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Riser Difference Uncertainty Methodology Based on Tank AY-101 Wall Thickness Measurements with Application to Tank AN-107

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Abstract

The DST Integrity Plan (RPP-7574, 2003, *Double-Shell Tank Integrity Program Plan*, Rev. 1A, CH2M HILL Hanford Group, Inc., Richland, Washington.) requires the ultrasonic wall thickness measurement of two vertical scans of the tank primary wall while using a single riser location. The resulting measurements are then used in extreme value methodology to predict the minimum wall thickness expected for the entire tank. The representativeness of using a single riser in this manner to draw conclusions about the entire circumference of a tank has been questioned. The only data available with which to address the representativeness question comes from Tank AY-101 since only for that tank have multiple risers been used for such inspection. The purpose of this report is to 1) further characterize AY-101 riser differences (relative to prior work); 2) propose a methodology for incorporating a “riser difference” uncertainty for subsequent tanks for which only a single riser is used, and 3) specifically apply the methodology to measurements made from a single riser in Tank AN-107.

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Summary

The DST Integrity Plan (RPP-7574, 2003, *Double-Shell Tank Integrity Program Plan*, Rev. 1A, CH2M HILL Hanford Group, Inc., Richland, Washington.) requires the ultrasonic wall thickness measurement of two vertical scans of the tank primary wall while using a single riser location. The resulting measurements are then used in extreme value methodology to predict the minimum wall thickness expected for the entire tank. The representativeness of using a single riser in this manner to draw conclusions about the entire circumference of a tank has been questioned. The only data available with which to address the representativeness question comes from Tank AY-101 since only for that tank have multiple risers been used for such inspection. The purpose of this report is to 1) further characterize AY-101 riser differences (relative to prior work); 2) propose a methodology for incorporating a "riser difference" uncertainty for subsequent tanks for which only a single riser is used, and 3) specifically apply the methodology to measurements made from a single riser in Tank AN-107.

The AY-101 ultrasonic testing (UT) measurements from multiple risers have previously been used to estimate an uncertainty associated with riser differences (contained in the presentation by Weier, *Statistical Analysis of Riser Differences for Estimating Minimum Tank Wall Thickness Using Ultrasound Data,* July 13, 2004 Expert Panel Workshop). In that work statistical variance component modeling for measurements within the Plate 2 and Plate 3 shell courses had suggested a standard deviation associated with such riser differences might be estimated as 0.009 inch.

In this report, an alternative empirical approach was examined that used repeated re-sampling of the AY-101 Plate 2, 3, and 4 data to simulate inspections using only a single riser with two vertical paths. This was done repeatedly and individually for each riser; this approach resulted in riser standard deviation estimates in the 0.012 to 0.013 inch range. However, these results were heavily impacted by a much greater observed variability in the Riser 90 results. The results within the other risers were much more consistent. And since Riser 90 had lacked data from Plate 4, it was necessary to augment it with the Plate 4 measurements from another riser to facilitate the vertical path re-sampling approach. This necessity, and the strong impact Riser 90 then had, caused the authors some discomfort in that the 0.012 to 0.013 inch riser standard deviation range might be overly pessimistic. For this reason, and due to the much more consistent results within Risers 88, 89, and 91, and also due to the original variance component modeling approach estimate of 0.009 inch, a compromise value of 0.010 inch was selected. This riser uncertainty is denoted by the standard deviation σ_{riser}.

Another source of uncertainty in estimating the minimum wall thickness in a tank is that associated with the extreme value estimation process for data from the single riser. The adequacy of the fit of an assumed Weibull distribution, and the amount of data available, both impact this uncertainty. Generally, the more data available, the smaller will be the estimation uncertainty, and the tighter the resulting confidence bounds. This estimation uncertainty is denoted by the standard deviation σ_{est}.

For the AY-101 re-sampling, the magnitude of σ_{est} results in upper 95% confidence bounds for the maximum wall thickness loss being from 25% to 35% greater than the associated point estimates. This results from 40 to 46 re-sampled measurements representing two vertical paths at 20 to 23 heights. Inspecting additional paths from a single riser could result in tighter confidence bounds based on this estimation uncertainty by providing more measurements. For

example, in the empirical re-sampling study of AY-101, increasing the number of paths from 2 to 3 to 4 for one of the risers reduced the confidence bounds from being 28% greater than the corresponding point estimates for two paths to 23% greater for 3 paths and to 18% greater for 4 paths.

When a new tank is inspected using a single riser, an analogous σ_{est} value will result from the goodness of Weibull fit and from the number of measurements available. This can then be combined with the σ_{riser} uncertainty to get a total extreme value uncertainty as

$$\sigma_{total} = \text{sqrt}\,[\,\sigma^2_{est} + \sigma^2_{riser}\,].$$

This methodology was applied to AN-107 measurements that indeed consisted of two vertical paths from a single riser. Unfortunately, a presumed measurement anomaly resulted in the second path results diverging from those of the first path partway down the tank wall in a manner that current quality control practices would have prevented. At the recommendation of subject matter experts, the measurement data were corrected for these analyses to compensate for the anomaly; both the original data and the "corrected" data results are presented as follows:

AN-107 Maximum Wall Thickness Loss (in inches**)**

Case	**Point Estimate**	**Est. Uncertainty 95% Conf. Bound**	**Est. and Riser Uncertainty 95% Conf. Bound**
Original Data	0.094	0.139	0.146
Corrected Data	0.043	0.059	0.068

The dramatic difference in the two cases was due to the measurement anomaly generating 1) several larger measured losses, and 2) a very poor fit of the Weibull distribution for that original data. The measurement anomaly resulted in a bi-modal distribution that was more likely a mixture of two distributions. This bimodal nature was removed in the corrected data case and resulted in a much better distributional fit, as well as reducing the larger measured losses.

Even though more data were available for AN-107 than had been in the AY-101 re-sampling study (34 measurements per vertical path for 68 total), the "Est." 95% confidence bound, 0.059 inch, is about 37% greater than the point estimate, 0.043, in the corrected data case. The bounds were typically tighter than this for the fewer measurements used for the AY-101 re-sampling (25% to 35% depending on the riser). Recall this source of uncertainty could be reduced through the measurement of more vertical paths from the single riser.

Follow-on work will include similar analyses to that done for AN-107 for several more tanks that have also had the two vertical paths measured from a single riser.

Introduction/Background

The DST Integrity Plan requires wall thickness inspections of the inner tank walls using ultrasonic measurement equipment. The minimum wall thickness on each of many 15 inch wide by 12 inch long UT images is reported. A vertical path of about 34 such images is made from the top to the bottom of the tank wall. An adjacent second path is then made thereby generating a total of about 68 such minimum wall thickness values.

To predict a minimum wall thickness value for the entire tank, these values are used to fit an extreme value distribution (three-parameter Weibull), and an extreme value is extrapolated to the smallest thickness expected if enough images were measured to cover the entire tank wall. The specific statistical methodology is given in [1]*Statistical Analyses of AY-101 Ultrasonic Measurements of Wall Thickness* by Weier.

In addition to estimating the expected minimum wall thickness in that report, confidence bounds were also provided that reflect the uncertainty in such an estimate. This uncertainty will be directly affected by the goodness of the fit of the Weibull distribution to the measurements results as well as by the number of measurements used. Generally, the more measurements that are available, the smaller the uncertainty, and the tighter the confidence bounds.

A particular concern with the DST Integrity Plan estimation approach is the use of only a single riser to obtain the two vertical scan paths. While this gives a considerable amount of information of wall thickness variability in the vertical direction, it gives no information about potential variability in wall thickness circumferentially around the tank. It is the case that more variability would be expected vertically than circumferentially, but concern remains regarding the "statistical representativeness" in using a single riser.

Work originally presented to an Expert Panel[2] addressed this issue by considering riser differences within tank AY-101, the only DST with substantial wall thickness measurements taken from multiple risers. Four different risers were used for Tank AY-101. Figure 1 shows the data for the Plate 2 and Plate 3 courses. The LAI on the figure is the liquid air interface at which waste levels resided for a substantial time thereby resulting in greater amounts of corrosion at that height on the tank wall.

Note that these plate courses had nominal thickness 0.5 inch, but in Plate 2, the remaining minimum wall thickness in many of the UT images still exceeded 0.5 inch, so clearly the original wall thickness was greater. And an obvious difference between the measurement results between the Plate 2 and Plate 3 course can be seen. This is most likely due to different manufacturing lots making up the two courses with the Plate 3 course having smaller nominal thickness (by about 0.030 inch) than the Plate 2 course (outside the LAI).

