S

ENGINEERING CHANGE NOTICE

Page 1 of 2

1. ECN 672001

Proj. ECN

2. ECN Category (mark one)	3. Originator's Name, Organization, MSIN, and Telephone No.	4. USQ Required?	5. Date
Supplemental ☐ Direct Revision ☒ Change ECN ☐ Temporary ☐ Standby ☐ Supersedure ☐ Cancel/Void ☐	L. J. Julyk, CHG. R3-83 376-4608	☐ Yes ☒ No	03/14/02
	6. Project Title/No./Work Order No.	7. Bldg./Sys./Fac. No.	8. Approval Designator E.Q
	9. Document Numbers Changed by this ECN (includes sheet no. and rev.) RPP-5346, Rev. 1	10. Related ECN No(s). N/A	11. Related PO No. N/A

12a. Modification Work	12b. Work Package No.	12c. Modification Work Completed	12d. Restored to Original Condition (Temp. or Standby ECNs only)
☐ Yes (fill out Blk. 12b) ☒ No (NA Blks. 12b, 12c, 12d)	N/A	N/A Design Authority/Cog. Engineer Signature & Date	N/A Design Authority/Cog. Engineer Signature & Date

13a. Description of Change

13b. Design Baseline Document? ☐ Yes ☐ No

RPP-5346, Rev.1 was changed to institute new high level waste physical properties as given in RPP-9805, Rev. 1, Values of Particle Size, Particle Density, and Slurry Viscosity to use in Waste Feed Delivery Transfer System Analysis.

14a. Justification (mark one)	14b. Justification Details
Criteria Change ☒ Design Improvement ☐ Environmental ☐ Facility Deactivation ☐ As-Found ☐ Facilitate Const. ☐ Const. Error/Omission ☐ Design Error/Omission ☐	Information developed after the release of RPP-5346, Rev.1 justifies release of Rev. 2.

15. Distribution (Include name, MSIN, and no. of copies)

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16. Design Verification Required	17. Cost Impact				18. Schedule Impact (days)	
	ENGINEERING		CONSTRUCTION			
☐ Yes	Additional ☐	$ N/A	Additional ☐	$ N/A	Improvement ☐	N/A
☒ No	Savings ☐	$ N/A	Savings ☐	$ N/A	Delay ☐	

19. Change Impact Review: Indicate the related documents (other than the engineering documents identified on Side 1) that will be affected by the change described in Block 13. Enter the affected document number in Block 20.

SDD/DD	☐	Seismic/Stress Analysis	☐	Tank Calibration Manual	☐
Functional Design Criteria	☐	Stress/Design Report	☐	Health Physics Procedure	☐
Operating Specification	☐	Interface Control Drawing	☐	Spares Multiple Unit Listing	☐
Criticality Specification	☐	Calibration Procedure	☐	Test Procedures/Specification	☐
Conceptual Design Report	☐	Installation Procedure	☐	Component Index	☐
Equipment Spec.	☐	Maintenance Procedure	☐	ASME Coded Item	☐
Const. Spec.	☐	Engineering Procedure	☐	Human Factor Consideration	☐
Procurement Spec.	☐	Operating Instruction	☐	Computer Software	☐
Vendor Information	☐	Operating Procedure	☐	Electric Circuit Schedule	☐
OM Manual	☐	Operational Safety Requirement	☐	ICRS Procedure	☐
FSAR/SAR	☐	IEFD Drawing	☐	Process Control Manual/Plan	☐
Safety Equipment List	☐	Cell Arrangement Drawing	☐	Process Flow Chart	☐
Radiation Work Permit	☐	Essential Material Specification	☐	Purchase Requisition	☐
Environmental Impact Statement	☐	Fac. Proc. Samp. Schedule	☐	Tickler File	☐
Environmental Report	☐	Inspection Plan	☐		☐
Environmental Permit	☐	Inventory Adjustment Request	☐		☐

20. Other Affected Documents: (NOTE: Documents listed below will not be revised by this ECN.) Signatures below indicate that the signing organization has been notified of other affected documents listed below.

Document Number/Revision	Document Number/Revision	Document Number/Revision

21. Approvals

	Signature	Date		Signature	Date
Design Authority			Design Agent		
Cog. Eng.	L. J. Julyk	3/21/02	PE		
Cog. Mgr.	A. H. Friberg	3/21/02	QA		
QA	W. L. Adams	3/21/02	Safety		
N54L Safety	T. G. Goetz	3/21/02	Design		
Environ.			Environ.		
Other	T. J. Conrads	3/21/02	Other		
Independent Reviewer	S. D. Estey	3/21/02			

DEPARTMENT OF ENERGY

Signature or a Control Number that tracks the Approval Signature

ADDITIONAL

DISTRIBUTION SHEET

To	From	Page 1 of 1
Distribution	Design Engineering	Date 3/21/02
Project Title/Work Order: Waste Feed Delivery Transfer System Analysis RPP-5346 REV. 2		EDT No.
		ECN No. 672001

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Waste Feed Delivery Transfer System Analysis

L.J. Julyk
CH2M Hill Hanford Group, Inc.
Richland, WA 99352
U.S. Department of Energy Contract DE-AC27-99RL14047

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Key Words: Double-Shell Tank, Waste Feed Delivery, Engineering Basis, Waste Transfer System, Transfer Piping, Transfer Pumps

Abstract: This document provides a documented basis for the required design pressure rating and pump pressure capacity of the Hanford Site waste-transfer system in support of the waste feed delivery to the immobiliztion plant for processing. The scope of the analysis includes the 200 East Area double-shell tank waste transfer pipeline system and the associated transfer system pumps for all Phase 1B and Phase 2 waste transfers from AN, AP, AW, AY, and AZ Tank Farms.

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RECORD OF REVISION

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Page 1

(2) Title: Waste Feed Delivery Transfer System Analysis EDT # 628097, May 5, 2000.

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RPP-5346
Revision 2

Waste Feed Delivery Transfer System Analysis

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

CH2MHILL
Hanford Group, Inc.
Richland, Washington
Contractor for the U.S. Department of Energy
Office of River Protection under Contract DE-AC06-99RL14047

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RPP-5346
Revision 2

Waste Feed Delivery Transfer System Analysis

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March 2002

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RPP-5346 REV 2

WASTE FEED DELIVERY TRANSFER SYSTEM ANALYSIS

March 2002

L. J. Julyk

CH2M HILL Hanford Group, Inc.

Prepared for:
U.S. Department of Energy
Office of River Protection

Richland, Washington

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CHECKLIST FOR INDEPENDENT REVIEW

Document: Waste Feed Delivery Transfer System Analysis

Author: L. J. Julyk

Yes	No	N/A	
[✓]	[ ]	[ ]	Problem completely defined.
[✓]	[ ]	[ ]	Necessary assumptions explicitly stated and supported.
[✓]	[ ]	[ ]	Computer codes and data files documented.
[✓]	[ ]	[ ]	Data used in calculations explicitly stated in document.
[ ]	[ ]	[ ]	Data checked for consistency with original source information as applicable.
[✓]	[ ]	[ ]	Mathematical derivations checked including dimensional consistency of results.
[✓]	[ ]	[ ]	Models appropriate and used within range of validity or use outside range of established validity justified.
[ ]	[ ]	[✓]	Hand calculations checked for errors.
[✓]	[ ]	[ ]	Code run streams correct and consistent with analysis documentation.
[✓]	[ ]	[ ]	Code output consistent with input and with results reported in analysis documentation.
[✓]	[ ]	[ ]	Acceptability limits on analytical results applicable and supported limits checked against sources.
[✓]	[ ]	[ ]	Safety margins consistent with good engineering practices.
[✓]	[ ]	[ ]	Conclusions consistent with analytical results and applicable limits.
[✓]	[ ]	[ ]	Results and conclusions address all points required in the problem statement.

S. D. Estey S D Estey — 3/19/2002

Reviewer — Date

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EXECUTIVE SUMMARY

This engineering analysis documents the results of a study to develop a basis for the design and operating pressure requirements of the waste feed delivery (WFD) transfer pumps and the minimum design pressure rating required of the transfer pipeline system located within the Hanford Site tank farm facilities. The scope of the analysis includes Phase 1 waste transfers from the AN, AP, AW, AY, and AZ tank farms in the 200 East Area to the proposed Waste Treatment Plant (WTP) as well as inter-farm tank-to-tank transfers. This analysis does not evaluate the existing cross-site transfer pipeline system for waste transfers between the Hanford Site 200 West and 200 East Areas. The analysis focuses on the hydraulics of the waste transfer system using available *in situ* waste-characterization data to characterize the physical properties of the transferred waste streams within the specified low-activity waste (LAW) and high-level waste (HLW) envelope definitions. The analysis also compares the predicted minimum design pressure requirements determined by this analysis to the limiting pressure ratings of 1.9 and 2.7 MPa (275 and 400 lbf/in^2) of the existing and planned project upgrades to the WFD transfer system. Although project upgrade pipelines have specified design pressures of 6.9 and 10 MPa (1,000 and 1,490 lbf/in^2), all pipeline transfer routes are limited to the lesser of the specified pipe design pressure limit and the jumper connector pressure limit of 2.7 MPa (400 lbf/in^2)[1].

This analysis does not address the potential for chemical precipitation or crystallization which is a function of the solubility characteristics of the dissolved multi-constituents of the waste feed, their chemical interaction, pH, and temperature. Nor does this analysis address the dynamic behavior of agglomerate formation and breakup during transfer or the re-suspension of particles following a loss of flow for an extended period of time. Proper line flushing between batch transfers is assumed.

Each transfer route includes one or more pipeline segments, where each segment connects one valve pit to another. Many of the pipeline segments are used in common in the various transfer routes. Currently proposed waste transfer routes were identified for Phase 1 transfers using

[1] Jumper connectors are currently qualified to only 1.7 MPa (250 lbf/in^2) by historic leak tests (RPP-5793 and RPP-6984) and to 2.7 MPa (400 lbf/in^2) by recent analysis (RPP-8359). Plans for jumper connector qualifying leak tests to a pressure of at least 2.7 MPa (400 lbf/in^2) are under development.

Hanford Tank Waste Operations Simulator (HTWOS) results given in the *Tank Farm Contractor Operation and Utilization Plan* (HNF-SD-WM-SP-012). Although the transfer plan is not final, it is sufficiently mature to provide representative data for a valid assessment. The transfer routes that were evaluated comprise the existing transfer-system infrastructure and the modifications that are planned or in progress for Projects W-211, W-314 and W-521.

If we could accurately predict the transfer-specific waste physical properties for all waste transfers, it would be possible to assign a minimum required pressure rating for each pipe segment based on the predicted maximum pressure drop for all planned transfers in common with each pipe segment. The pressure drop information is used to determine the pump design requirements and adequacy of the WFD transfer pipeline system. Calculation of the pipeline system pressure drop requires knowledge of the transferred waste physical properties at the transferred waste temperature (including heat up from mixer pumps), a complete description of the pipeline system transfer routes, and the current and projected end-of-life pipe roughness for existing and planned pipeline segments.

Waste physical properties include density and viscosity of the carrier liquid; size distribution, density, and concentration of insoluble particles; and the effect of particle concentration on the viscosity of the mixed slurry. The description of the pipeline system transfer routes includes the dimensions of the pipe (size); layout (including net elevation change); identification of pipe components (elbows, bends, valves, connectors, etc.); and identification of the material of construction (carbon steel or stainless steel), design pressure rating, and installation date for each pipe segment that forms each transfer route. Current pipe roughness and potential change in roughness caused by corrosion over the expected usage time period must be considered for both the existing 20-year old carbon steel segments and the existing and planned stainless steel segments of the pipeline system. Pipe roughness predictions are based on the corrosion evaluation given in Appendix C.

In the absence of complete transfer-specific waste-property data for each transfer, a final plan for waste transfers, and uncertainties in existing pipeline roughness, transfer-specific/transfer route pressure drops for each of the waste transfers could not be calculated with a high degree of confidence at this time. Because of the lack of transfer-specific waste physical property data, the commonality of the pipeline segments used in the various transfer routes, and the need to provide

maximum flexibility in transfer strategy for utilization of the of transfer system a conservative analysis is required to ensure sufficient robustness in the transfer system.

Calculation of the required design and operating pressure for the WFD transfer system requires the determination of the minimum flow velocity (critical velocity) to prevent the insoluble particles in the transferred waste from settling in the pipeline. Settling of waste insoluble particles could lead to pipeline plugging, unstable pump operation, increased worker radiation exposure, or more frequent flushing with smaller batch volumes of transferred waste. Although it is recognized that no published critical velocity correlations are directly applicable to the multi-constituent broadband particle size distributions (PSD) typical of Hanford HLW slurries, the Oroskar and Turian (1980) correlation was selected based on recommendations from two literature surveys: HNF-2728, *Flow Velocity Analysis for Avoidance of Solids Deposition During Transport of Hanford Tank Waste Slurries*; and RPP-7185, *Critical Transport Velocity: A Review of Correlations and Models*. A factor of 1.3 is applied to the predicted critical velocity to account for uncertainties in the empirical-based critical velocity correlation and to ensure that the transport velocity is sufficiently greater than the predicted critical velocity to prevent unstable flow conditions that can occur near the critical velocity.

The required minimum operating pressure for the pipeline is then determined from the calculated pressure drops in the pipeline system at the factored predicted critical velocity. The pressure-drop correlation for the transport of heterogeneous slurries with broadband PSDs given in Wasp et al. (1977), "*Solid-Liquid Flow Slurry Pipeline Transportation*" is used to predict the pressure losses in the transfer pipeline routes. The required minimum design pressure for the pipeline is obtained by appropriately factoring the minimum operating pressure to account for the pump maximum dead head pressure and the range of slurry bulk density to be accommodated. The critical velocity and pressure drop correlations were selected based on current conservative estimates of the transferred waste physical properties to date.

One of the important controlling waste parameters is the particle size distribution (PSD). The assessment of the WFD system in Revision 0 of RPP-5346 was conducted for a broadband PSD with the median particle size ranging from 40 (nominal) to 400 μm (bounding). Predicted pressure drops at the predicted critical flow velocity for this conservative estimate of the PSD

exceeded the limiting operating pressures for many of the pipeline transfer routes, particularly as the median particle size approached the bounding 400 μm.

A subsequent statistical reassessment of the available particle size data was reported in RPP-6427, *Assessment of Available Particle Size Data to Support an Analysis of the Waste Feed Delivery Transfer System.* From the statistical analysis of historical particle size data from three (AW-103, AZ-101, and C-104) of ten HLW tanks, the report concluded that with 95% confidence, the median particle size is not expected to exceed 275 μm in at least 95% of the ten HLW tanks. The statistical mean of the median particle size for the three HLW tanks considered was 110 μm. The revised PSD estimate was evaluated in Revision 1 of RPP-5346 but the predicted pressure drops did not provide sufficient relief from exceeding the limiting system pressures of the pipeline transfer routes at the required flow rate. Additional laboratory work was recommended in RPP-6427 to help resolve apparent anomalies in particle size measurement results between instruments[2], uncertainties in particle densities, and to investigate existence of particle agglomerates and their potential breakup when passing through transfer pumps or under turbulent pipe flow conditions.

An extensive laboratory analysis of HLW particle sizes was conducted in an attempt to address these uncertainties. Results are reported in HNF-8862, *Particle Property Analyses of High-Level Waste Tank Sludges.* A multi-company panel of experts was formed to review the results of the laboratory analysis and other available Hanford waste physical property data to provide recommend particle size, particle density, and viscosity information for the WFD transfer system analysis. This revision to RPP-5346 applies the expert panel recommendations on particle size, particle density, and viscosity reported in RPP-9805, *Values of Particle Size, Particle Density, and Slurry Viscosity to Use in Waste Feed Delivery Transfer System Analysis.*

In the earlier HLW PSD measurements used in the statistical analysis reported in RPP-6427, the samples were held in a 15-mL observation cell, where the particulate matter was kept in suspension with a small magnetic stirring bar. In the more recent measurements (HNF-8862),

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[2] Data obtained from analysis of Hanford HLW samples in the Horiba™ Model LA-910 particle size analyzer with its greater size range yielded larger particle size values than all instruments used previously that had smaller or equal measurement size ranges. Horiba is a trademark of Horiba, Ltd., Kyoto, Japan.

which also used the Horiba™ Model LA-910 particle size analyzer, the sample particulates were suspended by recirculating roughly 300 mL of the sample in a flow loop that passes through the measurement cell. In light of the agglomerated nature of the particles, the difference between the instrument configurations was found to be critical. By comparing the particle size data reported in RPP-6427 and HNF-8862, it is clear that even the minimum shear forces required to maintain the waste particles in suspension by turbulence in a flowing stream are greater than the shear applied in the small stirred cell.

The PSD data reported in HNF-8862 was obtained from seven (AW-103, AY-101, AY-102, AZ-102, C-104, C-107, and SY-102) tanks representing Phase 1 HLW tank feeds of ten HLW tanks. The PSD data was subdivided into two groups depending on the level of agitation applied to the samples. In the first group the samples were minimally agitated and in the second group the samples were strongly agitated (sonicated). The resulting mean, upper limit of one-sided 95% confidence interval on the mean (UL 95), and upper limit to a one-sided 95/95 tolerance limit (95/95 TL) were statically determined for each group.

The recent laboratory program was conducted to produce better estimates of particle size and particle density in the HLW feeds. 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. Hence, the approach taken by the expert panel was to select a conservative (upper bound) solid density value and realistic (best estimates) for the PSD and slurry viscosity. This selection approach for these three waste properties is expected to support a reasonably conservative assessment of the WFD transport system. Because PSD data from the strongly agitated samples could not be reliably correlated to the level of shearing from the transfer pumps or turbulent pipe flow conditions, the minimally agitated PSD data was selected as a best-estimate of the PSD for the WFD transfer system analysis.

This revised analysis updates the equivalent pipeline lengths for the transfer routes and the waste transfer temperature to include mixer pump induced heating for HLW transfers as well as updated particle size, particle density, and slurry viscosity data. In addition, the pump curve for

the Project W-211 prototype transfer pump was included in the analysis. Results from the analysis are summarized briefly below.

Critical velocities and pressure drops through each of the proposed waste transfer routes between tanks and tank-to-WTP were calculated for the recommended waste properties, as well as for variations in waste properties, within the specified LAW and HLW envelope definitions. Results from the analysis (see Appendices E and D) provide an indication of the sensitivity of the predicted critical velocity and corresponding pressure drop in the identified transfer pipeline routes to variations in the waste physical properties and pipe roughness. Although the predicted pressure drops are transfer-route specific because of the differences in pipeline length and change in elevation, some general observations can be given by grouping the transfer routes into the following two groups based on the pipeline transfer route system pressure limit:

- Pipeline Transfer Routes Limited to 2.7 MPa (400 lbf/in^2)
  - Tank-to-tank and tank-to-WTP transfers of LAW and HLW are not expected to exceed the pipeline limiting pressure at either the predicted critical velocity (< 3 ft/s for LAW[3] and < 4 ft/s for HLW) or target flow rate of 140 gal/min (~6.1 ft/s).
  - The pipeline limiting pressure is not expected to be exceeded with application of the Project W-211 prototype variable speed transfer pump at its full speed dead head pressure.
  - Tank-to-tank and tank-to-WTP transfers with application of the Project W-211 prototype transfer pump should be able to reach the target flow rate of 140 gal/min (~6.1 ft/s); except potentially for tank-to-WTP transfers with solid concentrations approaching 10 vol% if the viscosity approaches 30 cP (bounding viscosity case) rather than the excepted 10 cP (best-estimate viscosity case).
- Pipelines Transfer Routes Limited to 1.9 MPa (275 lbf/in^2)

[3] This is based on a conservative assumed 2 vol% solids concentration for LAW transfers.

- Tank-to-tank and tank-to-WTP transfers of LAW and HLW are not expected to exceed the pipeline limiting pressure at the predicted critical velocity (< 3 ft/s for LAW and < 4 ft/s for HLW).
- Tank-to-tank and tank-to-WTP transfers of LAW and HLW are not expected to exceed the pipeline limiting pressure at the target flow rate of 140 gal/min (~6.1 ft/s), except where the equivalent pipe length exceeds approximately 4,800 ft.
- The pipeline limiting pressure is expected to be exceeded with application of the Project W-211 prototype variable speed transfer pump at its full speed (3,560 rev/min) dead head pressure unless the pump speed is limited to approximately 3,000 rev/min or pressure relief valves are provided.

Because the jumper connectors are leak test qualified to only 1.7 MPa (250 lbf/in^2), the above assumes that the jumper connectors can be leak test qualified to pressures that meet or exceed the above pipeline transfer route limiting pressures of 2.7 and 1.9 MPa (400 and 275 lbf/in^2), respectively. Plans for jumper connector qualifying leak tests to a pressure of at least 2.7 MPa (400 lbf/in^2) are under development.

Fortunately, the planned Phase 1 HLW transfers to the WTP are through transfer routes (AN-104, AY-101, AY-102, AZ-101, and AZ-102 to WTP) limited to 2.7 MPa (400 lbf/in^2). In the subsequent balance of mission (BOM) phase, one time transfers of HLW to the WTP are planned from AW-103 and AW-104 to WTP through transfer routes that are limited to 1.9 MPa (275 lbf/in^2). However, tank-to-tank transfers through transfer routes limited to 1.9 MPa (275 lbf/in^2) may be problematic as well (see Appendix D for transfer-route specific limitations).

