

AN ASSESSMENT OF THE UNCERTAINTY IN THE WASTE VOLUME OF THE HANFORD SITE SINGLE-SHELL AND DOUBLE-SHELL TANKS

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ABSTRACT

This paper presents a study to determine the uncertainty in the volume estimates of the Hanford Site single-shell and double-shell tanks. Through a detailed analysis of the standard method for estimating waste volume from surface level measurements, a number of systematic biases were identified as well as the five main sources of uncertainty. As a result of systematic biases, the current volume estimates may overstate the total tank waste volume by as much as 460,000 gallons. The surface level measurements for all 177 tanks were analyzed between January 1, 1990 and January 7, 1999. The surface level data was investigated using several analysis of variance (ANOVA) models to estimate the main parameters of volume uncertainty for each of 177 tanks. This paper also presents a new finite element-based approach, called the voxel method, that was developed to estimate Hanford tank waste volumes. The new method accurately reflects the different shape of each type of tank, eliminates the systematic biases, and accounts for the sources of uncertainty. Using a Monte Carlo simulation model based on the voxel approach, this study generated a volume probability distribution for each of the 177 tanks. The volume distributions were combined with probability distributions of waste density and analyte concentration to derive overall inventory distributions for 73 analytes in 177 tanks.

BACKGROUND

As a result of the production of plutonium and other site activities at Hanford, approximately 52 million gallons of high-level radioactive waste are stored in 149 single-shell tanks (SSTs) and 28 double-shell tanks. The tank wastes originated from several different Pu extraction processes and waste volume reduction campaigns. A more complete description of the Hanford Site waste storage tanks and how they were operated can be found in *A History of the 200 Area Tank Farms* (Anderson 1990) (1). The Tank Waste Remediation System (TWRS) was created in 1991 to safely manage and dispose of these radioactive wastes stored in the tanks. To support safe operations and development of waste disposal systems, the chemical composition of the wastes, in the form of chemical inventories, are generally required on a global or tank-specific basis. Several major efforts have attempted to establish defensible inventories of the tanks. The Tank Waste Characterization Program has systematically sampled and analyzed tank wastes since 1989.

In FY 1996 an effort was initiated to establish the best-basis standard inventory for chemicals and radionuclides in Hanford Site waste tanks. These best-basis inventories were reported during FY 1997 for each of the 177 tanks on a global and tank-specific basis. The 25 chemicals and 46 radionuclides comprising the best-basis inventories represent greater than 99.9% of the chemical mass and total radioactivity. The selected chemical and radioactive analytes also represent the greatest tank waste concerns from a safe storage, retrieval, pretreatment, disposal,

and regulatory perspective based on requirements in applicable Data Quality Objectives. Although the best-basis inventories represent the best single-point estimate of tank contents, many end-users of the inventory data need uncertainty estimates to bound assumptions regarding source terms in support of safety analyses, risk assessments, process designs, and other areas where bounding analyses are required. Consequently, in addition to the single-point estimates of tank inventories, reliable mean concentration estimates and uncertainties are required in support of efforts to calculate, evaluate, and reconcile global and tank-specific inventories.

An effort was initiated in FY 1998 to determine the uncertainty bounds around the Hanford Engineering Analysis of Best-Basis (HEABB) estimates. This uncertainty estimation effort considered three major sources of variability in this approach: the variability associated with the estimates of constituent concentration, waste density, and waste volume. A detailed description of the methodology for determining the inventory uncertainty can be found in *Methodology for Uncertainty Estimation of Hanford Tank Chemical and Radionuclide Inventories and Concentrations* (Chen et al 1998) (2). This paper will present the details of the effort to determine the volume uncertainty that was essential in developing the inventory uncertainty estimates.

STANDARD METHOD FOR ESTIMATING TOTAL WASTE VOLUME IN HANFORD TANKS

The standard method used at Hanford to estimate the total volume of waste converts waste height to volume using a conversion factor nominally based on the radius of the tank. The waste height is typically determined from a single surface-level measurement from a single riser in a 75-foot diameter tank using one of several measuring devices. These measurement instruments include an FIC (manufactured by Food Instrument Company), a manual tape, and an ENRAF (not an acronym). These devices measure the distance from the top of the riser to the surface of the waste. With knowledge of the absolute elevation of the riser top and the bottom of the tank sidewall, the height of the waste above the tank sidewall can be determined. The portion of the tank above the bottom of the tank sidewall is considered to be a nominal cylinder of known radius with a single volume-to-height ratio. Most tanks have a dished bottom below the cylindrical portion of the tank. The standard volume estimation method accounts for the dish by adding a nominal dish volume to the volume of waste in the cylindrical portion of the tank. A cross section of a typical Hanford tank is shown in Figure 1.