The actual nominal thicknesses of various plates are unknown, so variability due to this feature must simply be combined with the actual variation in the true remaining thickness that is due to differing corrosion loss amounts. In a similar manner, measurement uncertainty has not been

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[1] D.R.Weier, Statistical Analyses of AY-101 Ultrasonic Measurements of Wall Thickness, PNNL-14106, October, 2002.
[2] D.R.Weier, 2004, "Statistical Analysis of Riser Differences for Estimating Minimum Tank Wall Thickness Using Ultrasound Data," in Terry, M., 2004, *Expert Panel Workshop for Hanford Site Double-Shell Tank Waste Chemistry Optimization*, RPP-RPT-22126. CH2MHill Hanford Group, Inc. Richland WA.

rigorously examined and cannot be isolated in the measurement results. As a result, when a remaining minimum wall thickness value is reported, it is actually a minimum "measured" wall thickness which incorporates a feasible worse case combination of variabilities due to the original nominal thickness of plates, the measurement error incurred, and the corrosion variability.

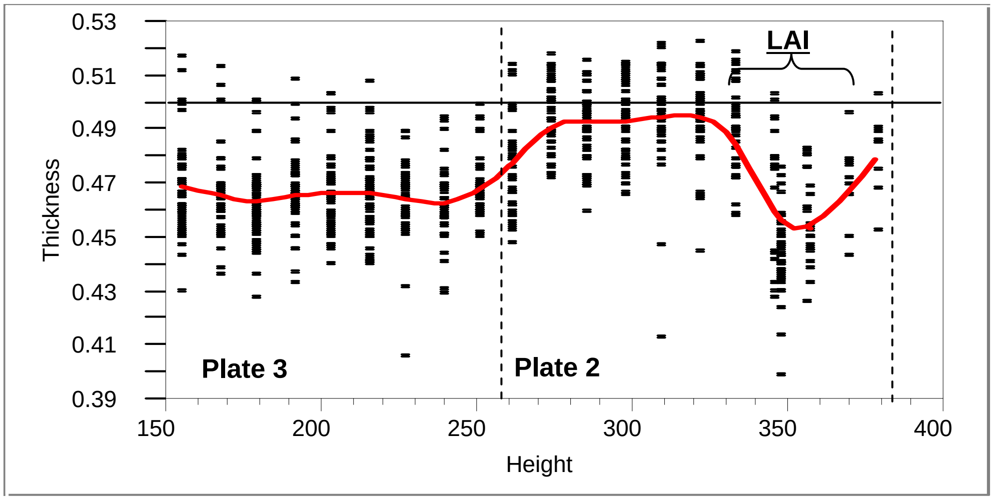


Figure 1: AY-101 Plate 2 and 3 Measurement Results

Due to the apparent differences between the Plate 2 and 3 courses, and in the LAI results, three sub-populations were considered for AY-101: Plate 3, Plate 2 outside the LAI, and the LAI. The following "minimum wall thickness" or "maximum loss" results were obtained:

Table 1: AY-101 Minimum "Measured Wall Thickness" Estimates (units are inches)

	Estimates		95% Confidence Bounds	
	Wall Thickness	Loss	Wall Thickness	Loss
LAI	0.401	0.099	0.391	0.100
Plate 3	0.421	0.079	0.418	0.082
Plate 2	0.425	0.074	0.417	0.083

In subsequent tanks that have many fewer measurements, taken from a single riser, insufficient data will be available to determine if such plate course differences should similarly be considered. And if subgroups of measurements were used, the distribution fitting to so few measurements would result in prohibitively extreme confidence bounds.

Figure 2 shows the same AY-101 Plate 2 and 3 measurement results in Figure 1 by riser. When subsequent tanks are measured, there is legitimate concern how representative a single riser might be. And if it is not particularly representative, how "far off" might the answers obtained be? Such "riser uncertainty" was to be estimated based on the only data available, that from AY-101, and a methodology developed for applying that uncertainty to the results for a subsequent tank that is measured using only a single riser.

Note in Figure 2 that within Plate 3, Risers 89, 90, and 91 have similar remaining wall thickness at about 0.46 inch while Riser 88 is instead at about 0.48 inch. And in Plate 2 outside the LAI, while Riser 88 doesn't have enough measurements to make a determination, Risers 89 and

90 are at about 0.48 inch, Riser 91 is a 0.050 inch. These two examples show how riser differences could lead to different estimated Weibull distributions and extrapolated minimum overall thickness.   The goal is to determine the potential impact on the estimates in a subsequent tank.

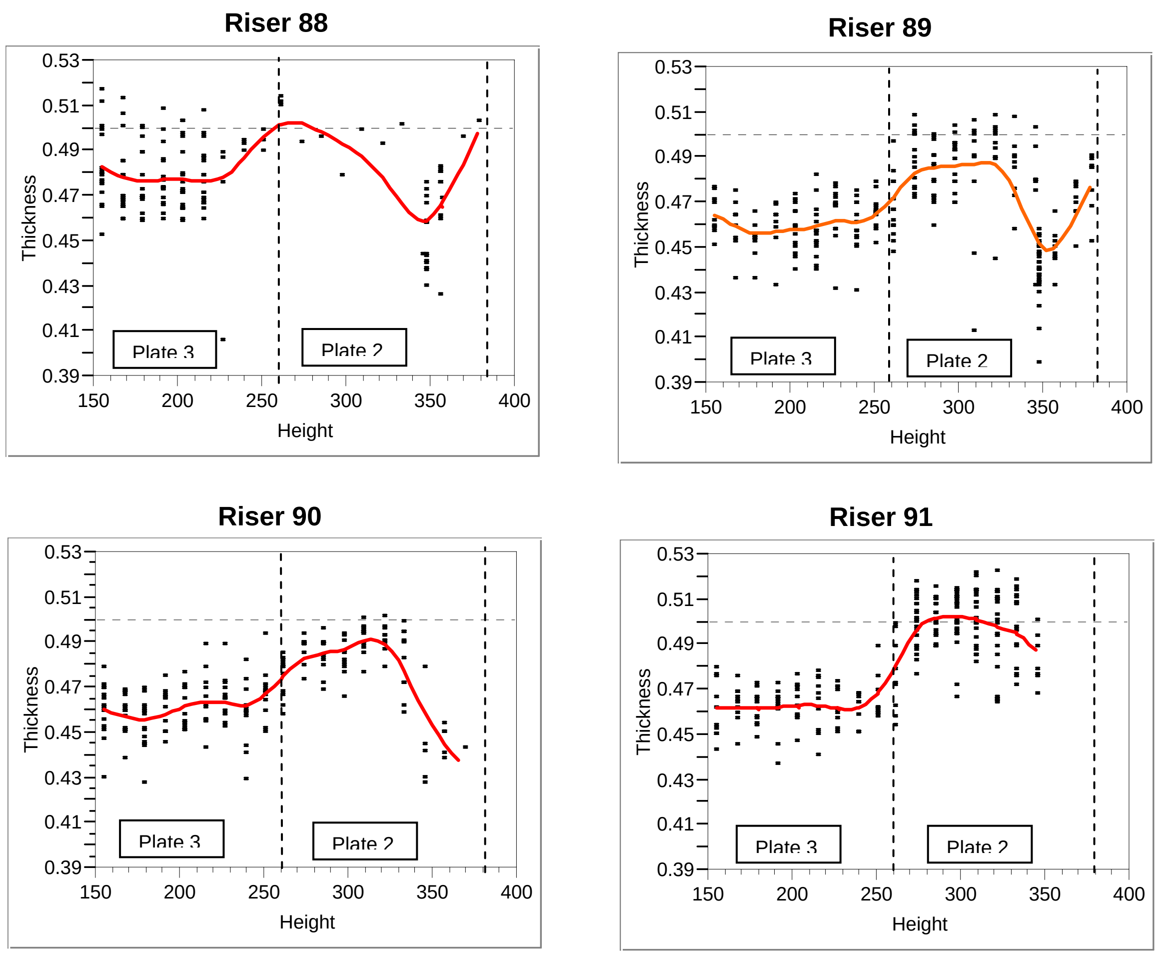


Figure 2: AY-101 Plate 2 and 3 Measurement Results by Riser

A statistical approach that characterizes the variability between risers in tank AY-101 that was discussed at the Expert Panel meeting involved a statistical variance components model. Wall thicknesses were modeled as:

> Wall Thickness = overall mean + Riser(within Tank) + Plate + Elevation(within Plate) + Riser by Elevation interaction + Error.

