of steel, and tank height levels, it is reasonable to treat these strips as a random selection of strips. Current UT technology allows any strip to be inspected within a tank, unless obstructions inherent to the structure of the tank prevent access to that strip. If an obstruction prevents inspection of a particular strip, the closest neighboring strip will be inspected. The pre-2010 data will be complemented with the UT-SSP data as strips are inspected.

Confidence Curves for Sampling LW Tanks

The CCP has mitigated general corrosion, pitting corrosion, and stress corrosion cracking on the interior of the 27 ISI LW tanks. These tanks form one population since the majority of the tanks have been in compliance with the CCP since being placed in service. Confidence curves for UT inspection of strips from all ISI LW tanks are based on application of the hypergeometric distribution. The target population is all strips contained within the 27 ISI LW tanks. Because each tank consists of approximately 360 strips, the 27 ISI LW tanks can be thought of as a collection of 9,720 strips. The hypergeometric distribution for the probability of obtaining *x* strips from the worst 5% of the population in a random sample of size *n* is:

$$P(x)=\frac{\binom{D}{x}\binom{N-D}{n-x}}{\binom{N}{n}}=\frac{\left(\frac{D!}{x!(D-x)!}\right)\left(\frac{(N-D)!}{(n-x)!(N-D-n+x)!}\right)}{\frac{N!}{n!(N-n)!}}, \qquad (1)$$

where $a \le x \le b$, $a=\max\left[0,n-(N-D)\right]$, $b=\min\left[D,n\right]$, *N* represents the number of strips in the population, *D* represents the number of worst strips (i.e., $D=0.05(N)$), and *N-D* represents the remaining number of strips in the population. The number of strips selected for UT is represented by n, of which x are from the worst 5% of all strips and n-x are the remaining number of strips in the sample. The number of worst strips x in the sample cannot exceed the minimum of n and D [equivalently, min(n,D)]. For any positive integer k, $k! = (k)(k-1)(k-2)...1$ and is called k factorial (for $k = 0$, $0! \equiv 1$ by definition).

The probability of inspecting no strips from the worst 5% is determined from $P(x)$ with x=0 and simplifies to

$$P(0) = \left(\frac{N-D}{N}\right)\left(\frac{N-1-D}{N-1}\right)\left(\frac{N-2-D}{N-2}\right)...\left(\frac{N-n+1-D}{N-n+1}\right) \quad (2)$$

The probability of inspecting at least one strip from the worst 5% of all strips is:

$$P_{1+} = 1 - P(0) \quad (3)$$

The number of strips selected for UT, n, should be selected so that $P_{1+} = 1 - P(0) \geq 0.999$ to meet the 99.9%/5% criteria. In this paper, $100(P_{1+})$ is referred to as “confidence.”

To have sampled at least one strip from the worst 5% with 99.9% confidence, 134 strips would have to be randomly selected and inspected. Stratified random sampling has been shown to meet this criterion by inspecting at least 5 strips per each of the 27 LW tanks. The stratified random sampling has been implemented within each tank by specifying that one strip per quadrant be randomly selected and UT inspected. When complemented with one fixed strip per tank, this will ensure that at least one strip from the worst 5% will have been inspected with at least 99.9% confidence. In addition, the data to date will be statistically compared with and possibly combined with the UT-SSP data if statistically appropriate. A confidence curve (Figure 6) shows the rate at which the confidence increases as the number of inspected strips increases, eventually reaching 99.9% confidence as additional strips are tested. Thus far, 104 independent strips have been inspected across all tanks, including historical inspections. A statistical analysis of the data indicates that at this coverage level there is a 99.5% confidence level that one of the worst 5% of all the vertical strips was inspected. That is, there is a relatively high likelihood that the SRS inspection program has covered one of the most corroded areas of any of the Type III/IIIA waste tanks. These data further support the conclusion that there are no significant indications of wall thinning or pitting. Random sampling will continue to increase the confidence that one of the worst 5% has been inspected.

CONCLUSIONS

As a vehicle for the interim storage of LW, these tanks are an integral part of defense and environmental waste remediation. Maintaining and ensuring the integrity and safety of the tanks is imperative. This may be accomplished with routine inspections and an active CCP. However, because of their enormous size and accessibility constraints, inspections are challenging and costly. Moreover, the time required for extensive inspections would exceed the in-service tank lifetimes. Therefore, it is impractical that even 5% of one LW tank should be inspected annually. Our sampling strategy enables the ISI program to overcome these barriers and develop profiles of individual tanks that collectively provide a high confidence in the safety and integrity of the overall tank population. The results demonstrate that the service life of the LW tanks will exceed their operational needs.

With the use of the faster UT technology and statistical sampling and analysis, there is a high confidence that corrosion and pitting are observable and can be quickly mitigated to prevent compromise. The inspection of each of the waste tanks accounts for the variable chemical conditions within the population and lessens the impact of individual biases. Utilizing stratified quadrant sampling in coordination with the baseline strip within each tank provides randomness while still considering the enormous girth of the tanks, preventing reliance on any assumptions of circumferential uniformity. The use of vertical strips ensures that thinning and pitting are observed over the entire height of the tank, accounting for the dynamic volume, waste stratification, and constitution of a LW tank over decades of service.

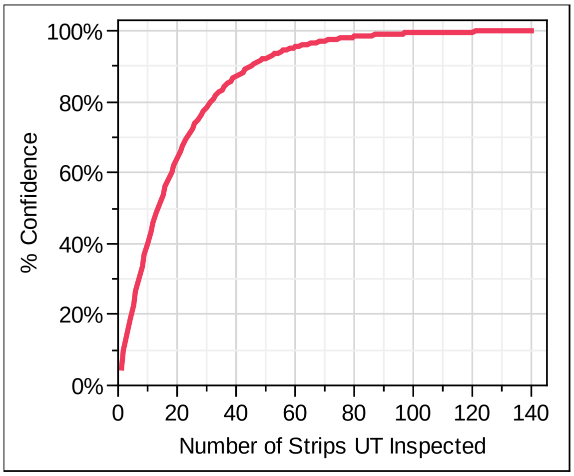


Figure 6: Confidence Curve for the Probability of Inspecting at Least One Strip from the Worst 5% across All Tanks.

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