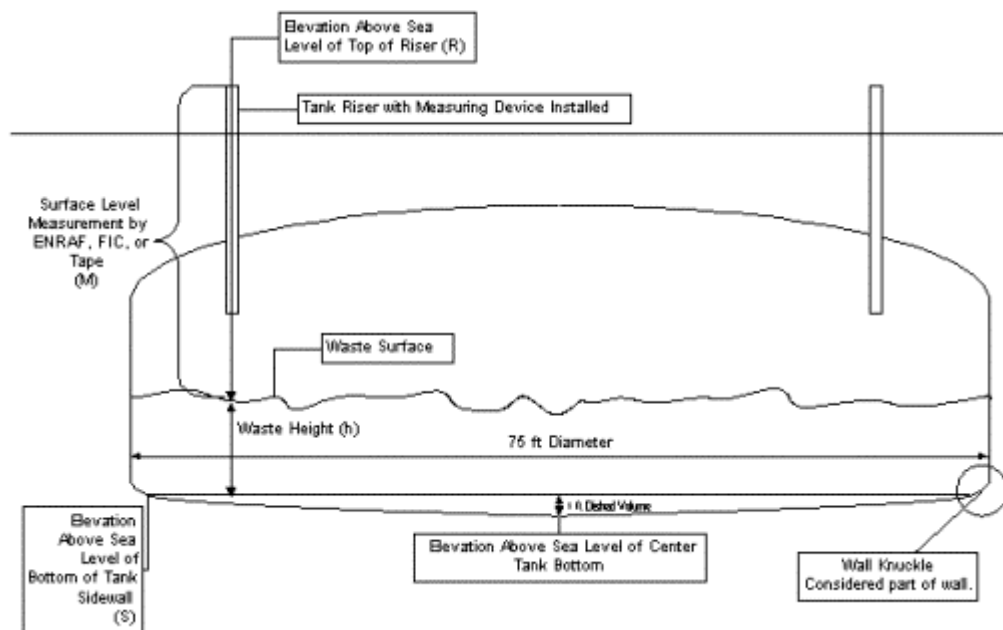


Figure 1. Typical Hanford Site Tank Surface Level Measurement Features

The standard volume determination method can be described by Equations 1 and 2.

$$V_{Total} = h \times F + D \quad \text{Eq. 1}$$

$$h = [(R - S) - M] \times 12 \text{ in/ft} \quad \text{Eq. 2}$$

where

h Waste height above tank sidewall bottom.

F A conversion factor transforming waste height into volume. The tank volumes are calculated using a

conversion factor of 2,750 gallons/inch of waste height for 75-ft. diameter tanks and 196 gallons/inch for

20-foot diameter tanks.

D Volume of the dished bottom. For 75-ft. diameter tanks $D = 12,500$ gallons and for 20-ft. diameter tanks

$D = 590$ gallons. For tanks with a flat bottom, this parameter is zero.

R Absolute elevation above sea level of the top of the riser.

S Absolute elevation above sea level of the tank side wall bottom.

M Measurement of the distance from the top of the riser to the surface of the waste.

TYPES OF HANFORD SITE UNDERGROUND STORAGE TANKS

This study has found that the Hanford site tanks can be categorized into six (6) types based upon shape and size (see Table I). The tank types were identified during a review of cross sectional drawings of all Hanford tank farms. The structural characteristics that influence volume uncertainty are tank radius, presence of a dished bottom, radius of dished bottom, radius of

curvature of dished bottom, volume of dish, and presence and radius of sidewall knuckle. It should be noted that some Type 1 tanks differ in terms of total volume capacity due to differences in the height of the tank sidewalls. However, for the purposes of this study, these tanks have the same volume determination characteristics in terms of the parameters aforementioned.

Table I. Types of Hanford Site Underground Storage Tanks

Type	Description	Volume Characteristics
Type 1	Early 100 series SSTs – 108 tanks B, BX, BY, C, S, T, TX, TY U Farms	36.5 foot radius Dished bottom, - 12 inch depth - 404.875 inch radius - 6,836.157 inch radius of curvature - Dish volume approx. 13,380 gallons 48 inch round knuckle
Type 2	DSTs – 28 tanks AN, AP, AW, AY, AZ, SY Farms	37.5 foot radius DSTS Flat bottom 12 inch rounded knuckle
Type 3	200 Series SSTs – 16 tanks B,C,T,U Farms	10 foot radius Dished bottom, - 6 inch depth - 96 inch radius - 771 inch radius of curvature - Dish volume approx. 376 gallons
Type 4	SX Farm SSTs - 15 tanks	37.5 foot radius Dished bottom, - 12 inch depth - 450 inch radius - 8,443.5 inch radius of curvature - Dish volume approx. 16,527 gallons Square knuckle
Type 5	A Farm SSTs - 4 tanks	37.5 foot radius Flat bottom Square knuckle
Type 6	AX Farm - 4 tanks	37.5 foot radius Flat bottom 6 inch rounded knuckle

SOURCES OF TOTAL VOLUME UNCERTAINTY

The standard volume determination method introduces five (5) primary sources of uncertainty to the resulting calculated volume. These sources of uncertainty and the equation parameters affected by these uncertainties have been summarized in Table II.

Table II. Sources of Total Volume Uncertainty

Source of Uncertainty	Parameter Effected by Uncertainty	Description of Uncertainty
σ_R	R	Uncertainty in absolute elevation of riser top
σ_S	S	Uncertainty in absolute elevation of bottom of tank sidewall
σ_F	F	Uncertainty in volume conversion factor
σ_h	h	Uncertainty in waste height due to non-level surface (riser-to-riser)
σ_{MS}	M	Measurement uncertainty due to sensor installation
σ_{MN}	M	Measurement uncertainty due to instrument noise

Absolute Riser Top and Tank Sidewall Bottom Elevation Uncertainty

The standard method for estimating tank volume calculates the waste height above the tank sidewall bottom by subtracting the distance from the riser top to the surface of the waste from the distance between the riser top and the bottom of the tank sidewall (see Equation 2). The distance between the riser top and bottom of the tank sidewall is determined by subtracting the elevation above sea level of the riser top (R) from the elevation above sea level of the tank sidewall bottom (S). σ_R and σ_S respectively represent the uncertainties in the reported riser top and sidewall bottom elevations.

Uncertainty in Volume Conversion Factor

Volume is calculated by the standard method from waste height using a nominal conversion factor of 2,750 gallons/inch for the 75-foot diameter tanks and 196 gallons/inch for the 20-foot diameter tanks. These conversion factors are approximately based on the geometry of a cylinder such that $F = \pi r^2$. However, DST as-built drawings indicate that there were construction tolerances of ± 2 inches for tank radius (Drawing No. H-2-71975). σ_F is defined as the uncertainty in the conversion factor due to variability in the actual tank radius. Construction tolerances were only reported on as-built drawings for DSTs. It will be assumed that the tolerances were the same for SSTs. It is also assumed that the construction tolerances were reported as a 2σ tolerance. Therefore, $\sigma_F = 1$ inch.