Each of the factors in the model would in some way contribute to the wall thickness at the various locations. Error would be due to uncharacterized variability factors such as manufacturing, corrosion differences, and measurement error. In this somewhat complex modeling approach, the mean, Plate, and Elevation would be “fixed” effects. For their various levels, we’d be interested in differences between the mean thicknesses. In contrast, Riser is a “random” component since it is simply a random subset of riser locations we could have used for inspection. We are therefore interested in the variance, or standard deviation, between

Risers, and as a result, variance components are estimated for both Riser(within Tank) and its interaction term. The associated standard deviations in inches are given in the Table 2. The final row in the table gives the square root of the sum of squares of the two Riser variance components, and this would be a standard deviation quantity associated with riser differences. The four columns are different variance component estimation methods used by the particular statistical software. The bottom line is that riser differences could be considered to contribute a standard deviation of about 0.009 inches.

Table 2: Variance Component Results for AY-101 Plate 2 and 3 Measurements:
(values are standard deviations in inches)

	MIVQUE(0)	Type 1	Max Like	Restr Max Like
SD[Riser(Tank)]	*0.006*	*0.006*	*0.005*	*0.005*
*SD(Riser*Elevation)*	*0.007*	*0.007*	*0.003*	*0.007*
SD(Error)	0.014	0.013	0.014	0.014
SD(Riser)	*0.009*	*0.009*	*0.006*	*0.009*

At the time this work was completed, the path forward on how this result might be used on a subsequent tank was not yet established. As follow-up work, an alternative riser difference uncertainty estimation approach was proposed. Rather than the modeling approach above, the alternative was an empirical study that would return to the AY-101 data and “pretend” than only two paths down a single riser had been used. So for each riser, as shown in Figure 2, two measurements were randomly selected at each elevation to simulate two paths being measured. Some consideration was given to actually identifying existing vertical paths from when the measurements were generated, but the data do not support this approach. The Weibull estimation approach was then used, as it would be on a subsequent tank inspected from a single riser. Point estimates were generated for each such re-sampling along with associated confidence bounds.

A more complete AY-101 data set was used that included measurements from Plate courses other than 2 and 3. These data are shown in Figure 3, but since different nominal thicknesses are now involved in other plates, the displayed values are material loss from nominal. Very few measurements were available in Plates 1 and 5, and in the lower sections of Plate 4. If these few measurements were used, they could have significant effect on the results since they would essentially have to be included in every re-sampling. For this reason the re-sampling only goes through Plate 2 below the LAI, Plate 3, and the upper sections of Plate 4. And even for these limited heights, Riser 91 has no Plate 4 measurements. For this reason Riser 91 is augmented by the Riser 90 Plate 4 measurements so a more extensive vertical path can be used in Riser 90 as well. This will be indicated by the notation “90aug” in the following. The specific heights used for each riser are given later in Table 3.

In each riser, the random selection of two measurements at each elevation was then repeated many times (1000) to see how sensitive the estimates and confidence bounds were to the particular random set of measurements selected. This accomplishes three things. It shows 1) how much uncertainty (and the resulting magnitude of confidence bounds) might be expected when only two vertical paths of measurements are used in the estimation process, 2) how different estimates and bounds can be within a riser just due to the particular set of measurements that happen to be obtained, and 3) what is the magnitude of differences in estimates between the four risers. The result obtained for this latter feature is analogous to the variance component result above, and should be more intuitively understandable to the non-statistician.

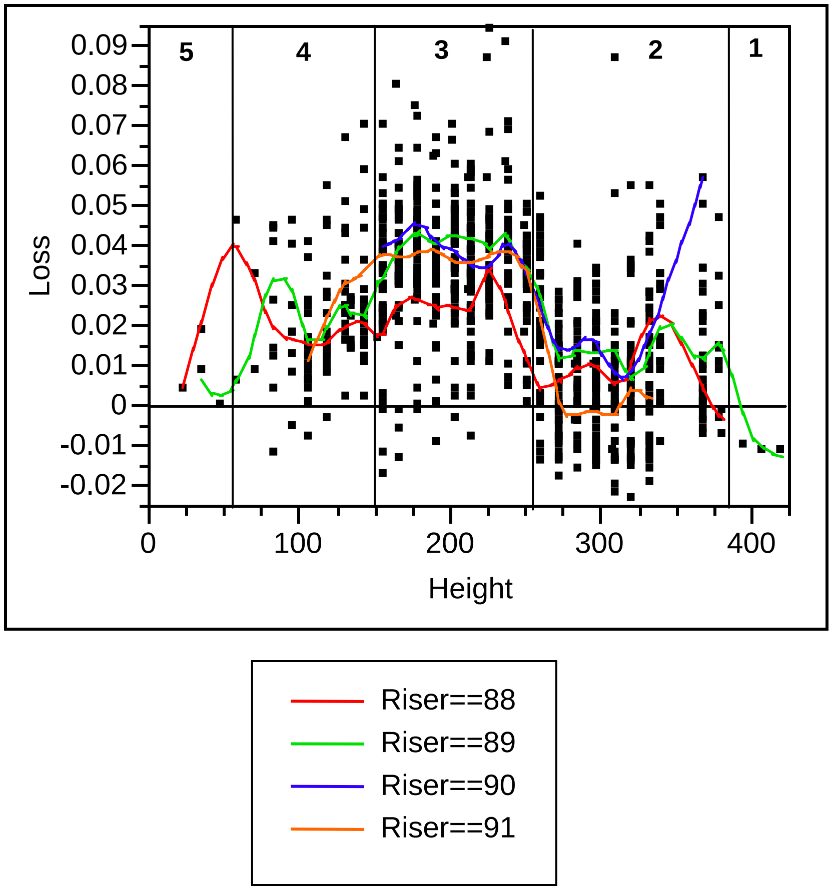


Figure 3: Full Set of AY-101 Measurements

Note again in Figure 3 how Riser 88 shows less loss than other risers in what would be Plate 3 (around Height 200), and Riser 91 shows less loss in what would be Plate 2 outside the LAI (around Height 300). Subsets of this data were used to simulate the two vertical path inspections within each riser. Note the vertical strings of measurement on the figures. These occur at one foot increments, so these data were used in the random selection of two measurements at each height to approximate the dataset that would be obtained from two paths.

Two vertical paths from a riser will be simulated by randomly selecting two measurements from each height. A three-parameter Weibull distribution will be fit with an extreme value extrapolated well out in the tail to approximate the worst case value that would be obtained if the entire tanks wall surface (Plates 1 through 5) were inspected. Uncertainties on the Weibull parameters can also be generated from the selected measurements with confidence bounds on the worst case loss percentile then computed using variance propagation of the parameter uncertainties. This process was repeated 1000 times for each riser by taking different random selections of the data. In this way distributions of worst case losses, and their confidence bounds, are generated for each riser.

Note that each UT image In the AY-101 data consists of a 3.5 by 12 inch scan. The total number of such images needed to inspect the entire tank is obtained by computing the entire surface area of the tank and dividing by the area in a single image. This results in needing over 20,000 images to inspect a tank, and that is how far into the tail of the fitted Weibull the desired estimate lays. In contrast for subsequent tanks, including AN-107 discussed later in this report, 12 by 15 inch images are used, so then only something over 6000 images would be needed to inspect all tank wall surfaces.

Discussion of AY-101 Results

Figure 4 illustrates the results of the empirical examination of AY-101 wall thicknesses. Recall in the original work on AY-101, separate extreme wall thickness estimates were obtained for Plate 3, Plate 2 outside the LAI, and the LAI. That is not done now since only two vertical paths are assumed measured from a single riser. If an obvious LAI is encountered in a subsequent tank, those measurements should probably be omitted with special attention given to the LAI area. And in fact, the LAI data for AY-101 was not included in the following.

In Figure 4, section a, consider the top row of curves consisting of black and red points. Each black point represents another Riser 91 simulated maximum wall thickness loss that is obtained by extrapolating out into the tail of an estimated three parameter Weibull distribution. That is, for each black point, a new two-path random selection of measurements was made for Riser 91 with new Weibull parameters estimated and extrapolation giving an estimated worst case loss for the entire tank.

The horizontal axis gives the wall thickness loss from the assumed nominal plate thickness based on tank wall specifications for the various tank riser courses. The resulting “s-curve” of black points for Riser 91 represents the cumulative distribution of the simulated 1000 losses. A median value for this distribution could be obtained by going from the middle height of this black curve down to the horizontal axis as indicated by the left-most vertical dotted line. It will be seen in the last row of Table 3 that this value is 0.084 inches. This says that for Riser 91, the estimated worst case maximum loss based on two vertical paths as simulated by re-sampling AY-101 measurements will exceed 0.084 inches one-half the time. And obviously the other half of such estimates will be less than that value.

