S

JAN 3 0 2002

ENGINEERING DATA TRANSMITTAL

1. EDT 628423

2. To: (Receiving Organization) Distribution	3. From: (Originating Organization) Inventory and Flowsheet Engineering	4. Related EDT No.: N/A
5. Proj./Prog./Dept./Div.: RPP/WFD	6. Design Authority/Design Agent/Cog. Engr.: J. R. Jewett/373-1228	7. Purchase Order No.: N/A
8. Originator Remarks: Document transmitted for approval and release.		9. Equip./Component No.: N/A
		10. System/Bldg./Facility: Tank Farms
11. Receiver Remarks:	11A. Design Baseline Document? []Yes [X] No	12. Major Assm. Dwg. No.: N/A
		13. Permit/Permit Application No.: N/A
		14. Required Response Date: January 16, 2002

15. DATA TRANSMITTED

(A) Item No.	(B) Document/Drawing No.	(C) Sheet No.	(D) Rev. No.	(E) Title or Description of Data Transmitted	(F) Approval Designator	(G) Reason for Transmittal	(H) Originator Disposition	(I) Receiver Disposition
1	RPP-9805	---	0	Values of Particle Size, Particle Density, and Slurry Viscosity to use in Waste Feed Delivery Transfer System Analysis	Q	1	1	

16. KEY

Approval Designator (F)	Reason for Transmittal (G)		Disposition (H) & (I)	
E, S, Q, D or N/A (see WHC-CM-3-5, Sec. 12.7)	1. Approval 2. Release 3. Information	4. Review 5. Post-Review 6. Dist. (Receipt Acknow. Required)	1. Approved 2. Approved w/comment 3. Disapproved w/comment	4. Reviewed no/comment 5. Reviewed w/comment 6. Receipt acknowledged

17. SIGNATURE/DISTRIBUTION
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JR Jewett Signature of EDT Originator — Date 1/30/02	TJ Connolly Authorized Representative for Receiving Organization — Date 1/30/02	NW Kirch Design Authority/ Cognizant Manager — Date 1/30/02	Ctrl. No. N/A [] Approved [] Approved w/comments [] Disapproved w/comments

BD-7400-172-2 (10/97)

VALUES OF PARTICLE SIZE, PARTICLE DENSITY, AND SLURRY VISCOSITY TO USE IN WASTE FEED DELIVERY TRANSFER SYSTEM ANALYSIS

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EDT/ECN: ~~928423~~ 628423 1/30/02 UC: 721
Org Code: 7G300 Charge Code: 110310/BA00
B&R Code: EW3130000 Total Pages: 6062

Key Words: Particle, density, slurry, viscosity, waste, physical property.

Abstract: Recommended values have been developed for particle size distribution, particle density, and slurry viscosity that maybe used in slurry flow calculations that support the design of the piping system that is being modified to deliver Hanford wastes from the underground storage tanks to the planned Waste Treatment Plant for vitrification.

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1/30/02
Release Approval Date

DATE: HANFORD RELEASE
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Printed in the United States of America

RPP-9805
Revision 0

Values of Particle Size, Particle Density, And Slurry Viscosity to Use in Waste Feed Delivery Transfer System Analysis

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ABBREVIATIONS

cP	centipoise
ESP®	"Environmental Simulation Program" (trademark of OLI Systems, Inc., Morristown, NJ
ft/s	feet per second
g/L	grams per liter
g/mL	grams per milliliter
LAW	Low Activity Waste
HLW	High-Level Waste
M	molar/moles per liter
nm	nanometers
PSD	Particle size distribution
RPP	River Protection Project
s^{-1}	reciprocal seconds
SST	single-shell tank
TWINS	Tank Waste Information Network System
vol%	volume percent
WTP	Waste Treatment Plant
°C	degrees Celsius
μm	micrometers
α	Volume fraction of solids in a slurry or sludge
%	percent

NOTE: Each large underground tank at the Hanford Site has an equipment designation of the form "241-F-1XX," where the "F" is a one- or two-letter designation for a group of tanks (a "tank farm") and the "XX" is a sequence number indicating the particular tank within the farm. In this paper, the tank designations have been shortened to the form "F-1XX."

ALGEBRAIC SYMBOLS

a, b, c, d, n	adjustable constants (Eq. 5.6, Eq. 5.7)
ci (i = 0,1,2,3,4)	adjustable constants (Eq. 5.4)
C	fraction of solids in a slurry or sludge, stated in g/L
C_V	solid volume fraction of an in-tank sludge
D	fractal dimension (Eq. 4.1) or pipe diameter (Eq. 5.8)
K	tabulated value to calculate tolerance limit
n	porosity of the solid layer after the sludge is centrifuged and standing liquid is decanted
r	radius of primary particle
R	radius of agglomerate particle
S.D.	standard deviation of the measurements
t(0.05, df=n)	quantile from Student's "t" distribution for a one-sided 95% confidence interval with n degrees of freedom
$\overline{X}$	mean particle size

x	volume fraction of the resulting solid layer after the sludge is centrifuged and standing liquid decanted
y	weight fraction of the solids within the sludge layer
V	linear (face) flow velocity in a pipe
V_P	volume fraction of solids in a slurry, sludge, or agglomerate particle
95% UL	upper limit of a one-sided 95% confidence interval on the mean
95/95 TL	upper limit to a one-sided 95/95 tolerance limit (95% confidence limit for 95% of the population)
γ	strain rate (i.e., shear rate)
μ_L	viscosity of a liquid
μ_M	viscosity of slurry or a sludge
ρ_B	bulk density of the sludge
ρ_C	bulk density of the sludge before it is centrifuged
ρ_{CS}	solid density of the sludge after the sludge is centrifuged and standing liquid decanted
ρ_{CL}, ρ_{CL}	density of liquid in the sludge
ρ_S	density of solids in the sludge.
χ^2	sum of squares of differences between measurements and corresponding values estimated by a regressive equation.

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1.0 OBJECTIVE/PURPOSE

The objective of this document is to provide recommended values for three waste properties to be used in a planned revision of the Waste Feed Delivery Transfer System Analysis (Julyk et al. 2001). These properties are particle size distribution (PSD), particle density, and slurry viscosity. In this document, the results of laboratory and engineering studies will be collated and summarized to provide a succinct source of physical property data for use in the hydraulic analysis of the transfer system.

2.0 BACKGROUND

The goal of the River Protection Project (RPP) is to vitrify the nuclear waste stored in the Hanford Site's underground storage tank system (tank farms) in a new Waste Treatment Plant (WTP) to be built adjacent to the Hanford Site's 200 East processing area. The Waste Feed Delivery Transfer System Analysis document provides calculations of pipeline pressure drops (head losses) to be expected during the transfers of waste from the tank farms to the WTP and during the required staging transfers between tanks in the farms. The transfers required for Phase 1 of the RPP have been planned in detail, and these transfers are used in the analysis as an indicator of the system requirements for the entire life of the RPP.

Two types of waste are to be delivered to the WTP. These are termed Low-Activity Waste (LAW) feeds and High-Level Waste (HLW) feeds. The LAW feeds are highly alkaline aqueous solutions containing high concentrations of sodium salts (primarily $NaNO_3$ and $NaNO_2$). For purposes of pressure drop calculations, LAW feed is considered to contain essentially no solids.

On the other hand, HLW feed will contain relatively insoluble tank solids. These solids are primarily oxides and hydroxides of the metals used in the fabrication and reprocessing of nuclear fuels. The solids are to be slurried with water and/or dilute tank supernatants in batches containing no more than 200 grams of solids per liter of feed (Kirkbride et al. 2001).

The calculation of pressure drops for LAW feed flows is straightforward because the waste is a single-phase liquid. However, calculations for HLW feeds have been hampered by a lack of reliable information concerning the physical characteristics of the waste. The waste characteristics essential for the pressure drop calculations are particle size distribution, particle density, and slurry viscosity as a function of solids content, strain rate (related to the slurry pipe flow velocity), and temperature.

A laboratory program was conducted this year to produce better estimates of particle size and particle density in the HLW feeds, and viscosity measurements have been obtained in another laboratory program conducted over the past few years. These programs have yielded many measurements of HLW particle sizes and slurry viscosity measurements for a few HLW tanks. However, there are hardly any direct measurements of solid density; therefore, HLW solid density is least known among these three waste properties.

Therefore, the approach taken for this study was to select a conservative (upper bound) solid density value and realistic values (best estimates) of particle sizes and slurry viscosities. The selection approach for these three waste properties is expected to support a reasonably conservative assessment of the waste feed delivery transport system.

3.0 PARTICLE SIZE

A large effort was mounted this year to improve the state of knowledge of the physical nature of the solids in HLW feeds. The results of this work (Bechtold et al. 2002) provide the most comprehensive source available for particle size distributions in these wastes. Particle size distributions for composite samples from seven of the ten Phase 1 HLW feed tanks were measured using laser-scattering particle size analyzers at two different laboratories. These measurements were made under a variety of instrumental conditions, including various flow rates through the sample loop, various stirring rates in the sample reservoir, and before and after subjecting the particles to ultrasonic energy. The measurements were made on dilute suspensions of the sludges in 1M NaOH/1M $NaNO_3$ solution. Supporting particle size information was obtained by sieving and settling tests and microscopic observations.

These activities, coupled with theoretical considerations obtained from the scientific literature, gave good evidence that the solids contain very tiny waste particles (on the order of nanometers in size) that readily form accretions, i.e., agglomerate particles, ranging in size from a few micrometers to nearly a millimeter. However, moderate hydrodynamic shear forces readily disrupt the largest of these agglomerate particles, resulting in mixtures where most of the solids volume is present in particles of just a few micrometers. For example, in a synthetic waste slurry, typical 10-μm agglomerate particles may be reduced in size to 4.6 μm after undergoing 100 times greater strain (shear) rate than the original strain rate imposed upon them (Bunker et al. 2000).

3.1 INPUT DATA

Because it is difficult and perhaps unreliable to scale the laboratory data to the hydrodynamic conditions that are expected to exist during the actual process transfers of waste, laboratory data obtained under conditions of minimal turbulence/disturbance were selected to develop the design-basis value for the slurry flow calculations. Particles present during conditions of minimal turbulence/disturbance represent the largest particles that will be present in a moving stream and, therefore, will provide conservative estimates of pressure drop during slurry flow.

Of all the PSD measurements reported in Bechtold et al. (2002), the largest particle sizes were obtained with the Horiba[1] LA-910 analyzer at 222-S Laboratory (operated by Fluor Hanford) in the first observations after introducing each sample into the analyzer. Further measurements were obtained on each sample as it continued to be circulated through the analyzer; the distributions generally became smaller on successive measurements. The measurements obtained with the Microtrac[2] X-100 analyzer at Pacific Northwest National Laboratory (operated by Battelle Memorial Institute) also gave smaller distributions than the initial measurements in the Horiba. Therefore, the initial measurements for each sample obtained in the Horiba analyzer were regarded as having conditions of minimal turbulence/disturbance.

[1] Horiba, LTD., Kyoto, Japan.
[2] Microtrac, Inc., Montgomeryville, Pennsylvania.

3.2 METHOD OF ANALYSIS

The mean and standard deviation of the particle size distribution for minimal agitation were computed for each of the seven tanks. The results are given in Table 3-1. In this table, "S.D." means standard deviation, and "Count" is the number of measurements used in the computations.

"Percentile" indicates the percentage of the particulate volume that is present in particles having diameters less than the indicated values. For instance, at the 50th percentile (also called the median), half of the solids volume exists in particles with diameters less than the indicated mean.

For tank AZ-102, one measurement (designated AZ102910-6/1/0/0, from sample S01T001652) was found to be so grossly different from the rest of the data that an error was suspected; therefore, it was omitted from the computations.

Table 3-1. Summary Statistics by Tank, Minimal Agitation (μm)

Tank	Percentile	1.0 %	5.0 %	25.0%	50.0 %	75.0 %	95.0 %	99.0 %
AW-103	Mean	0.73	1.11	3.36	6.86	29.88	194.04	268.03
	S.D.	0.58	0.76	0.35	1.98	49.06	223.69	284.54
	Count	8	8	8	8	8	8	8
AY-101	Mean	0.61	1.16	5.03	9.00	15.33	260.73	393.15
	S.D.	0.05	0.08	0.27	0.47	1.63	136.16	95.79
	Count	4	4	4	4	4	4	4
AY-102	Mean	0.69	0.86	1.33	2.38	5.33	11.53	16.18
	S.D.	0.02	0.03	0.06	0.17	1.17	3.15	4.53
	Count	4	4	4	4	4	4	4
AZ-102	Mean	1.36	2.36	6.96	15.58	112.99	181.86	240.56
	S.D.	0.11	0.47	2.56	8.69	175.12	236.50	310.53
	Count	5	5	5	5	5	5	5
C-104	Mean	0.22	0.54	2.81	7.29	31.78	188.08	331.99
	S.D.	0.00	0.05	0.12	0.54	6.35	54.09	76.84
	Count	4	4	4	4	4	4	4
C-107	Mean	0.87	1.26	3.43	6.58	10.24	16.24	21.00
	S.D.	0.02	0.02	0.08	0.30	0.78	1.91	2.74
	Count	4	4	4	4	4	4	4
SY-102	Mean	0.32	1.02	2.65	4.60	8.70	130.66	187.41
	S.D.	0.00	0.00	0.16	0.56	2.53	166.14	237.30
	Count	2	2	2	2	2	2	2

The individual tank means in Table 3-1 were averaged to give the overall means and standard deviations reported in Table 3-2. In this table, 95% UL and 95/95 TL denote the upper limit to a one-sided 95% confidence limit on the mean and the upper limit to a one-sided 95/95 tolerance limit respectively. The means, standard deviations, confidence limits, and tolerance limits

provide statistics that can be applied to the waste in all the HLW tanks taken as a whole (assuming that the tanks samples are a random sample of all the tanks).

The interpretation of one-sided 95% confidence limit is as follows. We are 95% confident that the "true" mean for all the wastes will be less than the computed value. The 95% UL is calculated as

$$95\%\text{UL} = \overline{X} + t(0.05, df = 6) \times \text{S.D.}/\sqrt{7} \ ,$$

where

$\overline{X}$ is the mean,
S.D. is the standard deviation, and
t(0.05, *df*=6) is the quantile from "Student's t" distribution for a one-sided 95% confidence interval on the mean with six degrees of freedom (the number of tanks minus one).

However, it is also useful to have an estimate of the maximum particle sizes that may be encountered in any particular tank. The tolerance limit provides this information. The interpretation of the one-sided 95/95 tolerance limit is as in the following example. The 95/95 TL value for the 50th percentile is 22 μm. This means that we are 95 percent confident that at least 95 percent of the tanks will have a median particle size no larger than 22 μm. The tolerance limit is calculated as

$$95/95\text{TL} = \overline{X} + K \times \text{S.D.},$$

where

K, corresponding to 7 tanks, is 3.399 (NBS 1963).