Uncertainty In Waste Height Due To Non-Level Surface (Riser-To-Riser)

The standard method assumes that a single waste height is representative across the entire 75-foot diameter of the tank. Reviews of waste height measurements from different risers in the same tank indicate that significant differences exist between risers. Waste height gradients of 2 feet have been observed in some tanks. Review of tank surface photographs also indicates significant variations in the waste surface levels across tanks. σ_h has been defined as the uncertainty in waste height due to a non-level surface. This uncertainty is often referred to as the riser-to-riser uncertainty. σ_h will be estimated from an ANOVA model fit to the surface level data from all 177 tanks.

Measurement Uncertainty Due To Sensor Installation

The surface level measurement instrumentation used at Hanford provides observations of the relative difference between the top of the riser and the surface of the waste. At the time of installation, each instrument is calibrated to provide absolute heights of the waste above the tank sidewall. An uncertainty is introduced due to the difference between the calibrated waste height read by the instrument and the true value of the waste height. σ_{MS} has been defined as the uncertainty introduced by the initial instrument installation calibration. σ_{MS} will also be estimated from the surface level measurement data using an ANOVA model.

Measurement Uncertainty Due To Instrument Noise

The surface level measurement devices exhibit day-to-day variations in waste height due to inherent "noise". σ_{MN} has been defined as the uncertainty in waste volume due to instrument noise. σ_{MN} will also be estimated from the surface level measurement data.

TOTAL VOLUME BIAS

In addition to the sources of uncertainty described above, the standard volume method introduces a number of systematic biases to the resulting volume. A volume bias consistently estimates volume as either higher or lower than the true volume. These biases are due to simplifying assumptions used by the standard method and are specific to the volume characteristics of the tank types previously identified in Table I.

There are three types of volume bias identified for each tank type. These biases are associated with the volume of the dished bottom (where applicable), the volume of the region of the tank influenced by rounded knuckles, and the conversion factor used for 100 series (37.5-foot radius) tanks. The magnitude of the three types of biases is the difference between the nominal value used by the standard volume method and the actual volume based upon the geometric shape of the tank.

Volume Bias of Dished Bottom

The standard volume determination method uses a nominal value of 12,500 gallons for 100 series dished bottom tanks and 590 gallons for 200 series tanks. As indicated in Table I, Tank Types 1, 3, and 4 have dished bottoms. The as-built cross sectional drawings for Type 1, 3, and 4 tanks indicate that the dished bottoms are spherical segments with a given diameter, depth, and

$$\text{Volume} = \frac{1}{6} \pi h (3r^2 + h^2) \quad \text{Eq. 3}$$

radius of curvature (see Table I). The volume of a spherical segment is given by Equation 3 (Perry's 1984) (3).

where

h = depth of the dished bottom

r = radius of base of spherical segment (radius of dish)

Volume Bias of the Sidewall Knuckle

A knuckle connects the tank sidewall to the tank bottom. Most of the tanks (158 out of 177) have rounded knuckles that vary in radius from 6 inches upwards of 48 inches. The standard volume estimation method presumes that the tank region above the bottom is a cylinder with the same radius as the tank (i.e. 450 inches for 100 series tanks). However, in the region of the knuckle, the volume is less than that of a cylinder because the knuckle reduces the radius of the tank in that region (see Figure 2). The standard volume method over-estimates volume by as much as 5,729 gallons for Type 1 tanks if the height of waste in the tank is greater than the radius of the knuckle (48 inches).

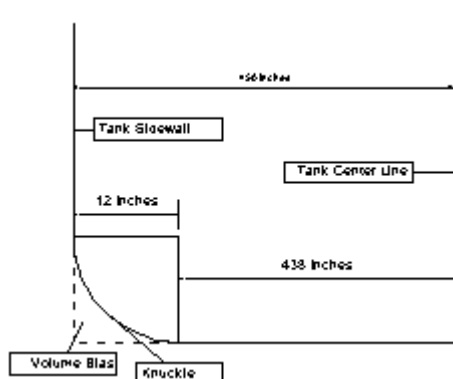


Figure 2. Knuckle of a DST (Type 2)

Volume Bias of Conversion Factor

The standard method uses a volume conversion factor of 2,750 gallons/inch. However, a cylinder with a radius of 450 inches (37.5 feet) has a height to volume ratio of 2,754 gallons per inch. Therefore, the use of the nominal conversion factor underestimates volume by 4 gallons per inch. If one divides the total waste volume in all tanks (~52 million gallons) by the 177 tanks, the average waste height would be approximately 100 inches. Therefore, on average, the nominal conversion factor underestimates volume by 400 gallons per tank.

Total Volume Bias

Table III reports the three types of biases for each of the 6 tank types. The table also calculates a total bias. Note that some of the volume biases overreport volume and others underreport

volume. The magnitude and direction of the total volume bias ranges dramatically. The most prevalent tank type (Type 1) overestimates volume by as much as 4,449 gallons per tank. There are 108 Type 1 tanks and the bias could potentially be as large as 480,492 gallons for Type 1 tanks alone. On the other hand, Type 4 tanks underreport volume by as much as 4,427 gallons per tank. There are 15 of these tanks (SX Farm) and thus the volume bias of these 15 tanks could be as large as 66,405 gallons.

A FINITE ELEMENT APPROACH TO ESTIMATING TOTAL WASTE VOLUME

A new method for estimating tank waste volume was developed in order to systematically account for the actual shape of the tank (eliminate volume bias) and to incorporate the sources of uncertainty. It was also desired to build a framework that could accommodate future enhancements. The new approach divides the tank into a number of small finite elements (called voxels). The volume for each voxel can be estimated based on the local conditions at each finite element, and the total volume is calculated by summing the volumes of each voxel. The voxel framework was then incorporated into a Monte Carlo simulation model to repetitively evaluate uncertainty parameters and generate a total volume uncertainty distribution for each tank.