The adjacent vertical dotted line cuts off the top five percent of the Riser 91 black points giving the maximum loss that would have been the 95th percentile of those obtained. The last row of Table 3 gives this value as 0.104. So had such a measurement process, with two vertical paths of UT measurements, been used in Riser 91 of AY-101, half the time the resulting worst case loss would have been above or below 0.084 inches, and 95% of the time it would have been less than 0.104 inches.

For every black point representing a new maximum wall thickness loss based on another re-sampling, the corresponding 95% confidence bound was computed and is represented by one of the red points. Note that such bounds generally run about 20 percent larger than the corresponding black points. The last two columns in the last row of Table 4 show the median and 95th percentile of such confidence bounds are respectively 0.114 and 0.145.

Note how much larger these confidence bounds are, relative to the point estimates, than was the case for the AY-101 estimation results given in Table 1. This is due to the considerably less data used. In Table 1, hundreds of measurements were used for Plate 2 or 3, resulting in relatively tight confidence bounds. Here we only have 44 points for each point estimate, and confidence bounds are therefore considerably larger.

Now consider the bottom set of curves on Figure 4a. The odd “double curve” shape is due to a single outlying value in the measurements for Riser 88. The lower parts of the curves results if the outlying value is not included in the random selection while the upper parts of the curves result when the outlying value is selected. This particular outlying value could not be

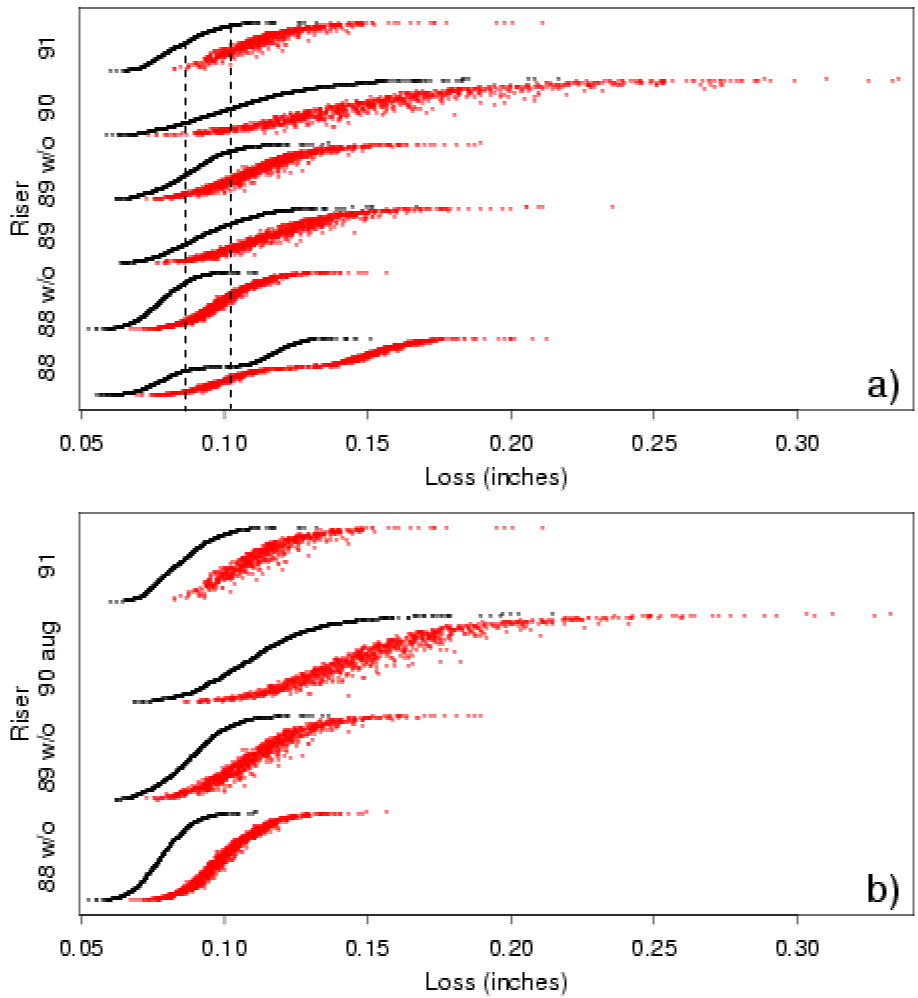


Figure 4: AY-101 Plate Single Riser Simulation Results

reasonably accommodated by the original AY-101 estimation work. It was discussed in that work how it is clearly due to some phenomenon other than that generating the other measurements. For this reason it will be omitted from the current analyses. When that is done, the next higher set of curves result, labeled 88 w/o for "without outlier". The considerable influence of this outlier can be seen in comparing these sets of curves. Further Riser 88 results will be for the "without outlier" case. Riser 89 also has such an outlier. Although a "double curve" does not result as was the case for Riser 88, the considerable influence of the outlier can be seen in the extended tails of the Riser 89 case as compared to the "Riser 89 w/o" case. The "w/o" case will be used here as well.

One more issue was the need to augment Riser 90 with Plate 4 measurements from Riser 91. The extensive spread of the Riser 90 results in Figure 4a is partially due to fewer heights being available and therefore less data and greater uncertainties. This is offset somewhat by using the Plate 4 Riser 91 measurements to augment Riser 90. It was hoped this would have bigger impact, but it only has minimal improvement. The omission of the Riser 88 and 89 outliers and augmentation of Riser 90 gives the final results used in Figure 4b.

An alternative way of displaying the maximum loss estimates (black points in Figure 4b) by riser is in the Figure 5 boxplots. The vertical spread of the rectangular box shows the middle 50 percent of the loss estimates. Again the Riser 90 results stand out as being considerably larger. The largest resulting point estimates are shown by the horizontal line segments above the boxes. Note that in Riser 90, some of these actually exceeded 0.20 inch. Had a single riser been used in AY-101 with only two vertical paths, and Riser 91 was selected, a very large maximum loss could have very well resulted. Such a result would have had serious consequences regarding for AY-101's suitability for use. This does indicate the potential risk incurred in using only a single riser.

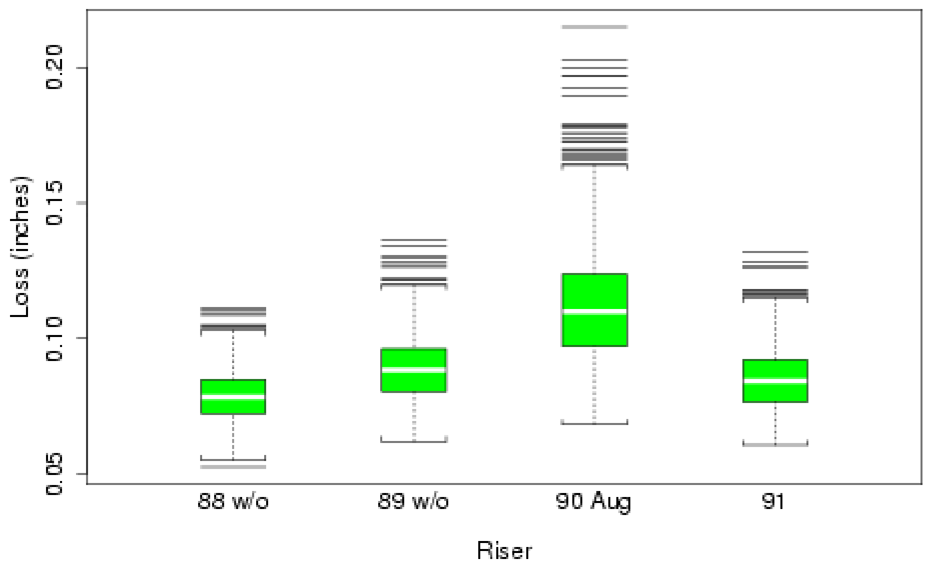


Figure 5: Boxplots of AY-101 Plate Single Riser Simulation Results

The resulting summary information for the four risers is given in Table 3. The column labeled "Num" is the number of heights available for that riser for the re-sampling. Twice that number would be the number of measurements available for the Weibull distribution fitting. The first pair of columns labeled "Median" and "95%" are for the maximum wall loss point estimates (black points in Figure 4). The second set of columns labeled this way is for the corresponding upper 95% confidence bounds on the maximum wall loss (red points in Figure 4).

Table 3: AY-101 Plate 2 and 3 Measurement Results by Riser

Re-sampling Results (2 Measurements each riser)

			Point Estimates		95% Confidence Bounds	
Riser	Num	Heights	Median	95th %	Median	95th%
88 w/o	22	84-334	0.078	0.094	0.100	0.124
89 w/o	23	84-340	0.088	0.110	0.111	0.146
90 aug	20	108-334	0.110	0.153	0.148	0.224
91	20	108-334	0.084	0.104	0.114	0.145

Obviously from Figures 4b and 5, and from Table 3, Riser 90 stands out with considerably greater losses indicated. Further examination of the Riser 90 data shows four exceptionally large losses. The tail extending much further to the right results when more than one of these values is included in the random selection. They cannot be considered outliers however since there are four of them. Note that the impact of the four large values is also compounded in that only 20 heights are available for Riser 90, so only 40 measurements are available for the distribution fitting.