An understanding of waste physical properties is fundamental for reliable waste transfers. The waste property values recommended in RPP-9805, *Values of Particle Size, Particle Density, and Slurry Viscosity to Use in Waste Feed Delivery Transfer* (PSD based on minimally agitated mean PSD data with the median value of 7.5 μm, conservative solid density of 2.9 kg/L, and the realistic, but still somewhat conservative slurry viscosity correlation) are expected to yield pipeline pressure drops at the required critical velocity roughly 50% higher than pressure drops estimated with more realistic waste property values. This difference is mainly due to the

reduction in required critical velocity with more realistic waste property values. However, the predicted pressure drops at the target flow rate of 140 gal/min (~6.1 ft/s) are expected to be only roughly 10% higher than pressure drops estimated with more realistic waste property values. Although this potential 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 this analysis to reflect more accurate predicted pressure drops.

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LIST OF TERMS

BOL	beginning of life (for transfer operations)
DST	double-shell tank
EOL	end of life (for transfer operations)
HLW	high-level waste
HTWOS	Hanford Tank Waste Operation Simulator
ID	internal diameter
LAW	low-activity waste
LCO	limiting condition of operation
PUREX	Plutonium-Uranium Extraction (facility)
PSD	particle size distribution
TC	thermocouple
TSR	technical safety requirement
vol%	volume percent
WFD	waste feed delivery
wt%	weight percent
WTP	Waste Treatment and Immobilization Plant

UNITS

°C	degrees Celsius
cP	centipoise = 0.001 kg/m-s
°F	degrees Fahrenheit
ft	feet = 0.3048 meters (m)
in.	inch = 2.54 centimeters (cm)
kg	kilogram
kg/L	kilogram per liter
L	liter
lbf/in^2	pounds force per square inch = 0.006895 megapascals (MPa)
m	meter
mil	0.001 inch (in.)
mm	millimeter
MPa	megapascal
s	second (unit of time)
µm	micrometer

ENGLISH SYMBOLS USED IN EQUATIONS

C_D	coefficient of drag
C_L	liquid phase volume fraction
C_s	particulate solid phase volume fraction
d_p, d_{50}	particulate solid phase median size diameter
D	pipe inside diameter
f	pipe friction factor (Darcy) for slurry
f_d	$f - f_v$, pipe friction factor for heterogeneous particulate solid phase of slurry
f_{dj}	heterogeneous contribution to the friction factor for j^{th} particle size in particle size distribution
f_v	pipe friction factor for homogeneous "vehicle" liquid phase of slurry
g	gravitational acceleration
h	fluid head
h_L	head loss
L	length of pipe
n	hindered settling velocity exponent
p	pressure
R	flow regime designation
Re_p	particle Reynolds number
Re_{pipe}	pipe flow Reynolds number
v	slurry velocity
v_{cr}	generic term for critical velocity
v_s	settling velocity
v^*	friction velocity
v_∞	characteristic velocity of a settling particulate
$x_{caustic}$	fraction of dissolved solids composed of sodium hydroxide
x_{salt}	fraction of dissolved solids composed of sodium salts and other salts

GREEK SYMBOLS USED IN EQUATIONS

α_{pump}	pump head operating-to-shutoff factor = 1.3 (typical)
γ	ratio of hindered settling velocity to critical velocity
θ	angle of pipeline relative to horizontal (positive for upward flow)
κ_{cv}	percent root mean square deviation from critical velocity experimental data
ρ_b, ρ_m	bulk density of waste = $C_s \rho_s + (1 - C_s)\rho_L$
ρ_L	carrier liquid phase density
ρ_s	particulate solid phase density
ρ_v	homogeneous "vehicle" density
ρ_{water}	density of water
χ	fraction of the turbulent fluid eddies that possess a velocity larger than the particulate settling velocity
ϕ_{dj}	$\phi_{sj} - \phi_{vj}$, solid concentration of jth binned particle size of the PSD remaining in heterogeneous phase of slurry
ϕ_{sj}	solid concentration at pipe centerline for j^{th} binned particle size of the PSD
ϕ_v	total volume percent solids attributed to homogeneous "vehicle" phase of slurry
ϕ_{vj}	solid concentration for j^{th} binned particle size of the PSD attributed to homogeneous "vehicle" phase of slurry
β	ratio of mass transport coefficient to momentum transport coefficient (see Equation 9)
κ	von Karman boundary-layer constant (see Equation 9)
ε	roughness of pipe
μ_L	carrier liquid phase viscosity
μ_v	homogeneous "vehicle" viscosity
μ_{water}	viscosity of water
Δh	head loss per unit length of pipe

1.0 INTRODUCTION

CH2M HILL Hanford Group, Inc., is responsible for transferring waste at the Hanford Site from waste storage tanks to the Waste Treatment Plant (WTP) for vitrification. As part of the planning process for waste feed delivery (WFD), the capability of the waste transfer system is being evaluated. The waste transfer system comprises transfer pumps, transfer pipelines, transfer system valves, and associated structures and instrumentation used to transport waste between storage tanks and from storage tanks to the WTP. Waste will be pumped out of the tanks using new transfer pumps and will be delivered to the WTP through a combination of new and existing transfer pipelines. Double-Shell Tank (DST) Subsystem specifications provide the basis for the conceptual design of the new and replacement equipment required to provide a safe and reliable system for transferring waste. These specifications will include design criteria for parameters such as pipe size, pipe material, range of flow rates, transfer pump operating conditions, and waste characteristics that include the physical properties of the waste during transfer. This analysis provides a documented basis for DST subsystem specifications for piping and pumps in support of the WFD mission to transfer low-activity waste (LAW) and high-level waste (HLW) within their envelope definitions to the WTP.

Waste has been transferred successfully between tanks at the Hanford Site for more than 50 years. Although a number of pipelines have been plugged during that period, the cause of the plugging generally was attributed to the precipitation of salts as the waste cooled in the pipeline. Previous slurry transfers in the tank farms typically were maintained above a specified flow velocity to ensure that any solids that might be present in the waste would not settle out during the transfer. For approximately the last 20 years, the minimum flow velocity was specified in terms of a minimum Reynolds number of 20,000. In an 80 mm (3-in.) nominal diameter pipeline, this equates to a flow velocity of approximately 1.8 m/s (6 ft/s). To meet the mission of delivering waste feed to the WTP, the existing transfer system must be extended to the location of the proposed WTP. This extension of the transfer system adds approximately 1,100 m (3,600 ft) of equivalent pipe length to connect the existing transfer system to the WTP receiving tanks. Before the preparation of this analysis, several preliminary pressure-drop calculations were performed to evaluate the adequacy of the new waste transfer routes to the WTP. The results of the calculations indicated that the existing transfer pipelines might not be adequate to meet the needs of the WFD program.

The scope of the analysis includes Phase 1 waste transfers from the AN, AP, AW, AY, and AZ tank farms in the 200 East Area to the proposed WTP as well as inter-farm tank-to-tank transfers. This analysis does not evaluate the existing cross-site transfer pipeline system for waste transfers between the Hanford Site 200 West and 200 East Areas. The analysis focuses on the hydraulics of the waste transfer system using available waste physical property data. The analysis also compares the predicted minimum design pressure requirements determined by this analysis to the limiting pressure ratings of 1.9 and 2.7 MPa (275 and 400 lbf/in^2) of the existing and planned project upgrades to the WFD transfer system. Although project upgrade pipelines have specified design pressures of 6.9 and 10 MPa (1,000 and 1,490 lbf/in^2), all pipeline transfer

routes are limited to the lesser of the specified pipe design pressure limit and the jumper connector pressure limit of 2.7 MPa (400 lbf/in^2)[4].

This analysis is concerned with the hydraulics of the waste as it is transported through the transfer system. The transported waste is considered to be a slurry because it comprises a mixture of insoluble particles (solids) and liquid. The Hanford Site tank wastes cover a broad range of chemical compositions with a diversity of physical and rheological properties. This analysis does not address the potential for chemical precipitation or crystallization which is a function of the solubility characteristics of the dissolved multi-constituents of the waste feed, their chemical interaction, pH, and temperature. Nor does this analysis address the dynamic behavior of agglomerate formation and breakup during transfer or the re-suspension of particles following a loss of flow for an extended period of time. Proper line flushing between batch transfers is assumed.

Waste transfer routes were identified for Phase 1 transfers using Hanford Tank Waste Operations Simulator (HTWOS) results given in the *Tank Farm Contractor Operation and Utilization Plan* (HNF-SD-WM-SP-012). Although the transfer plan is not final, it is sufficiently mature to provide representative data for a valid assessment. The physical characteristics of each of these waste transfer routes were identified and used as the basis for the pressure-drop calculations. Transfer system physical characteristics include pipe size, equivalent lengths of the carbon steel and stainless steel portions of the transfer pipeline, changes in elevation over the transport route, and pipe interior surface roughness. The transfer routes that were evaluated comprise the existing transfer-system infrastructure and the modifications that are planned or in progress for Projects W-211, W-314 and W-521. Each transfer route includes one or more pipeline segments, where each segment connects one valve pit to another. Many of the pipeline segments are used in common in the various transfer routes.

The preferred approach is to identify the transfer waste physical properties for each transfer and then calculate the pressure drop through the planned transfer routes using the transfer-specific waste properties. The pressure drop information is used to determine the pipe and pump design pressure requirements. Calculation of the pipeline system pressure drop requires knowledge of the transferred waste physical properties at the transferred waste temperature (including heat up from mixer pumps), a complete description of the pipeline system transfer route, and the current and projected end-of-life pipe roughness. Waste properties include the liquid density, liquid viscosity, particle density, particle size distribution (PSD) by volume, and volume percent solids.

However, on reviewing currently available waste-physical property information, it was found that there is insufficient transfer-specific waste physical property data available to perform transfer-specific pressure drop calculations. Additionally, the WFD plan for waste transfers, which identifies individual tank-to-tank and tank-to-WTP waste transfer routes, has not been finalized. Identification of individual waste transfer routes is required to determine the physical route of the transfer pipeline for estimating the system pressure drop and determining the pump design requirements and the minimum pressure rating of the piping.

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[4] Jumper connectors are currently qualified to only 1.7 MPa (250 lbf/in^2) by historic leak tests (RPP-5793 and RPP-6984) and to 2.7 MPa (400 lbf/in^2) by recent analysis (RPP-8359). Plans for jumper connector qualifying leak tests to a pressure of at least 2.7 MPa (400 lbf/in^2) are under development.

In the absence of complete transfer-specific waste-property data for each transfer and a final plan for waste transfers, transfer-specific/transfer route pressure drops for each of the waste transfers could not be calculated with a high degree of confidence at this time. Because of the lack of transfer-specific waste physical property data, the commonality of the pipeline segments used in the various transfer routes, and the need to provide maximum flexibility in transfer strategy for utilization of the of transfer system a conservative analysis is required to ensure sufficient robustness in the transfer system. Included in the analysis is a set of design basis waste properties. The analysis provides a means to assess the sensitivity of the results to variations in the waste transfer conditions and to provide a screening tool for quickly evaluating particular transfer conditions.

This revised analysis updates the equivalent pipeline lengths for the WFD transfer routes and the waste transfer temperature to include mixer pump induced heating of the waste for HLW transfers. In addition, this revised analysis applies the recent expert panel recommended particle size distribution, particle density, and viscosity for the WFD transfer system analysis (Jewett et al. 2002). An extensive laboratory program was conducted to produce better estimates of particle size and particle density in the HLW feeds. Results are reported in HNF-8862. Viscosity measurements have been obtained in another laboratory program conducted over the past few years. A multi-company panel of experts was formed to review the results of the laboratory analysis and other available Hanford waste physical property data to provide recommend particle size, particle density, and viscosity information for the WFD transfer system analysis.

Results from these analyses can be used as a basis for establishing design requirements and assessing the sensitivity of the various independent parameters on the pressure requirements of the WFD system. The results can be used also in determining any need for engineering changes (re-rating of existing or planned pipeline segments, upgrading connectors, installation of booster pumps, etc.), operational changes (shorter batch transfers, more frequent flushes, etc.), or changes in transfer strategy (reduction in insoluble particle concentration, use of intermediate staging tank, etc.). In addition, these results can be used to focus direction on any need for additional data (waste physical properties, pipe roughness, correlation validation, etc.).

Correlations for determining critical velocity and pressure drop resulting from friction losses in the waste transfer system are discussed in Section 2.0. The various sources of information for the waste properties and transfer system characteristics are identified and some of the shortcomings in the data are discussed in Section 3.0. An evaluation of the results of the analysis is included in Section 4.0, along with a description of some of the uncertainties associated with the analysis. Conclusions and recommendations are presented in Section 5.0. References cited in the text are listed in Section 6.0.

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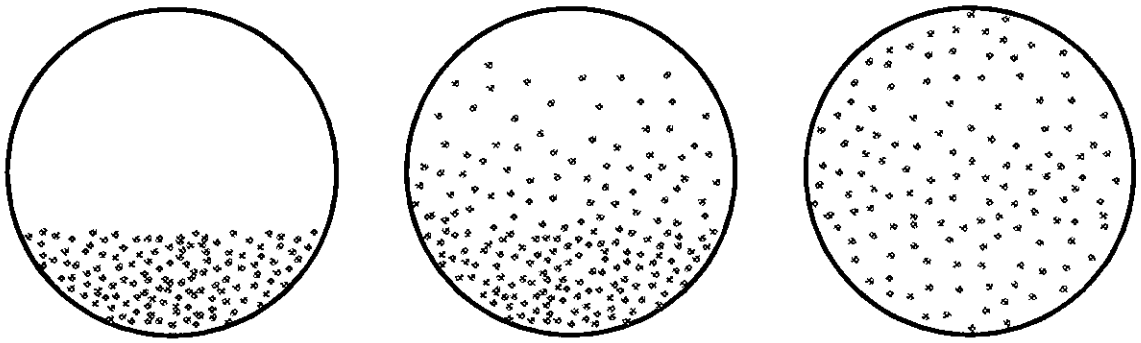
2.0 WASTE FLOW CHARACTERISTICS

Transfer of waste from the tanks to the WTP will require pumping a mixture of liquids and solids through the waste transfer system. These mixtures are commonly referred to as suspensions or slurries. Prediction of the flow characteristics of a slurry often is more difficult than for a single-phase fluid because of the large number of variables required to describe the flow and the complexity of the solid-to-liquid interactions. Before the flow characteristics of the transfer system can be analyzed, the behavior of the slurry must be classified.

2.1 CLASSIFICATION OF SLURRIES

A large number of empirically based correlations have been developed to describe the behavior of slurries as they flow through piping systems. The correlations of interest in this analysis address flows with solids that are fully suspended. These correlations are divided broadly into two categories that treat the slurry as either a homogeneous mixture or a heterogeneous mixture. Within each of these categories, the slurry may be treated as either a single-phase or a multi-phase mixture. Although transport slurry may be classified as either homogeneous or heterogeneous, it is far more common for the slurry to exhibit characteristics of both. Figure 2-1 shows a comparison of the distribution of solids for different categories of flow. The proper classification of slurry behavior is essential if the flow characteristics of the transfer system are to be modeled accurately.

Figure 2-1. Flow Regimes.



Fully Segregated Flow (Moving or Stationary Bed) | Heterogeneous Flow | Homogeneous Flow

Homogeneous flow describes the condition where the solid particles are distributed uniformly throughout the cross-section of the pipe. An inherently homogeneous flow generally is found in slurries containing high concentrations of solids and small particle sizes (i.e., particle diameter <50 μm). Homogeneous behavior also can be found in slurries with larger particle sizes where the solid-to-liquid density ratio is small or in slurries that flow with sufficient turbulence to distribute the particles evenly. The effect of the small particles in a homogeneous slurry is to increase the viscosity of the mixture as the solids concentration increases. At higher concentrations, the mixture likely will begin to exhibit non-Newtonian behavior. The point at

which non-Newtonian behavior begins is difficult to predict because it is a function of the particle size distribution (PSD), particle shape, solids concentration, solid-to-liquid density ratio, and particle surface forces. Another characteristic of homogeneous flow is that the viscous or turbulent forces are dominant and the particle inertial forces are small. In the case of inherently homogeneous slurries, this characteristic results in a slurry that can flow at very low velocities without settling and allows the slurry to be treated as a single-phase fluid. Examples of slurries that are inherently homogeneous include concentrated suspensions of fine limestone, paint, and ink.

Heterogeneous flow occurs when the solid particles are not distributed evenly across the cross section of the pipe although the particles are in suspension. The flow is characterized by a vertical concentration gradient in a horizontal pipe. Heterogeneous flow generally is found in slurries with low concentrations of solids and larger particle sizes. It also can be found in slurries with smaller particle sizes when the solid-to-liquid density ratio is large. The larger particles found in heterogeneous flow do not have a significant effect on the viscosity of the mixture, and the flow is usually Newtonian in nature. Slurries with a broadband distribution of particle sizes may exhibit non-Newtonian behavior as the fine particles change the behavior of the liquid phase and the larger particles are carried along in a heterogeneous suspension. The particle inertial forces are more significant in heterogeneous flow because of the mass of the particles; therefore, the liquid and solid phases of the mixture are considered separately. Examples of slurries that behave heterogeneously include mixtures of sand or coal in water.

Although no single waste characteristic can be used to classify the behavior of a slurry, the particle size and the ratio of particle density to liquid density are important parameters. Documented PSDs for the double-shell tanks (DST) cover a wide range of values. Some tanks, such as Tank 241-SY-101, contain particles that range from <1 μm to >1000 μm (O'Rourke 1999, *Results of Viscosity Measurements of Tank 241-SY-101 Samples*). Similarly, Tank 241-AW-101 covers a range of ~6 μm to >1000 μm (HNF-4964, *Results of Dilution Studies with Waste from Tank 241-AW-101*). Tank 241-AZ-101 has a range of 5 μm to 225 μm (WHC-SD-WM-ER-410, *Tank Characterization Report for Double-Shell Tank 241-AZ-101*). Other tanks have narrower distributions, such as Tank 241-AN-104 with a range of <1 μm to 40 μm (HNF-3352, *Results of Dilution Studies with Waste from Tank 241-AN-104*) and Tank 241-AN-105 with a range of <1 μm to 40 μm (HNF-SD-WM-DTR-046, *Results of Dilution Studies with Waste from Tank 241-AN-105*). Based on the data available, the range of particle sizes is so broad that the waste slurry that will be transferred cannot be classified as exhibiting either homogeneous or heterogeneous behavior. The waste slurry will exhibit some combination of homogeneous and heterogeneous behavior depending on the mixture velocity, the ratio of particle density to liquid density, and the PSD by volume.

Within the categories of homogeneous and heterogeneous slurries, the rheology of the slurry can be classified as either Newtonian or non-Newtonian. Viscosity is a measure of a fluid's resistance to deformation and is defined as the ratio of shear stress to shear rate. For a Newtonian fluid, the ratio of shear stress to shear rate is constant over a defined range of shear rates. In a Newtonian slurry, the viscosity does not change as the flow velocity in the transfer system pipe changes. Typical non-Newtonian slurries are characterized by viscosities that increase (shear thickening) or decrease (shear thinning) with increasing flow velocity and often have a yield strength that must be overcome before flow will occur. Viscosity measurements are

not available for a majority of the tank waste, and the data that are available do not necessarily reflect the condition of the waste when it will be pumped through the waste transfer system. HLW tanks will be mixed to homogenize the waste, which will then be pumped to the WTP. For LAW tanks the supernatant will be pumped off first, the remaining solids will be dissolved, and the remaining waste will be transferred to the WTP. The content of some tanks will be mixed together, potentially changing the rheology of the waste before it is transferred to the WTP. To properly model the flow characteristics of the waste, it is necessary to understand its rheology. In the absence of specific data, and given that it is extremely difficult to accurately predict the viscosity of a mixture based on its individual constituents only, some simplifying assumptions have been made.