Table 3-2. Particle Size Distribution Obtained under Conditions of Minimal Agitation (μm)

Percentile	1.0 %	5.0 %	25.0%	50.0 %	75.0 %	95.0 %	99.0 %
Mean	0.7	1.2	3.7	7.5	31	140	210
Std Dev	0.4	0.6	1.8	4.2	38	94	145
95% UL	1	1.6	5	11	58	210	310
95/95 TL	2	3.1	10	22	160	460	700

3.3 RESULTS (RECOMMENDATION)

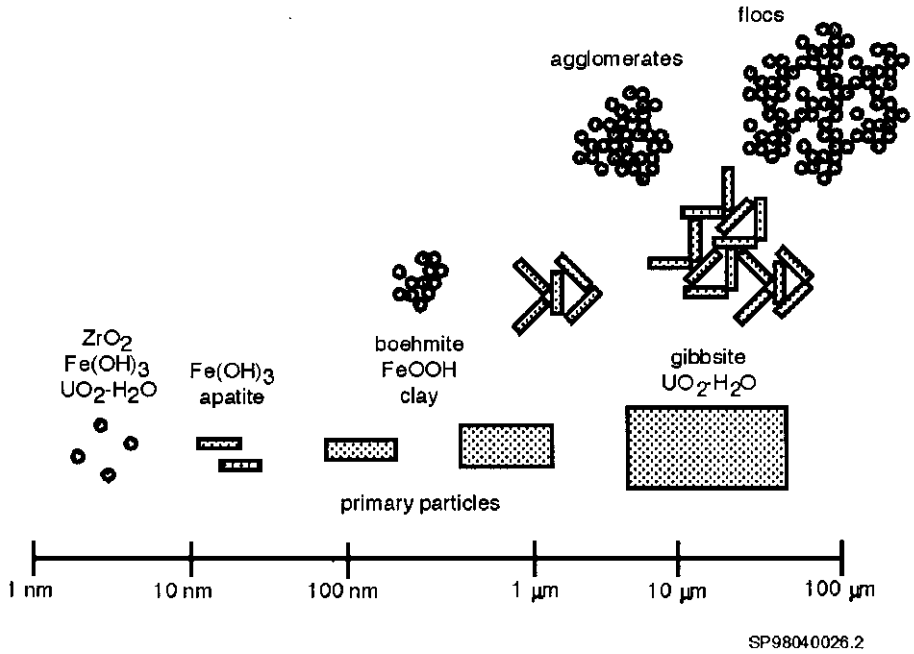
The particle size distribution recommended for use in the waste feed delivery transport system assessment is a mean distribution representing measurements made for seven HLW tanks under conditions of minimal agitation. The median size (50th percentile) of this distribution is 7.5 μm; the distribution is shown in Table 3-2 on the row labeled "Mean." The 95/95 tolerance limit distribution shown in Table 3-2 (95/95 TL) is also provided only as additional information.

4.0 PARTICLE DENSITY

4.1 AGGLOMERATION

The Hanford Site tank waste contains widely diverse solids, ranging from tiny primary particles, to agglomerates that may be quite diffuse in structure. The sizes of these particles may vary over five orders of magnitude, as shown diagrammatically in Figure 4-1. As shown in this figure, the smallest particles are many oxides and hydrous oxides, including ZrO_2 and FeOOH, whose diameters are in the 3 to 6 nm range. Other particles such as boehmite (AlOOH) and apatite are in the 0.1 to 1 μm size range. These submicron primary particles found in many HLW tanks form agglomerates typically 1 to 10 μm in size, but can reach 100 μm or more (Herting 1997, Bunker et al. 2000). Some of the largest primary particles are gibbsite ($Al(OH)_3$) and uranium phosphate, which can exceed 20 μm in size. Some agglomerates and flocs can be as large as hundreds of microns. Although many tank wastes contain both primary particles and agglomerates, many sludges consist of 1 to 10 μm agglomerates of submicron-sized primary particles (Herting 1997). This fact is confirmed by transmission election microscopy measurements of some tank wastes (e.g., Onishi et al. 1996).

Figure 4-1. Various Solids and Sizes in Hanford Tank Waste (Bunker et al. 2000)



The phenomenon of agglomeration is important to consider when recommending a particle density to be used as a design basis for a slurry transport system. Although the small dense primary particles in the waste may approach their theoretical mineral densities, the agglomerated

particles may have exceedingly low "effective" densities, corresponding to their diffuse or porous structure. This so-called "effective" density is important in determining how well a particle of a given overall diameter is carried along in the slurry.

As discussed in more detail in the appendix, agglomerates and flocs tend to be fractal objects. The volume fraction of primary particles, V_P within the agglomerate may be expressed as (Bunker et al. 2000)

$$V_P = \left(\frac{R}{r}\right)^{D-3} \tag{4-1}$$

where

D = fractal dimension
R = agglomerate size
r = primary particle size.

Experiments performed on synthetic slurries of typical minerals found in HLW assist in understanding particle behavior in actual wastes. For example, a boehmite agglomerate was found to have D = 1.8 to 2.2 (Bunker et al. 2000). With $R \approx 1.5$ μm and $r \approx 0.05$ μm, Equation 4-1 yields the boehmite volume fraction within the boehmite agglomerate to be $V_P = 0.017$ to 0.066. Therefore, the primary particles of boehmite occupy only 1.7 to 6.6 vol% of the boehmite agglomerate.

Although the concept of effective density is easy to describe, it is very difficult to measure in the Hanford Site waste slurries. Some of the difficulties involve the presence of dissolved solids in the interstitial solution and the fragility of the agglomerate structure. The most direct determination of density would involve measuring the mass and volume of the material. However, in the case of these agglomerate particles, measurements of both the mass and volume are confounded by the risk of destroying the structure of the particles when separating them from the surrounding liquid. An attempt to measure the effective density indirectly from settling rate measurements (Bechtold et al. 2002) was not successful, probably because the particles were broken up by the stirring action used to suspend them.

4.2 INPUT DATA

Because effective densities of HLW particles have not been directly measured, a conservative alternative is to use the densities of the "true" (dry-basis) solids, i.e., the density of the component particles of the agglomerates. The effective density of the agglomerated particles that actually exist in a moving waste stream is equal to the volume-weighted average density of the dry-basis solids and the interstitial liquor incorporated within them. As discussed above, the solid fraction of the agglomerates may be quite low. Therefore, the use of dry-basis densities in slurry flow calculations can be expected to yield very conservative estimates of head losses due to slurry flow.

Densities of the dry-basis solids have been calculated for eight HLW tanks. These densities are based on the mineral (dry-basis) compositions of the solids in eight HLW tanks, as estimated by the chemical equilibrium code ESP[3] using the "best-basis" analytical data (Tank Waste Information Network System [TWINS], http://twins.pnl.gov) as input (Orme et al. 2001). The major constituents of these compositions are shown in Table 4-1. The densities of these dry-basis solids were calculated as the weighted averages of the book-value densities of the compounds determined to be in the solids. These densities are given in Table 4-2.

Table 4-1. Major Constituents in the Dry-Basis Compositions of the Solids in Eight HLW Tanks

Compound	Tanks							
	AW-103	AY-101	AY-102	AZ-101	AZ-102	C-104	C-107	SY-102
$Al(OH)_3$	9.0	26.4	30.6	57.8	46.9	39.6	25.4	53.6
Bi_2O_3							5.9	
Cr_2O_3								9.2
$FeO(OH)$		27.9	37.4	26.1	33.6	7.5	17.5	7.3
$KAlSiO_4$					6.1			
$Mn(OH)_2$			8.2					
$Na_2C_2O_4$		13.7						
$Na_2U_2O_7$	11.4					12.1		
$Na_7F(PO_4)_2.19H_2O$							30.6	19.3
$NaAlCO_3(OH)_2$		9.3	15.1					
$NaAlSiO_4$		14.9				8.5	15.2	
NaF	36.5					9.4		
ZrO_2	36.4			7.3		14.9		

Table 4-2. Densities of Dry Solids Calculated for HLW Feeds, in g/mL

Tank	Density
AW-103	3.5
AY-101	2.9
AY-102	3.1
AZ-101	3.0
AZ-102	3.1
C-104	3.1
C-107	2.2
SY-102	2.3

[3] Environmenal Simulations Program (ESP) is a registered trademark of OLI Systems, Morris Plains, New Jersey.

4.3 METHOD OF ANALYSIS

The average of the solids densities in Table 4-2 is 2.9 g/mL, with a 95% confidence interval of 2.6 to 3.2 g/mL. Note that tank AW-103 lies outside this interval. The density of solids in this tank exceeds the other densities because of the great amount of zirconium (from fuel cladding) in this tank. An alternative calculation would be to weight the densities according to the mass of solids in each tank. This weighted average calculation also produces the same result – 2.9 g/mL. As a matter of interest, the 95/95-tolerance limit for the density of true dry solids in HLW tanks was calculated to be 3.9 g/mL.

4.4 ALTERNATIVE APPROACH

An alternative approach to estimate the effective density of the solids is through the use of known bulk physical properties of the waste (e.g., bulk sludge density before and after centrifugation and liquid density) and in-tank sludge conditions (e.g., porosity, solid volume fraction). These concepts are discussed in detail in the appendix.

Although there are some rigorous approaches to determine the agglomerate sizes and densities, as discussed in the appendix, there is neither enough data nor time to use these approaches for this evaluation. Therefore, the various combinations of the following equations were used to estimate solid densities and volume fractions for 10 HLW tanks: AZ-101, AZ-102, SY-102, AY-101, AY-102, AW-101, AW-102, C-104, C-106, and C-107. The solid densities obtained by these equations reflect the inclusion of interstitial liquid in the bulk, as is the case for agglomerated particles.

$$\rho_C = x\{(1-n)\rho_{CS} + n \cdot \rho_{CL}\} + (1-x)\rho_{CL} \quad \text{for centrifuged sludge} \qquad (4\text{-}2)$$

$$C_V = x(1-n) \qquad (4\text{-}3)$$

$$\rho_B = C_V \cdot \rho_S + (1-C_V)\rho_L \quad \text{for sludge} \qquad (4\text{-}4)$$

$$\frac{C_V \cdot \rho_S}{\rho_B} = y \quad \text{or} \quad \frac{(1-C_V)\rho_L}{\rho_B} = 1-y \quad \text{for sludge} \qquad (4\text{-}5)$$

where

- C_V = solid volume fraction of an in-tank sludge,
- n = porosity of the solid layer after the sludge is centrifuged and standing liquid decanted,
- x = volume fraction of the resulting solid layer after the sludge is centrifuged and standing liquid decanted,
- y = weight fraction of the solids within the sludge layer,
- ρ_B = bulk density of the sludge,
- ρ_C = bulk density of the sludge before it is centrifuged,

ρ_{CS} = solid density of the sludge after the sludge is centrifuged and standing liquid decanted,

ρ_{CL} = liquid density of the sludge after the sludge is centrifuged, and

ρ_S = density of solids in the sludge.

Measured values related to Equations 4-2 through 4-5 are shown in Table 4-3. Most of these measured values were obtained from tank characterization reports and the TWINS database; in addition, specific studies were previously performed to obtain these values for specific tanks such as AZ-101 and AZ-102. The appendix describes in detail how these equations were used to obtain the solid density value for each of these tanks.

Table 4-3. Measured Data for Ten Hanford HLW Tanks

Tanks	Sludge Bulk Density, ρ_B g/mL	Liquid Density, ρ_L g/mL	Weight Fraction of the Solid within Sludge, y	Solid Volume Fraction C_V	Solid Density, ρ_S g/mL	Centrifuged Sludge Density ρ_C g/mL	Centrifuged Liquid Density, ρ_{CL} g/mL	Sludge Volume Reduction Due to Centrifuge x
AZ-101	1.67 1.62	1.2 1.2				1.67 1.62	1.22 1.22	0.71 0.76
AZ-102	1.49	1.1				1.49	1.13	0.64
SY-102	1.56	1.03	0.605					
AY-101	1.59	1.0		0.657			1.14	
AY-102	1.4 1.4	1.0 0.99	0.456					
AW-103	1.43	1.00				1.75	1.0	0.97
AW-104	1.44	0.988						
C-104	1.46 to 1.97	1.10						
C-106	1.17	1.55			2.28			
C-107	1.17	1.44		0.662				

Table 4-4 summarizes estimated and measured physical properties of these 10 high-activity tank wastes, reflecting the agglomeration of the solids. The last column shows solid concentrations if all the waste (supernatant liquid and sludge/saltcake) in a tank is completely mixed. These are the highest possible pipeline concentrations of solids if the tank contents were retrieved without any in-tank or in-line dilution.

Table 4-4. Estimated Waste Physical Properties and Conditions

Tanks	Liquid Density, ρ_L g/mL	Solid Density, ρ_S g/mL	Solid Volume in Sludge, C_V vol%	Porosity in Sludge	Fully Mixed Solid Volume, C_{pipe} vol%
AZ-101	1.20	2.19	45.0	0.550	2.5
AZ-102	1.10	1.97	45	0.55	4.7
SY-102	1.25	2.24	32.5	0.675	3.7
AY-101	1.00	1.90	65.7	0.343	38.8
AY-102	0.99	2.68	23.8	0.762	6.90
AW-103	1.00	1.96	45.0	0.550	12.1
AW-104	0.988	1.99	45.0	0.550	34.2
C-104	1.10	3.11[a]	29.6	0.704	N/A[b]
C-106	1.17	2.28	34.2	0.658	N/A[b]
C-107	1.17	1.44	66.2	0.338	N/A[b]
Average	1.10	2.18	43.2	0.568	14.7

Notes:

[a] Weighted average of dry-basis particle density (see Table 4-2) because not enough physical data were available to calculate this value.

[b] Not applicable; these are single-shell tanks.

The average of the solid densities in this table is 2.2 g/mL, in comparison to the 2.9-g/mL value obtained from the dry-basis solids in Table 4-1.

4.5 SENSITIVITY ANALYSIS ON THE EFFECT OF SOLIDS DENSITY ON CRITICAL VELOCITY AND PRESSURE DROP FOR PIPELINE SLURRY FLOW

A brief sensitivity analysis was conducted to evaluate the effect of the solid density on the critical velocity and pressure drop of pipeline slurry flow. This analysis provides some assessment of the degree of conservativeness afforded by adopting a solid density of 2.9 g/mL, corresponding to the densities of the dry-basis solids.

For a slurry pipe flow moving at or above the critical velocity, all solids are suspended. The pressure drop of a slurry pipe flow is at a minimum at the critical velocity. Therefore, the slurry flow should be operated somewhat above this critical velocity to (i) avoid the potential pipe plugging due to the solid settling and (ii) transfer the slurry at close to the minimum pump requirement.