Note that the magnitudes of the median upper 95% confidence bounds are about 25% to 35% greater than the medians of the point estimates; for example for Riser 91, a 0.114 median confidence bound is obtained as compared to a 0.084 median wall thickness loss, which is about a 35% increase. This is a reflection of the uncertainty in fitting a Weibull distribution, in its estimated parameters, and in extrapolating far into its tail with only a modest amount of data. If a similar amount of data is used for subsequent tanks with single risers, this same source of uncertainty will unavoidably have similar impact.

This source of uncertainty could be decreased by simply getting more data from the single riser selected. To illustrate this, three measurements were instead selected in the AY-101 re-sampling rather than only two. This represents three vertical paths rather than only two vertical paths. And then similarly, the analysis was again repeated using four selected measurements to approximate four vertical paths. Results are shown in Figure 6 and in Table 4.

From Table 4, this can be seen to have little impact on the medians of the wall thickness losses. This is reasonable since we are still estimating the same basic loss quantities. However, the upper 95 percentiles are closer to the medians as more paths are used. Similarly, upper 95% confidence bound medians, and their 95th percentiles are all tighter as well. This shows how additional vertical paths can decrease the uncertainty in this estimation process.

This can be seen in Figure 6, parts a, b, and c. As the number of paths increase, the locations of the medians of the black points are generally unchanged, but the tails of the distributions tightens towards the medians from both directions, indicating the decreased uncertainty with larger amounts of data. Similarly the red point distributions are tighter and closer to the black point distributions.

In particular, consider Riser 88 results as the number of paths increases. The medians of the 2, 3, and 4 path cases are respectively 0.078, 0.079, and 0.078 for virtually no change. But the medians of the confidence bounds for 2, 3, and 4 paths are 0.100, 0.098, and 0.094, which are respectively about 28%, 23%, and 18% greater than the wall loss medians. This shows how the greater number of paths will give tighter confidence bounds. This is one option to consider in reducing uncertainties in the estimates, at least for tanks that have not already been inspected.

When the estimation approach is later applied to AN-107 measurements from a single riser in this report, 34 heights are available, and even with only two paths, 68 measurements are available, which is more like the three path case here with the fewer heights. So some of this uncertainty improvement will already be realized due to more measurements being taken per path. But even then, it could be improved even further with yet another vertical path.

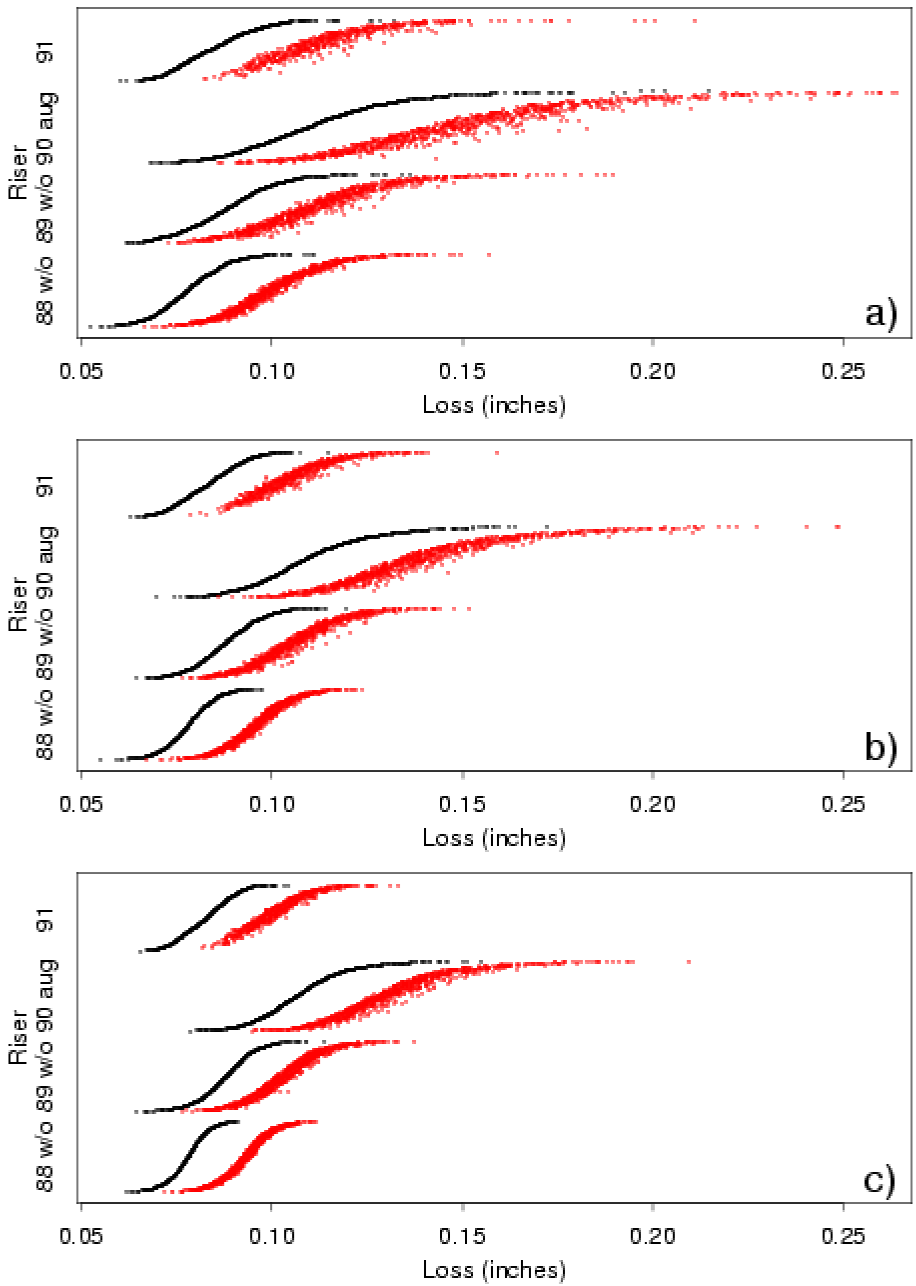


Figure 6: Impact of More Vertical Paths for AY-101

The other source of uncertainty, and the primary focus of this work, is the uncertainty that should be associated with using only a single riser to obtain the measurements. Call the uncertainty discussed above the estimation uncertainty, denoted by a standard deviation σ_{est}. This will be determined in a future tank by the number of paths or measurements made and the goodness of the Weibull distribution fit. Indeed this uncertainty could be decreased by using more vertical paths down the single riser.

Table 4: Impact of More Vertical Paths for AY-101

				Re-sampling Results			
				Point Estimates		95% Confidence Bounds	
	Riser	Num	Heights	Median	95th %	Median	95th%
2 paths per riser	88 w/o	22	84-334	0.078	0.094	0.100	0.124
	89 w/o	23	84-340	0.088	0.110	0.111	0.146
	90 aug	20	108-334	0.110	0.153	0.148	0.224
	91	20	108-334	0.084	0.104	0.114	0.145
3 paths per riser	88 w/o	22	84-334	0.079	0.089	0.097	0.111
	89 w/o	23	84-340	0.088	0.103	0.106	0.127
	90 aug	20	108-334	0.108	0.140	0.136	0.188
	91	20	108-334	0.084	0.098	0.107	0.128
4 paths per riser	88 w/o	22	84-334	0.078	0.086	0.094	0.104
	89 w/o	23	84-340	0.088	0.100	0.104	0.120
	90 aug	20	108-334	0.107	0.129	0.130	0.163
	91	20	108-334	0.083	0.094	0.102	0.117

Call the other source of uncertainty the riser uncertainty, say as indicated by the standard deviation σ_{riser}. The only source of data on which this uncertainty can be based is from AY-101, the only tank with multiple riser inspections. Note that the modeling discussed earlier suggested that this uncertainty standard deviation could be about 0.009. Another estimation approach, based on the AY-101 empirical re-sampling, is now available. Consider how different the median wall thickness losses are in Table 4 above; and note this doesn't change dramatically as the number of paths increases, although the outlying Riser 90 results do tighten up somewhat with more paths.