Table III. Summary of Tank Volume Biases

	Tank Type					
	1	2	3	4	5	6
Radius of Tank (ft)	37.5	37.5	10	37.5	37.5	37.5
Height of Dished Bottom (in)	12	-	6	12	-	-
Radius of Knuckle (in)	48	12	24	-	-	6
Nominal Volume of Dish	12,500	-	590	12,500	-	-
Actual Volume of Dish	13,380	-	376	16,527	-	-
Nominal Conversion Factor (gal/in)	2,750	2,750	196	2,750	2,750	2,750
Actual Volume Conversion Factor (gal/in)	2,754	2,754	196	2,754	2,754	2,754
Volume Bias of Dish (gal)	(880)	-	214	(4,027)	-	-
Volume Bias of Knuckle (gal)	5,729	1,493	726	-	-	751
Volume Bias of Conversion Factor (gal)*	(400)	(400)		(400)	(400)	(400)
Total Volume Bias per Tank (gal)	4,449	1,093	940	(4,427)	(400)	351
No. of Tanks	108	28	16	15	6	4
Total Volume Bias (gal)	480,507	30,599	15,044	(66,405)	(2,400)	1,406
Grand Total Bias (Gal)						458,750

Voxel Frame of Reference

Since the tanks are generally cylindrical in shape, a polar coordinate system was first considered. However, the finite elements of a polar coordinate system have greatly different cross-sectional areas and hence the proportional contributions of each finite element to the overall total volume would be vastly different. Therefore, a new coordinate reference system was developed. The basic concept behind this coordinate system is that each finite element, called a voxel, would have equal cross-sectional areas. Although the shape and cross-sectional dimensions might be different, the cross-sectional areas would be equal. In such a system, the proportional volume contribution of each voxel would be the same. The voxel reference system is shown in Figure 3.

The unique identity of each voxel is given by the pair, (R, θ) , where R is the number of voxel lengths in the radial direction and θ is the voxel number in the axial direction. If the length of a voxel in the radial direction is L , then the center most voxel (1,1) is a circle with a radius of L and an area of πL^2 . By definition, the areas of all voxels are equal and hence equal to πL^2 . The number of voxels with equal cross-sectional areas has been derived as $n=2R-1$, where R is the number of rings from the center of the frame of reference.

For the 1st ring ($R=1$), n equals 1 and represents the centermost circle of Figure 3. When $R=2$ then $n=3$, i.e. there are three voxels in the second ring. The nominal length of a voxel (L) used by this study is 6 inches. Therefore, the cross-sectional area of a voxel is approximately 133 in^2 . For a 100 series tank (37.5-ft radius) the tank would be divided into 75 rings and R would vary from 1 to 75. There are 5,625 voxels in a 100 series tank. This is equal to the number of rings, R^0 , squared (75^2). Similarly, for 200 series tanks there would be 20 rings and 400 voxels.

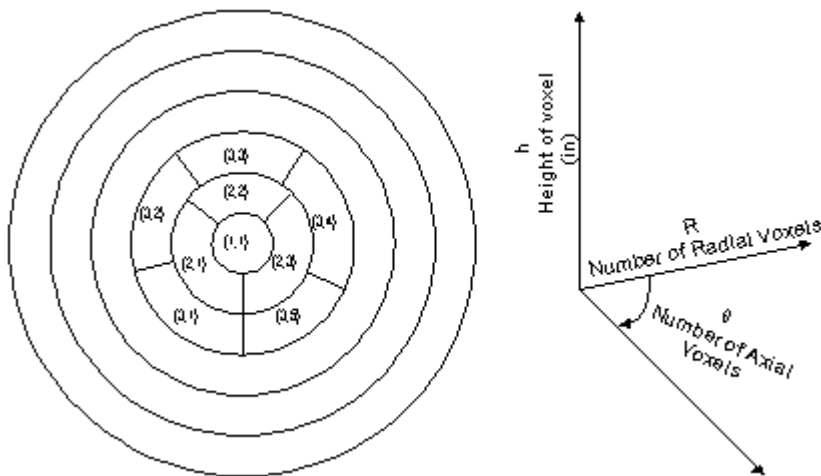


Figure 3. Voxel Frame of Reference

Volume of a Voxel

An individual voxel (R, θ) is shown in Figure 4. The right side of the voxel is R voxel lengths from the center of the tank. The left side is $R-1$ voxel lengths from the center. L_i is the length of the voxel for iteration i of the Monte Carlo simulation. The cross-sectional area of the voxel for iteration i is πL_i^2 . The waste height above the tank sidewall bottom for voxel (R, θ) is $h_{i,R,\theta}$. The distance from the tank sidewall bottom to the bottom of the tank at voxel location (R, θ) is $h_{B,R}$.

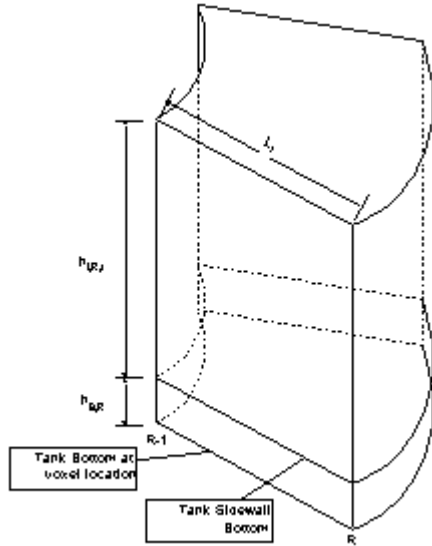


Figure 4. Volume of a Voxel

Based on the dimensions and shape to the tank bottom (presence of dish, depth of dish, radius of curvature of dish), a profile of the tank bottom was developed for each tank type defined in Table I. The profile calculates the distance from the tank sidewall bottom to the bottom of the tank, $h_{B,R}$, as a function of R .