For this sensitivity analysis, six solid density values – 1.8, 2.2, 2.6, 2.9, 3.2 and 3.9 g/mL – were used. All other values required for the analysis were assigned to be representative of the HLW pipeline transfer conditions. Values used were: liquid density, 1.1 g/mL; liquid viscosity, 1.5 cP; solid sizes as given in the row labeled "Mean" in Table 3-2 (median size 7.5 μm); slurry viscosity calculated by the best estimate equation (Equation 5-12) described in Section 5.0; diameter of stainless steel pipeline, 3 inches; and solid volume fraction, 10 vol%. The critical velocity was estimated by means of both the Oroskar and Turian (1980) and the Wasp models

(Wasp et al. 1977), and the associated pressure drops at the critical velocities was obtained by the Wasp model (Wasp et al. 1977).

Calculated critical velocities and the associated pressure drops over one mile at these critical velocities for six solid densities are shown in Figures 4-2 and 4-3, respectively.

Figure 4-2. Variation of Critical Velocity with Solid Density

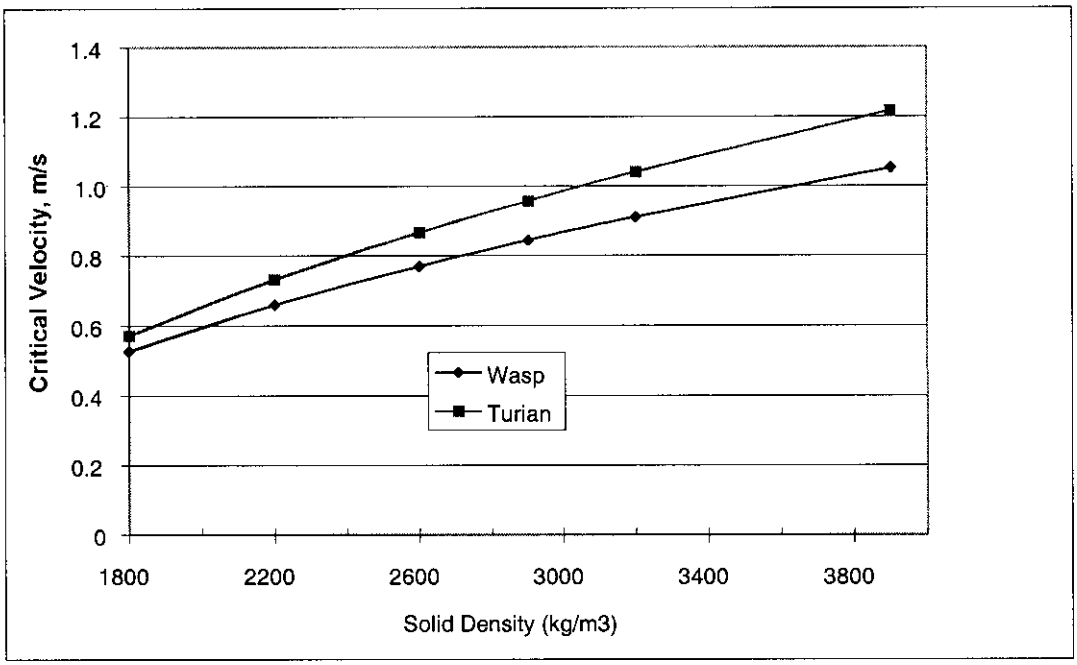
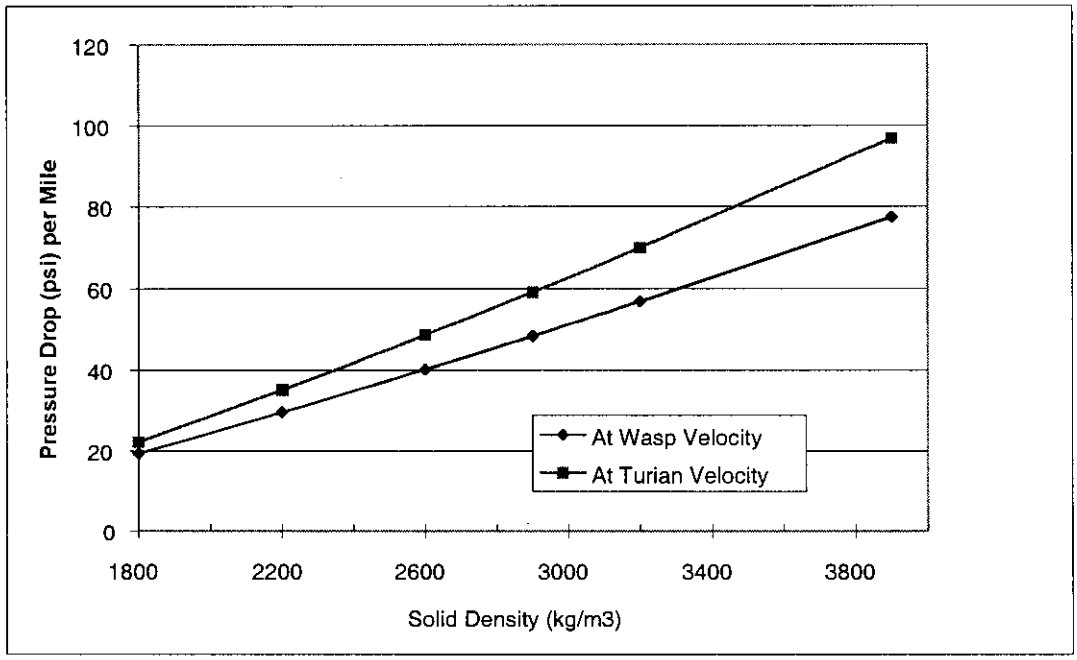


Figure 4-3. Variation of Pressure Drop with Solid Density



As shown in these figures, both critical velocity and pressure drop increase monotonically with the solid density. The critical velocity and associated pressure drop with 2.9-g/mL solid density are approximately 30 percent and 70 percent greater than those with 2.2-g/mL solid density. Therefore, the pressure drop with the weighted average of the true solid densities is 70 percent more conservative than that of the 2.2-g/mL solid density value that accounts for agglomeration. The critical velocity and associated pressure drop with 3.9-g/mL solid density are approximately 60 to 65 percent and 280 percent greater than those obtained with 2.2-g/mL solid density.

As described in the appendix, when the mass/volume fraction of solids (the product of the solid density and the volume fraction of solids) is held constant, the pressure drop at the required critical velocity increases with increasing density of solids and corresponding (and corresponding decrease of solid volume fraction). This is demonstrated in Figures A-2 and A-3 of the appendix). Therefore, selecting the greater solid density yields the greater pressure drop, resulting in the more conservative waste feed delivery assessment.

4.6 RESULTS (RECOMMENDATION)

The average of the dry-basis densities of the solids in eight HLW tanks, calculated to be 2.9 g/mL, is the value recommended for estimating pressure losses due to slurry flow. A sensitivity analysis indicates that this selection of the solid density results in conservatism of roughly 70 percent in calculating pipeline pressure drops. This conservatism arises because the value ignores the beneficial effect of agglomeration, which probably reduces the effective density of the solids to a value of around 2.2 g/mL. The 70 percent conservatism is not considered excessive, because the solid density is the least known waste property required for the pipeline transfer assessment.

5.0 SLURRY VISCOSITY

5.1 INPUT DATA

Viscosity measurements of HLW feed slurry samples have been obtained (Callaway 2000; O'Rourke 2001; Warrant 2001; Warrant 2002) for four HLW tanks – AY-101, AZ-101, C-104, and AZ-102. Data from three tanks, AY-101, AZ-101, and C-104, were used for this evaluation because the measurements for AZ-102 are quite recent, and solids concentration information was not yet available.

A rapid scan of the viscosity data shows that the measured values for sludge/slurry wastes in tanks AY-102 and AZ-101 are significantly lower than for those in tank C-104 at the higher solids loadings. (Some measurements for tank C-104 exceed 40 cP.) All viscosities measured for tank AY-102 and AZ-101 wastes are below 7 cP for strain rates between 100 and 200 s^{-1}, which are the expected strain rates for pipeline waste slurry flows of 3 to 6 ft/s. Some of these viscosity data are shown in Table 5-1. In Table 5-1, note that AY-102 viscosities are true viscosity values, while those of tanks AZ-101 and C-104 are apparent viscosity. Apparent viscosities are based on the assumption that the fluid flow is Newtonian; these values are equal to or higher than the true viscosities.

5.2 METHOD OF ANALYSIS

The laboratory reported the solids loading as "grams of dry solids per liter of slurry." The pipeline design calculations require the solids loading to be stated as volume fraction of solids. To convert from the reported units, the particles were assumed to have the density given in Table 4-1; for these tanks, the densities were all close to 3 g/mL. The volume fraction, C_V was therefore calculated as:

$$C_V = \frac{0.001\,C}{\rho_{solid}}\,, \tag{5-1}$$

where

C is the grams of dry solids per liter of slurry reported by the laboratory, and ρ_{solid} is the particle density from Table 4-2.

As an example, a tank AY-102 slurry was reported to have 210 g solids/L (See Table 5-1). The volume fraction of solids was calculated as:

$$C_V = \frac{(0.001)\,(210)}{3.095} = 0.0679 \tag{5-2}$$

This calculation was performed for each data point.

Table 5-1. Viscosity Measurements for Three HLW Feed Tanks

Tank	Viscosity (cP)	Solids Content (g/L)	Temperature (°C)	Tank	Viscosity (cP)	Solids Content (g/L)	Temperature (°C)
AY-102	1.78	0	27	C-104	7.9	200	45
AY-102	1.12	0	45	C-104	31.2	300	45
AY-102	0.32	0	65	C-104	23.5	620	45
AY-102	3.01	151.6	27	C-104	1.5	0	65
AY-102	1.73	151.6	45	C-104	1.3	60	65
AY-102	0.89	151.6	65	C-104	1.8	100	65
AY-102	2.29	75.8	27	C-104	3.7	140	65
AY-102	0.93	75.8	45	C-104	7.3	200	65
AY-102	1.06	75.8	65	C-104	32.5	300	65
AY-102	2.05	101	27	C-104	18.9	620	65
AY-102	1.19	101	45	AZ-101	2.25	0	27.7
AY-102	1.29	101	65	AZ-101	2.34	0	44.9
AY-102	3.64	210	27	AZ-101	1.66	0	64.9
AY-102	2.66	210	45	AZ-101	2.28	18.4	27.6
AY-102	1.73	210	65	AZ-101	1.97	18.4	44.9
AY-102	1.36	210	27	AZ-101	2.26	18.4	64.9
C-104	1.7	0	27	AZ-101	2.95	36.8	27.3
C-104	2.6	60	27	AZ-101	2.09	36.8	45.1
C-104	3.2	100	27	AZ-101	2.19	36.8	64.7
C-104	5.5	140	27	AZ-101	3.23	155	27.4
C-104	8	200	27	AZ-101	1.90	155	45.1
C-104	29.7	300	27	AZ-101	2.27	155	64.9
C-104	43.6	620	27	AZ-101	7.19	301	27.4
C-104	1.6	0	45	AZ-101	7.03	301	27.3
C-104	1.5	60	45	AZ-101	4.41	301	44.9
C-104	2.4	100	45	AZ-101	5.63	301	44.9
C-104	4.6	140	45	AZ-101	2.91	301	64.7

To transfer the slurry through a pipeline, the pipeline slurry flow must (i) be fast enough to suspend all solids, (ii) be a turbulent flow, and (iii) overcome the slurry's yield strength, if any. The viscosities of the liquid and slurry affect these three criteria in a somewhat contradictory way. For example, as the **liquid** viscosity decreases, the slurry velocity required to suspend all the solids increases (Oroskar and Turian 1980), but a greater **slurry** viscosity results in greater pipeline pressure drop to move the slurry (Wasp et al. 1977), if all other conditions are the same. Therefore, conservatism is assured by selecting the lower bound values for the **liquid** viscosity and upper bound for the **slurry** viscosity.

The slurry viscosity may be estimated by several different equations (Wasp et al. 1977). Einstein expressed the mixture viscosity of laminar slurry as

$$\mu_M = \mu_L(1 + 2.5C_V) \tag{5-3}$$

where μ_L is the liquid viscosity.

Equation 5-3 is not valid for solid concentrations much greater than 1 vol%. There are many formulas for more concentrated solid suspensions (e.g., Landel et al. 1963; Wasp et al. 1977), including those of the following polynomial expressions

$$\mu_M = \mu_L(1 + a_1C_V + a_2C_V^2 + a_3C_V^3 + a_4C_V^4 + ...) \tag{5-4}$$

where a_1, a_2, a_3, and a_4 are constants.

Thomas (1965) developed the following more commonly used expression by modifying the above Einstein formula:

$$\mu_M = \mu_L\{1 + 2.5C_V + 10.05C_V^2 + 0.00273\exp(16.6C_V)\} \tag{5-5}$$

The Wasp model (Wasp et al. 1997) uses the Einstein formula modified by Thomas (Equation 5-5) as a default, if no viscosity data are available. Because the slurry viscosity is a complex function of liquid viscosity, solid volume fraction, strain rate (if the slurry is non-Newtonian), temperature, slurry chemistry, etc, if slurry viscosity values for a specific application are available, it is better to use them than slurry viscosity values obtained from various equations discussed above. For example, the commonly used Thomas formula is known to under-estimate the slurry viscosity for solid concentrations of several vol% or higher (Ebadian et al. 2001, Onishi et al. 2002).

Furthermore, many Hanford Site sludge and saltcake wastes exhibit a shear-thinning, non-Newtonian behavior, showing the waste reduces its viscosity, as the strain rate increases (Gray et al. 1993, Stewart et al. 1996, Herting 1997). The effect of the strain rate becomes greater as the solid volume fraction increases. The temperature also affects viscosity, which generally is lower with higher temperature. Therefore, temperatures were originally used in the preliminary examination of the data. However, viscosity values shown in Table 5-1 do not always indicate this trend, possibly reflecting waste chemistry and some possible measuring errors. Furthermore, the temperature effect was not nearly as important as the volume fraction solids, strain rates, or tank-to-tank variation. Therefore, temperature variation was ignored.

The following slurry viscosity expression was formed by multiplying the Thomas formula format (but not his formula itself) by the strain rate γ:

$$\mu_M = \mu_L\{1 + aC_V + bC_V^2 + c\exp(dC_V)\} \cdot \gamma^n \tag{5-6}$$

where, μ_L, a, b, c, d, and n are parameters to be evaluated.

The liquid viscosity in this case ($C_V = 0$) is represented by $\mu_L(1+c)\gamma^n$. The following slightly modified format was also considered, where the liquid viscosity in this formula would be $\mu_L\gamma^n$:

$$\mu_M = \mu_L[1 + aC_V + bC_V^2 + c\{\exp(dC_V) - 1\}]\cdot\gamma^n \tag{5-7}$$

For the shear-thinning viscosity, n must be negative. For a turbulent pipe flow, the strain rate is expressed by (Wasp et al. 1977):

$$\gamma = \frac{8V}{D} \tag{5-8}$$

where,

D is the pipe diameter (in this study D = 3 inches) and
V is the slurry flow velocity.