If the standard deviations are computed between the four riser wall thickness medians of the losses above, the results for 2, 3, and 4 paths are standard deviations respectively of 0.0138 inch, 0.0127 inch, and 0.0125 inch. Note in Figure 3 that the earlier 0.009 inch result for a riser uncertainty standard deviation, based on the statistical modeling, referred to only Plates 2 and 3, which are represented by the vast amount of the data in the figure. When the upper section of Plate 4 is added, and in particular when Riser 90 is augmented with Riser 91 data, and the empirical re-sampling approach is used instead, the resulting riser uncertainty standard deviation values 0.0125 to 0.0138 result. And note these values are largely driven by the considerably greater variability in Riser 90 results. It is somewhat disconcerting that a significant part of this variability might also rely on the fact that Plate 4 data was not available in Riser 90 and the Riser 91 Plate 4 data had to be substituted.

Having done this work, the authors have some concern that these latter results give somewhat too much weight to the relatively small amount of data in Plate 4, in particular with the Riser 90 augmentation. This could suggest that the original Plate 2 and 3 modeling results, and the corresponding riser uncertainty value of 0.009, be accorded somewhat more significance. For this reason a final riser uncertainty estimate, that combines the two approaches, is proposed as

0.010 inch. Note that the truth is likely somewhere in the 0.009 to 0.012 range. Whether the specific value used should be 0.010, or perhaps 0.011, is likely of less importance than the suitability of the assumption that needs to be made that this degree of riser difference is indeed what would also be encountered in subsequent tanks.

Discussion of AN-107 Results

In the subsequent application to tank AN-107, a σ_{est} influence will inherently result from once again fitting a three parameter Weibull distribution, extrapolating to the tail, and incorporating parameter uncertainty through variance propagation to obtain an uncertainty associated with the point estimate of maximum wall thickness loss. In the AY-101 application, this would have led directly to the upper 95% confidence bounds, but for AN-107 it will also be combined with the σ_{riser} uncertainty as obtained from AY-101. Obviously the assumption is being made that the kind of riser differences observed in Tank AY-101 would also be expected in Tank AN-107. The same assumption would need to be made to incorporate riser difference uncertainty for any subsequent tank as well.

Note in the top portion of Figure 7 that most wall thickness losses are positive numbers. Some are however negative, which means a wall thickness gain. This could only occur with faulty measurements, or more likely, from the fact that the true initial nominal thicknesses were considerably greater than the design nominal value. Instead of using the design nominal thicknesses, one could assume that fairly pristine places still reside on each plate down each riser and use the observed maximum wall thickness as a better estimate of the original nominal thickness. By doing this, the bottom portion of Figure 7 shows the revised AY-101 losses (called New Loss on the figure). The change in AY-101 results would be minimal; if anything it appears that a somewhat smaller riser difference uncertainty might be obtained, but this work was not done since the bulk of AY-101 measurements were indeed losses. However, this becomes more of an issue in Tank AN-107.

Figure 8 shows the same comparison for the AN-107 measurements. Note the terms “Height” and “Elevation” refer to the same feature. When wall thickness losses are obtained from the tank design nominal values, most measurements are negative for AN-107 and therefore actually gains in wall thickness. It seems unreasonable to estimate the maximum loss when most of the data indicate a gain. Instead the bottom portion of the figure is obtained by estimating a new nominal value for each plate from observed maximum wall thicknesses in a plate.

For those modified losses in the bottom section of Figure 8, the red path 1 values appear quite reasonable. And starting at the higher elevations, path 2 measurements track very well with path 1. But at about elevation 300 the measurement paths diverge considerably. This is likely a measurement method problem. The authors are told that subsequent measurement quality controls would not now allow this path 2 divergence to continue in the manner shown. For this reason, the AN-107 analysis will be done both for the original data, and for data corrected to eliminate this apparent measurement problem.   A further explanation for considering such a data shift is given in a short Appendix as provided by CH2MHill contractor, Herbert S. Berman, for whom this work was performed.

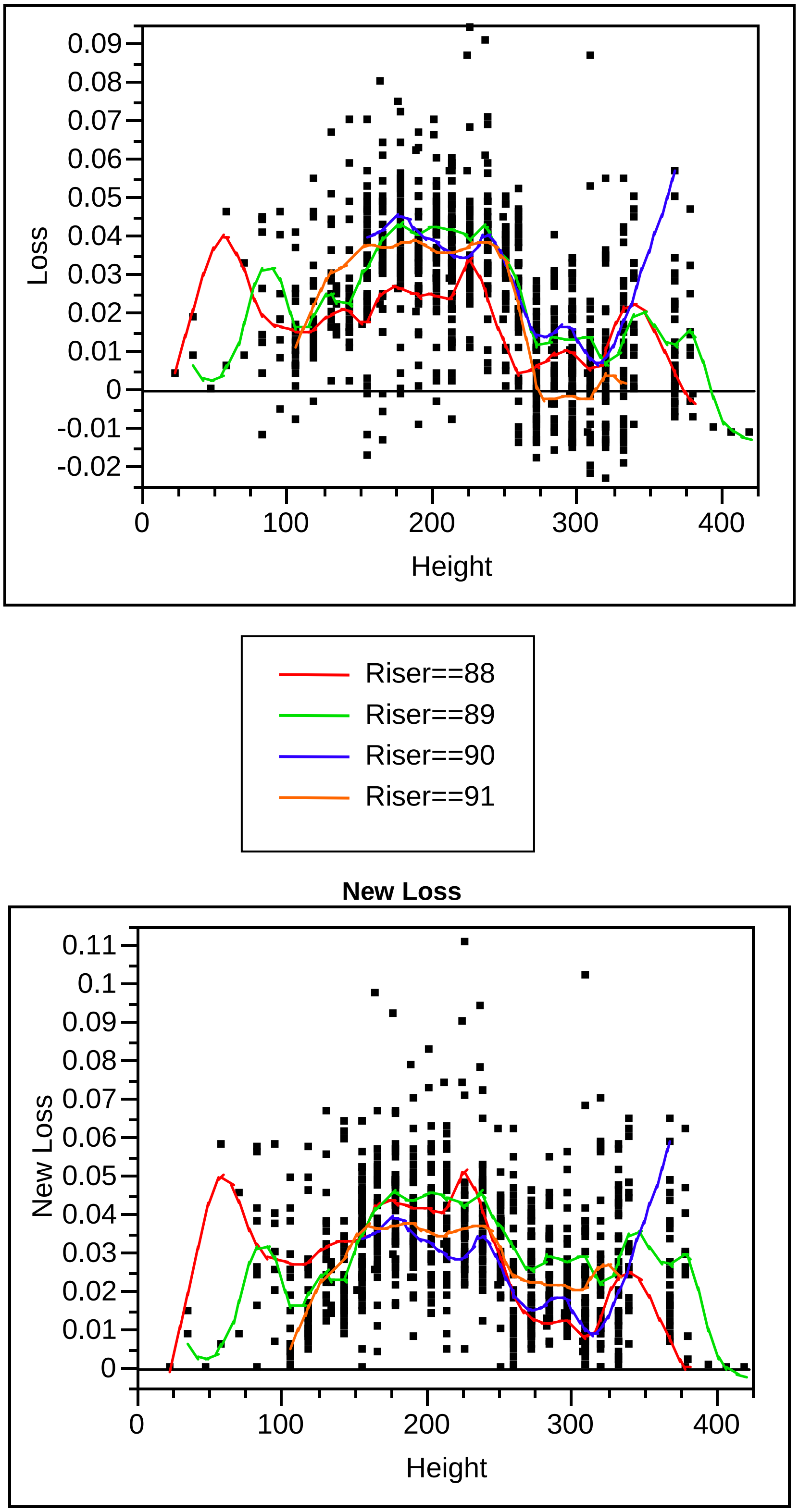
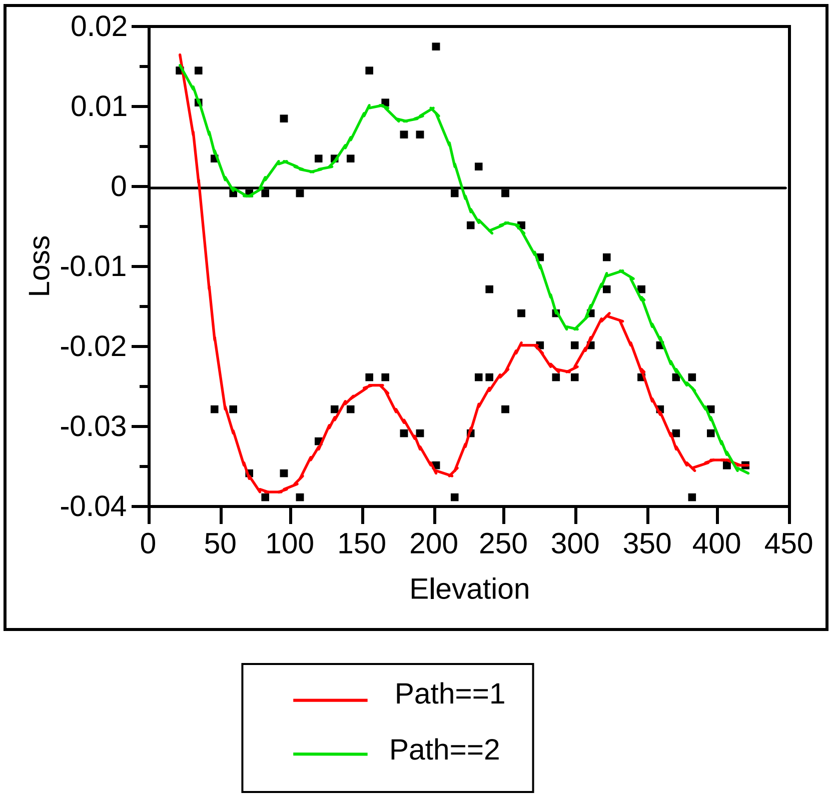