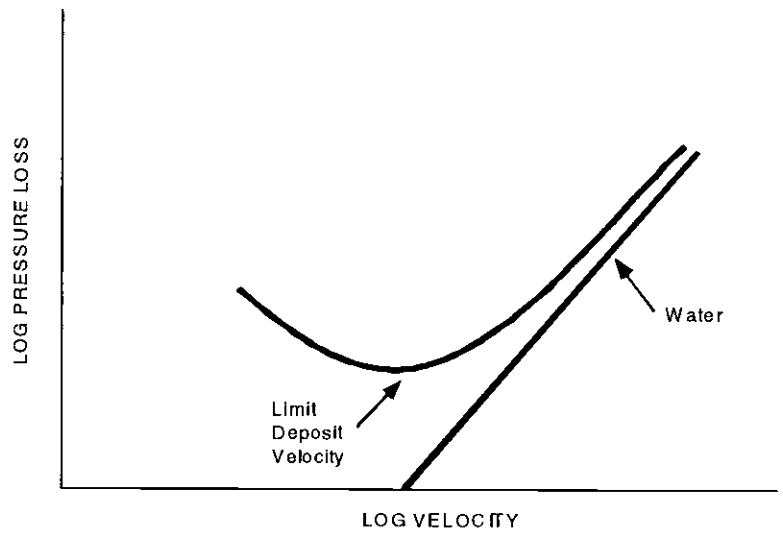
Documented viscosity measurements indicate that the waste samples are predominately Newtonian. However, some samples exhibit non-Newtonian behavior. When reviewing the non-Newtonian test data, it was noted that most of the measurements were performed on tank samples that are not representative of the condition of the waste when it will be pumped. The waste samples typically are representative of in situ tank conditions and do not duplicate the dissolution of salts and mixing of the waste that will occur before being transferred. Dissolution and mixing in the tank has the effect of reducing the solids volume percent below the levels that would be found in a sample taken from a settled, undiluted tank. As the volume percent of solids is reduced, the behavior of the waste will tend toward Newtonian behavior. The non-Newtonian behavior primarily is a result of the presence of the solids in the slurry. It is important to note that there is the possibility that some wastes may be non-Newtonian when they are transferred. As more representative sample data are obtained, it may be possible to predict non-Newtonian behavior. Based on the data available and the anticipated waste characteristics, the waste that will be pumped through the transfer system will be modeled as Newtonian for the purposes of this analysis.

In analyzing the waste transfer system, it is necessary to determine the critical velocity and the relationship between flow rate and pressure drop. The critical velocity is the minimum velocity that should be maintained to ensure stable and reliable operation of the system. Knowledge of pressure drop through the waste transfer system is required to establish the pipe design pressure and pump head requirements. Because the number and range of variables affecting slurry flow are large and the mechanics of the solid-to-liquid interactions are complex, no purely analytical solutions are available. Instead, the equations presented in this analysis are correlations based on published data that were developed to predict critical velocity and pressure drop in slurry pipelines. The correlation for critical velocity is described in Section 2.2. The correlation for predicting pressure drop is discussed in Section 2.3. For a more detailed discussion of slurry flow and the derivation of these correlations, see Oroskar and Turian 1980, "The Critical Velocity in Pipeline Flow of Slurries;" HNF-2728, *Flow Velocity Analysis For Avoidance of Solids Deposition During Transport of Hanford Tank Waste Slurries*; RPP-7185, *Critical Transport Velocity: A Review of Correlations and Models*; and Wasp et al. 1977, "Solid-Liquid Flow Slurry Pipeline Transportation."

2.2 CRITICAL VELOCITY

In heterogeneous flow, operation of the waste transfer system below a specified minimum velocity will result in solids settling or sliding along the bottom of the pipe. Continued operation below the critical velocity eventually will lead to plugging of the pipe. The critical velocity for heterogeneous slurry flow is the velocity at which the solids begin to settle and is called the limit deposit velocity. The limit deposit or deposition velocity for heterogeneous slurry flow is usually in the turbulent flow regime. Figure 2-2 shows the relationship between pressure loss and flow velocity for heterogeneous slurry flow.

Figure 2-2. Pressure Loss versus Velocity for Heterogeneous Slurry Flow. (Wasp et al. 1977)

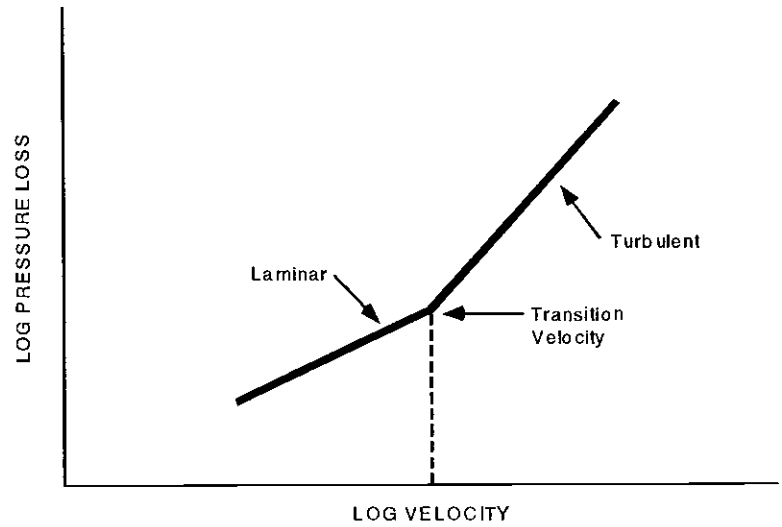


In homogeneous flow, the critical velocity corresponds to the point at which the flow transitions to a turbulent flow regime. In purely homogeneous flow, deposition of solids does not occur below some minimum velocity. Nevertheless, it is desirable to maintain flow above the laminar-to-turbulent transition region (Reynolds number approximately >4,000) to ensure stable flow. In this analysis, both the limit deposit velocity and the transition velocity are calculated, and the greater of the two values is identified as the critical velocity. Figure 2-3 shows the relationship between pressure loss and flow velocity for inherently homogeneous slurry flow.

The concept of critical velocity is very useful in designing slurry transport systems. If the flow rate is less than the critical velocity, buildup of solids will occur and the line will possibly plug. If flow is maintained above the critical velocity, plugging of the transfer line as a result of solids settling out will be avoided. All that remains is to predict the critical velocity accurately. When working with heterogeneous slurries, a large number of correlations are available to predict the limit deposit velocity. Most of the correlations are derived empirically for a specific range of slurry properties. If the correlations are applied to slurries other than those for which they were derived, agreement is generally poor between the various correlations and actual operating and test data. When designing a transport system for a known slurry composition, it is always preferable to determine the critical velocity by test. In the absence of actual test data, some correlations have been shown to be more accurate than others. An evaluation of seven different correlations reviewed in HNF-2728 found that the Oroskar and Turian (1980) correlation was the

most sophisticated and yielded the most conservative results over the range of waste characteristics expected at the Hanford Site. Figure F-15 of Appendix F compares a number of correlations in addition to comparisons given in HNF-2728.

Figure 2-3. Pressure Loss versus Velocity for Homogeneous Slurry Flow. (Wasp et al. 1977)



The Oroskar and Turian (1980) empirical equation was developed as an extension of their semitheoretical correlation to improve the accuracy of the critical velocity prediction. It is based on extensive slurry flow research and was slightly more accurate than the semitheoretical correlation. The Oroskar and Turian (1980) correlation for limit deposit velocity is given by

$$v_{cr} = \sqrt{g\, d_p \left(\frac{\rho_s}{\rho_L} - 1\right)}\; 1.85\, C_s^{0.1536} C_L^{0.3564} \left(\frac{d_p}{D}\right)^{-0.378} \left(\frac{D \rho_L \sqrt{g\, d_p \left(\frac{\rho_s}{\rho_L} - 1\right)}}{\mu_L}\right)^{0.09} \chi^{0.30} \qquad (1)$$

where

v_{cr} = critical velocity
g = gravitational acceleration
d_p = median particle diameter, d_{50}
ρ_s = solids density
ρ_L = liquid density
C_s = solids volume fraction
C_L = liquid volume fraction = 1 - C_s
D = pipe inside diameter
ρ_L = liquid viscosity
χ = eddy velocity factor.

In formulating their correlation for critical velocity, Oroskar and Turian (1980) developed the concept that the turbulent eddy currents in the slurry flow are responsible for keeping the solids suspended. Because only a fraction of the eddies are effective in lifting the particles, the eddy velocity factor was derived to account for this effect and is given by

$$\chi = \frac{2}{\sqrt{\pi}}\left[\frac{2\gamma}{\sqrt{\pi}}\exp\left(\frac{-4\gamma^2}{\pi}\right)+\frac{\sqrt{\pi}}{2}\left(1-\mathrm{erf}\left(\frac{2\gamma}{\sqrt{\pi}}\right)\right)\right] \tag{2}$$

where

$$\gamma = \frac{v_s}{v_{cr}} \tag{3}$$

v_s = particle hindered settling velocity,
erf = error function.

See Figure F-4 of Appendix F for a plot of χ versus γ. The hindered settling velocity, v_s, is the settling velocity of a particle that takes into account collisions with other particles, and is a function of the concentration of particles in the slurry:

$$v_s = v_\infty \left(C_L\right)^n \tag{4}$$

where

$$n = 4.65 - \frac{2.32}{\sqrt{0.5\pi}}\int_{-\infty}^{\infty}\exp\left(\frac{-\log\left(\mathrm{Re}_p\right)^2}{0.5}\right)d\left(\log\left(\mathrm{Re}_p\right)\right) \tag{5}$$

and the particle Reynolds number is defined as

$$\mathrm{Re}_p = \frac{d_p v_\infty \rho_L}{\mu_L} \tag{6}$$

The analytical expression for "n" given in Equation 5 was derived by Estey and Hu (HNF-2728) as an approximation to the graphical relation given by Oroskar and Turian (1980). See Figure F-3 of Appendix F for plot of "n" versus the particle Reynolds number. The particle Reynolds number is approximated by assuming the particles are spherical.

The terminal (free fall) settling velocity, v_∞, of a spherical particle in a stagnant unbounded liquid is given by

$$v_\infty = \sqrt{\frac{\frac{4}{3}d_p\left(\frac{\rho_s}{\rho_L}-1\right)g}{C_D}} \tag{7}$$

The drag coefficient, C_D, for a sphere is given by:

$$C_D = \left[\left(\frac{24}{Re_p} \right)^{1/2} + 0.34035 \left(Re_p^{0.06071} + \frac{1}{1.72013 + 0.018\, Re_p} \right) \right]^2 \tag{8}$$

See Figure F-2 of Appendix F for plot of drag coefficient versus the particle Reynolds number. Note that an iterative procedure is required to obtain v_∞ because it is implicitly defined in Equation 7 through the particle Reynolds number (Equation 6) as used in Equation 8 for the particle drag coefficient.

The above empirical correlation (Equation 1) is one of the better correlations for predicting critical velocity, with an overall 21.8% root mean square deviation compared with experimental data (Oroskar and Turian 1980). Note that the critical velocity, v_{cr}, is implicitly defined in Equation 1 with the introduction of Equations 2 and 3. Hence, an iterative procedure is required to obtain the critical velocity.

Equation 1 is based on data from single-component density particles forming narrowband PSDs. The lower limit of the median particle size data used in the development of Equation 1 was 100 μm. The use of Equation 1 for multi-component density particles, broadband PSDs, and/or median particle sizes less than 100 μm requires extrapolation beyond the database used in the development of Equation 1. Hence, Equation 1 should be used with caution when applied for any of these conditions. The insoluble particles in Hanford waste can best be characterized as multi-component density particles forming broadband PSDs with median particle sizes by volume ranging from 5 μm to potentially 275 to 400 μm.

In an attempt to account for the beneficial effect of the finer particles in the broadband PSDs, the Oroskar and Turian critical velocity correlation is applied with the "vehicle" density and viscosity and "bed" solids concentration as determined in Section 2.3. This is defined as the "Wasp-modified" Oroskar and Turian critical velocity method.

Although it is recognized that no published critical velocity correlations are directly applicable to the multi-constituent broadband PSDs typical of Hanford HLW slurries, the Oroskar and Turian (1980) correlation was selected based on recommendations from two literature surveys: HNF-2728, *Flow Velocity Analysis for Avoidance of Solids Deposition During Transport of Hanford Tank Waste Slurries*; and RPP-7185, *Critical Transport Velocity: A Review of Correlations and Models*. In RPP-7185 the authors recommended the Oroskar and Turian (1980) and Gillies and Shook (1991) correlations as the most likely candidates for use in the WFD analysis. The Gillies and Shook correlation (see Section 6.2.4 of Appendix F) was developed for broadly graded slurries consisting of a mixture of particles at least 150 μm in diameter and much smaller particles in a pseudohomogeneous vehicle. As such, the Gillies and Shook correlation was considered potentially more capable of better predictions of the behavior of tank solids than the equation of Oroskar and Turian, which is the result of multi-linear regression of a large amount of literature data, much of it for monosized particles. However, because of the arbitrary cutoff between the coarse and fine particles of 74 μm and uncertainties in the detail character of the PSD, the Gillies and Shook correlation should be used with caution.

Because no satisfactory deposition critical velocity correlation exists for the broadband PSD typical of Hanford HLW, Wasp[5] proposed the following "stability" criterion in place of the deposition critical velocity criterion. Wasp's criterion for a stable pipeline flow (constant discharge pressure and minimized plugging tendency) is that the "bed" pressure drop is equal to or less than 5% of the total pressure drop. The "bed" pressure drop (see Section 2.3 below) is defined as the excess pressure drop over that which would occur in a homogeneous fluid of the same bulk properties.

2.3 PRESSURE-DROP CORRELATIONS

There are a number of correlations that have been proposed for predicting pressure drop in slurry transport systems. The correlations generally fall into the semitheoretical or empirical categories. The weakness with most of the correlations is their inability to predict the pressure drop accurately for slurries with a wide range of slurry properties and flow regimes. Wasp et al. (1977) proposed a correlation for calculating pipeline pressure loss for a slurry with a broadband PSD that accounts for a combination of heterogeneous and homogeneous flow. The correlation employs the concept of a "two-phase vehicle" to describe the homogeneous portion of the flow. It postulates that the concentration and size distribution of the particles that are found at the top of the pipe are equally distributed throughout the pipe. These equally distributed particles and the carrier liquid form the homogeneous "vehicle" portion of the slurry. The method adjusts the density and viscosity of the carrier liquid to account for the effects of the smaller particles in the homogeneous portion of the slurry. The particles that are not equally distributed across the pipe comprise the heterogeneous portion of the slurry. These particles are suspended and carried along by the homogeneous "vehicle" portion of the slurry. Using this concept, the total pressure drop in the system is calculated by summing the pressure-drop contribution from the homogeneous "vehicle" and the additional pressure drop resulting from the remaining heterogeneous suspension.

The Wasp et al. (1977) correlation defines a criterion for determining which portion of the slurry is treated as part of the "vehicle" based on experimental data from Ismail (1952), "Turbulent Transfer Mechanism and Suspended Sediment in Closed Channels." The correlation considers a slurry to be homogeneous when the ratio of the solid concentration (ϕ) at 0.08 inside pipe diameter (D) from the top of the pipe to the solid concentration (ϕ_s) at the pipe centerline is at least 0.8. Wasp et al. (1977) provided the following empirical relationship for determining the concentration ratio for each particle size in the PSD that joins the carrier liquid to form the homogeneous "vehicle" phase:

$$\log_{10}\frac{\phi_{vj}}{\phi_{sj}} = -\left(\frac{1.8v_{-j}}{\beta\kappa v^*}\right) \tag{9}$$

[5] Personal communication on March 2, 2002 with Edward J. Wasp, President of STI International Associates, San Rafael, California.

where

ϕ_{sj} = solid concentration at pipe centerline for j^{th} binned particle size in the PSD

ϕ_{vj} = solid concentration for j^{th} binned particle size in the PSD that joins with the carrier liquid to form the homogeneous "vehicle" portion of the slurry

β = constant for a given particle size, varying from 1.0 for fine particles less than approximately 100 μm to 1.3 for coarse particles on the order of 0.1 mm. A value of $\beta = 1.0$ was used in this analysis.

κ = von Karman boundary-layer constant, varying from 0.4 for clear liquids to 0.25 for large solids concentrations. A value of $\kappa = 0.4$ was used in this analysis.

The terminal settling velocity, $v_{\infty j}$, for the jth binned particle size in the PSD is calculated from Equation 7 but using the "vehicle" modified carrier liquid density (ρ_v) and viscosity (ρ_v) properties as defined below.

The friction velocity, v^*, is defined as

$$v^* = v\sqrt{\frac{f_w}{8}} \tag{10}$$

where

f_w = $f_v + f_d \cos\theta$

f_v = homogeneous "vehicle" contribution to the friction factor

f_d = $f_w - f_v$ = heterogeneous "bed" contribution to the friction factor in a horizontal pipe

v = bulk velocity of the slurry.

The $\cos\theta$ factor accounts for pipe slope from horizontal per Blevins (1984), *Applied Fluid Dynamics Handbook.*

The homogeneous "vehicle" friction factor, f_v, is calculated using an equation developed in Churchill (1977), "Friction Factor Equation Spans All Fluids Regimes," which is valid for the laminar, transition, and turbulent flow regimes and is given by

$$f_v = 8\left[\left(\frac{8}{Re_{pipe}}\right)^{12} + (A+B)^{-3/2}\right]^{1/12} \tag{11}$$

where

$$A = \left[2.457 \ln \left(\frac{1}{\left(\frac{7}{Re_{pipe}} \right)^{0.9} + 0.27 \left(\frac{\varepsilon}{D} \right)} \right) \right]^{16} \tag{12}$$

ε = roughness of pipe

$$B = \left(\frac{37{,}530}{Re_{pipe}} \right)^{16} \tag{13}$$

See Figure F-11 in Appendix F for plot of the Darcy friction factor given by Equation 11 versus pipe Reynolds number and pipe roughness. The pipe Reynolds number, Re_{pipe}, is calculated as follows:

$$Re_{pipe} = \frac{\rho_v v D}{\mu_v} \tag{14}$$

where

ρ_v = density of the homogeneous "vehicle" phase of slurry
μ_v = viscosity of the homogeneous "vehicle" phase of slurry.

The viscosity of the "vehicle", μ_v, can be calculated using the correlation given in Thomas (1965), "Transport Characteristics of Suspensions: Part VIII. A Note on the Viscosity of Newtonian Suspension of Uniform Spherical Particles," as

$$\mu_v = \mu_L \left(1 + 2.5\, \Phi_v + 10.05\, \Phi_v^2 + 0.00273 \exp\left(16.6\, \Phi_v \right) \right) \qquad \text{Thomas relation} \tag{15}$$

where

Φ_v = total "vehicle" solids concentration = $\Sigma\, \phi_{vj}$, summed over each binned particle size in the PSD.

The viscosity of the carrier liquid, μ_L, is described in Appendix A and is given as

$$\mu_L = \mu_{water} \left[x_{salt} \left(1 + 1.071 \left(\frac{\rho_L}{\rho_{water}} - 1 \right) \right) + x_{caustic} \exp\left(\left(7.143 \left(\frac{\rho_L}{\rho_{water}} - 1 \right) \right)^{1.15} \right) \right] \tag{16}$$

where

μ_L = viscosity of carrier liquid
μ_{water} = viscosity of water at temperature
ρ_{water} = density of water at temperature
ρ_L = density of carrier liquid
x_{salt} = fraction of dissolved solids composed of salts (assume equal to 0.9 if not known)
$x_{caustic}$ = $(1 - x_{salt})$
= the fraction of dissolved solids composed of caustic (sodium hydroxide).

The "vehicle" liquid density, which reduces to the bulk density as Φ_v approaches C_s, is given by

$$\rho_v = \rho_s \Phi_v + \rho_L (1 - \Phi_v) \tag{17}$$

A graph of "vehicle" to liquid viscosity (Thomas) and density ratios versus solids content is shown in Figure 2-4a. The Thomas relation is valid for low concentrations of solids (< 2 vol%) but generally under predicts the viscosity at higher solids concentration. The Thomas relation given in Equation 15 may be used if no viscosity data is available. As part of the recent expert panel review of the Hanford HLW physical properties (Jewett et al. 2002), the following best-estimate and bounding viscosity relations, respectively were recommended for the WFD transfer system analysis based on regression analysis of Hanford HLW viscosity data:

$$\mu_v = 2.0[1 + 2.5\Phi_v + 10.05\Phi_v^2 + 1.3\{\exp(17\Phi_v) - 1\}] \cdot \gamma^{-0.06} \quad \text{best-estimate} \tag{18}$$

$$\mu_v = 1.6\,(1 + 2.5\Phi_v + 10.05\Phi_v^2 + 21\exp 39\Phi_v) \cdot \gamma^{-0.75} \quad \text{bounding-estimate} \tag{19}$$

where the strain rate, γ, for a turbulent pipe flow is expressed by (Wasp et al. 1977)

$$\gamma = \frac{8\,v}{D} \tag{20}$$

and D is the pipe diameter and v is the slurry flow velocity. A comparison of the Thomas viscosity correlation to the best-estimate and bounding viscosity relations is shown in Figure 2-4b. Note the strong strain rate dependence in the bounding viscosity estimate and the weak dependence in the best-estimate viscosity relation. These relations were considered valid for $0 < \Phi_v < 10$ vol%. Note that Equations 18 and 19 are independent of temperature. The temperature dependence was found not to be significant compared to the solids concentration, strain rate, and tank-to-tank variations (Jewett et al. 2002).

Figure 2-4a. "Vehicle" to Liquid Density and Viscosity (Thomas) Ratios versus "Vehicle" Solids Concentration.