Tanks C-104, AY-102, and AZ-101 have the most complete rheology data among tanks AW-103, AY-101, AY-102, SY-102, AZ-101, AZ-102, C-103, C-104, and C-107 data available in an electronic form (TWINS database). The viscosities of tank C-104 slurries are generally greater than those for the other two tanks for which data are available (see Table 5-1), with the largest difference being at the highest volume fractions. Because tank AY-102 and AZ-101 data in electronic forms were not available until near the end of this study, and tank C-104 data contain measured shear stress, strain rate, and solid volume fraction, the adequacy of Equations 5-6 and 5-7 formats was first tested with tank C-104 data to represent the slurry viscosity. With the measured shear stresses and strain rates, the apparent slurry viscosity (therefore, conservative viscosity values) was obtained by dividing the shear stress by the strain rates. Because the velocity of the waste slurry flow in 200-Area 3-inch pipelines is expected to be between 3 and 6 ft/s, the corresponding strain rates are 96 to 192 s^{-1} based on Equation 5-9. Therefore, viscosity data for only the strain rates between 100 and 200 s^{-1} were used.

The "Solver" feature in Microsoft Excel[4] was used to perform the regression to determine six parameters, μ_L, a, b, c, d, and n. After performing regression analysis for several different ways (allowing one to six of these parameters to be determined by the "Solver"), a value of 2.5 was assigned to the coefficient "a," because it has a relatively small impact on the slurry viscosity for most of the solid volume fraction range and is a part of the original Einstein equation. In addition, a value of 1.6 was selected for μ_L through a previously conducted preliminary regression analysis.

The solver was used to minimize the sum of the squares of the differences between the viscosity data and calculated viscosity based on Equations 5-6 or 5-7 with varying the parameters of b, c, d, and n. Equations 5-6 and 5-7 with the coefficients determined by the regression are shown in Equations 5-9 and 5-10. The regression analysis indicated that these two equations have

[4]EXCEL™ is a registered trademark of Microsoft, Redmond, Washington.

basically the same degree of fit. Note that the negative value of n in these equations provides the shear-thinning viscosity behavior.

$$\mu_M = 1.6(1 + 2.5C_V + 10.05C_V^2 + 21\exp 39C_V) \cdot \gamma^{-0.75} \tag{5-9}$$

and

$$\mu_M = 1.6[1 + 2.5C_V + 1890C_V^2 + 32\{\exp(35.8C_V) - 1\}] \cdot \gamma^{-0.766} \tag{5-10}$$

Comparison between the viscosity data and values calculated by Equations 5-9 and 5-10 is shown in Figures 5-1 and 5-2, respectively. These figures show reasonable agreement between data and calculated viscosity, with Equation 5-9 providing a slightly better agreement in lower solid volume fraction ranges of zero to 0.03. Therefore, Equation 5-9 was selected between these two equations. Equation 5-9 produces a liquid viscosity of 0.7 to 1.1 cP, representing a very low viscosity of HLW, when the solid volume fraction is set to zero and the strain rate is between 100 and 200 s^{-1}. In Figures 5-1 and 5-2, calculated values shown in two solid lines are with the fixed strain rates of 100 and 200 s^{-1}, but for the actual regression analysis, the measured viscosities at strain rates varying from 100 to 200 s^{-1} were used. This testing indicates that the forms of Equations 5-9 and 5-10 are adequate to represent the waste viscosity.

Figure 5-1. Viscosity Data for C-104 Waste and Calculated Values from Equation 5-9

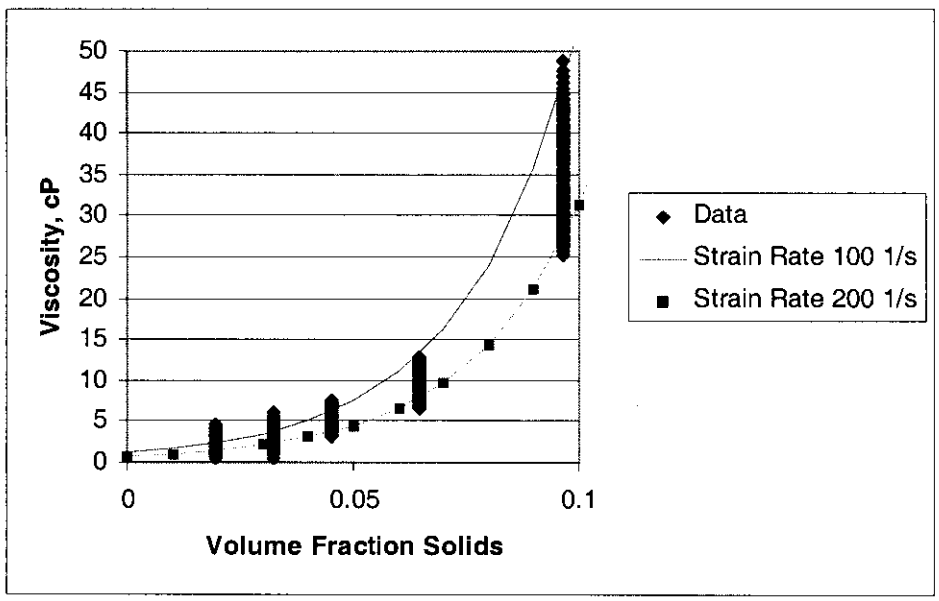
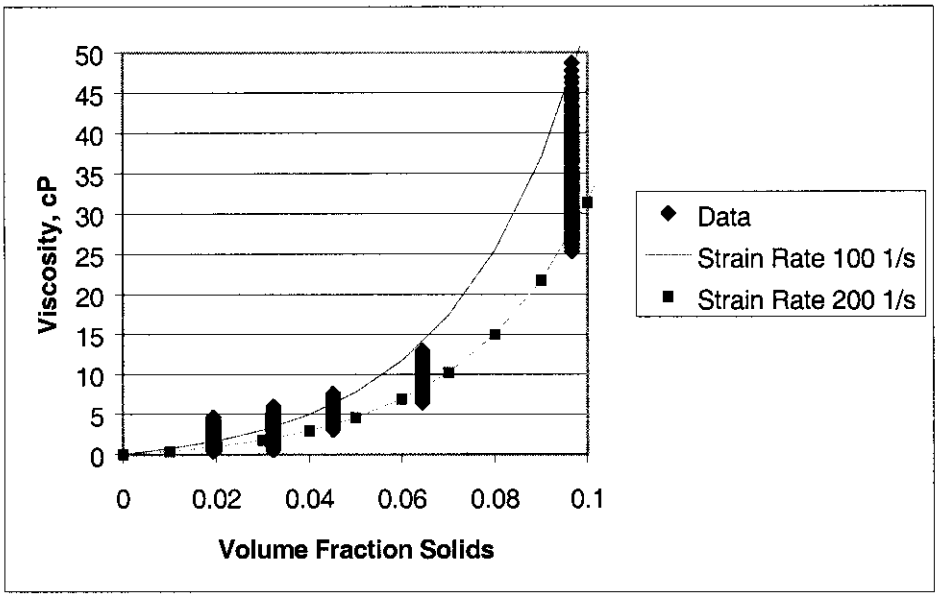


Figure 5-2. Viscosity Data for C-104 Waste and Calculated Values from Equation 5-10



These same viscosity equation forms were then used for all the data shown in Table 5-1 for three tanks (AY-102, AZ-101 and C-104), together with some representative viscosity values at 10 vol% and all C-104 data for solid volume fraction of 20 vol% for the strain rates of 100 to 200 s^{-1}. The C-104 viscosity values at up to 20 vol% were also used, because there was no basis to determine whether the viscosity values at 10 or 20 vol% solid volume fraction were more accurate. Because viscosity values shown in Table 5-1 were obtained over a range of 100 to 300 s^{-1} for tanks AZ-102 and C-104, and at varying strain rate for tank AY-102, a strain rate of 150 s^{-1} was assigned. For most tanks, when the strain rate is around 200 to 300 s^{-1}, the waste exhibits Newtonian behavior (constant viscosity), especially at low solid concentrations (Herting 1997). Values of a = 2.5 and $\mu_L = 2.0$ were assigned in the combined case of these three tank wastes. Because this case has widely divergent viscosity values for C-104 waste at 10 and 20 vol% solids (see Figures 5-3 and 5-4), the regression produced poor results. (The resulting equations predicted relatively constant viscosity values over the entire volume fraction range of 0 to 20 vol%.) Therefore, the regression analysis results for this case were not acceptable. Therefore, the coefficients b, c, d, and n were adjusted to achieve a visual fit.

Resulting slurry expressions are

$$\mu_M = 2.0\{1 + 2.5C_V + 10.05C_V^2 + 1.3\{\exp(17C_V)\}\cdot\gamma^{-0.06} \tag{5-11}$$

and

$$\mu_M = 2.0[1 + 2.5C_V + 10.05C_V^2 + 1.3\{\exp(17C_V) - 1\}]\cdot\gamma^{-0.06} \tag{5-12}$$

The negative value of n = -0.06 shows the weak shear-thinning viscosity behavior, as exhibited by many Hanford Site dilute slurries (Gray et al. 1993, Herting 1997). Figures 5-3 and 5-4 show the viscosity data and curves calculated by Equations 5-11 and 5-12. The two equations give basically the same fit, except Equation 5-12 fits better in the lower solid volume fraction range. These fits were judged reasonable, considering the between-tank differences. Therefore, Equation 5-12 is recommended for calculations of slurry viscosity. When the solid volume fraction is set to zero and the strain rate is between 100 and 200 s^{-1}, Equation 5-12 gives the liquid viscosity to be 1.5 cP, which is relatively low for HLW liquid viscosities.

Figure 5-3. Viscosity Data for C-104, AY-102, and AZ-101 Waste and Values Calculated with Equation 5-11

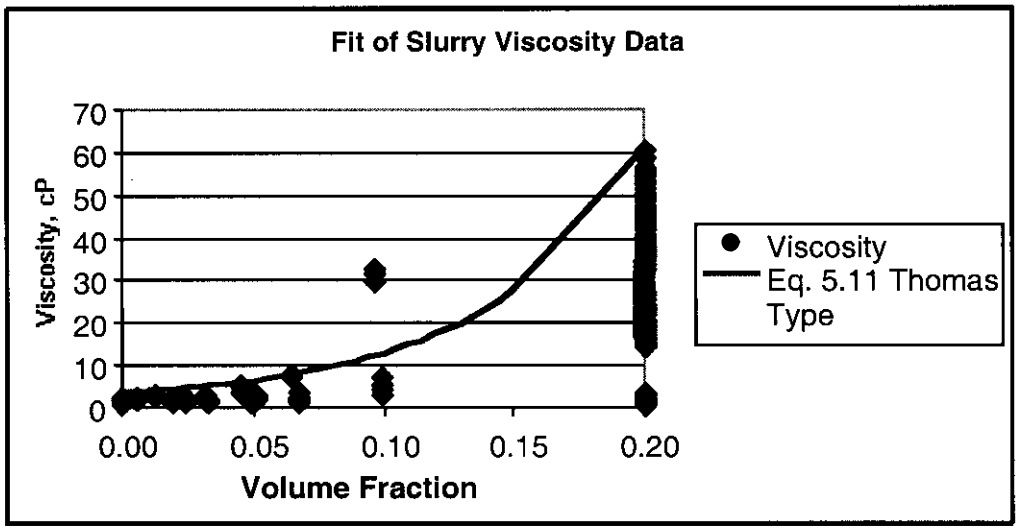
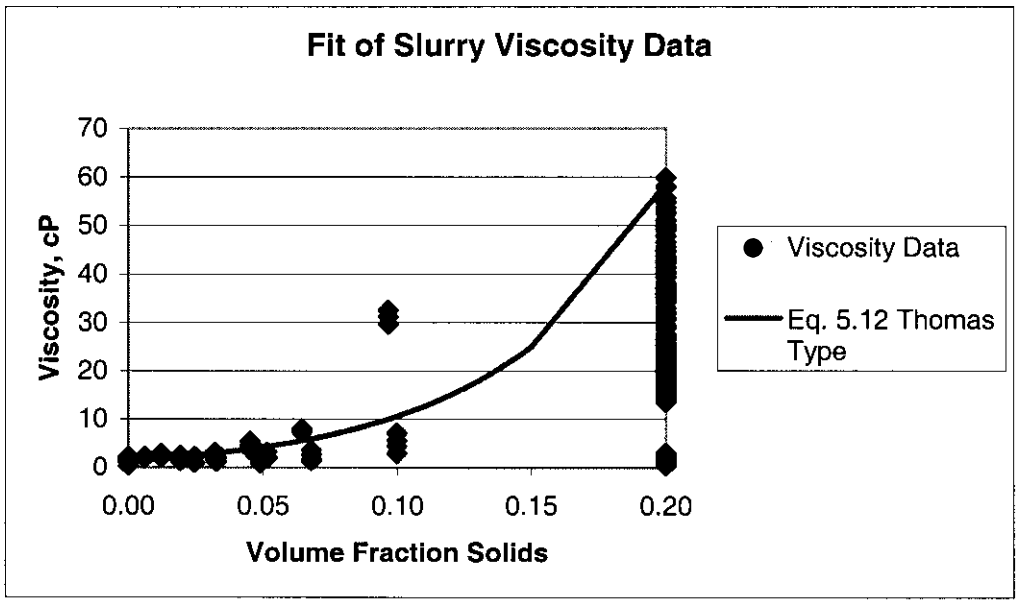


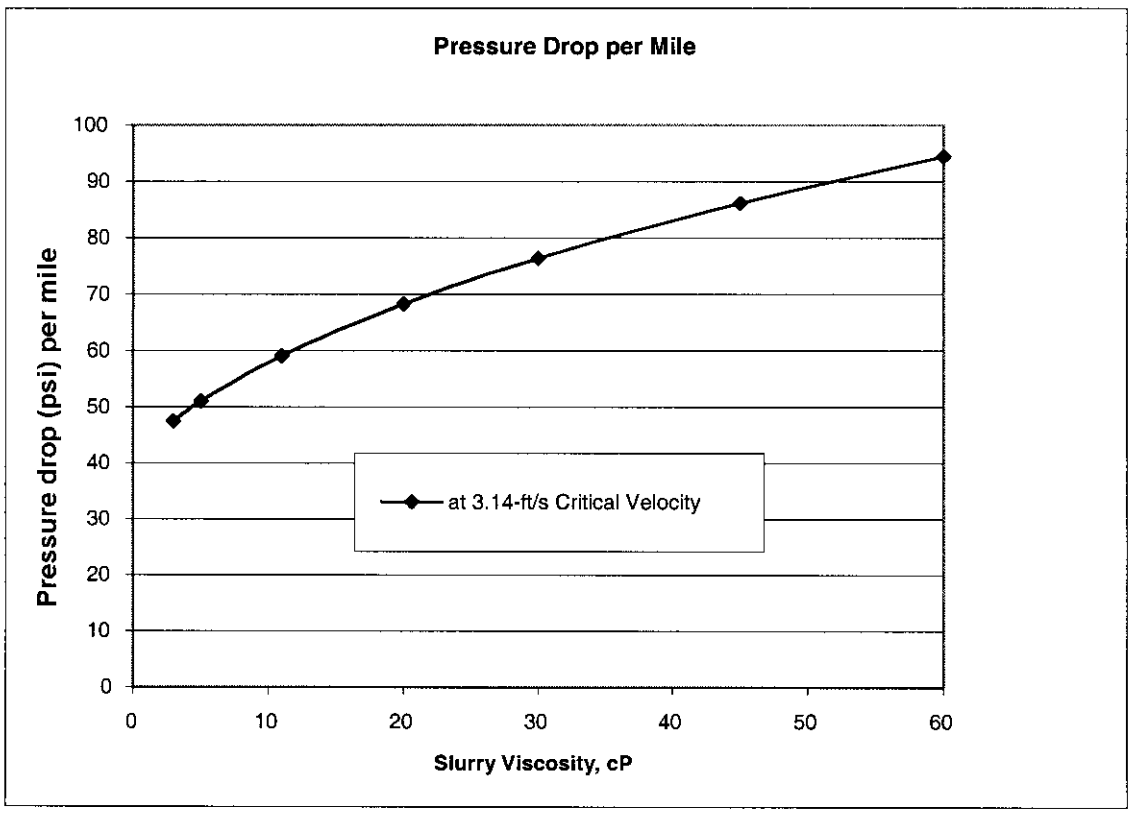
Figure 5-4. Viscosity Data for C-104, AY-102, AZ-101 Waste and Calculated Values with Equation 5-12



After tank AY-102 and tank AZ-101 rheology and other relevant data (shear stress, strain rates, apparent viscosity values, and solid volume fraction) became available in TWINS database (http://twins.pnl.gov) at the end of January 2002, scanning the viscosity columns shows that the all measured viscosities of tank AY-102 and tank AZ-101 sludge/slurry wastes are below 7 cP for the strain rates of between 100 and 200 s^{-1}; therefore, the use of Equations 5-12 and 5-9 are conservative, but still reasonable choice for tank AY-102 and tank AZ-101 wastes.