The volume of the voxel (R, θ) is given by Equation 4.

$$V_{(R,\theta)} = (\pi L_i^2) \times (h_{i,R,\theta} + h_{B,R}) \quad \text{Eq. 4}$$

MONTE CARLO SIMULATION

A Monte Carlo simulation model was developed to integrate the voxel approach and the sources of volume uncertainty. The Monte Carlo simulation could be iterated to generate volume probability distributions for each tank. Figure 5 shows a logic flowchart of the Monte Carlo simulation.

The first step cycles through each of the 177 tanks. For each tank the model estimates the volume 1000 times to provide a robust volume distribution. This represents a total of 177,000 different volume estimates. For each individual volume iteration (i), the model first calculates the waste height above the tank sidewall bottom by adding to the nominal waste height (h_0) realizations of the uncertainties effecting the waste heights. There are four distinct sources of uncertainty that directly effect the estimate of waste height, σ_h , σ_{MS} , σ_{MN} , and σ_R . See Table II for a complete description of these sources of uncertainty. These uncertainties can be considered normal distributions centered on zero and the realizations of these uncertainties are adjustments to h_0 for that particular iteration of the model. The nominal waste height, h_0 , can be determined by one of two methods. The ANOVA models used to evaluate the waste surface level data for each tank will provide a least squares mean value of the waste height. This is often referred to as the LSMean. The HEABB Inventory also includes a point estimate for volume for each tank. This point estimate can be converted to a nominal waste height by back calculating using the standard volume method discussed earlier in this report. For the purposes of this study, the HEABB volumes were used to calculate the nominal waste heights. The differences between these two methods and the ramifications on the resulting volume uncertainties will be the basis for further studies.

The next item to be calculated by the Monte Carlo simulation model is the voxel length to be used for the iteration. If L_0 is the design radius of the tank in inches (450 inches for 100 series tanks and 120 inches for 200 series tanks) and $n(0, \sigma_F)$ is a realization of the construction

$$L_i = [L_0 + n(0, \sigma_F)] \left[\frac{L_0}{6} \right] \quad \text{Eq. 5}$$

tolerance for the tank radius, then the voxel length for iteration i can be determined as

The area of a voxel for iteration i is then calculated as $A_i = \pi L_i^2$. There is an uncertainty associated with the absolute height of the tank sidewall bottom. For each iteration a tank bottom adjustment is calculated as $B_i = n(0, \sigma_R)$. The model then iterates through each voxel in a tank. R ranges from 1 to $L_0/6$ and θ ranges from 1 to $2R-1$. The volume of a voxel is calculated by the

$$V_{R,\theta} = A_i [h_i + B_i + (h_{B,R} - h_{B,R-1}) / 2] \quad \text{Eq. 6}$$

model by Equation 6 such that

For a particular voxel, the distance below the tank sidewall bottom used by the model is the average of the distance at R and R-1. It should be noted that because the tank bottom in the region of the knuckle is above the tank sidewall bottom, $h_{B,R}$ is negative in that region. If the nominal waste height is less than the radius of the knuckle, then the sum of h_i and $(h_{B,R} - h_{B,R-1})$ would be negative for some voxels. This would incorrectly introduce negative voxel volumes to the tank volume summation. Therefore, a test of the sign of the summation of h_i and $(h_{B,R} - h_{B,R-1})$ is performed prior to calculating the voxel volume. If the sign is negative, the voxel volume is set to zero.