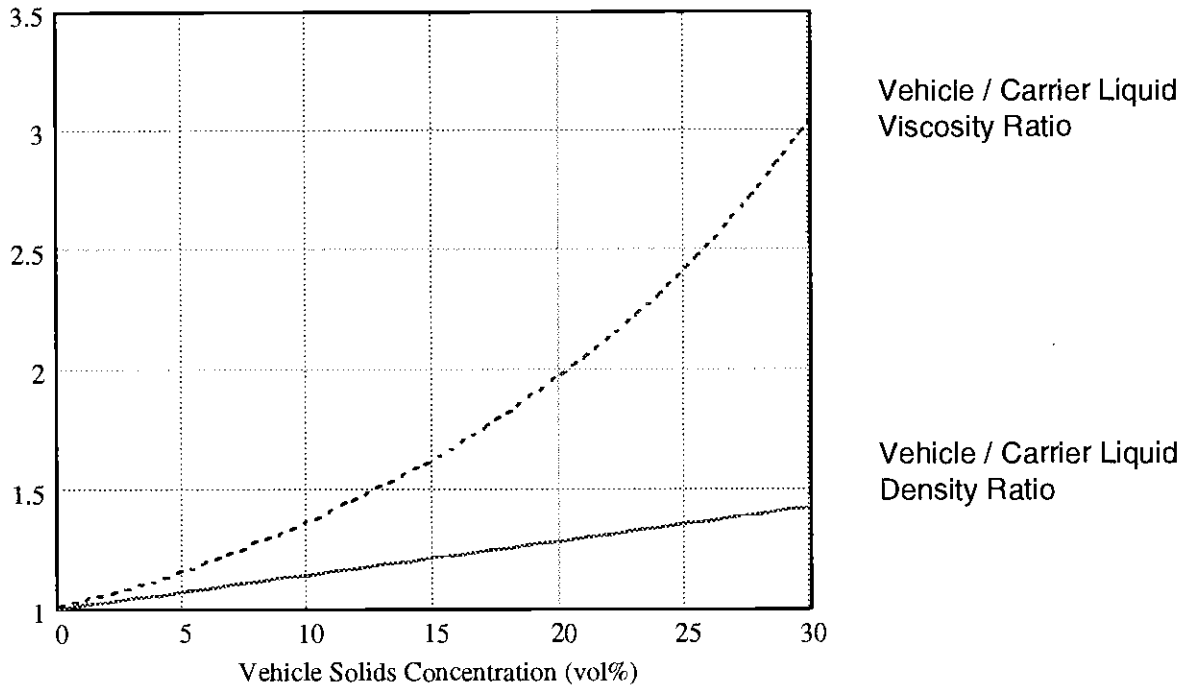
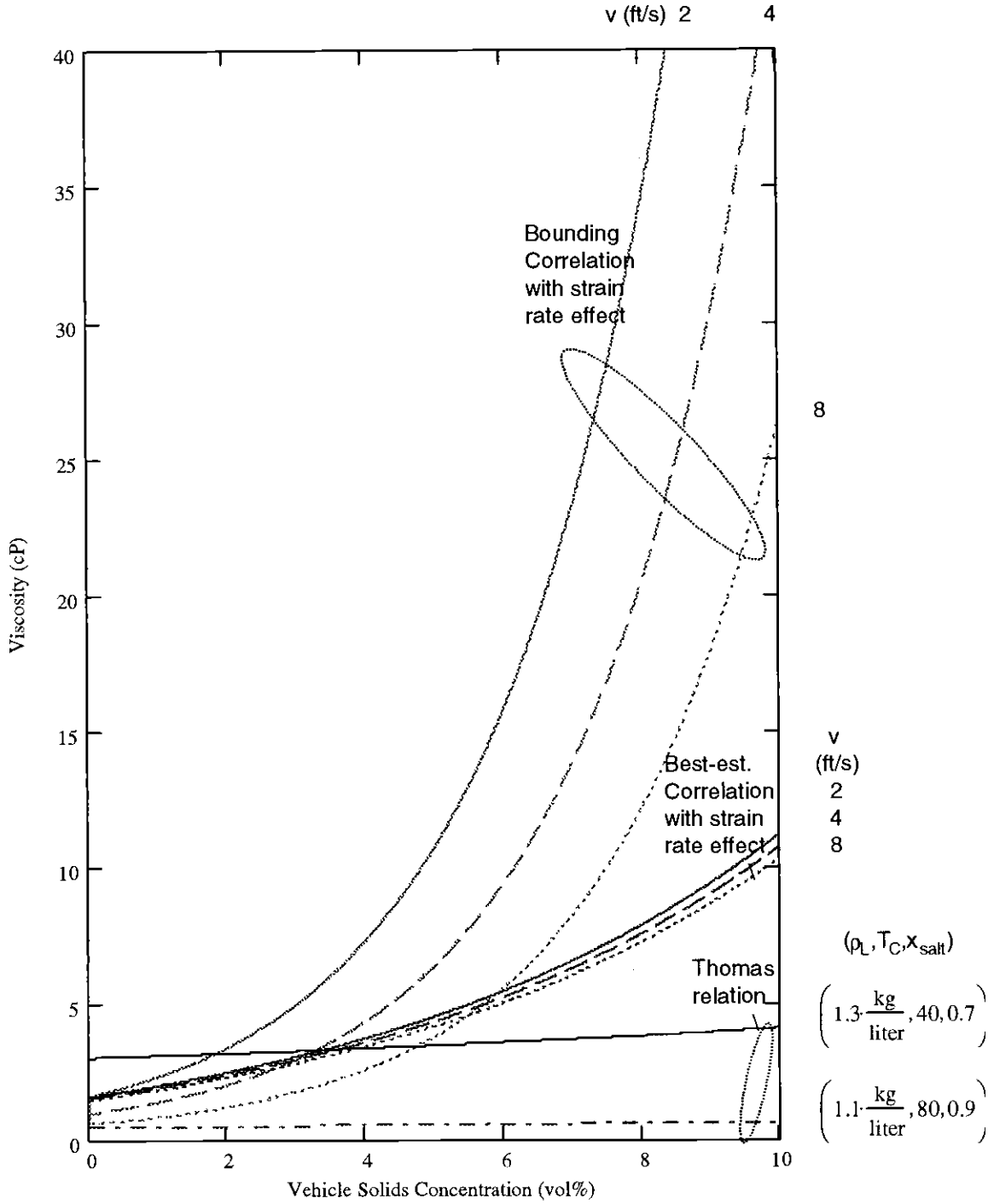


Figure 2-4b. Comparison of Viscosity Correlations.



The determination of pressure loss in a piping system using the Wasp et al. (1977) correlation involves an iterative process. The first iteration assumes that the solids form part of the "vehicle." The head loss in the system that is attributable to the "vehicle" is calculated using Darcy's formula

$$\Delta h_v = \frac{h_L}{L} = \frac{f_v v^2}{2gD} \tag{21}$$

where

f_v = pipe friction factor (Darcy) for "vehicle" (Equation 11)
Δh_v = head loss per unit length of pipe attributed to homogeneous "vehicle"
h_L = head loss
L = length of pipeline.

The ratio of ϕ_v/ϕ_s for each size fraction of particles is calculated and multiplied by the volume percent solids of that size fraction to determine the "vehicle" portion of the slurry. The balance of the solids is assumed to be part of the heterogeneous suspension. A second iteration is performed to determine the head loss attributable to the "vehicle." The head loss attributable to the heterogeneous "bed" portion of the slurry is calculated for each size fraction of particles using the correlation in Durand (1953), "The Hydraulic Transportation of Coal and Other Materials in Pipes," as

$$\Delta h_{dj} = 82 \cdot \Delta h_{carrier}\, \phi_{dj} \left[\frac{g\, D \left(\frac{\rho_s}{\rho_L} - 1 \right)}{v^2 \sqrt{C_{Dj}}} \right]^{1.5} = \frac{f_{dj} v^2}{2gD} \tag{22}$$

where

f_{dj} = heterogeneous "bed" contribution to the friction factor for j^{th} binned particle size in the PSD

$\Delta h_{carrier}$ = head loss per unit length attributable to "vehicle" relative to carrier liquid, i.e.,

= $\Delta h_v \frac{\rho_v}{\rho_L}$

ϕ_{dj} = heterogeneous volume percent solids for j^{th} binned particle size fraction of the PSD

= $\phi_{sj} - \phi_{vj}$

C_{Dj} = drag coefficient of jth binned particle size of the PSD using Equation 8 with carrier liquid density (ρ_L) and viscosity (μ_L) properties.

The head losses for each of the size fraction of the PSD are added together to determine the total head loss attributable to the heterogeneous portion of the slurry. This is added to the head loss for the "vehicle" to obtain the total friction head loss. The "vehicle" head loss must be converted to the carrier liquid before adding it to the heterogeneous portion of the slurry to maintain a consistent basis. Additional iterations are performed until the difference in head loss between successive iterations converges within some small tolerances. The described methodology has been modified slightly for this analysis to include the effects of elevation changes along the pipe route. The equation for pressure loss includes a cos θ factor to account for friction losses as the slurry travels through an inclined pipe according to Blevins (1984), *Applied Fluid Dynamics Handbook* (see Equation 10). The resulting total head loss, including the change in elevation, is given by

$$h_L = \frac{Lv^2}{2gD}(f_w) + \left[\left(\frac{\rho_s}{\rho_L} - 1\right)C_s + 1\right] L \sin\theta \tag{23}$$

where

h_L = head loss

θ = angle of inclination of pipeline from horizontal.

Because some transfer routes contain a combination of carbon steel and stainless steel pipe lengths, the pressure drop is calculated for each respective length with the corresponding pipe roughness for carbon and stainless steel (see Section 3.2.2) to obtain the total head (or pressure, $\Delta p_L = \rho_L\, g\, h_L$) loss.

2.4 EFFECT OF VARIATIONS ON CRITICAL VELOCITY AND PRESSURE DROP

The variables required to determine critical velocity and pressure drop have been identified in Sections 2.2 and 2.3, respectively. While it is evident that the equations are nonlinear, it is not obvious what effect a change in these variables will have on the critical velocity and pipeline pressure drop. Table 2-1 lists the key variables and indicates the general impact that a variation will have on critical velocity and pipeline pressure drop. The effect on pressure drop assumes that the flow velocity is above the critical velocity.

Table 2-1. Key Variables.

Variable	Change	Critical Velocity	Pressure Drop
Liquid density	raise	↓	↑
	lower	↑	↓
Liquid viscosity	raise	↓	↑
	lower	↑	↓
Solids size	raise	↑	↑
	lower	↓	↓
Solids density	raise	↑	↑
	lower	↓	↓
Solids volume fraction	raise	↑	↑
	lower	↓	↓
Pipe inside diameter	raise	↑	↓
	lower	↓	↑
Pipe roughness	raise	n/a	↑
	lower	n/a	↓
Pipe length	raise	n/a	↑
	lower	n/a	↓
Pipe incline to horizontal	raise	n/a	↑
	lower	n/a	↓
Flow velocity	raise	n/a	↑
	lower	n/a	↓

3.0 WASTE TRANSPORT BEHAVIOR

The WFD mission is to transfer LAW and HLW within their envelope definitions to the WTP. LAW consists of the tank waste liquids (and dissolved salt cake) and contains the bulk of the tank waste chemicals and certain radionuclides. The LAW (supernatant) feeds may contain up to 2 wt% solids (insoluble particles), which corresponds to less than 1 vol% solids. Solids are defined as the product of centrifuging the LAW feed, separating and drying the solids, and removing` the dissolved solids contribution. HLW consists of the long-half-life radioactive tank waste solids and the radionuclides separated from the LAW fraction. The HLW (slurry) feeds may contain from 10 to 200 g of unwashed solids per liter of waste (0.3 to 6.7 vol% solids for an assumed solids dry density of 3 kg/L), except for feeds from waste Tanks 241-AZ-101 and 241-AZ-102, where minimum solids content does not apply. Note that the limits on insoluble particle (solids) concentration are on a whole-tank basis. Because the HLW is retrieved in multiple batches from a single tank that is certified only once, in-batch as well as batch-to-batch variations could exceed the above concentration limits.

The rheological and physical properties of the waste and the physical characteristics of the transfer system define the behavior of the waste during transport. The correlations developed for predicting pipeline pressure drop and estimating critical velocity are based on a combination of heterogeneous and homogeneous flow. The correlations predict the waste behavior based on the individual characteristics of the liquid and solid components of the slurry. Waste properties include liquid density, liquid viscosity, solids density, solids size and distribution, and solids volume fraction. A discussion of these properties is provided in Section 3.1. Physical characteristics of the waste transfer system include pipe inside diameter, length of pipe in the transfer route, elevation changes in the transfer route, and surface roughness of the inside of the pipe. These characteristics are discussed in Section 3.2. The pressure ratings of the existing pipelines are also identified in Section 3.2.

3.1 WASTE PROPERTIES

Accurate measurement of waste properties is essential to the accurate prediction of critical velocity and system pressure losses. The group of waste transfers identified in Phase 1 of the HNF-SD-WM-SP-012, *Tank Farm Contractor Operation and Utilization Plan,* focuses on transfers from DSTs in the 200 East Area. An initial review of characterization data for the DSTs was performed to determine if sufficient data were available to support an analysis of waste transfers based on tank specific data. It was found that supernatant density data were available for most of the tanks. Solids volume percent data based on whole-tank basis were available from HTWOS for the Phase 1 transfers. HTWOS maintains an inventory of the liquid and solid components of the waste as it is transferred between tanks. Calculated solids density data were available for ~40% of the tanks but transfer-specific particle density data is not available. In situ data for supernatant viscosity and particle size were available for <30% of the DSTs. However, as-transferred viscosity and particle size data are not available.

An indication of the carrier liquid density for HLW transfers can be obtained from a review of the HTWOS results. A summary of data from a group of seven HLW transfers is given in

Table 3-1. The specific gravity of the carrier liquid for this group of HLW transfers ranges from 1.07 to 1.39.

Table 3-1. HLW Tank–Specific *In Situ* Carrier Liquid Properties.

HLW Batch Group →		1	2	3	4	5	6	7	Statistics	
Source Tank(s) 241-#→		AZ-101	AZ-102	AY-102 C-106	AY-101 C-104	SY-102	C-107 AW-103	AW-103 AW-104		
Staging Tank 241-#→		AZ-101	AZ-102	AY-102	AY-101	AZ-101	AY-102	AW-104	Mean	SD
Liquid volume (gal)	V_L	797,364	837,243	514,915	833,525	533,997	804,433	795,138		
Liquid mass (kg)	M_L	3,774,605	3,574,896	2,078,907	3,463,302	2,461,888	3,511,180	4,183,148		
Specific gravity	SpG	1.25	1.13	1.07	1.10	1.22	1.15	1.39	1.19	0.11
Fraction dissolved solids	C	0.29	0.15	0.09	0.10	0.28	0.21	0.41	0.22	0.12
Fraction caustic (NaOH)	$C_{caustic}$	0.03	0.00	0.00	0.03	0.04	0.04	0.09	0.04	0.03
Fraction salts	C_{salt}	0.26	0.15	0.09	0.07	0.24	0.17	0.32	0.18	0.09
$C_{caustic}$ /C	$x_{caustic}$	0.11	0.03	0.01	0.29	0.16	0.20	0.23	0.15	0.10
C_{salt} /C	x_{salt}	0.89	0.97	0.99	0.71	0.84	0.80	0.77	0.85	0.10
Undissolved solids (vol%)	C_s	1.02	1.70	4.41	6.47	3.09	4.88	1.66	3.32	2.01

To convert gallons to liters multiply by 3.785.

HLW = high-level waste.
SD = standard deviation.

The waste properties must be characterized for the expected transfer conditions rather than the *in situ* conditions in the storage tank. In LAW transfers the supernatant will be pumped off first, the remaining solids will be dissolved, and the remaining waste will be transferred to the WTP. Hence, the solids content will be minimal and the temperature of the waste transferred will be near the original average waste temperature for the tank. *In situ* average waste temperatures for the DSTs are summarized in Table 3-2. The in situ average waste temperature for DSTs ranges from approximately 16 to 57 °C(60 to 135 °F). HLW tanks are highlighted in gray in Table 3-2. The tanks with the hottest average waste temperature are the HLW Tanks 241-AZ-101 and 241-AZ-102.

The transfer of the HLW poses the greatest challenge because of the greater volume of solids, which requires higher flow rates to maintain the suspension of the solids to prevent line plugging or unstable operation. The HLW tanks are mixed to obtain a near homogenous dispersion of the solids for transfer to the WTP. Pumping occurs while the mixer pump(s) are running. Because of the mixer pump induced heat up, the temperature of the transferred HLW will be higher than the *in situ* average waste temperature for the tank. A representative maximum waste transfer temperature of 80 °C (175 °F) was selected to account for heat up of the waste from mixer pump operation during transfer of HLW. This temperature is not necessarily bounding, particularly as

Table 3-2. Double-Shell Tank *In Situ* Temperature.

Tank 241-#	Riser(s) Containing TC Tree	Number of TCs on Tree	Number of TC's on Tree Providing Uninterrupted Data	Data Recording Method	Data Frequency	TC Tree Readings from 6/1/1999 to 6/1/2000			
						Average		Standard Deviation	
						(°F)	(°C)	(°F)	(°C)
AN-101	4A	18	11	TMACS	Daily	64.1	17.8	4.2	2.3
AN-102	4A	18	16	TMACS	Daily	86	30.0	2.3	1.3
AN-103	4A	18	18	TMACS	Daily	96	35.6	8.5	4.7
	15A	22	15	TMACS	Daily	93.4	34.1	9.8	5.4
AN-104	4A	18	18	TMACS	Daily	93.9	34.4	6.4	3.6
	15A	22	22	TMACS	Daily	94.2	34.6	6.8	3.8
AN-105	4A	18	17	TMACS	Daily	91.2	32.9	5.7	3.2
	15A	22	21	TMACS	Daily	91.3	32.9	5.3	2.9
AN-106	4A	18	17	TMACS	Daily	63	17.2	5	2.8
AN-107	4A	18	18	TMACS	Daily	82.9	28.3	2.9	1.6
AP-101	4	18	7	Manual	Weekly	65.6	18.7	2.4	1.3
AP-102	4	18	7	Manual	Weekly	67	19.4	2.2	1.2
AP-103	4	18	7	Manual	Weekly	62.5	16.9	3.2	1.8
AP-104	4	18	7	Manual	Weekly	65.8	18.8	6	3.3
AP-105	4	18	7	Manual	Weekly	65.9	18.8	2.2	1.2
AP-106	4	18	7	Manual	Weekly	65.3	18.5	5.6	3.1
AP-107	4	18	6	Manual	Weekly	58.6	14.8	5.1	2.8
AP-108	4	18	7	Manual	Weekly	62.6	17.0	4.5	2.5
AW-101	6	18	18	TMACS	Daily	91.3	32.9	6	3.3
	17	22	22	TMACS	Daily	90.8	32.7	5.4	3.0
AW-102	6	18	18	TMACS	Daily	65.9	18.8	3.9	2.2
AW-103	6	18	18	TMACS	Daily	63.4	17.4	3	1.7
AW-104	6	18	18	TMACS	Daily	69.5	20.8	4.7	2.6
AW-105	6	18	18	TMACS	Daily	60.9	16.1	3.6	2.0
AW-106	6	18	17	TMACS	Daily	83.9	28.8	9.9	5.5
AY-101	Various	11	11	Manual	Weekly	95.7	35.4	12	6.7
AY-102	Various	12	11	Manual	Weekly	98.1	36.7	13.3	7.4
AZ-101	Various	10	5	Manual	Weekly	135	57.2	9.8	5.4
AZ-102	Various	11	10	Manual	Weekly	126.2	52.3	16	8.9
SY-101	17B	22	21	TMACS	Daily	110.5	43.6	14.8	8.2
	17C	22	21	TMACS	Daily	110.1	43.4	15	8.3
SY-102	4A	18	18	TMACS	Daily	85.2	29.6	10	5.6
SY-103	4A	12	12	TMACS	Daily	87.8	31.0	3.2	1.8
	17B	22	21	TMACS	Daily	86.1	30.1	4.5	2.5
					Average	83.2	28.5	6.6	3.6
					Standard Deviation	19.3	10.7		
				HLW Tanks only	Average	93.0	33.9	8.4	4.7
					Standard Deviation	25.9	14.4		
					min	60.9	16.1		
					max	135.0	57.2		

HLW = high-level waste.
TC = thermocouple
TMACS = Tank Monitoring and Control System.

the waste level decreases during waste transfer. Current safety controls to prevent tank bumps would limit this temperature to 90 °C (195 °F) in the bulk liquid or to 102 °C (215 °F) for the bottom 4.6 m (15 ft) of waste in the tank (HNF-SD-WM-TSR-006, *Tank Waste Remediation System Technical Safety Requirements*).