A sensitivity analysis was conducted for the effect of slurry viscosity on the pipeline pressure drop to validate the selection of Equations 5-9 and 5-12 for calculating the slurry viscosity. Seven cases were evaluated, with slurry viscosities ranging from 3 to 60 cP. Other values were assigned to be representative of the HLW pipeline transfer conditions: The liquid density was fixed at 1.1 g/mL, the liquid viscosity at 1.5 cP, the density of the solids at 2.9 g/mL, particle sizes at the "mean" distribution with median size 7.5 μm shown in Table 3-2, the stainless steel pipeline diameter at 3 inches, and the volume fraction of solids at 10 vol%. The critical velocity was estimated with the Oroskar and Turian model (1980) and the associated pressure drop at the critical velocity by the Wasp model (Wasp et al. 1977). The critical velocities for all these seven cases are independent of the slurry viscosity, and were calculated to be 3.14 ft/s.

Figure 5-5. Predicted Pressure Drop Variation with Slurry Viscosity



The associated pressure drops over one mile at this critical velocity are shown in Figure 5-5. As shown in this figure, the pressure drop increases monotonically with the slurry viscosity. Equation 5-12 yields the slurry viscosity to be 11 cP for under the conditions listed above, while Equation 5-9 yields 53 cP. However, most of the viscosities measured for tank AY-102 and tank AZ-101 data show the slurry to be less than 5 cP. Therefore, using Figure 5-5, it is apparent that Equations 5-12 and 5-9 over-estimate the pressure drop by roughly 15 and 75 percent, respectively. Moreover, these predicted slurry viscosity values are based mostly on the apparent viscosity instead of true viscosity; therefore, additional conservativeness is built in even by using Equation 5-12 for the slurry viscosity calculations. (Note that the slurry flow will be laminar above a slurry viscosity of 40 cP under these conditions. Therefore, for viscosities above 40 cP, the flow rate would have to be increased to achieve turbulent flow, resulting in an even higher pressure drop).

5.3 RESULTS

The recommendation is to use Equation 5-12 for the slurry viscosity.

$$\mu_M = 2.0[1 + 2.5C_V + 10.05C_V^2 + 1.3\{\exp(17C_V) - 1\}] \cdot \gamma^{-0.06} \qquad (5\text{-}12)$$

Equation 5-9 may be used as an upper bound for slurry viscosity.

5.4 DISCUSSION OF LIMITATIONS

The viscosity correlations presented above have some weaknesses. One weakness is the relatively small number of tanks for which viscosities have been obtained for various defined solids loadings. Data for additional tanks would improve the certainty of the final correlation. Furthermore, most viscosity values used in this evaluation were "apparent" viscosity and are equal to or greater than the true viscosity of the slurry.

The analysis is also weakened because of the assumption that had to be made about the particle density. An assumed particle density of 3 g/mL was used to make the conversion from the laboratory-supplied solids concentration in g/L to volume percent solids. Volume fraction of solids, although required for the slurry flow calculations in RPP-5346 (Julyk et al. 2001), is a quantity virtually unmeasurable by laboratory methods, because of experimental difficulties involved with interstitial solids and voids in agglomerate particles. If 2 g/mL were used for the particle density, all the volume fractions would be calculated to 50 percent larger.

Certain aspects of the basic data from the laboratory should be pointed out. These limit the range of observed measurements. The viscosity measurements are done with a device that measures the torque required to turn a cylindrical spindle centered in a close-fitting cylindrical cup containing the waste. One laboratory report (Bechtold et al. 2002) remarks: "Operation at very low shear stress accentuates the artificial effects of mechanical torque signal measurements; including nonzero shear stress versus shear rate intercepts and thereby, distorted apparent

viscosities at low shear stress." Essentially, this means that measurements of samples with low viscosities are questionable.

Another measurement issue has to do with suspension of the solids. The viscosity measurement requires laminar flow in the annulus between the spindle and the cup. Without turbulence (e.g., eddies), there is no mechanism to keep the solids suspended. The measurement will be biased if solids settle out of the measuring zone during the measurement. The viscosity would in effect be measured at a solids concentration less than the expected concentration. The analysts are aware of this effect; therefore, the measurements are made as quickly as possible. However, some time must be allowed to bring the sample to the desired temperature.

The viscosity measurements have been performed under the "Tank T, Batch X" DQO (Data Quality Objective). This DQO states that the limit for the viscosity is 10 cP. The implication is that any value under 10 cP is acceptable and only values greater than that are problematic (Nguyen 1999). The laboratory chose an instrument that was a compromise between the desired accuracy and ease of operation in a hot cell. The instrument may not give good values at low viscosities (<10 cP) but the implication is that only values >10 cP will be a problem. This instrument seems to work well on those thicker slurries. If there is a need for greater accuracy in the lower values of viscosity, then the DQO needs to be amended and a different instrument may be required.

It should be pointed out that, among tanks AY-102, AZ-101, and C-104, only tank C-104 wastes had viscosities greater than 10 cP, and then only in the higher solids range. If required, this high viscosity could be reduced by dilution of the slurry.

6.0 CONCLUSIONS

Input values for particle size, particle density, and slurry viscosity have been recommended for calculations to support the design of piping systems for the transport of high-level waste slurries.

For particle size, the recommendation is to use a mean particle distribution of particles in a minimally agitated condition, with the median value of 7.5 μm. The 95/95 tolerance limit, with the median value of 22 μm, was also calculated. Although not recommended for the Waste Feed Delivery System analysis, the 95/95 tolerance limit distribution serves as an extreme upper bound for the sizes (during transport) of waste particles from any given waste tank.

For particle density, in the absence of direct measurements of the agglomerated solid density, the value 2.9 g/mL is recommended. This value is conservative because it corresponds to the density of completely solid particles, without the voids expected in agglomerate particles. The 95/95 tolerance limit representing the upper bound of density for the particles in any particular waste tank was calculated as 3.9 g/mL; this tolerance limit is not recommended because of its excessive conservatism. A solid density of 2.2 g/mL was also derived from bulk solids measurements; this value was rejected because it lacks conservatism.

For slurry viscosity, the non-linear relationship of undissolved solid concentration, strain rate, and liquid viscosity expressed by Equation 5-12 is recommended as the best estimate. This relationship is

$$\mu_M = 2.0[1 + 2.5C_V + 10.05C_V^2 + 1.3\{\exp(17C_V) - 1\}] \cdot \gamma^{-0.06} \tag{5-12}$$

Equation 5-9 is also provided as an upper bound. These slurry calculations must be regarded as rough guides, because of the apparently wide variation of the data and the relatively small number of tanks for which measurements have been made.

7.0 OPEN ITEMS/RECOMMENDATIONS

An understanding of waste physical properties is important for reliable waste transfers. The waste property values recommended here (the mean particle sizes, conservative solid density of 2.9 g/mL, and the realistic, but still somewhat conservative Equation 5-12 for the slurry viscosity) are expected to yield pipeline pressure drops roughly two times higher than pressure drops estimated with realistic waste property values. Although this over-estimate is appropriate for use as a design basis, there will be a continuing need to predict pipeline pressure drops to develop precise plans for each slurry transfer. As information from future waste samples accumulates and as simulant testing and theoretical studies continue, it may become possible to revise these values.

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APPENDIX A

SOLID DENSITIES AND VOLUME FRACTIONS OF HANFORD HIGH-LEVEL WASTE

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SOLID DENSITIES AND VOLUME FRACTIONS OF HANFORD HIGH-LEVEL WASTE

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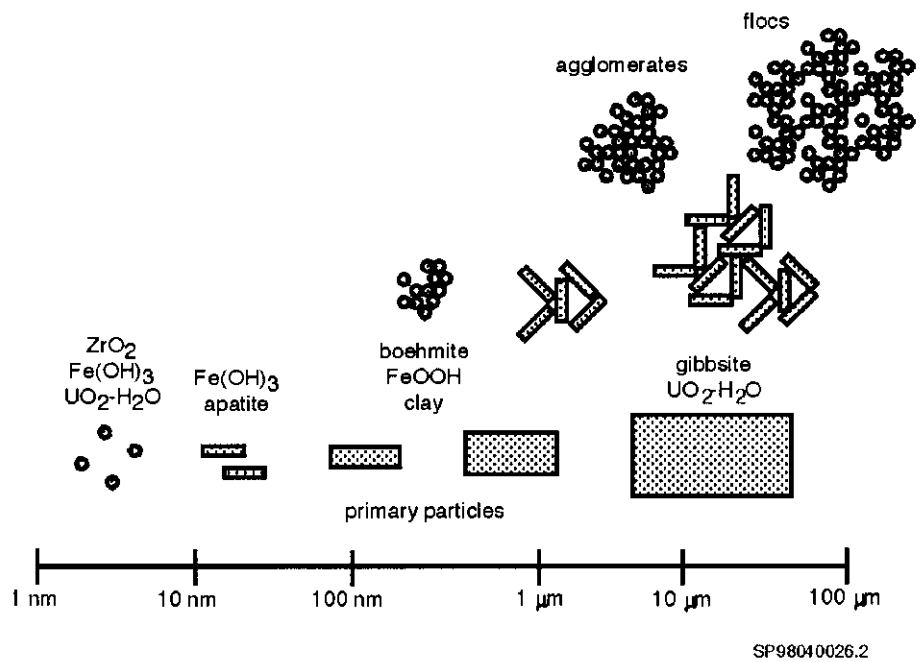
A.1.0 APPROACH

This appendix describes an alternative way to the weighted average of the densities of true solids to estimate the solid densities and volume fractions in the sludges of 10 high-level waste (HLW) tanks: 241-AZ-101, AZ-102, SY-102, AY-101, AY-102, AW-103, AW-104, C-104, C-106, and C-107. In general, only particle sizes and some slurry viscosity were measured directly, as discussed in Sections 3.0 and 5.0. Therefore, the solid density and volume fraction had to be determined indirectly. The solid density, and volume fraction of the sludge affect the critical velocity and associated pressure drop of a slurry pipe flow. Therefore, it is important that selected values of these two properties be consistent with the particle sizes, ranging from several microns to tens and hundreds of microns (See Tables 3-1 and 3-2).

The alternative approach is to account for the solid agglomeration to determine the solid density with the measured waste physical properties (e.g., liquid waste density, bulk sludge density) and sludge conditions (e.g., in-tank sludge porosity). Because there were only a few weeks to estimate these solid density values, the tank characterization reports of these ten tanks were used plus some other specific reports that were readily available. Therefore, this evaluation is not based on an in-depth study with all available data, nor were specific waste measurements conducted for this purpose.

The Hanford Site tank waste contains widely varying solids from primary true particles to agglomerates, with sizes varying five orders of magnitude, as an example shown in Figure A-1. As shown in this figure, the smallest particles are many hydrous oxides, including ZrO_2 and FeOOH, whose diameters are 3 to 6 nm. Other particles such as boehmite (AlOOH) and apatite are in 0.1 to1 μm in size. These submicron primary particles found in many HLW tanks form agglomerates typically 1 to10 μm in size but can reach 100 μm or more (Bunker et al. 2000). Some of the largest primary particles are gibbsite ($Al(OH)_3$) and uranium phosphate, which can exceed 20 μm in size. Agglomerates and flocs can be as large as hundreds of microns. Although many tank wastes contain both primary particles and agglomerates, most sludges consist of 1 to 10 μm agglomerates of submicron primary particles (Herting 1997). This fact is confirmed by transmission election microscopy measurements of some tank wastes (e.g., Onishi et al. 1996).

Figure A-1. Various Solids and Sizes in Hanford Tank Waste (Bunker et al. 2000)



The densities and sizes of primary particles [e.g., $Fe(OH)_3$, AlOOH, and $Al(OH)_3$] are known (CRC 1995), but not for those of agglomerates. Agglomerates and flocs tend to be fractal objects. The volume fraction of primary particles, V_P within agglomerate may be expressed as (Bunker et al. 2000):

$$V_P = \left(\frac{R}{r}\right)^{D-3} \tag{A-1}$$

where

D = fractal dimension
R = agglomerate size
r = primary particle size.

If a solid is a primary particle, D = 3.0. For a diffusion-limited agglomerate, D = 1.8 (Weitz et al. 1985). For example, a boehmite agglomerate has D = 1.8 to 2.2. With $R \approx 1.5$ µm and $r \approx 0.05$ µm, Equation A-1 yields the boehmite volume fraction within the boehmite agglomerate to be $V_P = 0.017$ to 0.066. Therefore, the primary particles of boehmite occupy only 1.7 to 6.6 vol% of the boehmite agglomerate.

As indicated by this boehmite example, agglomerate sizes are larger than primary particles making up these agglomerates and flocs; therefore, agglomerate densities are smaller than the true solid density. Therefore, the weighted average of primary particles in agglomerates and flocs provide the upper limits of the agglomerate densities.

The agglomerate densities and sizes are waste-specific and cannot be directly determined solely from known compositions of the primary particles. For example, the actual agglomerate size, R also depends on the force acting on the agglomerate particle, e.g., breaking up agglomerates and flocs in a moving slurry (Sontagg and Russel 1987). Bunker et al. (2000) express the size of agglomerate undergoing the stress as

$$R = b\gamma^{\frac{(D-1)}{2p(D-3)}} \tag{A-2}$$

where

b = constant

p = constant inversely proportional to the shear strength of the agglomerate

γ = strain (shear) rate.