Figure 7: Full Set of AY-101 Measurements



New Loss By Elevation

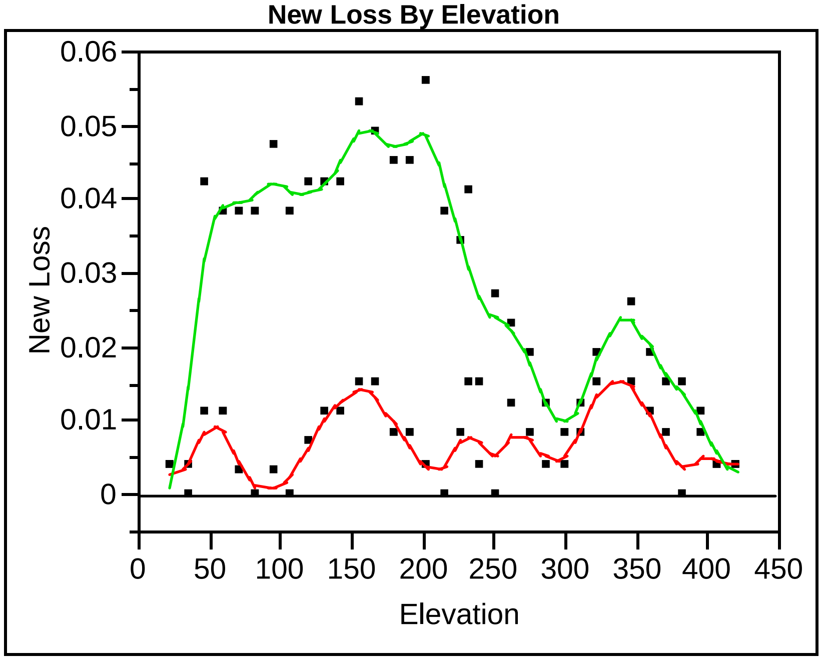


Figure 8: AN-107 Measurements

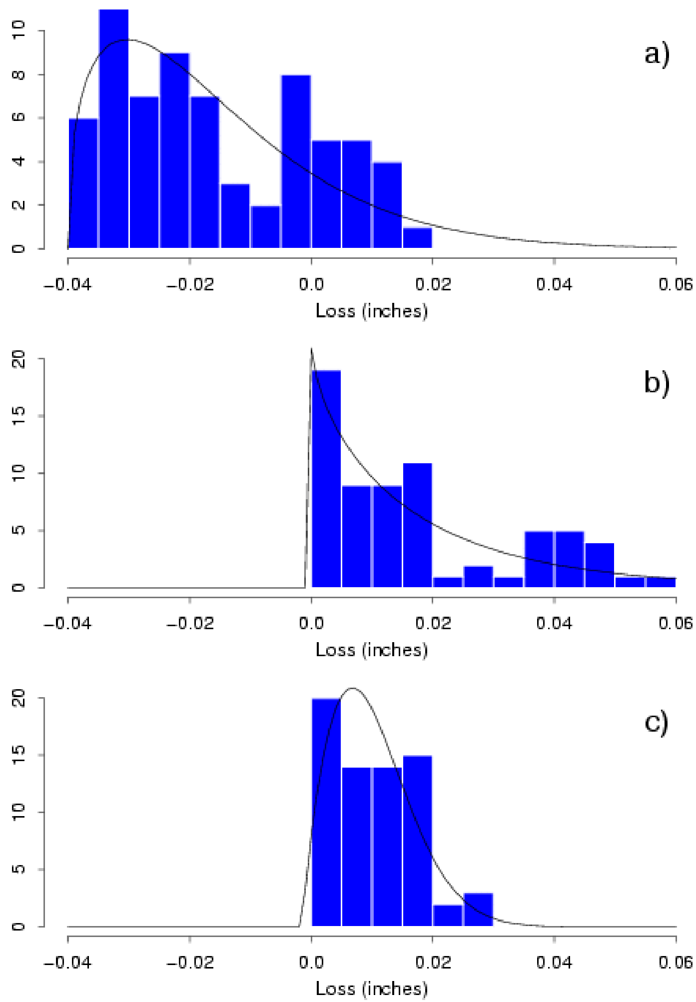


Figure 9: AN-107 Measurements; Three Cases

Figure 9 shows a sequence of histograms that reflect three ways to consider the AN-107 measurements. Part a of the figure is the original data as recorded and shown in the top of Figure 8. Again the negative values represent wall thickness gains, so use of this data to model wall thickness losses is somewhat disconcerting. None-the-less, a three-parameter Weibull distribution was successfully fit and led to the estimation results to be discussed in Table 5. The double hump feature of the histogram is problematical since the Weibull (and most other parametric distributions) cannot closely fit such a “bimodal” distribution. It is likely that the data actually represent a mixture of two distributions, and given the apparent measurement problem, that appears likely in this case.

For the AN-107 estimation, note that Plates 1, 2, and 3 are each 7 feet 8 inches tall; Plate 4 is 9 feet tall; and Plate 5 is two feet tall. This gives a total wall height of 34 feet, and 34 measurements are therefore available from each of two paths for 68 total measurements. The total tank wall area in these five plates is then computed based on the 34 foot height and a 75 foot diameter. Each UT image is 15 by 12 inches and therefore covers 1.25 square feet. When the total tank wall area is divided by 1.25, it shows that 6409 such images would be needed to inspect 100% of the tank wall. Therefore 1/6409 = 0.000156 is the Weibull percentile that we extrapolate to so as to estimate the worst case expected maximum loss for the entire tank.

Resulting estimates and confidence bounds are given in Table 5 and are discussed in the text that follows.

Table 5: AN-107 Results

Case	**Point Estimate**	**Est. Unc./Factor/ 95% Conf Bound**	**Est. and Riser Unc./Factor Combined 95% Conf Bound**
Original Data Losses (a)	0.094	0.027 / 1.67 0.139	0.029 / 1.81 0.146
Revised Data Losses (b)	0.198	N/A	N/A
Corrected Measurements (c)	0.046	0.010 / 1.67 0.059	0.014 / 1.81 0.068

The three rows in Table 5 represent the three data sets shown in Figure 9. The three columns represent three potential options in estimating the maximum wall thickness loss. Option 1 in the first column would be to simply use the point estimate of the maximum loss as the maximum expected loss. But this is not a very conservative approach since it does not address the many uncertainties involved that would result in a different value should the whole process be repeated, in particular in the same riser or even between risers.

But if this option were used, the three estimates in the first column would then result for AN-107. Note Figure 9a; the largest losses are around 0.02 inch, yet the predicted maximum loss in the entire tank is as large as 0.094 inch. This quite large result is due to the poor fit of the Weibull distribution. The considerable variability in the data with its bi-modal appearance, and the poor Weibull fit, combine to push the estimated 0.000156 quantile (as discussed above) well out to the right to obtain the 0.094 result.

For the second row of the table, the data represented in Figure 9b, which is obtained by computing losses from an estimated nominal thickness rather than from the design nominal, the estimate is even worse at 0.198. This is an unusable, nonsensical result since a Weibull fit that met convergence criteria could not be achieved for this bi-modal data.

When the measurement problem, and the bi-modality, is “resolved” by shifting the divergent Path 2 results 0.030 inch back towards the path 1 results, the third row results are obtained and correspond to Figure 9c. In other words, the hump on the right side of Figure 9b was shifted back into the left-side hump. The authors are assured that with current measurement quality controls, this resembles the data that would now be obtained. The improvement in results is dramatic since now the Weibull fit is much more reasonable. The estimated maximum loss is now only 0.046 inch.