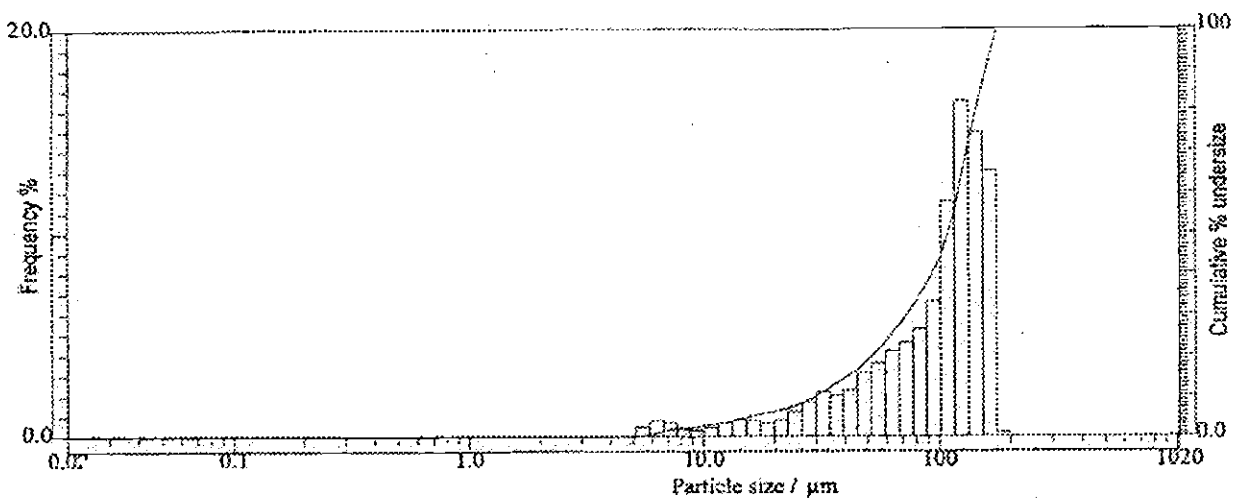
The expected solid particle concentration during the HLW Phase 1 transfers range from 1 to 6.5 vol% per Table 3-1 on a whole tank basis. Since the HLW is retrieved in multiple batches from a single tank that is only certified once, in-batch as well as batch-to-batch variations are expected which might exceed the envelope definitions to the WTP. In addition, portions of the WFD transfer pipeline also will be used in tank-to-tank transfers for pretreatment or staging activities that are not restricted by the LAW and HLW envelope definitions. Hence, a solid particle concentration of 10 vol% appears appropriate as a minimum design basis value.

Each transfer route includes one or more pipeline segments, where each segment is a pipeline from one pit to another pit. Many line segments are used in more than one transfer route. If we could accurately predict the waste properties for all waste transfers, it would be possible to assign a pressure rating for each line segment based on the highest pressure drop predicted through the segment. However, because of the lack of transfer-specific physical property data, commonality of pipeline sections used in the various transfer routes, and the need to provide maximum flexibility in use a conservative analysis is required to ensure sufficient robustness in the transfer system.

One of the more important waste parameters is the particle PSD. The specified particle size is the median value of the PSD by volume. PSD data was curve fit to a Rosin-Rammler distribution function (Shook and Roco 1991) and then shifted to obtain a distribution with the target median particle size of interest for analysis. The Rosin-Rammler distribution function is similar to a log-normal distribution function but provided a better fit to the PSD data (see Section 6.2.4 of Appendix F).

A graph of the PSD for Tank 241-C-104 is shown in Figure 3-1. The shape of the distribution curve in Figure 3-1 is typical of the PSDs used in initial analyses.

Figure 3-1. Tank 241-C-104 *In Situ* Particle Size Distribution.



The development of the design basis waste physical properties appropriate for the WFD mission has been an evolving process. The design basis waste properties for Projects W-058, W-211, and W-314 are shown in Table 3-3. Each of these projects has or is in the process of upgrading the waste transfer system. Based on the specified slurry specific gravity of 1.5 in Table 3-3 and assuming a liquid density of 1.1 kg/L, the corresponding solids density from Equation 17 is approximately 2.4 kg/L with 30 vol% solids. Similarly, for specified slurry specific gravity of 1.25 in Table 3-3 and assuming a liquid density of 1.1 kg/L, the corresponding solids density is approximately 1.85 kg/L kg/L with 20 vol% solids.

Table 3-3. Project Specified Waste-Property Comparison.

Property	Project W-058		Project W-211	Project W-314
Slurry Specific gravity	1.5	1.25	1.25	1.5
Liquid density, kg/L	--	--	--	--
Liquid viscosity, g/cm-s (cP)	0.3 (30)	0.1 (10)	0.1 (10)	0.3 (30)
Volume percent solids	30%	20%	20%	30%
Solids density, kg/L	--	--	--	--
Solids size[c], µm	0.5 – 4000	0.5 – 4000	0.5 – 4000	--
Temperature, °C	2 – 93	2 – 93	27 – 93[a]	27 – 116
Friction factor	0.0404[b]	--	--	--

[a]10 °C to 130 °C for aging waste tanks
[b]Non-Newtonian.
[c] 0 to 50 µm particles are assumed to comprise approximately 95% of the total.
50 to 500 µm particles are assumed to comprise <5% of the total.

3.1.1 Revision 0 Design Basis Waste Physical Properties

Based on the lack of necessary input data, Process Engineering was requested to provide an estimate of slurry properties. The initial estimate (see Appendix A) provides a summary of estimated nominal and "bounding" *in situ* waste properties to be used as a basis for the analysis of the waste transfer system. The estimated properties are summarized in Table 3-4. Some of the properties listed in Table 3-4 (i.e., particle size and liquid density) are based on limited actual test data. Other properties (i.e., volume percent solids, particle density, and viscosity) are based on known correlations or engineering judgment. It should be noted that the nominal and "bounding" cases are not defined in a strict sense. Nominal properties are intended to reflect an average HLW tank. Likewise, the "bounding" case may not envelope the extreme values of individual properties listed in Appendix A.

Table 3-4. Initial Estimate of HLW Slurry Physical Properties Based on *In Situ* Waste Properties per Revision 0 of RPP-5346.

Property	Nominal	Bounding
Median particle size, d_p, (μm)	40	400
Volume percent solids, C_s, (vol%)	15%	30%
Liquid density, ρ_L, (kg/L)	1.21	1.46
Solids particle density, ρ_s, (kg/L)	2.5	3.0
Liquid viscosity, μ_L, (cP)	Eqn 16*	Eqn 16*

* The viscosity of the carrier liquid is a function of the density of the carrier liquid (water) and the fraction of dissolved salts and caustic as given by Equation 16. The effect of solids concentration on viscosity is given by Equation 15.

In the initial analysis of the "bounding" case, it became clear that either some restrictions on the waste physical properties would be necessary, or restrictions on transfer routes would have to be imposed, or modifications to the transfer pipeline system would have to be performed, or some combination thereof. Neither the existing nor planned project waste transfer systems have pipeline design pressures that would allow the bounding case waste to be transferred through the longest transfer routes currently identified unless the waste was transferred at a flow rate below the critical velocity. Transfers at a flow rate below the critical velocity would allow the solids to settle in the pipeline, thus leading to potential plugging of the pipeline or unstable operations.

3.1.2 Revision 1 Design Basis Waste Physical Properties

This led to a subsequent statistical reassessment of the available particle size data and a review of the various measurement instruments used in obtaining the data (RPP-6427). Discrepancies in the results obtained from the various measurement instruments used in determining the PSDs were apparent. Results from the Horiba™ Model LA-910 instrument, which had a larger measurement range (up to 1020 μm) than previous instruments used (up to 150 μm), typically indicated a broader PSD for the Hanford HLW. Results from the Horiba™ Model LA-910 instrument were assumed valid and were preferentially selected for statistical analysis. Based on the RPP-6427 analysis of the PSD data from three HLW tanks (241-AZ-101, 241-AW-103, and 241-C-104) measured with the Horiba™ Model LA-910 instrument it was concluded that:

- The estimate of the average median particle size diameter for these three tanks is approximately 110 μm.
- The estimate of the 95% confidence upper limit (UL95) for the average median particle size diameter in the population of the HLW tanks is 140 μm. That is, if all the HLW were combined, the median particle size diameter in the population would be less than 140 μm, with 95% confidence.

- The 95/95 tolerance limit (95/95TL) on the average median particle size diameter for a single HLW tank is approximately 275 μm. That is, with 95% confidence the median particle size diameter will not exceed 275 μm in 95% of the ten HLW tanks.

Assuming that the PSD data are from a random sample of the ten HLW tanks, it was reasonable to use the bounding value for the median particle size diameter of 275 μm as the design basis for the WFD transfer system. Revision 1 of RPP-5346 adopted the 275 μm median particle size as the design basis median particle size for the WFD transfer system but also considered the mean and UL95 values. In performing the pressure-drop analysis, the "grand-mean" PSD obtained from the statistical analysis in RPP-6427 was used as the design basis PSD. The grand-mean PSD data was curve fit to a Rosin-Rammler distribution function and then shifted to obtain a distribution with the target median particle size of interest for analysis. Plots of the PSDs are given in Figure 3-2.

The bounding solids particle density of 3 kg/L was retained in the analysis as the design basis particle density. The constituents and amount of absorbed liquid affect the effective density of the solid particles but the available data was not sufficient to justify a more accurate assessment at the time. Although agglomerates are known to form, the affect of agglomerates on the effective particle size and particle density has not been established for the Hanford HLW feed at this time.

A summary of the design basis waste transfer properties used in Revision 1 of RPP-5346 is given in Table 3-5 for both the HLW and LAW.

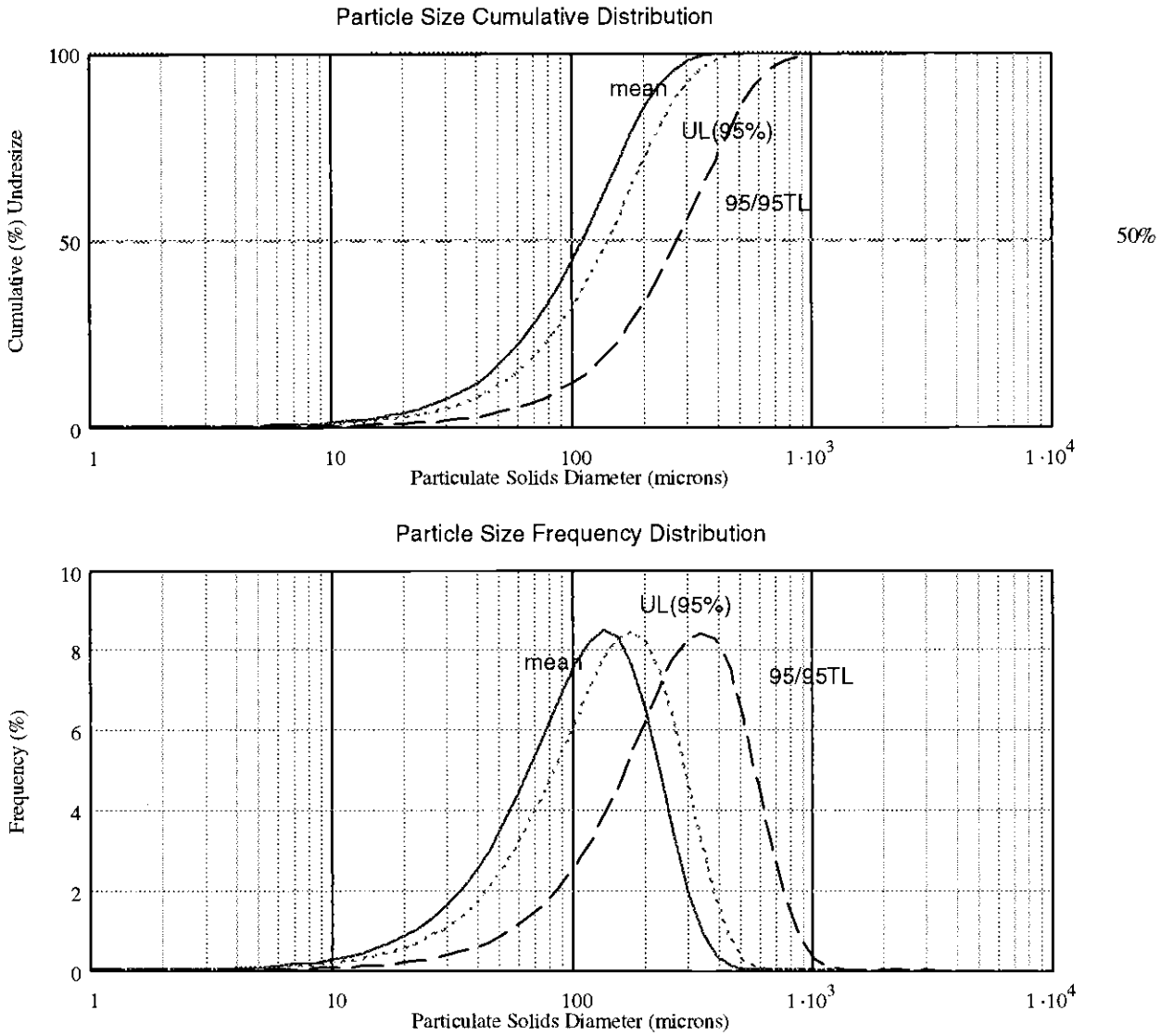
Table 3-5. Design Basis Waste Properties per Revision 1 of RPP-5346.

Property	High-Level Waste	Low-Activity Waste
Median particle size, d_p, (μm)	110 (best-estimate) and 275 (95/95 TL)	110 (best-estimate) and 275 (95/95 TL)
Volume percent solids, C_s, (vol%)	≤10%	≤2%
Liquid density, ρ_L, (kg/L)	1.1 and 1.4	1.3 and 1.4
Solids particle density, ρ_s, (kg/L)	3	3
Liquid viscosity, μ_L, (cP)	Eqn 16*	Eqn 16*
Temperature, T, (°C)	40 to 80	20 to 40

* The viscosity of the carrier liquid is a function of temperature through the density of the carrier liquid (water) and the fraction of dissolved salts and caustic as given by Equation 16. The effect of solids concentration on viscosity is given by Equation 15.

The revised PSD estimate given in RPP-6427 was evaluated in Revision 1 of RPP-5346 but the predicted pressure drops did not provide sufficient relief from exceeding the limiting system pressures of the pipeline transfer routes at the required flow rate.

Figure 3-2. Grand-Mean PSD (RPP-6427).



3.1.3 Revision 2 Design Basis Waste Physical Properties

Additional laboratory work was recommended in RPP-6427 to help resolve apparent anomalies in particle size measurement results between instruments, uncertainties in particle densities, and to investigate existence of particle agglomerates and their potential breakup when passing through transfer pumps or under turbulent pipe flow conditions. An extensive laboratory analysis of HLW particle sizes was conducted in an attempt to address these uncertainties. Results are reported in HNF-8862. A multi-company panel of experts was convened to review the results of the laboratory analysis and other available Hanford waste physical property data to provide recommend particle size, particle density, and viscosity information for the WFD transfer system analysis.

This Revision 2 of RPP-5346 applies the expert panel recommendations on particle size, particle density, and viscosity reported in RPP-9805. In the earlier HLW PSD measurements used in the statistical analysis reported in RPP-6427, the samples were held in a 15mL observation cell, where the particulate matter was kept in suspension with a small magnetic stirring bar. In the more recent measurements (HNF-8862), which also used the Horiba™ Model LA-910 particle size analyzer, the sample particulates were suspended by recirculating roughly 300 mL of the sample in a flow loop that passes through the measurement cell. In light of the agglomerated nature of the particles, the difference between the instrument configurations was found to be critical. By comparing the particle size data reported in RPP-6427 and HNF-8862, it is clear that even the minimum shear forces required to maintain the waste particles in suspension by turbulence in a flowing stream are greater than the shear applied in the small stirred cell.

The PSD data reported in HNF-8862 was obtained from seven (AW-103, AY-101, AY-102, AZ-102, C-104, C-107, and SY-102) tanks representing Phase 1 HLW tank feeds of ten HLW tanks. The PSD data was subdivided into two groups depending on the level of agitation applied to the samples. In the first group the samples were minimally agitated and in the second group the samples were strongly agitated (sonicated). The resulting mean, upper limit of one-sided 95% confidence interval on the mean (UL 95), and upper limit to a one-sided 95/95 tolerance limit (95/95 TL) were statically determined for each group.

The recent laboratory program was conducted to produce better estimates of particle size and particle density in the HLW feeds. 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. Hence, the approach taken by the expert panel was to select a conservative (upper bound) solid density value and realistic (best estimates) for the PSD and slurry viscosity.

This selection approach for these three waste properties is expected to support a reasonably conservative assessment of the WFD transport system. Because PSD data from the strongly agitated samples could not be reliably correlated to the level of shearing from the transfer pumps or turbulent pipe flow conditions, the minimally agitated PSD data was selected as a best-estimate of the PSD for the WFD transfer system analysis. The particle size distribution recommended for use in the waste feed delivery transport system assessment is the mean distribution from measurements made for seven HLW tanks under conditions of minimal agitation. The median particle size (50th percentile) of this distribution is 7.5 μm; the distribution is shown in Table 3-6 on the row labeled "Mean." The 95/95 tolerance limit distribution shown in Table 3-6 (95/95 TL) is also provided for sensitivity analysis. The recommended mean minimally agitated PSD appears to be more inline but is still conservative with the Project design criteria summarized in Table 3-3 above by comparison of their 95-percentiles.

Table 3-6. Recommended Particle Size Distribution (μm) Obtained under Conditions of Minimal Agitation (RPP-9805).

Percentile	1%	5%	25%	50%	75%	95%	99%
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

Plots of the recommended PSDs given in Table 3-8 are given in Figure 3-3.

The recommend solids density of 2.9 kg/L is conservative mean of tank constituent theoretical dry densities without voids expected in agglomerate particles. Hence, the recommended solids density is more conservative to the apparent solids densities in the various project design criteria given in Table 3-3. The recommended viscosity relation is the best-estimate relation given by Equation 18 with the bounding relation given by Equation 19 provided for sensitivity analysis. These viscosity relations are limited to 10 vol% solids but the resulting predicted viscosities (see Figure 2-4b) would be more inline with the values given in Table 3-3. A summary of the revised design basis waste properties used in Revision 2 of RPP-5346 is given in Table 3-7.

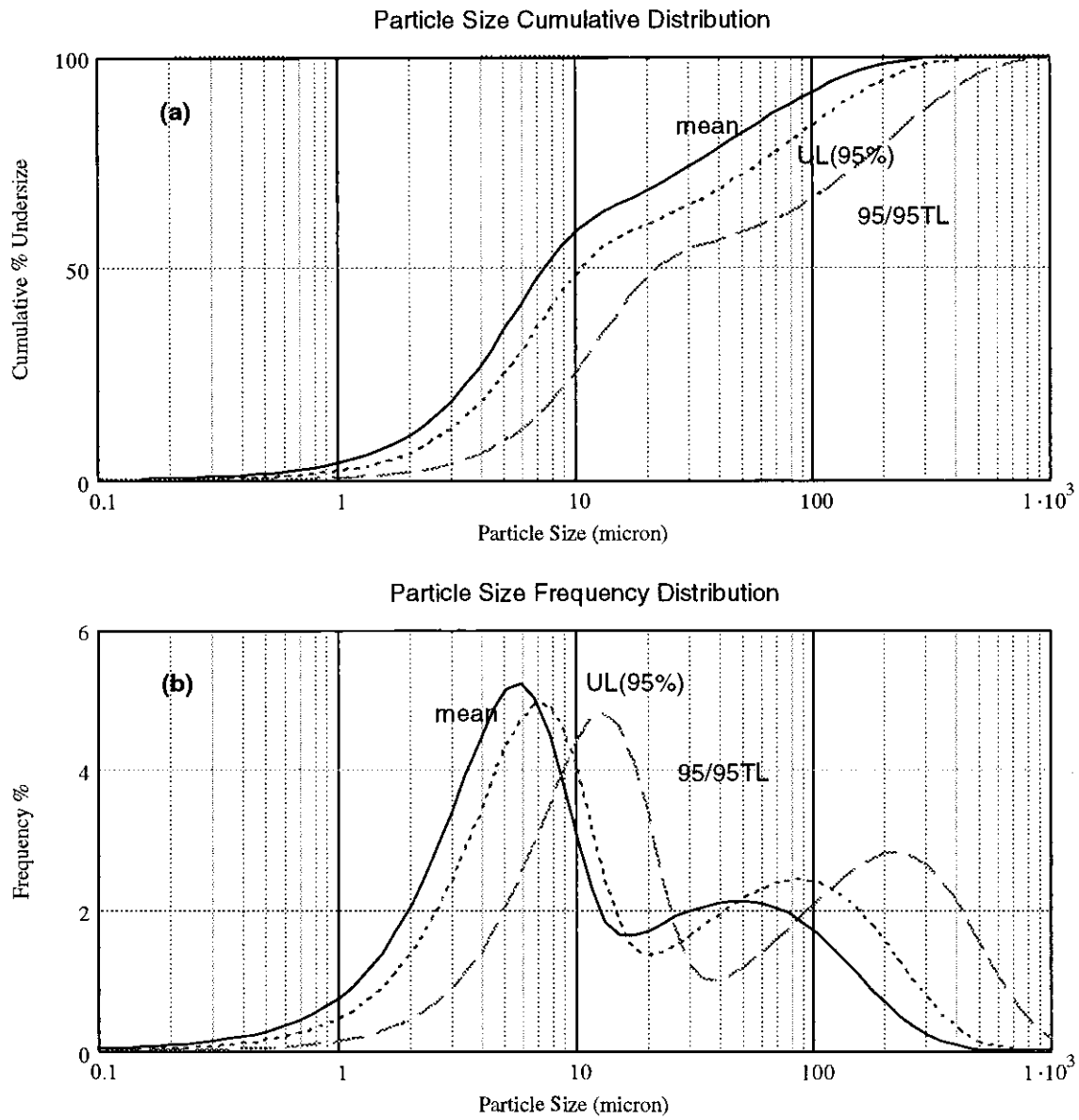
Table 3-7. Design Basis Waste Properties per Revision 2 of RPP-5346.