For D=2.2, p = 4.5 (a typical value), for example, Equation A-2 becomes

$$R = b\gamma^{-0.17} \tag{A-3}$$

Therefore, imposing 100 times more strain (shear) rate on an agglomerate reduces its size by 2.2 times (e.g., a 10-μm agglomerate becomes a 4.6 μm agglomerate) after undergoing 100 times greater strain (shear) rate.

These evaluations indicate that there is a need to account for the agglomeration to estimate the solid density and solid volume fraction of the sludge. Although there are some rigorous approaches to determine the agglomerate sizes and densities, as briefly discussed above, there are neither enough data nor time to use these approaches for this evaluation. Bulk sludge density, which consists of solids and interstitial solution in the sludge, has been measured for most of the tanks. Therefore, measured bulk waste property values were used to determine densities and volume fractions of the solids whose sizes are microns to tens and hundreds of microns (See Tables 3-1 and 3-2).

Various combinations of the following equations were used to determine the potential solid densities and in-tank solid volume fractions for 10 HLW tanks: AZ-101, AZ-102, SY-102, AY-101, AY-102, AW-101, AW-102, C-104, C-106, and C-107. The solid densities obtained by these equations with available data are still estimates, rather than the exact solid densities.

$$\rho_C = x\{(1-n)\rho_{CS} + n \cdot \rho_{CL}\} + (1-x)\rho_{CL} \quad \text{for centrifuged sludge} \tag{A-4}$$

$$C_V = x(1-n) \tag{A-5}$$

$$\rho_B = C_V \cdot \rho_S + (1-C_V)\rho_L \quad \text{for sludge} \tag{A-6}$$

$$\frac{C_V \cdot \rho_S}{\rho_B} = y \quad \text{or} \quad \frac{(1-C_V)\rho_L}{\rho_B} = 1-y \quad \text{for sludge} \tag{A-7}$$

where

C_V = solid volume fraction of a in-tank sludge

n = porosity of the solid layer after the sludge is centrifuged and standing liquid is decanted

x = volume fraction of the resulting solid layer after the sludge is centrifuged and standing liquid is decanted

y = weight fraction of the solids within the sludge layer

ρ_B = bulk density of the sludge

ρ_C = bulk density of the sludge before it is centrifuged

ρ_{CS} = solid density of the sludge after the sludge is centrifuged and standing liquid is decanted

ρ_{CL} = liquid density of the sludge after the sludge is centrifuged and standing liquid is decanted

ρ_S = density of solids in the sludge.

Equation A-6 and A-7 yield the following equations:

$$\rho_S = \frac{y \cdot \rho_B \cdot \rho_L}{\rho_L + y\rho_B - \rho_B} \tag{A-8}$$

$$C_V = 1 - \frac{(1-y)\rho_B}{\rho_L} \tag{A-9}$$

on the condition of

$$y > 1 - \frac{\rho_L}{\rho_B} \tag{A-10}$$

Therefore, Equations A-6 and A-7 can be used together only if Equation A-10 is satisfied.

Equations A-4 through A-6 are not necessary to provide definite solid densities and associated volume fractions, and in some cases they were used to confirm the reasonableness of estimated densities and volume fractions.

A.2.0 SOME CONSIDERATIONS ON SOLID DENSITY AND SLUDGE POROSITY

This section describes how sensitive the slurry pipe flow's critical velocity and pressure drop are to the solid density and solid volume fraction. The critical velocity is the velocity above which all the solids will be suspended during the pipeline transfer. Because the pressure drop of the slurry pipe flow is at minimum at the critical velocity, the slurry flow should be operated somewhat above this critical velocity to (1) avoid the potential pipe plugging due to the solid settling and (2) transfer the slurry at close to the minimum pump requirement.

This section will also present potentially suitable values of porosity (therefore, the solid volume fraction) of sludge based on the single-shell tank waste measurements, in light of the solid density/volume fraction sensitivity on the pipe flow velocity and pressure.

A.2.1 SENSITIVITY OF PIPELINE CRITICAL VELOCITY AND PRESSURE DROP ON SOLID DENSITY AND VOLUME FRACTION

A preliminary sensitivity analysis was performed to evaluate the solid density and volume fraction effects on the critical velocity and associated pressure drops for slurry pipe flows carrying the same mass (the product of the solid density and solid volume fraction). Six test cases were used in this analysis. The solid densities and solid volume fractions for these cases are given in Table A-1. Case 4 represents the reference case with the solid density of 2.9 g/mL and solid concentration of 7 vol%. The liquid viscosities and densities were assigned to be 1.5 cP and 1.1 g/mL, respectively, for all six cases. These are representative values for HLW (Waters et al. 1991; Gray et al. 1993; Ryan 1995a, 1995b; Onishi et al. 1996). Both the Oroskar and Turian (1980) and Wasp models (Wasp et al. 1977) were used to calculate the critical velocities. The Wasp model was used to estimate the pressure drops at the critical velocities determined by these models.

The slurry viscosity was calculated by the best estimate equation (Equation 5-12) described in Section 5.0. The solid particle sizes for all cases were assigned as the mean size distribution with the median size of 7.5 μm (See Table 3-2). Note that the slurry viscosity varied both with the solid volume fraction and with the pipe flow velocity (therefore, with the strain rate). Viscosity varied from 4.5 cP for Case 1 (the 1.8 g/mL case) to 14 cP for Case 6 (the 3.9 g/mL case).

Table A-1. Preliminary Sensitivity Analysis of Waste Pipeline Transfer

Test cases	Solid Density g/mL	Solid Concentration vol%
1	1.8	11.28
2	2.2	9.23
3	2.6	7.81
4	2.9	7.00
5	3.2	6.34
6	3.9	5.21

Estimated critical velocity and associated pressure drop are shown in Figures A-2 and A-3. These figures indicate that the larger the solid density, the greater the critical velocity and pressure drop to transport the same mass of solids. The required critical velocity and pressure drop are about 20 to 25 percent more for the solid density of 2.9 g/mL than those for 2.2 g/mL are. Therefore, if we select the greater solid density, the waste pipeline transfer assessment would produce conservative results.

Figure A-2. Estimated Critical Velocities

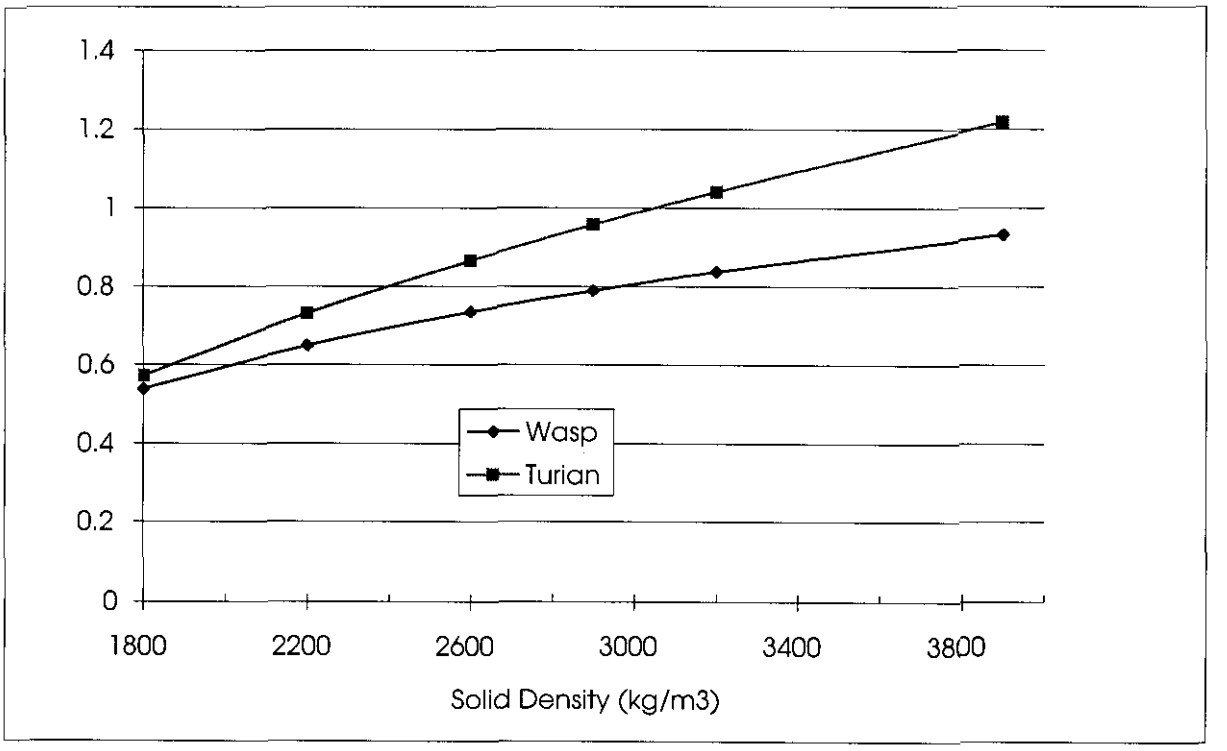
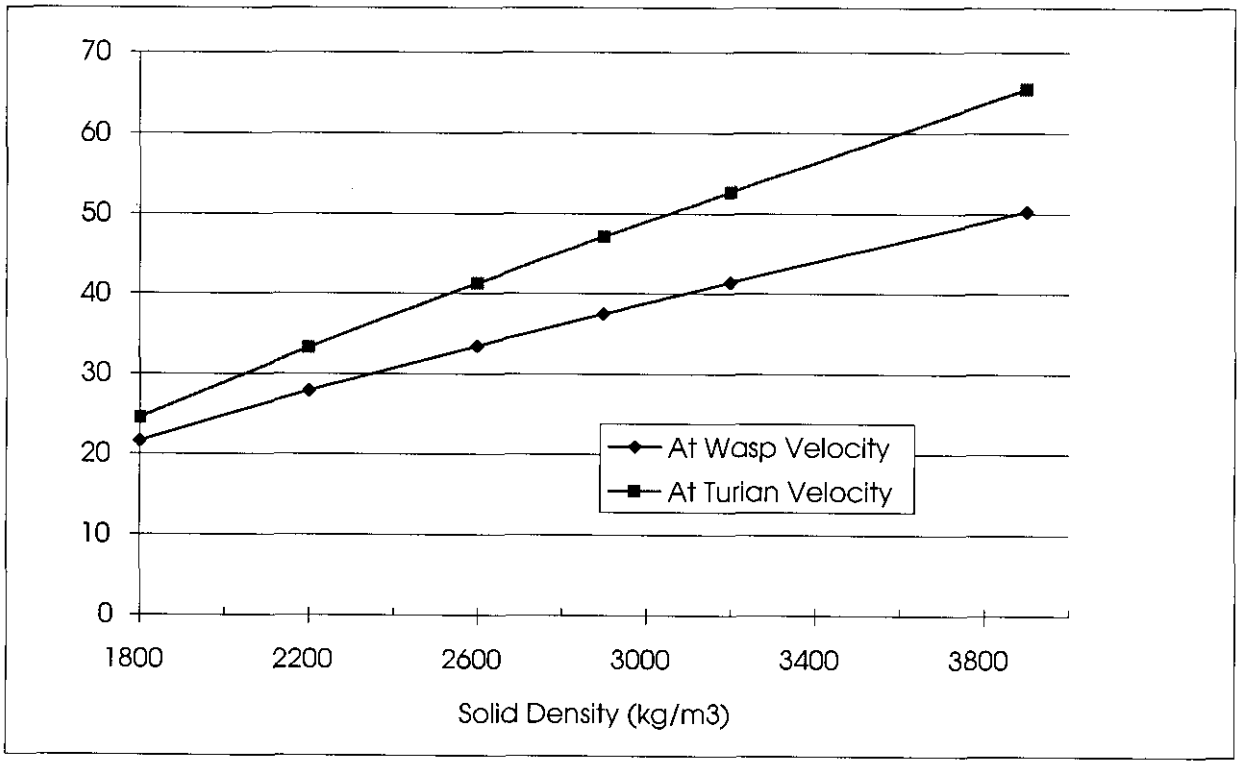


Figure A-3. Estimated Pressure Drops

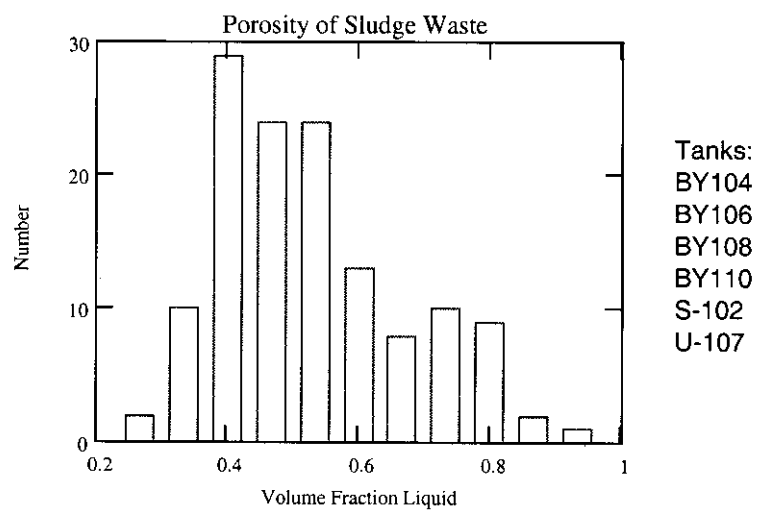


A.2.2 POROSITY OF THE SLUDGE

One of the key parameters to determine the solid density in this alternative approach is the porosity (and, therefore, the solid volume fraction) of the sludge, because the density of the bulk sludge (consisting of solids and interstitial solution) is most commonly measured for the Hanford Site tank wastes (see Equation A-6). Unfortunately, there are no systematic studies on the porosity of double-shell tank (DST) waste, but there were some studies conducted for the porosity of the single-shell tank (SST) waste. Therefore, even though many of these SST waste data may not be directly applicable to these 10 HLWs, available SST waste data were used to obtain some insight for potential values of porosity (therefore, the solid volume fraction) needed to estimate the solid density (See Equations A-4 through A-7).

Simmons (1995, 1996) evaluated porosity of various SST waste to determine moisture distributions in the sludge and saltcake, as well as salt-well pumping efficiency. Analyzing BY-104, BY-106, BY-108, BY-110, S-102, and U-107 of SSTs, Simmons (1998a) also reported porosity (actual porosity not the drainable porosity) of sludge in these six tanks, as the number of occurrence of a specific porosity value shown in Figure A-4. As shown in Figure A-4, the average porosity of the sludge of these six SSTs is 0.494, and the porosity of 0.4 to 0.55 contains about 60 percent of the all porosity values.