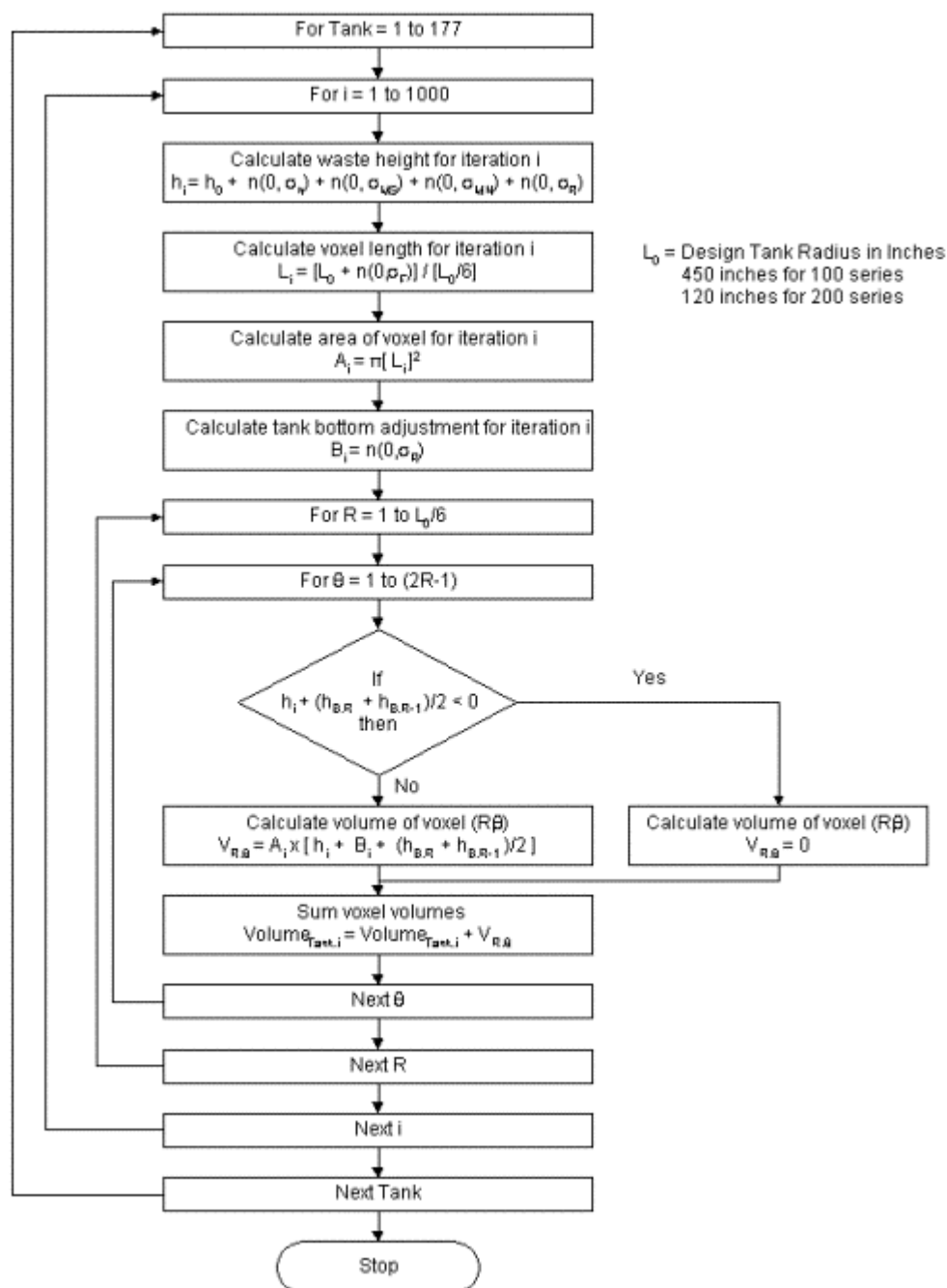


Figure 5. Monte Carlo Simulation Logic Flow Chart

DATA SOURCES FOR VOLUME UNCERTAINTY ESTIMATION

There are three primary sources of data that were used to estimate volume uncertainty in this study; 1) surface level measurements downloaded from TCD, 2) zipcord measurements provided by the Tank Characterization Program, and 3) riser elevation data.

SURFACE LEVEL DATA

A surface level dataset was downloaded from PC Surveillance Analysis Computer System (PCSACS) for all 177 tanks on January 7, 1999. The dataset contained all surface level measurements for the 177 tanks between the dates January 1, 1990 and January 7, 1999. The raw data set contained 505,250 records. The surface level data was processed to remove records labeled as suspect, to eliminate duplicate records, and to remove zero values (zero values, although labeled as “good” data, were considered suspect, since a zero value infers that no waste exists in that tank). All “Intrusion FIC” measurements were stripped from the data set. When a FIC was set to “Intrusion” mode, the FIC conductivity probe was lowered to a point a few inches above the surface of the waste. The probe was left in this position for an extended period of time to monitor for “intrusion” of materials into the tank. If intrusion was occurring, the waste level would rise and the conductivity probe would activate. However, when the probe did not activate, the recorded measurements were not really measurements of the waste surface because the real surface lies at some point lower than the height of the probe. To reduce inflated variances in active tanks, all records prior to the last known transaction into or out of a tank were deleted. The cleaned surface level data set contained 247,714 records. Tank measurements obtained from hand-held zipcords were added to the dataset. There were 112 zipcord measurements added so the final number of surface level measurements for analysis was 247,826. The data was then adjusted to ensure a common frame of reference for the entire dataset. Initially, all surface level data was reported as height of waste above the tank sidewall bottom. Tanks with a flat bottom were reported as height above the tank bottom. This allowed for a simple calculation for volume. In the mid-1990s, a new instrument type (ENRAF) was introduced to measure the surface level of the waste. On some of the tanks with the new instrument, the reference point was changed and the database began recording the measurements as height above the tank bottom. This introduced a 12-inch jump in the data for the particular tank. This change in reference point did not occur for all tanks with an ENRAF, nor did it occur always at the time of installation. For some tanks the change in reference point occurred well after the ENRAF was installed. To correctly interpret the surface level measurements, the data for all tanks with an ENRAF were closely inspected for unexplained jumps of approximately 12 inches. If these jumps were detected, then all data after that point were adjusted back to the common reference point of the bottom of the tank sidewall by subtracting 12 inches. There does not appear to be any pattern to when the measurement reference point was changed. The source database (PCSACS) should be carefully examined to bring all data points back to a common reference point.

ZIPCORD MEASUREMENTS

In addition to the routine surface level measurements conducted for tank surveillance, tank farm operators often perform a manual surface level measurement underneath a riser prior to initiating

activity, such as core sampling, in that riser. These non-routine measurements are usually taken with a “zipcord.” A zipcord is a portable conductivity meter that is lowered into the tank from a riser top. The zipcord measures the distance from the top of the riser to the surface of the waste. The zipcord measurements were converted to waste height above tank sidewall bottom using Equation 2. There were a total of 112 zipcord measurements from 55 different tanks. These measurements are some of the most valuable data in the surface level dataset because they come from additional horizontal locations in the tank and provide a more robust dataset to estimate the fluctuations in surface level across the diameter of a tank. However, zipcord measurements only provide a single-point estimate for the waste surface below that specific riser. These data records were added to the surface level measurement database.

RISER ELEVATIONS

The uncertainty in the absolute elevation above sea level of the riser top and the bottom of the tank sidewall was estimated from a dataset of multiple riser elevation measurements. The riser top elevations are reported on tank as-built drawings and in *Waste Tank Risers Available for Sampling* (Lipnicki 1997) (4). In the past few years, several benchmarking studies have remeasured the elevations of some riser tops. When combined with the earlier measurements of the riser top elevation, this data provides pairs of observations measuring the same parameter. There were 418 riser elevation measurements from 209 risers in 100 tanks. No dataset is available to estimate uncertainty of tank bottom elevation. Therefore, the uncertainty of tank bottom elevation is assumed to be the same as riser top elevation uncertainty.

ANALYSIS OF VARIANCE

The magnitude of three of the sources of uncertainty (σ_h , σ_{MN} , σ_{MS}) effecting volume were determined using analysis of variance (ANOVA) models on the surface level database previously described. Because the availability of data was not identical for each tank, no single model could be constructed to evaluate every uncertainty term for each tank. Therefore, a number of models were developed and fit to the tanks that possessed sufficient data to support those models. Five different ANOVA models were used to estimate the tank specific uncertainty parameters. These models are summarized in Table IV.