Property	High-Level Waste	Low-Activity Waste
Median particle size, d_p, (μm)	7.5 (best-estimate) and 22 (95/95 TL)	7.5 (best-estimate) and 22 (95/95 TL)
Volume percent solids, C_s, (vol%)	≤10%	≤2%
Liquid density, ρ_L, (kg/L)	1.1 to 1.3	1.2 to 1.4
Solids particle density, ρ_s, (kg/L)	2.9	2.9
Liquid viscosity, μ_L, (cP)	1.5 and 1.6 *	1.5 and 1.6 *
Temperature, T, (°C)	40 to 80 **	20 to 40 **

* Bounding viscosity at zero solids based on use of Equation 19.

** Solids concentration effect on viscosity is given by Equations 18 (best-estimate) and 19 (bounding), which are independent of temperature.

Figure 3-3. Recommended Particle Size Distribution Obtained under Conditions of Minimal Agitation (RPP-9805).



3.2 TRANSFER SYSTEM CHARACTERISTICS

3.2.1 Pipeline Diameter, Length, and Elevation Changes

The HTWOS models were used to identify waste transfers in Phase 1. Additionally, a sampling of transfer routes from Phase 2 was included in the list of waste transfers. HTWOS identifies the source and receiver tank for each transfer but does not provide information related to the actual route that the waste travels during the transfer. This analysis focused on the transfer routes

within the 200 East Area. The transfer routes that were analyzed are identified in Figure B-1 of Appendix B. Cross-site transfers from the 200 West Area are not included in this analysis.

Pipeline routing, pipe diameter, length of pipe for each transfer route, and elevation changes were identified from the physical piping drawings and from a previous study documented in HNF-2938, *Evaluation of 241-AN Tank Farm Supporting Phase 1 Privatization Waste Feed Delivery*. Pipelines in the transfer routes identified were found to be 80 mm (3-in.) nominal diameter, schedule-40 pipe. Transfer routes for pipelines that have not been installed were based on preliminary information from the projects. For the purpose of this analysis, it was assumed that new pipe will be 80 mm (3-in.) nominal diameter, schedule-40 pipe.

Equivalent pipe lengths were determined using the methodology described in Crane (1981), *Flow of Fluids Through Valves, Fittings, and Pipes*, which is assumed valid for slurry flows for this initial assessment. Equivalent pipe lengths for individual transfer routes are shown in Appendix B. Equivalent pipe lengths are used to simplify the analytical model for determining pressure drop while accounting for the friction losses in pipe fittings and valves. Equivalent lengths are based on the number of linear feet of pipe in each transfer route plus the number of feet of pipe that will provide a pressure drop equivalent to the pressure drop that would be experienced through a pipe fitting or valve. Because the future configuration of fittings and valves in the pump and valve pits is not well defined, a standard configuration of valves and fittings was assumed for these locations.

Transfers through valve pits were modeled by assuming that the flow passes through two 3-way valves (run), one 3-way valve (branch), three Plutonium-Uranium Extraction (PUREX) connectors, and five long-radius elbows. Transfers through pump pits were modeled by assuming that the flow passes through one 3-way valve (run), two PUREX connectors, and two long-radius elbows. The largest pressure drops in the pits occur in the PUREX connectors and in the three-way valves with the flow through the branch. Pressure drops through standard ball valves and through non-flow intrusive instrumentation is very low in comparison. If additional in-line components are present, then a greater pressure drop through the system would be expected.

The interface with the WTP requires that the transferred waste move some distance within the vitrification facility. The equivalent lengths identified in the WTP's calculations (see WTP calculation note in Appendix B) have been included in the equivalent pipe lengths listed in Appendix B for transfers to the vitrification facility.

Changes in elevation between end points of the transfer lines were identified from HNF-2938, physical piping drawings, preliminary project drawings, and the WTP's calculations. The elevations of end points of the transfer line were determined from the elevations of the nozzles inside the pump or valve pits. Details of the updated equivalent lengths and elevation changes are given in Appendix B.

3.2.2 Pipeline Roughness

Pipelines in the transfer routes were constructed from either carbon steel (ASTM A106 Grade B or A53 Type S, Grade B) or stainless steel (ASTM A312). The construction material of

pipelines that have not been installed was based on preliminary information from Projects W-314 and W-521. For the purpose of this analysis, it was assumed that new pipelines would be stainless steel.

The surface roughness of the interior of a pipe can be affected by corrosion and scale buildup because of the chemistry of the waste and flush water. The interior surface roughness also can be affected by erosion caused by abrasive solids in the waste and high waste flow rates. As the interior surface of the pipe deteriorates, the surface becomes irregular and rough and there may be a simultaneous reduction in the thickness of the pipe wall. Although the waste chemistry is controlled to reduce the effects of corrosion and scale buildup, waste transfer lines have failed in the past. The metallurgical analysis of a failed jumper in the 241-A-B valve pit in 1984 (WHC-SD-RE-TI-148, *Metallurgical Analysis of Leak Failure of 241-A-B Valve Pit Jumper*) is a good example of the combined effects of erosion/corrosion on the interior of a pipe. The photographs in WHC-SD-RE-TI-148 document the rough surface condition of the pipe even at locations where the pipe did not fail. The effects of this increasing surface roughness can change the flow characteristics of a pipe system significantly. Because the condition of the interior of the pipelines is not documented, surface roughness values were based on an evaluation by Anantamula and Divine (Appendix C). For the purpose of this analysis, the values shown in Table 3-8 were used.

Table 3-8. Pipe Surface Roughness Estimates.

Pipe Material	Surface Roughness	
	(mm)	(mil)
Carbon Steel, BOL (20 yr)	1.8*	70*
Stainless Steel, BOL (new)	0.05	2
Carbon Steel, EOL (50 yr)	3.8	150
Stainless Steel, EOL (40 yr)	0.25	10

BOL = beginning of life for transfers
EOL = end of life.
*Based on 95% confidence value at 20 yr (see Appendix H)

Erosion is expected to increase corrosion near elbows in the pipeline; however, the increase in corrosion is a result of removal of corrosion products. Under these conditions, a significant increase in the friction factor is not expected even though a rough, uneven surface is produced. Recent laboratory studies indicated that even at velocities approaching 4.6 m/s (15 ft/s), corrosion products are not removed from the steel surface and, therefore, the friction factors at the elbows are not expected to be significantly different from the straight sections of the pipe. As indicated in Appendix C, the surface roughness values reported are considered conservative for carbon steel since 98% relative humidity and lack of inhibiting effect from nitrite are assumed.

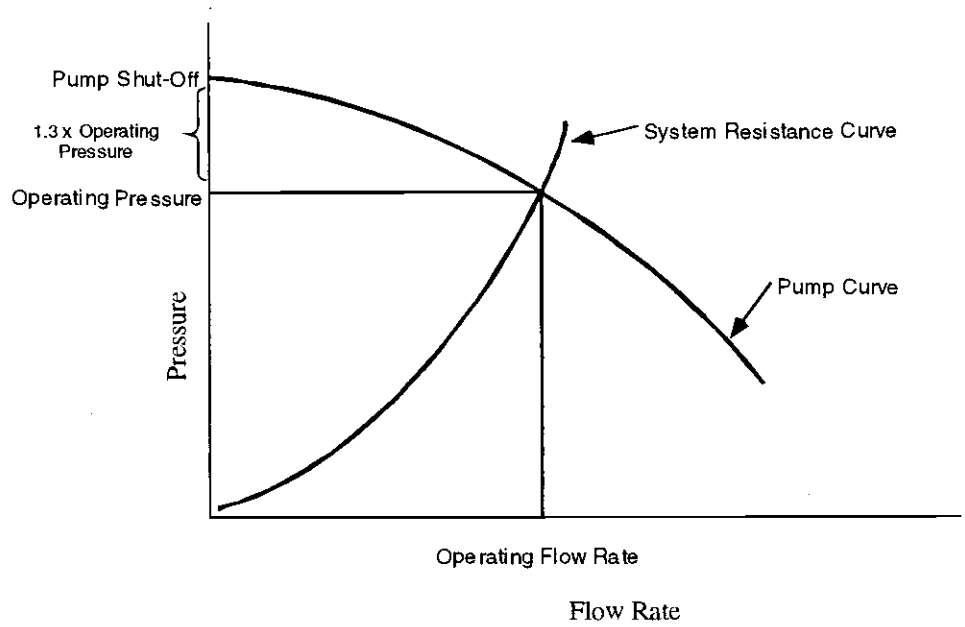
3.2.3 Pipeline Design Pressure

Most of the existing pipelines that will be used for waste retrieval have a design pressure of 2.7 MPa (400 lbf/in^2). Some carbon steel lines in AN and AW Tank Farms have design pressure ratings of 1.9 MPa (275 lbf/in^2) but have been hydrotested to 3.1 MPa (450 lbf/in^2) (HNF-2938). The pressure rating of the pipe provides an upper bound that limits the flow velocity through the system and the allowable shut-off head of the transfer pump.

In calculating the minimum design pressure required for the pipeline the range of the bulk density to be accommodated and the characteristics of the pump curve must be accounted for. To account for wastes of different densities, the pressure at the discharge of the pump must be adjusted. A centrifugal pump is rated in meters (or feet) of head. At a specified flow rate, the discharge head will remain constant, but the discharge pressure will vary if the density of the pumped liquid changes. The discharge pressure from a pump is estimated for a new density by the ratio of specific gravities or bulk densities.

The design pressure also is adjusted to account for a centrifugal pump with a head-flow characteristic that rises continuously to pump shutoff. Figure 3-4 shows a typical pump/system curve. For a centrifugal pump, a typical rise from operating point to shutoff is approximately 30%.

Figure 3-4. Typical Pump/System Curve.



Hence, the minimum design pressure required for a pipeline route is obtained from the following relation:

$$p_{design}^{\min} = \alpha_{pump} \, \Delta p_{\max} \, \frac{\rho_b^{\max}}{\rho_b \big|_{\Delta p_{\max}}} \tag{24}$$

where

p_{design}^{min} = minimum required design pressure rating for a given pipeline route

α_{pump} = pump operating-to-shutoff factor = 1.3 (typical)

Δp_{max} = maximum predicted pressure drop (from tables in Appendix D) for transfer route at required critical velocity

$\rho_b|_{\Delta p_{max}}$ = bulk density of waste for corresponding maximum predicted pressure drop

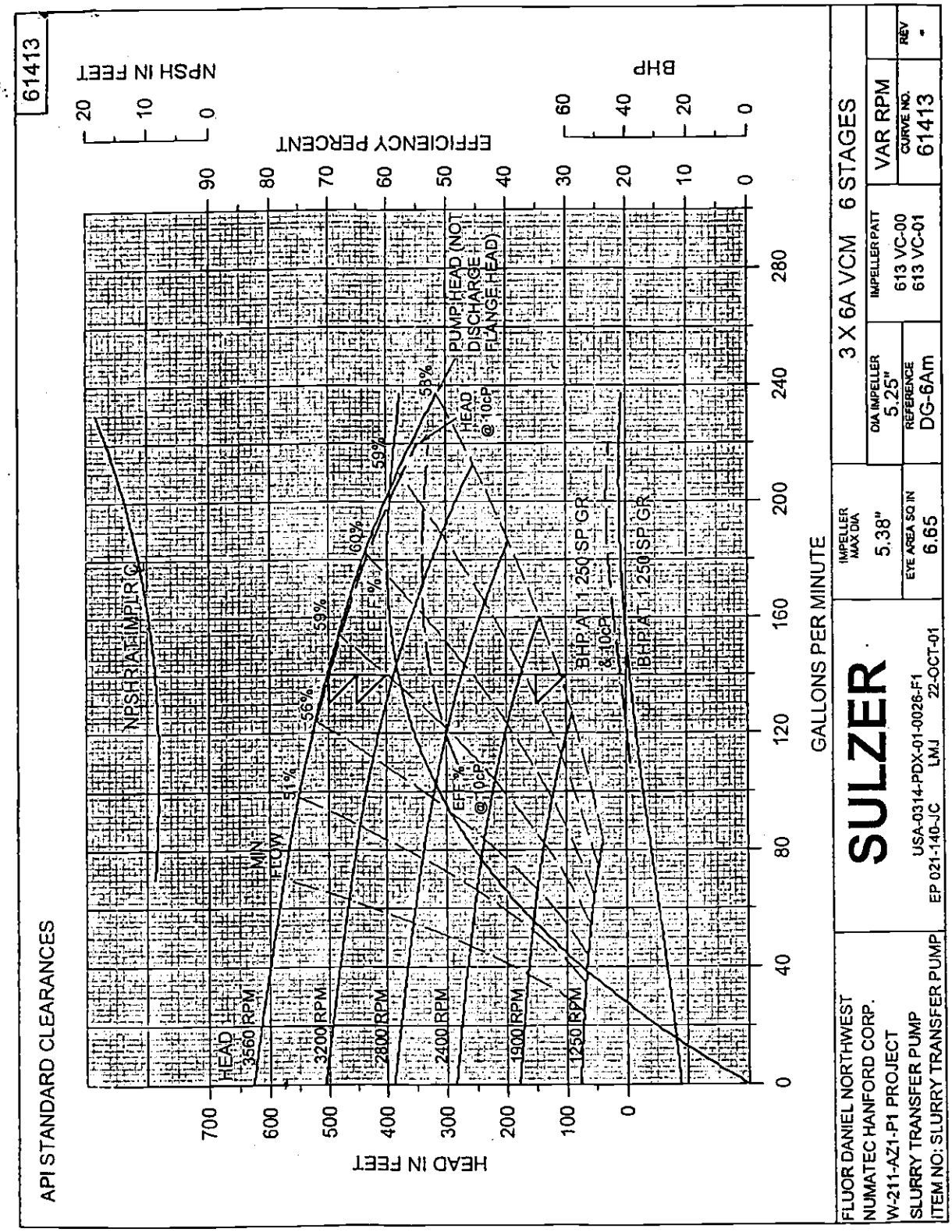
ρ_b^{max} = maximum bulk density of waste to be transferred = 1.56 kg/L for HLW design basis maximum liquid density of 1.4 kg/L and 10 vol% solids concentration.

The bulk density for the waste is given by

$$\rho_b = \rho_s C_s + \rho_L(1 - C_s) \tag{25}$$

where ρ_L, ρ_s, and C_s are the carrier liquid density, undissolved solids density, and solids volume fraction, respectively as defined previously. The above procedure is used if the actual pump curve is not available. In this analysis the Project W-211 transfer pump curve number 61413 shown in Figure 3-5 is applied. This is the pump proposed for DST waste transfers from 200 East Area.

Figure 3-5. Project W-211 Transfer Pump Curve Number 61413.



4.0 RESULTS

This section presents the results of the critical velocity and pressure-drop calculations for the recommended waste physical properties reported in RPP-9805. A general discussion of waste parameters investigated is provided in Section 4.1. Results of critical velocity and pressure-drop analyses are given in Sections 4.1.1 and 4.1.2, respectively. The sensitivity of the waste and pipe parameters on the pressure drop at critical velocity is presented in Section 4.2. Uncertainties in the waste and pipe parameters are discussed in Section 4.3.

4.1 PARAMETRIC ANALYSIS

The critical velocity and transfer line pressure drop were calculated for each of the transfers identified in the HTWOS model for Phase 1 waste feed delivery. The calculations were performed using the length of pipe specific to each transfer route, pipe wall roughness values for beginning of life (BOL) and end of life (EOL), and different combinations of waste characterization data. Beginning of life roughness values for the existing carbon steel pipelines included effects of estimated corrosion for approximately 20 years of exposure at a 95% confidence level (see Table 3-8). Equivalent pipe lengths were used to account for the various valves and fittings in the transfer routes, and changes in elevation were factored into the calculations. The transfer pipeline within the WTP facility also was included in the transfer pipeline routes. The different combinations of waste properties analyzed for each transfer route are summarized in Table 4-1. These different combinations provide an indication of the sensitivity of the transfer system to variations in waste properties.

Table 4-1. Summary of Parametric Cases – Waste Properties.

Case	Liquid Density (kg/L)	Solids Concentration (vol%)	Solids Density (kg/L)	Minimally Agitated PSD	Median Particle Size (μm)	Viscosity	Waste Type
1	1.1, 1.2, 1.3	10	2.9	Mean	7.5	Best-Estimate	HLW
2		10	2.9	95/95TL	22	Best-Estimate	HLW
3		10	2.9	Mean	7.5	Bounding	HLW
4	1.2, 1.3, 1.4	2	2.9	Mean	7.5	Best-Estimate	LAW
5	1.1, 1.2, 1.3	10	2.2	Mean	7.5	Best-Estimate	HLW*
6		5	2.9	Mean	7.5	Best-Estimate	HLW/LAW

*Agglomerate estimated solids density case.

4.1.1 Critical Velocity Analysis

Critical velocity is a function of the carrier liquid density and viscosity, solids diameter, density and volume fraction, and pipe diameter. Critical velocity values are tabulated in Appendix D for

each parametric case. The values of critical velocity are independent of transfer pipeline length. The critical velocity is calculated using Oroskar and Turian (1980) correlation (Equation 1) and a Wasp-modified Oroskar and Turian method with the "vehicle" density and viscosity and "bed" solids concentration as determined in Section 2.3 in place of the liquid density and viscosity and total solids concentration. A comparison also is performed to ensure that the flow is above the laminar-to-turbulent transition region in both cases. The predicted critical velocity is increased by 30% to account for the uncertainty in the correlation and provides a margin above the predicted value of critical velocity to ensure stable operation.

Table 4-2 summarizes the factored predicted critical velocities given in Appendix D for the cases defined in Table 4-1.

Table 4-2. Summary of Parametric Cases - Critical Velocity (ft/s) Results.

Liquid Density (kg/L)	1.1		1.2		1.3		1.4	
Case	Wasp-OT	OT	Wasp-OT	OT	Wasp-OT	OT	Wasp-OT	OT
1	2.6	3.4	2.4	3.2	2.3	3.0		
2	3.9	4.1	3.7	3.8	3.4	3.6		
3	4.6	3.4	4.5	3.2	4.3	3.0		
4			2.7	2.6	2.5	2.4	2.3	2.2
5	2.0	2.6	1.8	2.4	1.7	2.2		
6	2.9	3.2	2.7	2.9	2.6	2.7		

OT = Oroskar and Turian (1980) correlation
Wasp-OT = Wasp-modified Oroskar and Turian method

4.1.2 Pressure-Drop Analysis

The tables in Appendix D show the total equivalent length of pipe for each transfer route, the type of pipe material, and the total pressure drop at the critical velocity using values of pipe surface roughness predicted at BOL and EOL of the pipeline. The pipeline pressure drop was calculated using the Wasp method described in Section 2.3. The tables in Appendix D also show the predicted pressure drop at the target flow rate of 140 gal/min (~6.1 ft/s). Grayed cells identify pipelines for which the predicted pressure drop exceeds the pipeline limiting pressure. The values for predicted pressure drop for BOL and EOL pipe roughness were included to provide a range of possible values that might be expected during operation. In addition, for the Project W-211 transfer pump curve (see Figure 3-5), the maximum allowable flow rate (gal/min) for normal operation is given such that if the pump dead headed at the pump controlled speed indicated the pipeline limiting pressure would not be exceeded. The corresponding pressure drop at the allowable flow rate is also given. Grayed cells identify pipelines for which the predicted maximum allowable flow rate is less than the target flow rate of 140 gal/min (~6.1 ft/s).

Although the predicted pressure drops are transfer-route specific because of the differences in pipeline length and change in elevation, some general observations can be given by grouping the transfer routes into the following two groups based on the pipeline transfer route system pressure limit:

- Pipeline Transfer Routes Limited to 2.7 MPa (400 lbf/in^2)
  - Tank-to-tank and tank-to-WTP transfers of LAW and HLW are not expected to exceed the pipeline limiting pressure at either the predicted critical velocity (< 3 ft/s for LAW[6] and < 4 ft/s for HLW) or target flow rate of 140 gal/min (~6.1 ft/s).
  - The pipeline limiting pressure is not expected to be exceeded with application of the Project W-211 prototype variable speed transfer pump at its full speed dead head pressure.
  - Tank-to-tank and tank-to-WTP transfers with application of the Project W-211 prototype transfer pump should be able to reach the target flow rate of 140 gal/min (~6.1 ft/s); except potentially for tank-to-WTP transfers with solid concentrations approaching 10 vol% if the viscosity approaches 30 cP (bounding viscosity case) rather than the excepted 10 cP (best-estimate viscosity case).
- Pipelines Transfer Routes Limited to 1.9 MPa (275 lbf/in^2)
  - Tank-to-tank and tank-to-WTP transfers of LAW and HLW are not expected to exceed the pipeline limiting pressure at the predicted critical velocity (< 3 ft/s for LAW and < 4 ft/s for HLW).
  - Tank-to-tank and tank-to-WTP transfers of LAW and HLW are not expected to exceed the pipeline limiting pressure at the target flow rate of 140 gal/min (~6.1 ft/s), except where the equivalent pipe length exceeds approximately 4,800 ft.
  - The pipeline limiting pressure is expected to be exceeded with application of the Project W-211 prototype variable speed transfer pump at its full speed (3,560 rev/min) dead head pressure unless the pump speed is limited to approximately 3,000 rev/min or pressure relief valves are provided.