Figure A-4. Porosity for Sludge Waste for Six SSTs (Simmons 1998a)
(Volume Fraction Liquid = Porosity For Saturated Waste)



Simmons (1998b) also reported the porosities (both actual and drainable porosities) of the saltcake in these six tanks, as shown in Figures A-5 and A-6. Because not all the interstitial liquid would be drained (pumped out), the drainable porosity is smaller than the actual porosity in the sludge. The (actual) porosity averages 0.386 (Figure A-5), while the drainable porosity of these six SSTs averages 0.243 (Figure A-6). Therefore, the average difference between the actual and drainable porosity for the saltcake is 0.143 (= 0.386 – 0.243). Simmons' study also indicates that the porosity of the sludge, on average, is greater than the saltcake porosity by 0.11 (= 0.494 – 0.386).

Figure A-5. Porosity For Saltcake Waste For Six SSTs (Simmons 1998a) (Volume Fraction Liquid Equals Porosity For Saturated Waste)

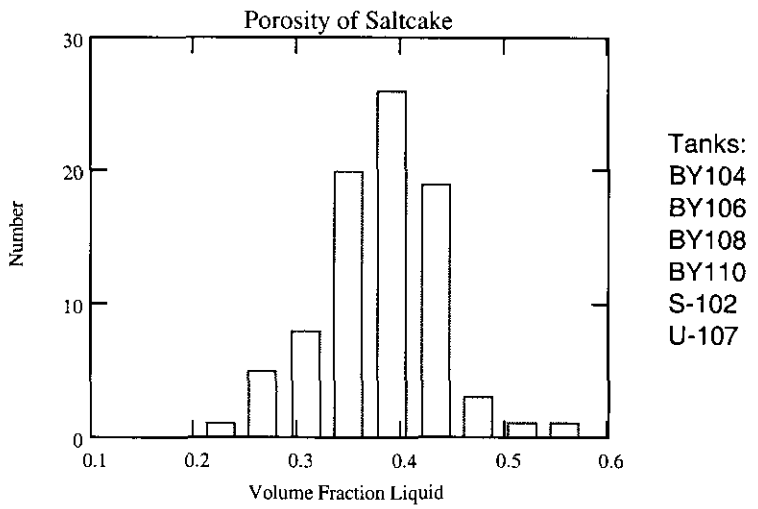
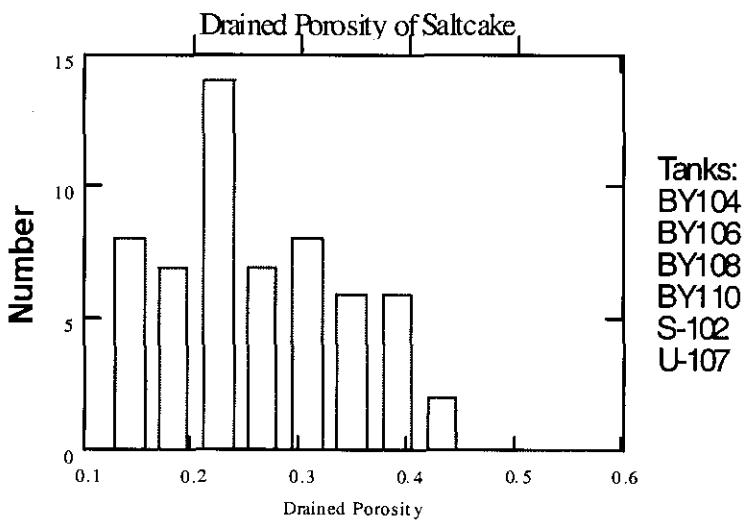


Figure A-6. Drainable Porosity, the Volume Fraction of Liquid that Has Drained, of Saltcake Waste (Simmons 1998a)



Simmons (1998b) and DeWeese (1988) also evaluated many more BY and TX SST tanks. Estimated drainable porosities for 22 BY and TX tanks are presented in Table A-2. Group 1 tanks represent waste with very slow decline of interstitial solution levels, while Group 2 tanks are those with much faster liquid level decline during saltwell pumping. The drainable porosity varies from 0.13 to 0.45, with an average of 0.30. As stated above, not all interstitial solution would be drained (pumped out); therefore, the actual porosity is greater than the drainable porosity. Simmons (1998b) estimated that actual porosities of the Groups 1 and 2 tank wastes are 0.43 and 0.455, respectively. As indicated in Figures A-5 and A-6, the difference between the actual and drainable porosities of the saltcake is estimated to be 0.143. Therefore, the actual porosities of Groups 1 and 2 may be estimated as 0.473 (= 0.33 + 0.143) and 0.443 (=0.30 + 0.143), respectively, if we assume that the actual and drainable porosity difference (0.143) for the saltcake also holds for these cases. These estimates (0.473 and 0.443) are close to values (0.43 and 0.455) obtained by Simmons, indicating these porosity evaluations appear to be valid.

Fort (2000) also evaluated drainable porosity for the saltcake and sludge of tanks BX-107, BX-112, C-102, C-107, C-110, T-107, TY-101, and TY-105. He reported that the drainable porosity of the SST sludge waste varies from 0.07 to 0.2, averaging 0.15. He reported the drainable porosity for C-107 sludge as 0.18. For saltcakes, the drainable porosity varies from 0.13 to 0.47 with an average of 0.25. Using 0.143 as the difference between the actual and drainable porosities, the actual porosity of the saltcake may vary from 0.273 to 0.613 with an average of 0.393, very close to the 0.386 shown in Figure A-5. Therefore, Simmons' (1998b) results are basically consistent with Fort (2000), DeWeese (1988), and the analyses in the Simmons (1998a) memorandum.

The natural soil has a porosity of 0.2 to 0.4 and a solid volume fraction of 0.6 to 0.8 because of its widely varying sizes and shapes and possibly to the long-term pressure imposed on it. Single-size spheres can have a maximum porosity of 0.47; therefore, $C_V \geq 1 - 0.47 = 0.53$. The porosity of random packing of hard spheres is 0.37; therefore, $C_V = 0.63$. These values are also consistent with Simmons (1998a) results.

Table A-2. Estimated Drainable Porosity of Some BY and TX Single-Shell Tanks (Simmons 1998a)

Tanks	Drainable Porosity
Group 1	
241-BY-104	0.34
241-BY-107	0.32
241-BY-108	0.23
241-BY-110	0.42
241-BY-111	0.37
241-BY-112	0.38
241-TX-102	0.36
241-TX-103	0.25
241-TX-106	0.41
241-TX-108	0.13

Table A-2. Estimated Drainable Porosity of Some BY and TX Single-Shell Tanks (Simmons 1998a)

Tanks	Drainable Porosity
241-TX-109	0.45
241-TX-118	0.35
Group 1 Average	0.33
Group 2	
241-BY-101	0.19
241-TX-105	0.30
241-TX-110	0.32
241-TX-111	0.18
241-TX-112	0.17
241-TX-113	0.35
241-TX-114	0.33
241-TX-115	0.25
241-TX-116	0.27
241-TX-117	0.27
Group 2 Average	0.26
Overall Average	0.30

As shown in Figure A-4, the porosity of roughly 60 percent of the SST sludge is between 0.4 and 0.55. Therefore, the majority of the solid volume fractions, C_V (=1- porosity) are between 0.45 and 0.6. As Equations A-4 through A-6 indicate, the greater the porosity (or the smaller the solid volume fraction, C_V), the greater the solid density, ρ_S, and ρ_{CS} for a given sludge bulk density. The greater values of the solid density, in turn require the greater critical velocity and pressure drop to transfer the waste slurry (therefore, the more the conservative estimates for the waste pipeline assessment), as discussed in Section A.2.1.

Therefore, the above porosity evaluations indicate that sludge porosity of 0.4 to 0.55 and the corresponding solid volume fraction, C_V of 0.45 to 0.60 are reasonable values for the sludge waste, and C_V of 0.45 is a slightly conservative choice for the sludge waste. Therefore, $C_V = 0.45$ was selected for these HLWs when there are no measured data available for the solid volume fraction.

A.3.0 ESTIMATES OF SOLID DENSITIES AND VOLUME FRACTIONS

In this section, Equations A-4 through A-6 were used to estimate potential solid densities and volume fractions in the sludges of 10 HLW tanks: AZ-101, AZ-102, SY-102, AY-101, AY-102, AW-101, AW-102, C-104, C-106, and C-107. The waste volumes of supernatant liquid and sludge/saltcake stored in these tanks are presented in Table A-3 (values listed in TWINS database) in December 2001; http://twins.pnl.gov).

Other measured values related to Equations A-4 through A-6 are shown in Table A-4. The significant digits of these values in Table A-4 represent the accuracy of their reported values. The two numbers reported in Table A-4 indicate the two sets of data we used to evaluate these waste properties. Most of these measured values were obtained from tank characterization reports and the TWINS database, unless specific studies were previously performed to obtain these values for specific tanks such as AZ-101 and AZ-102. An explicit source for each value is given in Sections A.3.1 through A.3.10.

Table A-5 summarizes estimated and measured physical properties of the 10 HLWs reflecting the agglomeration of the solids. The last column shows solid concentrations if all the waste (supernatant liquid and sludge/saltcake) in a tank is completely mixed, therefore indicating potential solid concentrations in slurry pile flows without in-tank or in-line dilution of the waste. The values in Table A-5 are derived in Sections A.3.1 through A.3.10.

Table A-3. Waste Volumes in Ten Hanford HLW Tanks

Tanks	Supernatant Volume kgal	Sludge Volume kgal	Saltcake Volume kgal	Total Waste Volume kgal	Ratio of Solid Layer Volume to Total Waste vol%
AZ-101	892	52	0	944	5.5
AZ-102	891	105	0	996	10.5
SY-102	963	71	0	1,034	6.9
AY-101	75	108	0	183	59.0
AY-102	451	184	0	635	29.0
AW-103[a]	789	273	40	1,162	26.9
AW-104[a]	93	66	157	316	70.6
C-104[b]	0	263	0	263	100
C-106[b]	42	6	0	48	14.3
C-107[b]	0	257	0	257	100

Notes:

[a] These tanks contain saltcake.

[b] These are SSTs.

Table A-4. Measured Data for Ten Hanford HLW Tanks

Tanks	Sludge Bulk Density, ρ_B g/mL	Liquid Density, ρ_L g/mL	Weight Fraction of the Solid Within Sludge, y	Solid Volume Fraction C_V	Solid Density, ρ_S g/mL	Centrifuged Sludge Density ρ_C g/mL	Centrifuged Liquid Density, ρ_{CL} g/mL	Sludge Volume Reduction Due to Centrifuge x
AZ-101	1,67 1.62	1.2 1.2				1,67 1.62	1.22 1.22	0.71 0.76
AZ-102	1.49	1.1				1.49	1.13	0.64
SY-102	1.56	1.03	0.605					
AY-101	1.59	1.0		0.657			1.14	
AY-102	1.4 1.4	1.0 0.99	0.456					
AW-103	1.43	1.00				1.75	1.0	0.97
AW-104	1.44	0.988						
C-104	1.46 to 1.97	1.10						
C-106	1.17	1.55			2.28			
C-107	1.17	1.44		0.662				

Table A-5. Estimated Waste Physical Properties and Conditions

Tanks	Liquid Density, ρ_L g/mL	Solid Density, ρ_S g/mL	Solid Volume in Sludge, C_V vol%	Porosity in Sludge	Fully Mixed Solid Volume, C_{pipe} vol%
AZ-101	1.20	2.19	45.0	0.550	2.5
AZ-102	1.10	1.97	45	0.55	4.7
SY-102	1.25	2.24	32.5	0.675	3.7
AY-101	1.00	1.90	65.7	0.343	38.8
AY-102	0.99	2.68	23.8	0.762	6.90
AW-103	1.00	1.96	45.0	0.550	12.1
AW-104	0.988	1.99	45.0	0.550	34.2
C-104	1.10	3.11[a]	29.6	0.704	N/A[b]
C-106	1.17	2.28	34.2	0.658	N/A[b]
C-107	1.17	1.44	66.2	0.338	N/A[b]
Average	1.10	2.18	43.2	0.568	14.7

Notes:

(a) Estimated as the primary true solid density (see Table 4-2 in the main part of this report) because not enough physical data were available to calculate this value.

(b) Not applicable because these are single-shell tanks.

A.3.1 TANK 241-AZ-101

A series of Tank Characterization Reports were reviewed for tank AZ-101 (Hodgson 1995a; Place 1997; Lambert 1998a; Templeton 1999, 2001a; Adams 2000a), as well as special study reports (Waters et al. 1991; Vail 1997; Morrey and Tingey 1995). As shown in the 2nd and 7th columns of Table A-4, there are two sets of data, before and after the sludge alone was centrifuged (Waters et al. 1991, Morrey and Tingey 1995). As discussed in Section A.2.2, the majority of the solid volume fractions, C_V in six SSTs range from $C_V = 0.45$ to 0.6. In the first set of measurements, the centrifuged sludge was reduced to 71 vol% of the original sludge volume; therefore, $x = 0.71$ in Equation A-5. From Equation A-5, the porosity n of the sludge after centrifugation becomes $n = 0.155$ to 0.366. As also discussed in Sections A.2.1 and A.2.2, the smaller the solid volume fraction, C_V or the greater the porosity, the greater the associated solid density becomes, which in turn requires greater critical velocity and pressure drop (see Figures A-2 and A-3). Therefore, $C_V = 0.45$ and the associated porosity of centrifuged sludge, $n = 0.372$ were selected, as reasonable but somewhat conservative selections.

From Equation A-6 with C_V=0.45, $\rho_B = 1.67$ g/mL, and $\rho_L = 1.2$ g/mL (see Table A-4), the solid density of AZ-101 was calculated to be $\rho_S = 2.23$ g/mL. In Equation A-4, with $x = 0.71$, $n = 0.37$, $\rho_C = 1.67$ g/mL, and $\rho_{CL} = 1.22$ g/mL, the solid density after the sludge was centrifuged was calculated to be $\rho_{CS} = 2.23$ g/mL. Therefore, $\rho_S = \rho_{CS}$.

For the second set of measurements (see Table A-4), the centrifuged sludge reduced its solid layer volume to 76 vol% of the original sludge volume; therefore, $x = 0.76$. With Equation A-5 and $C_V = 0.45$ to 0.6, the porosity of the centrifuged sludge becomes $n = 0.211$ to 0.408. Therefore we selected C_V= 0.45 and $n = 0.408$ as a conservative choice. With C_V=0.45, $\rho_B = 1.62$ g/mL, and $\rho_L = 1.2$ g/mL, Equation A-6 yielded the solid density as $\rho_S = 2.14$ g/mL. While Equation A-4 with $x = 0.76$, $n = 0.41$, $\rho_C = 1.62$ g/mL, and $\rho_{CL} = 1.62$ g/mL yields the centrifuged solid density $\rho_{CS} = 2.11$ g/mL. Therefore, $\rho_S \approx \rho_{CS}$. Note that the reported liquid density, ρ_L was 1.2 g/mL, having only two significant digits. Therefore, the small difference between ρ_S and ρ_{CS} is probably within the measurement accuracy.