Table IV. Summary of Tank Waste Volume ANOVA Models

Model Type	ANOVA Model	Total of Tanks	DST	SST	No. of Records
1 - Full Model	$Y_{ik} = \mu + R_i + S_{kj} + e_{ik}$	35	7	28	84,053
2 - Multiple Risers	$Y_i = \mu + R_i + e_i$	56	20	36	65,846
3 - Multiple Sensors	$Y_{ij} = \mu + S_i + e_{ij}$	43		43	74,207
4 - One Riser, One Sensor	$Y_i = \mu + e_i$	43	1	42	23,720
5 - Site-Wide Uncertainties	$Y_{ik} = \mu + T_i + R_{kj} + S_{kl} + e_{ik}$	177	28	149	247,826

The terms of the ANOVA model are defined below:

u	=	Overall Mean
R_i	=	Random Effect of Riser
$S_{j(i)}$	=	Random Effect of Sensor
T_i	=	Fixed Effect of Tank
e_{ijk}	=	Random Error (Measurement/Calibration)

The “full model” represents those tanks that have surface level measurements from multiple risers and from more than one sensor in at least one riser. The full model allows for independent calculation of all three sources of uncertainty for that tank. The “multiple risers” model was developed for tanks with data from multiple risers, but only a single sensor was used in any given riser. This model allows for independent calculation of two uncertainty terms (σ_h , σ_{MN}), but must rely on the site-wide default values for the sensor uncertainty term (σ_{MS}). The “multiple sensor” model has data from only a single riser in a given tank, but more than one sensor has been installed in that riser. This model provides values for σ_{MN} and σ_{MS} , but must use default site-wide values for σ_h . The fourth model is for those tanks with data from only a single riser and a single sensor. This model can evaluate only the “noise” term (σ_{MS}), and must use default values for σ_h and σ_{MN} . The last model in Table IV was used to evaluate the nominal site-wide default values for each uncertainty parameter.

In light of funding shortfalls in FY 1999, the ANOVA model results were not updated to reflect the dataset downloaded on January 6, 1999. The results that follow were generated with a dataset that reflects data only up to June 1998. It is believed that the ANOVA results from June 1998 are still reflective of the results that would be obtained with the more current data.

The site-wide default volume uncertainty values were:

Riser-to-Riser (σ_h)	=	8.76 inches
Sensor-to-Sensor (σ_{MS})	=	4.21 inches
Random Error (σ_{MN})	=	6.17 inches (not used for any tank)

Table V presents the ANOVA results for seven selected tanks. The shaded values were taken from the site-wide default model because these tanks did not have sufficient data available to support the full model.

Table V. ANOVA Results from Selected Tanks

Tank ID	LSMEAN (h_0) (Inches)	Riser-to-Riser (σ_h) (Inches)	Sensor-to-Sensor (σ_{MS}) (Inches)	Measurement Error (σ_{MN}) (Inches)
A101	352.3	9.51	4.21	0.878
A105	14.3	8.76	4.21	1.04
AN105	411.8	2.10	0.23	0.79
AW101	411.1	2.92	0.67	1.99
AW103	186.3	0.75	0.46	1.00
BX112	55.2	8.76	0.18	0.69
BY105	164.8	14.89	4.21	5.52

Analysis of Riser Elevation Uncertainty (σ_R)

Along with the uncertainties associated with riser-to-riser variability, sensor-to-sensor variability, and measurement/calibration error, the variability associated with riser elevation could also be estimated, since riser elevation data is readily available. The data structure, for 100 tanks, is such that two measurements of the riser elevation were taken for each riser. This paired data structure showed little variability between the pairs of measurements. Since the variability associated with riser elevation is so small, and not all 177 tanks had data associated with this uncertainty, all the available data for the 100 tanks was pooled together and a site-wide estimate was used for each tank. The estimated standard deviation associated with riser elevation is 0.597 inches. This value is used in the Monte Carlo simulation model for the terms σ_R and σ_S .

RESULTS FROM THE MONTE CARLO SIMULATION USING THE VOXEL METHOD

The Monte Carlo simulation model shown in Figure 5 was programmed on a computer to read data files containing the quantifications for the sources of uncertainty, nominal waste height, and tank bottom profile for each of the 177 tanks. The model performed 1000 iterations of the model for a total of 177,000 individual volume estimates. The 1000 iterations for each tank were then used to develop a volume probability distribution. The distribution mean, standard deviation, and the 5th, 25th, 50th, 75th and 95th percentiles for seven selected tanks are shown in Table VI.

Table VI. Volume Probability Distributions for Selected Tanks

TanK ID	Mean (Kgal)	Standard Deviation (Kgal)	5th Percentile (Kgal)	25th Percentile (Kgal)	Median (Kgal)	75th Percentile (Kgal)	95th Percentile (Kgal)
A101	959	27	912	940	960	980	1,000
A105	22	22	-	1	18	37	63
AN105	1,130	7	1,117	1,125	1,130	1,135	1,140
AW101	1,130	9	1,113	1,123	1,131	1,138	1,140
AW103	512	5	504	509	512	513	520
BX112	160	24	121	143	161	177	198
BY105	500	46	423	471	499	529	576

The nominal tank waste volume for Tank A101 was 959 kgallons. The results of the Monte Carlo simulation would indicate that there is only a 5% chance that the volume was less than 911.9 kgallons and a 25% chance the volume was less than 939.7 kgallons. There is an equal chance that the volume would be above or below 960 kgallons but only a 25% chance that it is above 980.2 kgallons. Finally, there is only a 5% chance the volume is greater than 1,000 kgallons. It should be noted that the probability distribution of some tanks is quite small (such as AW103) and span only a few kgallons, whereas other tanks have a much more significant span of possible volumes (such as BY105), which range by more than 150 kgallons from the 5th to the 95th percentile. The span of the volume probability distributions is a function of the magnitude of the sources of uncertainty from Table V. All results can be found in Ferryman, et al., 1998 (5).