But all of this ignores the uncertainty in this estimation process. As an improved approach, given in the second column, Option 2 would generate a confidence bounds that depend on the goodness of fit of the Weibull and the amount of data available. Recall for the AY-101 application, these bounds were quite tight since hundreds of measurements were available. Many fewer are now available, so these bounds will not be nearly as tight.

The standard error (deviation) of the estimate is listed as the first number in column 2 (called Est. Unc. in the table which represents "Estimate Uncertainty"). This is the quantity earlier referred to as σ_{est}. Given the amount of data available, and the related "degrees of freedom" associated with this uncertainty estimate, an appropriate multiplier of it to obtain an upper 95% confidence bound is then listed in the table as 1.67. So 1.67 times the standard error is added to the point estimate to obtain the upper 95% confidence bound as 0.139 inch, considerably larger than the 0.094 point estimate.

In the second row, this confidence bound cannot be obtained due to the incomplete convergence of the distribution fitting and the nonsensical result. But in the third row, with the corrected data, the 95% confidence bound is shown as 0.059, a much improved result.

But this option still does not consider riser differences, which is Option 3 and the primary purpose of this report. If the methodology is to be sufficiently rigorous so as to include σ_{est}, it seems that the earlier quantity σ_{riser} should be included as well. Recall that earlier discussion suggested the σ_{riser} value 0.010 for as a "compromise" value between earlier statistical modeling for the extensive AY-101 Plate 2 and 3 data and the empirical re-sampling results presented in this report.

This extra source of uncertainty due to riser differences is not simply "tacked on" on top of the other σ_{est} uncertainty sources. Rather the combined impact of σ_{est} and σ_{riser} would be related to the total uncertainty standard deviation indicated as

$$\sigma_{total} = \text{sqrt}\,[\,\sigma^2_{est} + \sigma^2_{riser}\,]\ . \qquad (1)$$

This σ_{total} uncertainty is the first value listed in column 3 (Est. and Riser Unc.); it is obtained from the σ_{est} value in column 1 and the σ_{riser} 0.010 value as in equation (1). For the original data in row one, the riser uncertainty has little additional impact since it is completely overshadowed by the much greater σ_{est} uncertainty (the original uncertainty value of 0.027 increases to the total uncertainty value 0.029). The appropriate multiplier for the total uncertainty to obtain a 95% confidence bound, based on the underlying degrees of freedom, is the 1.81 value shown in the table. Multiplying the total uncertainty by this and adding to the point estimate, the value 0.146 results.

Again the row 2 results do not support such an estimation approach. In row 3, the σ_{est} and σ_{riser} uncertainty values are more nearly the same, so the riser contribution is more significant for these data (the original uncertainty value of 0.010 increases to 0.014). The resulting confidence bound that incorporates both the estimation method uncertainty and the riser uncertainty based on riser differences as estimated in Tank AY-101 gives a maximum loss confidence bound of 0.068 for Tank AN-107.

This of course assumes that the data correction used to "fix" the measurement divergence anomaly is appropriate. Also recall the original data was mostly gains, so revised losses were obtained using an estimated original plate thickness from the maximum wall thickness observed within each plate. So the losses described are from the most "pristine" spot measured.

Conclusions

AY-101 UT measurements from multiple risers were used to estimate uncertainty associated with riser differences so appropriate adjustments could be made to wall thickness measurements obtained from a single riser in subsequent tanks. Previous statistical modeling within Plates 2 and 3 had suggested a standard deviation associated with riser differences might be estimated as 0.009 inch.

An alternative empirical approach was examined that used repeated re-sampling of the AY-101 data to simulate using only a single riser with only two vertical paths. To do this Riser 90 data had to be augmented with Plate 4 Riser 91 data since none were available in Plate 4. Resulting standard deviation estimates were in the 0.012 to 0.013 inch range, but these were heavily dependent on the much greater variability in the Riser 90 results. The results within the other risers were much more consistent. Since Riser 90 had used the augmented data, the authors decided that the original modeling approach estimate of 0.009, and the consistent results within Risers 88, 89, and 91, indicate that the 0.012 to 0.013 is overly pessimistic and propose a compromise value of 0.010 inch. This riser uncertainty is denoted by the standard deviation σ_{riser}.

Another source of uncertainty in estimating the minimum wall thickness in a tank is that associated with the fit of the Weibull distribution and the amount of data available. Generally the more data available, the smaller the uncertainty, and the tighter the resulting confidence bounds. This estimation uncertainty is denoted by the standard deviation σ_{est}.

For the AY-101 re-sampling, the magnitude of σ_{est} results in upper 95% confidence bounds for the maximum loss being from 25% to 35% greater than the associated point estimates. This results from 40 to 46 re-sampled measurements representing two vertical paths at 20 to 23 heights. For one of the risers, increasing the number of paths from 2 to 3 to 4 decreased a 28% increase for the confidence bounds for two paths to 23% for 3 paths and to 18% for 4 paths. This demonstrates how additional paths from a single riser can result in tighter confidence bounds by providing more measurements.

When a new tank is inspected, a new σ_{est} value will result during the estimation process. This can be combined with the σ_{riser} uncertainty to get a total uncertainty as $\sigma_{total} = \text{sqrt}\,[\sigma^2_{est} + \sigma^2_{riser}]$. This methodology was applied to AN-107 measurement consisting of two vertical paths from a single riser. A measurement anomaly resulted in the second path results diverging from those of the first path in a manner that current quality control practices would have prevented. Analyses were done both for the original data and "corrected" data. Results were as follows.

AN-107 Maximum Wall Thickness Loss (in inches**)**

Case	Point Estimate	Est. Uncertainty 95% Conf Bound	Est. and Riser Uncertainty 95% Conf Bound
Original Data	0.094	0.139	0.146
Corrected Data	0.043	0.059	0.068

The dramatic difference in the two cases was due to the very poor fit of a Weibull distribution for the original data. The measurement anomaly resulted in a bi-modal distribution that was in reality a mixture of two distributions. This was rectified in the corrected data case.

Even though more data was available for AN-107 than in the re-sampling of AY-101 (34 measurements per vertical path for 68 total), the “Est.” 95% confidence bound is about 37% greater than the point estimate in the corrected data case. The bounds were tighter than this for the fewer measurements used for AY-101 (25% to 35% depending on the riser). Again this source of uncertainty could be reduced through the measurement of more vertical paths from the single riser.

Note that in the corrected data case, the magnitudes of the two sources of uncertainty are almost identical. This suggests that additional vertical paths would be the more cost effective way to reduce upper 95% confidence bounds on the maximum loss rather than using multiple risers.

Also note that if the design nominal thicknesses were used for AN-107, most of the “losses” become “gains” since the current wall thicknesses still exceed the design specification, for this reason the AN-107 results use an estimated original plate thickness from the maximum wall thickness observed within each plate. So the losses described are from the most “pristine” spot measured.

<u>Appendix:</u> Rationale for UT Data Shift

From Herbert S. Berman, Perot Systems

The modern round of ultrasonic testing (UT) baseline measurements were initiated for the Hanford double-shell tanks (DSTs) in 1997. It was noted that the UT testing of the tank courses (plates at each DST level) often resulted in an apparent thickness shift of 20, 30 or 40 mils, from the previous scan. Investigation of this shift, after several DSTs UT characterizations had been completed, found that it was due to an equipment or software anomaly, and did not represent a plate thickness variation. Re-run of the same scan area, with the same equipment invariably resulted in the second scan exhibiting the expected plate thickness (i.e., the 20, 30 or 40 mil shift was gone).

That this was an equipment anomaly, versus a plate thickness issue was not recognized at the time of the DST 241-AN-107 UT characterization, since it was the first DST to be done for the present program. After this problem was recognized, and the UT equipment manufacturer had been unable to find/resolve this intermittent anomaly, the UT protocol was changed to immediately re-run the UT scan when the unexpected thickness shift was noted. As mentioned, the shift invariably disappears on re-scanning, and the second scan data is consistent with expected plate nominal thickness expectations.

Therefore, when this odd shift was noted in the AN-107 data being used for statistical analysis, it was considered appropriate to run the analysis with this equipment data artifact eliminated by appropriately deleting the thickness differential.

References

Weier, DR. 2002. *Statistical Analyses of AY-101 Ultrasonic Measurements of Wall Thickness*, PNNL-14106, Pacific Northwest National Laboratory, Richland, WA.

Weier, DR. 2004. “Statistical Analysis of Riser Differences for Estimating Minimum Tank Wall Thickness Using Ultrasound Data” in Terry, M. 2004. *Expert Panel Workshop for Hanford Site Double-Shell Tank Waste Chemistry Optimization*, RPP-RPT-22126. CH2MHill Hanford Group, Inc. Richland WA.

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