Because the jumper connectors are leak test qualified to only 1.7 MPa (250 lbf/in^2), the above assumes that the jumper connectors can be leak test qualified to pressures that meet or exceed the above pipeline transfer route limiting pressures of 2.7 and 1.9 MPa (400 and 275 lbf/in^2), respectively. Plans for jumper connector qualifying leak tests to a pressure of at least 2.7 MPa (400 lbf/in^2) are under development.

Fortunately, the planned Phase 1 HLW transfers to the WTP are through transfer routes (AN-104, AY-101, AY-102, AZ-101, and AZ-102 to WTP) limited to 2.7 MPa (400 lbf/in^2). These are identified in the Appendix D tables by an asterisk. In the subsequent balance of mission (BOM) phase, one time transfers of HLW to the WTP are planned from AW-103 and AW-104 to WTP through transfer routes that are limited to 1.9 MPa (275 lbf/in^2). These are identified in the Appendix D tables by double asterisk. However, tank-to-tank transfers through transfer routes limited to 1.9 MPa (275 lbf/in^2) may be problematic as well (see Appendix D for transfer-route specific limitations).

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[6] This is based on a conservative assumed 2 vol% solids concentration for LAW transfers.

4.2 SENSITIVITY

Although a classical sensitivity analysis was not performed, the results given in Appendices D and E may be used to gain an insight on the effects of the multi-parameters that affect the results. An updated Monte Carlo simulation analysis to include the revised recommended PSD, particle density, and viscosity relations would be useful in assessing the risks associated with the WFD transfers. It is important when assessing the sensitivity to not look just at point solutions but at the complete pressure drop curve such as given in Appendix E. Even the tables in Appendix D give results at two velocity points; at the predicted critical velocity and at the target velocity. As an example for the AN104-to-WTP transfer route with a liquid density of 1.1 kg/L, the increase in pressure between Case 1 and 2 is 45% at critical velocity while the pressure at the target velocity only increases by 2%. This large increase in pressure at the critical velocity is due mainly to the 20% increase in critical velocity. However, for the AN104-to-AN101 transfer route the increase in pressure is 68% at critical velocity while the pressure at the target velocity increases by 4%. Hence, the sensitivity of the various waste parameters on the pressure drop is transfer-route specific.

4.3 UNCERTAINTIES

This analysis is based on a number of assumptions that are critical to a proper understanding of the results. The areas of greatest uncertainty are discussed in this section.

4.3.1 Waste Characterization

Waste characteristics from the process flow sheets, the latest revisions of the tank characterization reports, letter reports from the laboratories, and the HTWOS model were reviewed. It was found that liquid viscosity data and particle diameter data for the DSTs generally were not available although this has improved. What data that was available was based on *in situ* conditions rather than at transfer conditions. Because of the lack of transfer-specific data, physical property estimates were provided by Process Engineering. In performing this analysis, some simplifying assumptions were made regarding the particle size and particle density. It was assumed that the density of solid particles is 2.9 kg/L. This density value is based on densities of dominant chemical constituents in the tanks. The potential effect of this assumption is to overstate the pressure drop in the transfer system significantly if the larger particles are less dense, would be dissolved in the tanks before transfer, or would be broken up when passed through the transfer pump. In addition, actual PSDs at transfer conditions has not been well characterized, particularly as the waste level in the tank decreases during a waste transfer where larger particles may be picked up and increased concentrations of particles may be transferred.

The volume percent solids in the HLW was estimated by increasing the highest solids content of any transfer identified in HTWOS by approximately 50%. This value was then used in the transfer analysis. The rationale for increasing the HTWOS value was to account for density gradients in the tanks during waste transfers. The rationale for using this value for transfers was to accommodate future changes in the tank retrieval sequence that could affect the volume percent solids for a particular transfer route.

This analysis was originally intended to address Phase 1 and Phase 2 transfers from the AN, AP, AW, AY, and AZ Tank Farms using transfer-specific waste properties. As more information becomes available, more accurate predictions may be possible for the full range of transfers.

4.3.2 Pipe Surface Roughness

The pipe surface roughness was determined by analysis based on assumed waste conditions, an extended 50-year life for the carbon steel pipeline segments and a 40-year life for the stainless steel pipelines. Pipe surface roughness has a large impact on the calculation of pressure drop in the carbon steel segments of the transfer route pipelines. The roughness values provided in Appendix C may not be conservative, but it is not possible to know without inspecting the insides of the pipeline segments or performing a pressure drop flow test under known controlled conditions.

4.3.3 Critical Velocity and Pressure-Drop Correlations

Although the critical velocity and pressure-drop correlations have been developed from the analysis of extensive test data, these correlations have not been validated through testing for the Hanford Site-specific waste characteristics.

The correlation used for determining critical velocity is empirically derived from data that does not include particles <100 μm in diameter. HNF-2728 recommends the use of the Oroskar and Turian (1980) correlation. HNF-2728 compares the correlation with another correlation that is based on flows with smaller particles (< 80 μm) and shows that the Oroskar and Turian (1980) correlation is conservative.

Additionally, the Oroskar and Turian (1980) correlation uses a median particle size to represent the distribution of particle sizes. This is a reasonable simplification for slurries with a narrow range of particle sizes. It can lead to underestimation of the critical velocity required to keep particles in suspension for slurries with a wide range of particle sizes. The stability criterion proposed by Wasp may be a better approach for the broadband PSDs typical of Hanford HLW (see discussion at end of Section 2.2 and sensitivity analysis given in Appendix E). The Wasp stability criterion was investigated in Appendix E. In the case of the mean PSD the Oroskar and Turian critical velocity was greater than the Wasp stability criterion velocity. However, in the 95/95 TL PSD the Wasp stability criterion velocity was greater than the Oroskar and Turian critical velocity.

4.3.4 Waste Rheology

The characterization data that are available indicate that the viscosity of the carrier liquid is sensitive to temperature, pH, and solids concentration. Consistent with current practice, this analysis assumes that the transfers will occur at a temperature that will not cause the waste to begin to gel or cause large changes in the liquid viscosity. Variations in temperature during a waste transfer resulting from cooling in the pipeline could change the results of this analysis substantially.

4.3.5 Waste Transfer Temperature

Calculation of the pipeline system pressure drop requires knowledge of the transferred waste physical properties at the transferred waste temperature, including heat up from mixer pumps. A representative maximum waste transfer temperature of 80 °C (175 °F) was selected to account for heat up of the waste from mixer pump operation during transfer of HLW. This temperature is not necessarily bounding, particularly as the waste level decreases during waste transfer. Current safety controls to prevent tank bumps limit this temperature to 90 °C (195 °F) in the bulk liquid or to 100 °C (215 °F) for the bottom 4.6 m (15 ft) of waste in the tank (HNF-SD-WM-TSR-006, *Tank Waste Remediation System Technical Safety Requirements*). However, the recommended viscosity relations were found to be insensitive to temperature range of interest compared to effects of solids concentration and strain rate.

5.0 CONCLUSION

Section 5.1 provides a discussion of the analysis and identifies potential deficiencies in the waste transfer system analysis. Section 5.2 provides recommendations to meet program needs and to evaluate the adequacy of the waste transfer system more accurately.

5.1 DISCUSSION

The intent of this analysis was to provide a documented basis for the minimum design pressure rating of the waste transfer system pipeline and a documented basis for the design and operating pressure of the transfer system pumps. Slurry correlations for heterogeneous and homogeneous flow were identified for estimating the critical velocity and the pressure drop through the waste transfer pipelines. Transfer system characteristics were reviewed for each of the transfers identified in Phase 1 of HTWOS. The transfers were consolidated into distinct transfer routes for evaluation of the transfer system fluid flow characteristics.

Note that a robust transfer system is preferred not only to handle a wide range of waste physical properties but also to accommodate the higher pressures required in potential unplugging operations. In addition, there are uncertainties in the waste physical properties of the Phase 2 transfers; as well as, uncertainties in the waste physical properties as the waste level decreases during waste transfer where larger particles may be picked up and the concentration of particles retrieved may be increased significantly.

5.2 RECOMMENDATIONS

Evaluation of the waste transfer system begins with an accurate characterization of the physical properties of the waste at transfer conditions. Evaluation also requires accurate information regarding the condition of the existing pipeline. Preparation of specifications to procure waste transfer system equipment before having accurate characterization data involves risk that the equipment will not meet the transfer system needs. It also can lead to unnecessarily modifying or replacing portions of the transfer system that may be adequate if accurate waste characterization data were available.

The current assessment of waste properties is considered to be conservative. Although this potential 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 necessary to revise this analysis or verify the assumed conservatism.

Measurements of key parameters (flow rate, pressure drop, bulk density, particle size distribution and liquid density) during initial slurry transfers to allow comparisons with predicted results are recommended until adequate experience has been obtained.

Because the jumper connectors are leak test qualified to only 1.7 MPa (250 lbf/in^2), the above assumes that the jumper connectors can be leak test qualified to pressures that meet or exceed the

above pipeline transfer route limiting pressures of 2.7 and 1.9 MPa (400 and 275 lbf/in^2), respectively. Plans for jumper connector qualifying leak tests to a pressure of at least 2.7 MPa (400 lbf/in^2) are under development. This testing should be completed to establish the operating pressure limits of the jumper connectors and verify that the assumed limit applied in this analysis is adequate.

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APPENDIX A

HANFORD TANK WASTE PHYSICAL PROPERTY ESTIMATES

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MEMORANDUM **CH2MHILL**

74B50-00-001R2

ALTERNATIVES GENERATION AND ANALYSIS FOR WASTE FEED DELIVERY TRANSFER PUMP DISCHARGE PRESSURE: HANFORD TANK WASTE PHYSICAL PROPERTY ESTIMATES

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FROM: Process Control

DATE: April 10, 2000

References:

(1) Internal Memorandum, "Alternatives Generation and Analysis for Waste Feed Delivery Transfer Pump Discharge Pressure: Hanford Tank Waste Physical Property Estimates," memorandum number 74B50-00-001R1, dated February 11, 2000.

(2) Internal Memorandum, "Memorandum of Understanding Requirements Action Memo for the Alternatives Generation and Analysis for Feed Delivery Transfer Pump Discharge Pressure Control," memorandum number 82400-99-093, dated December 30, 1999.

(3) Textbook, Shook, C.A. & M.C. Rocco, "*Slurry Flow - Principles and Practice*," Butterworth-Heineman, Stoneham, Massachusetts," published 1991.

(4) Handbook, Weast, C.W. & M.J. Astle, "*CRC Handbook of Chemistry and Physics*," 61st ed., CRC Press, Boca Raton, Florida," published 1980.

This memorandum revises Reference (1) that was created in response to Reference (2) direction. This revision incopropates text changes and corrects information presented in the Attachment.

74B50-00-001-R2.DOC

Pipeline transport of wastes containing solids (a slurry) can be considered a two-phase flow, as required to estimate a critical velocity. Additionally, such a slurry can be considered to have bulk, or homogeneous properties, that are useful in (but not the only method available for) determining pressure drops and power requirements for the respective piping system. This memo attempts to give bounds and best estimates of the waste properties at shear rates applicable to typical Hanford pipeline transport velocities.

The following definitions are needed to describe both two-phase and homogeneous slurry flow:

Subscript "$_c$" indicates the carrier liquid (i.e., the continuous phase) of the slurry. Also included in the carrier liquid are any dissolved soluble solids.

Subscript "$_d$" indicates the solid particulates (i.e., the dispersed phase) in the slurry. These particles can be both insoluble solids and precipitated soluble solids.

Subscript "$_m$" indicates the bulk property of the slurry (i.e., the mixed property of the two-phase fluid).

D = diameter of the spherical solid particulates in the waste

α = volume fraction

ρ = density

μ = **Newtonian** dynamic viscosity (this estimate does not describe the potential non-Newtonian behavior of some of the Hanford tank wastes. However, the non-Newtonian nature of these wastes should not be such as to create conditions that could terminate a waste transfer provided the waste can be initially mobilized and kept in suspension via sufficient flow velocity for the duration of the transfer.)

Physical Relationships

$$\alpha_c = \alpha_{water} + \alpha_{dissolved\ solids}$$
$$\alpha_d = \alpha_{insoluble\ solids} + \alpha_{precipitated\ soluble\ solids}$$
$$\alpha_c + \alpha_d = 1$$
$$\rho_m = \alpha_c\rho_c + \alpha_d\rho_d$$

The summary of the nominal and bounding **in-situ** waste properties are shown in Table 1:

Table 1: Slurry Physical Properties

Case ⇒ Property ⇓	Nominal	Bounding
D_d ①	40 μm	400 μm
α_c	0.85	0.70
α_d	0.15	0.30
ρ_c②	1.21	1.46
ρ_d③	2.50	3.00
ρ_m	1.40	1.92
μ_c	④	④
μ_m	⑤	⑤

Notes

① These solid particulate diameters are stated as the **median** of the distribution, meaning that one-half of the total particulate mass is contained in particles with diameters smaller than the stated diameter, with the other half of the total particulate mass being contained in particles with a larger diameter.

The solid particulates in the waste are assumed to be spherical. The spherical shape gives the minimum isotropic drag coefficient for a particle of a given mass. This property should result in minimizing slurry flow pressure drop (a non-conservative result) while maximizing slurry flow critical velocity (a conservative result). There are many Hanford tank waste solids size distribution data available that indicate, at least in a qualitative sense, that the mass distribution of the majority of solids are under 40 μm in size. However, there is data suggesting particulate sizes exist at, and may exceed, the limit of instrument detection (in some cases, approximately 1 mm - see Attachment).

② Values from analysis of Tank Characterization Data (TCD) liquid wastes with the nominal value corresponding to the 50th percentile and the bounding value corresponding to the 90th percentile. (see Attachment)

③ Waste true solids densities qualitatively estimated as an engineering judgement. As a comparison, densities of some dominant chemical constituents that are known to or may exist as solids in the tank wastes are shown in Table 2:

Table 2: True (Particulate) Solid Densities (gm/cc)*

Anion⇒ Cation⇓	$(OH)_x$	NO_3	NO_2	PO_4	C_2O_4	CO_3	$Fe(CN_6)$
Na_x	2.13	2.26	2.17	1.62	1.46	1.44 - 2.53	2.34
Al_x	2.42	?	?	2.57	?	?	?
Fe_x	3.40	~1.68	?	2.58 - 2.74	2.28	?	1.60
Cr_x	?	?	?	2.12 - 2.42	~2.47	?	?
$(NH_3)_x$	?	1.73	1.69	1.80 - 2.21	1.50	?	?

*density ranges indicates various waters of hydration
? density is unknown or compound is not documented

Table 2 gives some idea of a qualitative comparison to the estimated nominal and bounding solid densities of 2.50 and 3.00 gm/cc.

④ These μ_c estimates are conservative for pressure drop calculations but are not conservative for typical critical velocity correlations. In determining critical velocities, the most conservative assumption for μ_c is that it is equivalent to water. In contrast, for pressure drop calculations, higher values of μ_c result in higher pressure drops.

The viscosity of the carrier liquid is stated as:

$$\mu_c = \mu_{water}\left((x_{salt})*\left(1+1.071*(\frac{\rho_c}{\rho_{water}}-1)\right) + (x_{caustic})*\exp\left(\left(7.143*(\frac{\rho_c}{\rho_{water}}-1)\right)^{1.15}\right)\right)$$

utilizing the following definitions:

x_{salt} = the fraction of **dissolved solids** composed of sodium nitrate, sodium nitrite, and other water soluble salts.

$x_{caustic}$ = the fraction of **dissolved solids** composed of sodium hydroxide.

$$\text{Assume:} \quad x_{salt} = 0.9; \quad x_{caustic} = 0.1; \quad (x_{salt} + x_{caustic}) = 1$$

Over the temperature range of 0^0C to 100^0C, this assumption gives:

$$\rho_c = \rho_{water} * (1 + 0.00848 * (\text{wt\% dissolved solids}))$$

Over the temperature range of 0^0C to 100^0C (from Reference 4):

$$\rho_{water} = \frac{999.83952 + 16.945176(T) - 7.9870401 * 10^{-3}(T)^2 - 46.170461 * 10^{-6}(T)^3 + 105.56302 * 10^{-9}(T)^4 - 280.54253 * 10^{-12}(T)^5}{1000 * (1 + 16.879850 * 10^{-3}(T)^3)}$$

Over the temperature range of 0^0C to 20^0C (from Reference 4):

$$\mu_{water} = 100 * cP * \exp\left(\frac{2996}{998.333 + 8.1855 * (T - 20) + 0.00585 * (T - 20)^2} - 7.60390\right)$$

And, over the temperature range of 20^0C to 100^0C (from Reference 4):

$$\mu_{water} = 1.002 * cP * \exp\left(\frac{3.0560(20 - T) - 0.002425(T - 20)^2}{T + 105}\right)$$

⑤ No exact method exists for determining μ_m. Various researchers have proposed models that predict μ_m as a function of one or more variables in addition to μ_c, and the resultant value of μ_m is typically expressed as a multiple of μ_c. If the model utilizes only one variable, it is usually α_d.

As an example, several slurry viscosity models are documented in Reference (3). These include models from Einstein, Eiler, Thomas, Kreiger, and Vocadlo. For these referenced models that are applicable to concentrated slurries, a reasonable selection of the independent variables predicts results within a factor of 2.0 for a slurry when $\alpha_d = 0.3$.

The model of Thomas is reproduced here because it has only one independent variable (α_d):

$$\mu_m = \mu_c * \left(1 + 2.5 * \alpha_d + 10.05 * \alpha_d^2 + 0.00273 * \exp(16.6 * \alpha_d)\right)$$

S. D. Estey, Engineer
Process Control

sde/mjg

Attachment

Attachment to 74B50-00-001-R2

Comments by L. Jensen, February 8, 2000

This following summary data for PARTICLE VOLUME DISTRIBUTION is from Table 2-2, HNF-2728 by S Estey and AT Hu. The units are μm.

SST	Mean(μm)	min(μm)	max(μm)	date	Lab
B-106	3.64	0.2	6	1997	LANL
B-111	3.66	0.4	9	1995	PNL
BX-103	1.5	0.2	7	1997	LANL
BX-107	5.67	0.4	35	1995	PNL
BY-104	6.98	0.4	75	1996	PNL
BY-108	6.53	0.2	39	1997	PNL
BY-110	6.15	0.25	40	1996	PNL
C-103	1.06	0.4	2	1995	PNL
C-104	2.05	0.2	7	1997	LANL
C-105	2.16	0.2	7	1997	LANL
S-101	6.8	0.29	38	1997	PNL
S-104	6.78	0.2	30	1997	PNL
S-107	13.48	0.35	100	1996	PNL
S-111	47.7	0.9	120	1997	PNL
SX-108	12.8	0.2	112	1996	PNL
SX-113	1.84	0.2	6	1997	LANL
T-104	4.85	0.4	13	1995	PNL
T-111	4.82	0.4	12	1995	PNL
DST	Mean(um)	min(um)	max(um)	date	Lab
AN-104	5.68	0.7	19	1997	PNL
SY-102	9.32	0.2	105	1996	PNL
SY-103	9.71	0.4	30	1995	PNL

The follwing summary data for PARTICLE VOLUME DISTRIBUTION is from multiple internal memos by JF O'Rourke. The units are μm.

DST	median(μm)	sd(μm)	mode(μm)	mean(μm)	min(μm)	max(μm)	date	Inst.Max	Lab	Comments	
SY-101	183.60	82.70	237.80	164.80	0.22	451	1999	1020	222S		replicate samples?
SY-101	125.80	264.10	159.00	197.30	0.19	1019	1999	1020	222S		
AW-101	314.00	162.00	427.00	307.00	6.7	1020	1999	1020	222S	undiluted	
AW-101	946.00	224.00	952.00	884.00	29.9	1020	1999	1020	222S	diluted	replicate samples?
AW-101	940.00	283.00	952.00	833.00	11	1020	1999	1020	222S	diluted	
AN-104	4.85	12.80	31.30	13.40	0.5	31	1998	150	222S		
AN-105	4.28	13.48	41.61	10.47	0.5	45	1998	150	222S		replicate samples?
AN-105	5.76	23.80	66.90	19.35	0.5	70	1997	150	222S		
AN-105	3.24	2.87	4.25	3.72	0.5	30	1997	150	222S		
AN-105	4.95	12.35	31.30	12.00	0.5	50	1997	150	222S		
AN-105	4.48	14.70	45.70	12.40	0.5	50	1997	150	222S		
SST	median(μm)	sd(μm)	mode(μm)	mean(μm)	min(μm)	max(μm)	date	Inst.Max	Lab	Comments	
S-111	107.40	46.60	156.60	100.00	7.7	174.6	1999	1020	222S		replicate samples?
S-111	190.00	79.70	235.40	168.10	11.6	451	1999	1020	222S		
S-111	92.90	58.00	121.60	92.10	6.7	592	1999	1020	222S		
U-109	13.16	5.90	18.60	12.80	2.2	26	1999	150	222S		replicate samples?
U-109	17.30	9.00	24.60	15.90	2.6	34.3	1999	150	222S		
C-106	1.74	2.20	1.25	2.74	0.5	11	1996	150	222S		replicate samples?
C-106	4.00	5.26	4.75	6.40	0.5	28	1996	150	222S		

Comments:

1. There are not very many tanks with particle distribution data.
2. The analytical methods do not give results greater than 150 and 1020 μm. There may be particles larger than 150 and 1020, but not detected by the analytical method.
3. The DSTs appear to be separated in to two classes, one with a small median μm and the other with a large median μm. The reason is unknown.
4. The bounding value of 200 μm. is an underestimate of the median particle volume distribution or the maximum value. The analytical method maximum value of 1020 is reported for four samples.
5. Without having electronic copies of the original particle size data, it is not possible to give statistical measures of uncertainty associated with particle quantiles such as the median (50th percentile of the distribution) or values for the 25th or 75th percentile of the distribution.