CONCLUSIONS

Based on the results of this study, a number of important conclusions can be drawn, which can be categorized into three areas: bias, uncertainty, and data quality.

Bias

- Biases exist in the standard method currently used by the site to calculate waste volumes.
- **Oversimplification of the standard methods results in volume biases that overestimate total waste volume by as much as 460,000 gallons.** The finite element-based voxel method more closely models the volume characteristics of the tank farms, eliminating these known volume biases.

Uncertainty

- Six sources of uncertainty have been identified and quantified for each tank. The riser-to-riser variability in waste height is generally the predominant factor effecting waste volumes. The finite element-based voxel method identifies and accommodates these six known sources of uncertainty.

Data Quality

- The publicly available surface level measurement dataset requires substantial data processing and cleanup before accurate evaluation and analysis can be performed. The following observations concerning the dataset were made:
- Approximately 20% of the surface level records were considered suspect.
- Over 400 records still contained zero values after suspect data was removed.
- Nearly 1/7 of the “good” records were Intrusion FIC measurements, which are not actual surface level measurements.
- Many of the changes in surface level data were the result of waste transactions which are not indicated in the dataset.
- Nearly 1/5 of the tanks have a 12-inch jump in the data (change in reference point) due to installation of ENRAF instrumentation. This change in reference point does not seem to follow a logical pattern. Not all ENRAF with dished bottoms exhibited the change in reference point and many tanks had the reference point changed at some arbitrary date after the ENRAF was installed, not at the time of installation.
- Nearly half of the records were deleted from the dataset, for reason stated above, before performing meaningful analysis.
- Differences exist between the site estimates of waste height and the measured heights of waste height presented in the surface level dataset that was downloaded from the Surveillance Analysis Computer System (PCSACS) on January 6, 1999.
- Differences exist between the site estimates of total volume and the least squared means calculated from the surface level measurements downloaded from PCSACS on January 6, 1999.

RECOMMENDATIONS

The following recommendations are encouraged to be adopted to improve waste volume estimation and waste inventory calculations.

The voxel method of volume calculation should be adopted. A stand-alone volume calculation program can be written and made available site-wide. Such a program could accept data on tank name and either waste height or waste volume. The program would respectively return waste volume or waste height that accurately accounts for the specific geometry of the identified tank. This would eliminate the known volume biases.

A concerted effort should be conducted to collect and find additional zipcord data. Since the riser-to-riser variability is the driving factor effecting volume uncertainty, zipcord data is especially valuable because it provides surface level measurements from new locations within a tank. The existing set of zipcord measurements are single-point measurements and provide no information relative to the precision of these measurements.

The publicly available surface level database should be closely scrutinized.

Remove suspect data or at least identify is as suspect.

Flag Intrusion FIC data so that users are aware of the misconception that it is a surface level measurement.

Examine the quality criteria used to differentiate between “good” and “suspect” data.

Evaluate the process for calculating the waste heights from the actual measurement of the distance from the riser top to the surface of the waste.

Ensure that the database has a consistent frame of reference. Until recently, waste heights were always reported from the bottom of the tank sidewall. When ENRAF instruments were installed, some tanks began reporting data from a different reference point, the tank center bottom. This change in reference point was not consistently carried out for tanks with ENRAF equipment and is different from those without ENRAFs. All data should be reported from a common reference point.

The method for presenting the surface level information to the public should be re-evaluated. The current dataset requires substantial data processing and insight to correctly evaluate, and is prone to misinterpretation. Perhaps a more graphically-oriented presentation that plots surface level and indicates uncertainty bounds would be more meaningful to the public and lessen the likelihood of misinterpreting the information.

Methods for developing tank contour maps of the waste surface should be explored. A contour map would eliminate a major portion of the riser-to-riser variability, which is the largest contributor to volume uncertainty.

Methods for more accurately determining waste phase (sludge, supernatant, saltcake) volumes should be further developed, and uncertainties associated with those volumes estimated.

Neutron and gamma log scans are potentially useful tools in determining waste phase changes in each tank. Since this type of data is available for most tanks, methods should be explored to integrate this data into the voxel approach for estimating waste phase volumes and their associated uncertainties.

Evaluate the observed differences between site estimates of waste height and the surface level measurements downloaded from PCSACS on January 6, 1999, as well as the observed differences between site estimates of volume and least square means calculated from the measured surface level data obtained from PCSACS.

REFERENCES

Anderson 1990, "A History of the 200 Area Tank Farms", WHC-MR-0132, Westinghouse Hanford Company, Richland, Washington.

TA Ferryman, K.M. Remund, S.A. Hartley, F. Gao, C.A. Lopresti, T.J. Deforest, J.G. Hill, C.A. G. Chen, T.A. Weier, B.G. Amidan, D.K. Gemeinhart, February 1998, "Methodology for Uncertainty Estimation of Hanford Tank Chemical and Radionuclide Inventories and Concentrations", PNNL-11842, Pacific Northwest National Laboratory, Richland, Washington.

Perry's Chemical Engineer's Handbook, Sixth Edition, 1984, McGraw Hill Book Company, Page 2-12.

Lipnicki, J., 1997, "Waste Tank Risers Available for Sampling", HNF-SD-WM-TI-710, Rev. 4, Westinghouse Hanford Company, Richland, Washington.

TA Ferryman, BG Amidan, G Chen, SA Hartley, CA Lopresti, JG Hill, TJ DeForest, F Gao, KM Remund, BC Simpson, September 1998, "Summary of Uncertainty Estimation Results for Hanford Tank Chemical and Radionuclide Inventories", PNNL-12003, Pacific Northwest National Laboratory, Richland, Washington.