Therefore, the average solid density based on these two sets of data is $\rho_S = 2.19$ g/mL. With this solid density, Equation A-6 yield $C_V = 0.45$, as originally assigned. The corresponding porosity of the original sludge is 0.55 (=1 - C_V = 1 - 0.45). Because the sludge consists of 5.5 vol% of the total tank AZ-101 waste (see Table A-3), the total mixing of the tank AZ-101 supernatant liquid and sludge reduces the solid volume fraction to 2.5 vol% (= C_V times 5.5 vol%). Therefore, if the AZ-101 waste is fully mixed by two 300-horsepower mixer pumps (as in-situ mixer pump testing showed), the solid volume fraction of the AZ-101 slurry in the pipeline would be 2.5 vol% if neither in-tank nor in-line dilution is performed.

A.3.2 TANK 241-AZ-102

Tank Characterization Reports were reviewed for tank AZ-102 (Ryan 1995a; Schreiber 1995; Jones et al. 1997a; Lambert 1998b; Rasmussen 1999; Adams 2000b) and related study reports (Gray et al. 1993, Morrey and Tingey 1995). The available measured values are shown in Table A-4. Gray et al. (1993) analyzed a core sample and reported that the centrifuged sludge reduced its solid layer volume to 64 vol% of the original sludge volume; therefore, $x = 0.64$. Because the type of data available for tank AZ-102 is the same as that for tank AZ-101, the same approach was used to estimate the tank AZ-102 solid density and the volume fraction as for tank AZ-101.

With selected values of $C_V = 0.45$ to 0.60, which covers approximately 60 percent of all six SST sludge conditions, as discussed in Section A.2.2, Equation A-5 produced the porosity of the centrifuged sludge as $n = 0.063$ to 0.297. Therefore, $C_V = 0.45$ and $n = 0.30$ were selected to obtain a reasonably conservative solid density value, as discussed in Section A.2.2 and in the description of tank AZ-101 above.

Equation A-6, with C_V=0.45 as a somewhat conservative selection, $\rho_B = 1.49$ g/mL, and $\rho_L = 1.1$ g/mL, the solid density of AZ-102 was calculated to be $\rho_S = 1.97$ g/mL. In Equation A-4, with $x = 0.64$, $n = 0.30$, $\rho_C = 1.69$ g/mL, and $\rho_{CL} = 1.13$ g/mL, the solid density after the sludge is centrifuged is calculated to be $\rho_{CS} = 1.94$ g/mL. Therefore, $\rho_S \approx \rho_{CS}$.

The porosity in the sludge is 0.55 (= $1 - C_V$). Because the sludge consists of 10.5 vol% of the total tank AY-101 waste (see Table A.3), the solid concentration after the sludge is fully mixed with the supernatant liquid would be 4.7 vol%.

A.3.3 TANK 241-SY-102

Tank SY-102 received 525,000 gallons of SY-101 waste from December 1999 to March 2000 (Wells et al. 2000). Therefore, SY-102 currently contains both waste already there before the tank SY-101 waste transfer and waste transferred from tank SY-101. These two wastes were combined to obtain current waste conditions. The tank SY-102 sludge has $R \approx 5$ μm and $r \approx 1$ to 1.5 μm (See Equation A-2) (Bunker et al. 2000), indicating that tank SY-102 solids are agglomerated. Tank SY-102 Tank Characterization Reports were reviewed (DiCenso et al. 1995; Field 1998a; and Douglas et al. 1998). These reports indicate that the tank SY-102 sludge and liquid densities are $\rho_B = 1.56$ and $\rho_L = 1.03$ g/mL, respectively. Furthermore, these reports indicate that the weight fraction of the solids is 60.5 wt% of the sludge. Therefore, $y = 0.605$ in Equation A-7. Because Equation A-10 would be satisfied by these values, we used Equations A-6 and A-7 to obtain the solid density and solid volume fraction in the original sludge before the tank SY-101 waste transfer. These equations yield the solid density, $\rho_S = 2.35$ g/mL, and corresponding solid volume fraction, $C_V = 0.402$. Note that the original tank SY-102 sludge volume was 71,000 gallons; the total amount of solids in the sludge is 28,000 gallons (40.2 vol% of the total sludge volume of 71,000 gallons).

Wells et al. (2000) reported that the SY-101 waste (Adams 2000c) added to Tank SY-102 has solid and liquid densities of 2.20 and 1.49 g/mL, respectively. Furthermore, the solid volume fraction of the transferred waste was 16 vol%; therefore, transferred solids are 84,000 gallons (16 vol% of 525,000 gallons of total waste transfer). After the tank SY-101 solids were settled in tank SY-102, the tank SY-101 solid volume fraction in the settled layer was estimated to be $C_V = 0.30$ (Wells et al. 2000). Therefore, the weighted average of the solid density, ρ_S is

$$\rho_S = \left(\frac{28,500}{28,500+84,000}\right)\cdot(2.35)+\left(\frac{84,000}{28,500+84,000}\right)\cdot(2.20)=2.24\text{g/mL}$$

Similarly, the weighted average solid volume fraction is

$$C_V = \left(\frac{28,500}{28,500+84,000}\right)\cdot(0.402)+\left(\frac{84,000}{28,500+84,000}\right)\cdot(0.300)=0.325$$

the resulting porosity is 0.675 (= 1 – C_V = 1 - 0.325). The supernatant liquid level keeps changing as it is being transferred out of tank SY-102. If we assume that the tank is basically full (about 1,000,000 gallons), the fully mixed solid volume fraction would be

$$C_{pipe} = C_V \cdot \left(\frac{28,500+84,000}{1,000,000}\right) = 0.0367$$

A.3.4 TANK 241-AY-101

Four versions of the AY-101 Tank Characterization Reports were reviewed (Thompson and Stephens 1996; Shelton 1997a; Lambert 1998c; Templeton 2001b). Templeton (2001b) reported that the liquid, ρ_L, and sludge bulk densities, ρ_B, are 1.10 and 1.59 g/mL, respectively. He also reported that the centrifuged liquid density, ρ_{CL} was 1.14 g/mL after the sludge was centrifuged, but no other information was reported on the centrifuged sludge. The solid volume fraction, C_V, within the sludge was reported to be 0.657 (Thompson and Stephens 1996). This C_V value of 0.657 is slightly higher than the majority of the C_V range of 0.45 to 0.6 and corresponds to about 8 percent of the sludge having C_V values greater than or equal to this value, as studied by Simmons (1998a) (see Figure A-4 with porosity of 0.343 = 1 – C_V). As indicted in Section A.2.2, a greater C_V value results in a smaller solid density for a given sludge bulk density. Nonetheless, because this C_V value was reported, Equation A-5 was used to calculate the solid density with $C_V = 0.657$, ρ_L = 1/0 g/mL, and ρ_B = 1.59 g/mL, and obtained ρ_S = 1.90 g/mL.

The porosity in the sludge is 0.343 (= 1 – C_V). Because the sludge consists of 59 vol% of the total tank AY-101 waste (see Table A-3), the solid concentration after the sludge is fully mixed with the supernatant liquid would be 38.8 vol%, if the waste can be fully mixed.

A.3.5 TANK 241-AY-102

Tank AY-102 Tank Characterization Reports were reviewed (Ryan 1995b; Sasaki 1996, 1999a; Shelton 1997b; Lambert 1998d; Adams 2001a). These reports show that the supernatant and sludge bulk densities are 1.0 and 1.4 g/mL, respectively. Carothers et al. (1998) reported these values to be 0.99 and 1.4 g/mL, respectively. Casting (1994) also reported that the solid weight fraction within the sludge was 45.6 wt%. Therefore, $y = 0.456$. Equations A-6 and A-7 were used because Equation A-10 is satisfied in this case ($y = 0.456 > 1-1.0/1.4 = 0.286$).

Equations A-6 and A-7 give the solid density as $\rho_S = 2.68$ g/mL and the solid volume fraction as $C_V = 0.238$. Therefore, the porosity of the sludge is 0.762. (Note these values of C_V and porosity are outside of the range of $C_V = 0.45$ to 0.6, and based on Figure A-4, it represents approximately the top 17 percent of the porosity values.) Because the sludge consists of 29 vol% of the total tank AY-101 waste (see Table A-3), the solid concentration after the sludge is fully mixed with the supernatant liquid would be 6.9 vol%.

A.3.6 TANK 241-AW-103

The Tank Characterization Reports for AW-103 (Hodgson 1995b; Shelton 1997c; Field 1998b; Field et al. 1998; Adams 2001b) indicate that supernatant and sludge bulk densities are 1.00 and 1.43 g/mL, respectively. With the assigned value of $C_V = 0.45$ selected from the majority of the C_V ranges of 0.45 to 0.60, Equation A-6 yields the solid density as $\rho_S = 1.96$ g/mL.

With $C_V = 0.45$, the corresponding porosity of the tank AW-103 sludge is estimated to be 0.55. Furthermore, because the sludge consists of 26.9 vol% of the total tank AW-103 waste (see Table A-3), the solid concentration after the sludge is fully mixed with the supernatant liquid would be 12.1 vol%.

Tingey et al. (1990) also reported that the original sludge with its bulk density of 1.75 g/mL reduced its sludge volume to 97 vol% of its original volume due to the centrifuge. Therefore, $x = 0.97$. However, he did not report the centrifuged liquid density value. With the ranges of $C_V = 0.45$ to 0.6, and assuming the centrifuged liquid density is the same as the original interstitial solution density of $\rho_L = 1.00$ g/mL, Equation A-5 results in the porosity of the sludge after centrifuge is $n = 0.381$ to 0.536. By selecting $n = 0.54$ for a somewhat conservative evaluation, Equation A-4 yields a solid density after centrifuge as $\rho_{CS} = 2.68$ g/mL. This value is significantly greater than the solid density obtained from Equation A-6. Field et al. (1998) stated that all other sludge bulk density measurements indicate that its density is around 1.43 g/mL. They, therefore, dismissed the data from Tingey et al. (1990). Therefore, the solid density value obtained with the Tingey et al (1990) data was not used for this evaluation.

A.3.7 TANK 241-AW-104

The AW-104 Tank Characterization Reports (Tusler et al. 1995; Jones et al. 1997b; Field 1998c; McKinney 2001) and TWINS database (http://twins.pnl.gov) show mostly the liquid density of 0.988 g/mL and bulk sludge density of 1.44 g/mL. Some other values are also reported, but most of them are inconsistent with each other. Although there are some centrifuged sludge data reported, they are not complete enough (e.g., lacking the sludge volume fraction reduction value) for this analysis. Therefore, $\rho_L = 0.988$ g/mL and $\rho_B = 1.44$ g/mL with the assigned value of $C_V = 0.45$ were used as in many other tanks discussed above, to estimate the solid density. Equation A-6 yields the solid density to be $\rho_S = 1.99$ g/mL in this case.

This solid density value was checked against data obtained from two tank AW-104 grab samples containing very small amounts of solids, as reported in the TWINS database. The first grab sample data indicate that the bulk grab sample density was 0.996 g/mL with less than 2 vol% solids in the grab sample. The second grab sample analysis indicates that the grab sample density was 0.979 g/mL with also less than 2 vol% solids. With $\rho_L = 0.988$ g/mL and $C_V < 0.02$, the first data set indicates that $\rho_S > 1.89$ g/mL, while the second data set requires $\rho_S > 1.18$ g/mL. Although the data from these two grab samples did not permit determination of a specific solid density, the calculated solid density of $\rho_S = 1.99$ g/mL satisfies the results of these two grab samples.

With the solid volume fraction of 0.45, the corresponding porosity of the sludge is 0.55. As shown in Table A-2, the tank AW-104 sludge consists of 70.6 vol% of the total tank AW-104 waste. Therefore, the solid concentration would be 34.2 vol%, if the sludge can be fully mixed with the supernatant liquid without any in-tank or in-line dilution.

A.3.8 TANK 241-C-104

The Tank Characterization Reports for C-104 (Baldwin 1997a, 1997b; Place 1998a; and Adams 2000d) and TWINS database (http://twins.pnl.gov) present widely varying sludge bulk density, ranging from 1.46 to 1.97 g/mL with a rough average of 1.69 g/mL. This may be an indication that a very non-homogeneous sludge is present in tank C-104. The liquid density had a more uniform value of 1.09 to 1.1 g/mL. With the assigned $C_V = 0.45$, these varying bulk sludge densities would produce the solid density, $\rho_S = 1.91$ to 3.04 g/mL. Therefore, the solid density from these values was not estimated. Instead, the solid density, $\rho_S = 3.11$ g/mL was assumed, based on the weighted average of the densities of expected true solids (See Table 4-2).

With $\rho_S = 3.11$ g/mL, and the rough average of $\rho_B = 1.69$ g/mL, the average solid volume fraction in the sludge was then estimated by Equation A-6 to be $C_V = 0.296$. This C_V value, which is smaller than the C_V range of 0.45 to 0.6 as expected, was used for many tanks, because of the conservative value of the solid density selected for the C-104 tank waste. Since tank C-104, as well as tanks C-106 and C-107 are SSTs, no mixer pumps are currently planed for mixing wastes in these tanks. Therefore, the solid volume fractions were not estimated for these three SSTs if the solids are fully mixed with the liquid wastes.

A.3.9 TANK 241-C-106

The Tank Characterization Reports (Schreiber et al. 1996, Lambert 1997, Place 1998b, and Sasaki 1999b) reported liquid density and sludge bulk densities to be ρ_L = 1.14 to 1.16 g/mL and ρ_B = 1.43 to 1.44 g/mL, respectively. Casting (1994) also reported the interstitial liquid density as ρ_L = 1.14 to 1.22 g/mL. Bunker et al. (2000) reported that both tanks C-106 and C-107 have agglomerates.

Carothers et al. (1998) reported that the liquid, sludge bulk and solid densities to be ρ_L = 1.17 g/mL, ρ_L = 1.55 g/mL, and ρ_L = 2.28 g/mL, respectively. Because Carothers et al. (1998) specifically reported the solid densities, their values were used. With Equation A-6 and ρ_L = 1.17 g/mL, ρ_L = 1.55 g/mL, and ρ_L = 2.28 g/mL, the solid volume fraction in the sludge was estimated to be 0.342. The corresponding porosity is 0.658.

A.3.10 TANK 241-C-107

The Tank Characterization Reports for Tank C-107 (Bell et al. 1995; Lambert 1997; Place 1998b; Sasaki 1999b) report that there is no saltcake or supernatant liquid in this tank. There is no centrifuged sludge data reported without original samples consisting of the sludges alone. They reported liquid density and sludge bulk densities of ρ_L = 1.17 g/mL and ρ_B = 1.35 g/mL, while the solid volume fraction within the wet sludge was reported as C_V = 0.662. Therefore, although Bunker et al. (2000) suggested the solid volume fraction to be more around 0.3, the reported value of 0.662 was used in Equation A-6 to estimate in the solid density, ρ_S = 1.44 g/mL. The corresponding sludge porosity is 0.338.

The estimated waste properties and conditions for all 10 HLW tanks are summarized in Table A-4. The values listed are subject to the uncertainties discussed above.

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