Summary of Specific Gravity Results from the Tank Characterization Database.

A comparison between the (nominal, conservative, and bounding) density values given in memorandum 74B50-00-001, and the analytical results from the Tank Characterization Database (TCD) has been completed. The values in the memorandum compare well with the 50th, 75th, and 90th percentiles of values from laboratory assays.

The tanks used in the analysis were those which had liquid results for the following eight constituents: aluminum, hydroxide, nitrate, nitrite, percent water, sodium, specific gravity, and total organic carbon. Twenty-one single shell, and twenty double shell tanks, met this criteria. These tanks are listed in Table 1.

Table 1. Tanks used in Analysis.

Single Shell Tanks	Double Shell Tanks
241-A-101	241-AN-101
241-AX-101	241-AN-102
241-BY-103	241-AP-101
241-BY-105	241-AP-102
241-BY-106	241-AP-103
241-S-102	241-AP-104
241-S-103	241-AP-105
241-S-104	241-AP-106
241-S-106	241-AP-107
241-S-109	241-AP-108
241-S-111	241-AW-102
241-SX-101	241-AW-103
241-SX-103	241-AW-104
241-SX-105	241-AW-105
241-SX-106	241-AW-106
241-U-102	241-AY-101
241-U-103	241-AY-102
241-U-105	241-AZ-101
241-U-107	241-AZ-102
241-U-108	241-SY-102
241-U-109	

The pairwise correlations of the eight constituents are given in Table 2. A correlation of one (or negative one) indicate that the constituents have a linear relationship. When this occurs, the value of one constituent can be used to predict the value of another. As an example, the –0.98 correlation between percent water and sodium, means that percent water decreases, in a predictable manner, as sodium increases. Similarly, the 0.92 correlation between specific gravity and sodium, means that specific gravity increases as the sodium concentration increases.

Note that many of the constituents have correlations of 0.75 or greater. This is an indication that the waste tends to be either dilute, or concentrated, while the ratios of individual values to one another are fairly constant (at least for the analytes with large concentrations).

Table 2. Correlations.

Constituent	Al	OH	NO3	NO2	H20	Na	SPG	TOC
Aluminum	1.00	0.76	0.52	0.7	-0.80	0.80	0.80	0.081
Hydroxide	0.76	1.00	0.62	0.62	-0.77	0.78	0.75	-0.005
Nitrate	0.52	0.62	1.00	0.71	-0.84	0.85	0.77	0.30
Nitrite	0.70	0.62	0.71	1.00	-0.85	0.85	0.80	0.38
Percent Water	-0.80	-0.77	-0.84	-0.85	1.00	-0.98	-0.95	-0.34
Sodium	0.80	0.78	0.85	0.85	-0.98	1.00	0.92	0.35
Specific gravity	0.80	0.75	0.77	0.80	-0.95	0.92	1.00	0.28
Total organic carbon	0.081	-0.005	0.30	0.38	-0.34	0.35	0.28	1.00

The strong correlations given in Table 2 suggest that percentile estimates, calculated on a constituent by constituent basis, can be combined to produce reasonable estimates of dilute, or concentrated, waste.

Table 3. Percentile Estimates for Dilute, or Concentrated, Waste*.

Constituent	10th	25th	50th	75th	90th
Aluminum	0.01%	0.14%	0.97%	2.50%	3.19%
Hydroxide	0.11%	0.36%	1.40%	2.89%	3.60%
Nitrate	0.67%	2.78%	8.28%	12.72%	15.71%
Nitrite	0.13%	1.17%	3.68%	6.60%	9.67%
Percent Water	96.2%	85.9%	63.1%	51.0%	47.3%
Sodium	1.02%	4.12%	11.81%	15.69%	17.12%
Total organic carbon	0.02%	0.05%	0.14%	0.27%	0.40%
Specific gravity	1.01	1.08	1.28	1.43	1.47

- Results are on a weight basis.

By using the results in Table 3, and the equation on page three of the memorandum, viscosity estimates were calculated. The results are given in Table 4 (the weight percentages are approximate). Note that the viscosity associated with the 50th percentile, and the viscosity associated with the 90th percentile, are reasonably close to the "conservative" and "bounding" values given in the memorandum (1.7 versus 1.86 and 3.3 versus 3.04 respectively).

Table 4. Viscosity Estimates.

Constituent	10th	25th	50th	75th	90th
NaOH	0.44%	1.7%	5.3%	8.1%	9.3%
NaNO2 + NaNO3	1.48%	10.9%	19.8%	29.7%	36.8%
Percent Water	96.2%	85.9%	63.1%	51.0%	47.3%
Viscosity*	1.05	1.28	1.86	2.58	3.04

- Multiply this number by the viscosity of water.

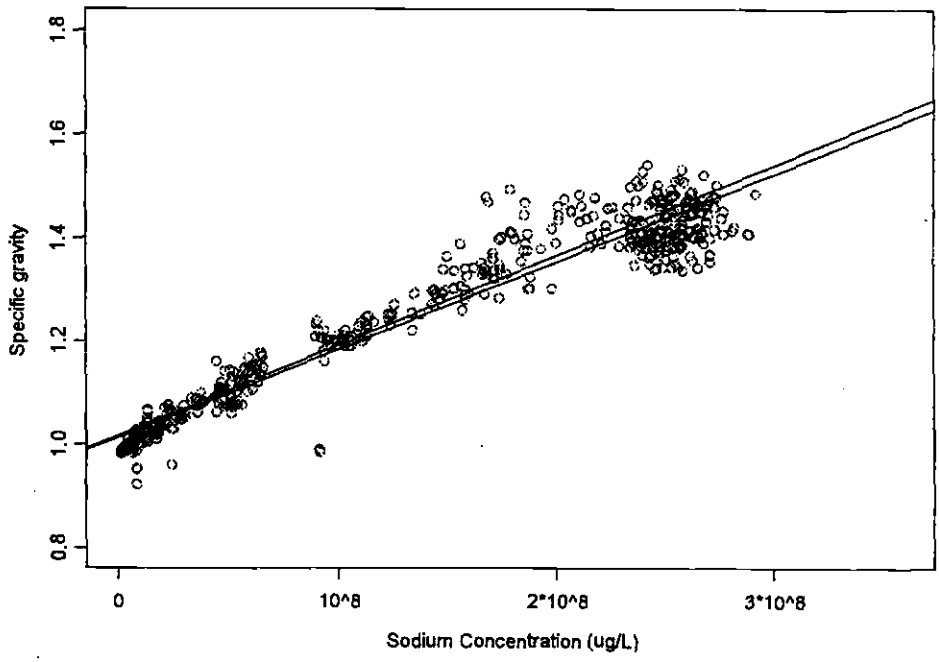
In the preceding analysis, all of the results from the 21 single shell, and 20 double shell tanks were combined. The 41 tanks used in the calculations were tanks that had data for each of eight major constituents.

An examination of all specific gravity results on TCD was also made. Except for tanks AN-106 and SY-103, all of the double-shell tanks had specific gravity data. In addition, fifty four of the 149 single shell tanks had specific gravity measurements. Note that the 75th and 90th percentiles are similar for the two tank types, but the double shell tanks have lower values for the other percentiles. These results indicate that, if the results above are applied to double shell tanks only, then the 10th, 25th, and 50th percentiles may be biased high (i.e. they are "conservative" estimates)

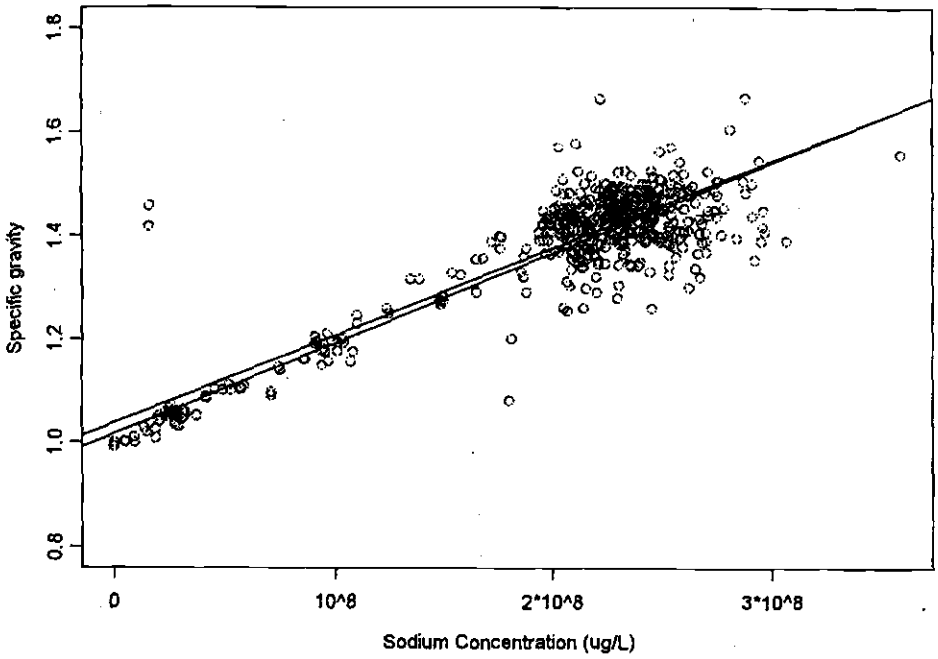
Table 5. Specific Gravity Results, All Tanks.

Tank Type	10th	25th	50th	75th	90th
Single Shell Tank	1.15	1.35	1.43	1.46	1.49
Double Shell Tank	1.00	1.05	1.21	1.40	1.46

Double-Shell Tanks: Specific Gravity versus Sodium Concentration



Single-Shell Tanks: Specific Gravity versus Sodium Concentration



APPENDIX B

HANFORD 200 EAST AREA WASTE FEED DELIVERY TRANSFER ROUTES

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CONTENTS

B-1 Hanford 200 East Area Waste Transfer System Layout B1-i

B-2 Hanford 200 East Area Waste Transfer Equivalent Pipeline Lengths and Elevation Tabulation B2-i

B-3 Equivalent Pipeline Length and Elevation Change in DOE Feed Lines from TFC to the DOE/WTP Interface (Preliminary) B3-i

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APPENDIX B-1

HANFORD 200 EAST AREA WASTE TRANSFER SYSTEM LAYOUT

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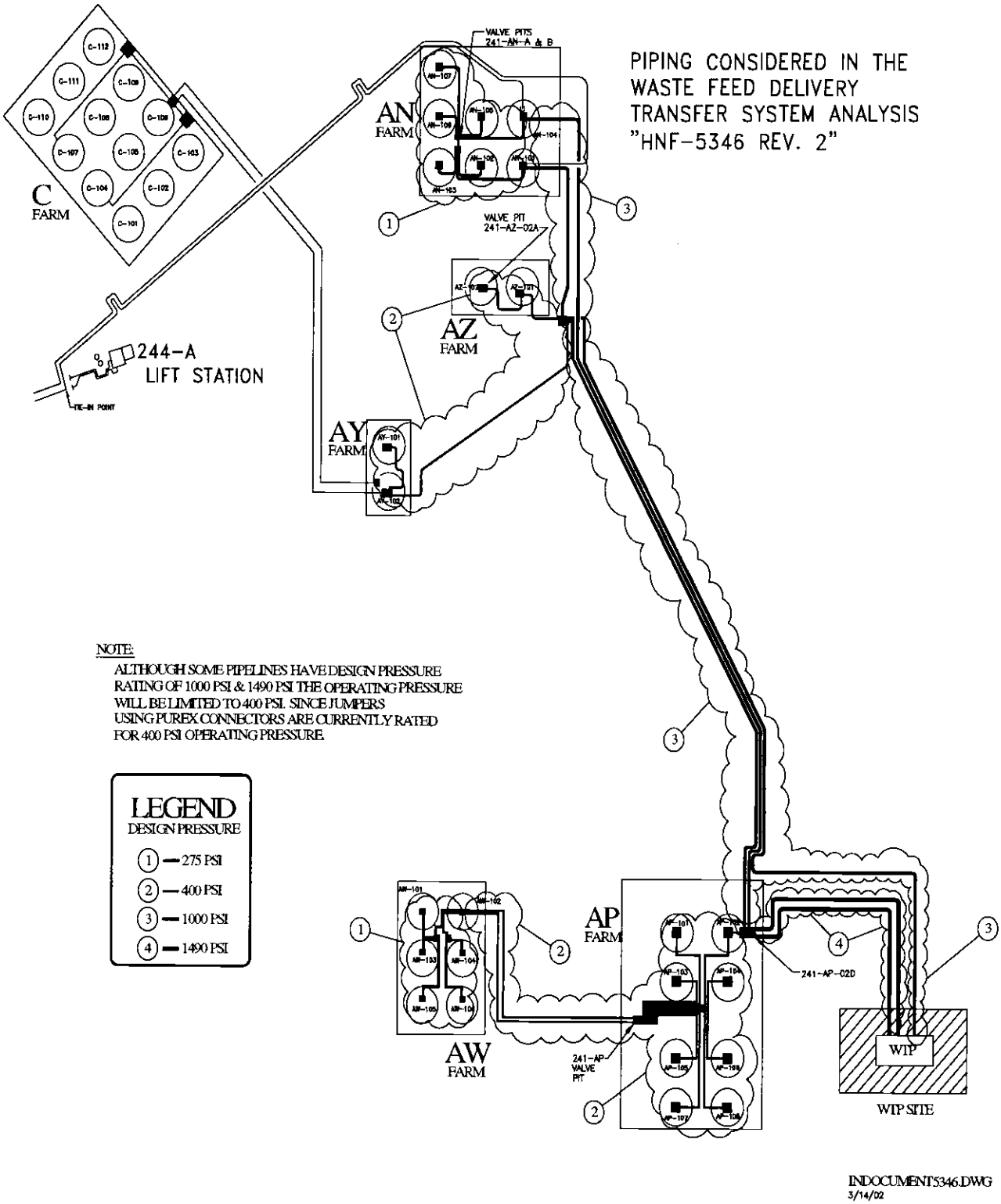
Figure B1-1. Waste Transfer System.



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APPENDIX B-2

HANFORD 200 EAST AREA WASTE TRANSFER EQUIVALENT PIPELINE LENGTHS AND ELEVATION TABULATION

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INTEROFFICE MEMO

CH2MHILL
Hanford Group, Inc.

From:	Design Engineering	7G100-01-AWC-048, Rev. 1
Phone:	373-9438	
Date:	March 13, 2002	
Subject:	TRANSMITTAL ENCASEMENT PIPE STUDY LINE LENGTH AND ELEVATION TABULATION	
To:	L. J. Julyk	R3-83
	T. C. Conrads	R3-83
Copies:	J. D. Galbraith CHECK BY JAG	R3-73
	A. H. Friberg	R3-83
Reference:	AP Farm/WTP Transfer System Simplification; Baseline Change Request (BCR) RPP-01-116, Rev. 0	

This transmittal revises correspondence 7G100-01-AWC-048, dated December 19, 2001. Attached is a revised Excel spreadsheet (Rev. 5, prepared January 23, 2002), tabulating line lengths and elevations for various proposed transfer routes between tanks in the AN, AP, AW, AY, and AZ tank farms and the proposed Waste Treatment Plant (WTP). Tables were revised to adjust design pressures identified for the transfer routes to reflect the maximum allowable design pressure within the constraints of the lowest maximum design pressure for a single leg within a specific transfer routing. Other information identified in the December 19, 2001 transmittal remains valid.

A.W. Clarkson
Engineer

im

Attachment

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	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	Line #	Farm:	Comments	Pressure: (psi)	Eq. Length CS	CS Different Source:	CS Jumpers:	Eq. Length SS	SS Different Source:	SS Jumpers:	From	Nozzle (Per Dwg B217D)	Elevation	Source	To	Nozzle (Per Dwg B217D)
2																
3	SN-261	AW	Line not shown on D153A	275	109.00						AW-A SN220=685.334; SN271=685.334	L16	685.334	D153A	AW-101 01A	A
4	SN-261	AN	Line not shown on D153A	275	264.00						AN-B	R15	666.160	H-2-71989	AN-101 01A	A
5	SN-262	AN	Line not shown on D153A	275	141.00						AN-B	R16	666.160	H-2-71989	AN-102 02A	A
6	SN-263	AW	Line not shown on D153A	275	127.00						AW-A SN220=685.334; SN271=685.334	L14	685.334	Est per D153A	AW-103 03A	A
7	SN-263	AN	Line not shown on D153A	275	112.00						AN-B	R14	666.460	Est per D153A	AN-103 03A	A
8	SN-264	AN		275	247.00						AN-A	L14	666.160	H-2-71989	AN-104 04A	A
9	SN-264	AW	Line not shown on D153A	275	115.00						AW-B SN271-SN219-SN262-SN268=685.229	R13	685.290	D153A	AW-104 04A	A
10	SN-265	AN		275	137.00					108.00	AN-A	L15	665.300	D153A	AN-105 05A	A
11	SN-265	AW	Line not shown on D153A	275	240.00						AW-A SN220=685.334; SN271=685.334	L15	685.334	D153A	AW-105 05A	A
12	SN-266	AW	Line not shown on D153A	275	226.00						AW-B SN271-SN219-SN262-SN268=685.229	R15	685.290	Est per D153A	AW-106 06A	A
13	SN-266	AN	Line not shown on D153A	275	127.00						AN-A	L13	665.300	Est per D153A	AN-106 06A	A
14	SN-267	AW	Line not shown on D153A	275	124.00					205.00	AW-A SN220=685.334; SN271=685.334	L1	685.334	D153A	AW-102 02A SN262=684.5, SN268=684.5	J
15	SN-267	AN	Line not shown on D153A	275	242.00						AN-A	L1	666.500	Est per D153A	AN-107 07A	A
16	SN-268	AW		275	88.00					205.00	AW-B SN271-SN219-SN262-SN268=685.229	R1	685.290	D153A	AW-102 02A SN262=684.5; SN268=684.5	H
17	SN-268	AN		275	51.00						AN-A	L-19	666.500	D153A	AN-B	R19
18	SN-272	AW	Line not shown on D153A	275	75.00						AW-102 02E	D	683.030	Est per D153A	AW-102 02A SN262=684.5; SN268=684.5	K
19	SN-609	AP		400	761.00						AP Valve pit	14	676.610	D153A	AW-102 02A SN262=684.5; SN268=684.5	V
20	SN-610	AP		400	800.00					205.00	AP Valve pit	13	676.610	D153A	AW-102 02A SN262=684.5; SN268=684.5	U
21	SN-611	AP	Line not shown on D153A	400	413.87					205.00	AP Valve pit	18	676.610	Est per D153A	AP-101 01A	A
22	SN-612	AP		400	431.00					100.00	AP Valve pit	19	676.610	D153A	AP-102 02A	A
23	SN-613	AP	Line not shown on D153A	400	306.00						AP Valve pit	17	676.610	D153A	AP-103 03A	A
24	SN-614	AP		400	314.00						AP Valve pit	20	676.610	Est D153A / H-14-104365	AP-104 04A	A
25	SN-615	AP	Line not shown on D153A	400	302.00						AP Valve pit	24	676.610	D153A	AP-105 05A	A
26	SN-616	AP		400	340.00						AP Valve pit	21	676.610	D153A	AP-106 06A	A
27	SN-617	AP	Line not shown on D153A	400	423.00						AP Valve pit	23	676.610	Est per D153A	AP-107-07	A
28	SN-618	AP		400	443.00						AP Valve pit	22	676.610	D153A	AP-108-08	E
29	SN-622	AP		1000				55.00		60' or 90'	AP-102 02D	A	675.890	D153A	AP-102 02A	Q
30	SN-630	AZ		1000				491.00			AZ VALVE PIT (NEW)	A	669.500	D153A	AN-101 01A	D
31	SN-631	AZ		400				130.00			AZ-102 02A	U13	670.500	D153A	AZ-101 01A	U11
32	SN-632	AZ		400				154.00		100' (0xA)	AZ VALVE PIT (NEW)	H	669.250	D153A	AZ-101 01A	U12
33	SN-633	AZ		400				843.00		100' (0xA)	AZ VALVE PIT (NEW)	F	669.500	D153A	AY-102 02A	U5
34	SN-634	AZ		1000				1,558.00			AZ VALVE PIT (NEW)	E	669.500	D153A	W-314/W-211 INTERFACE NE 241-AP	n/a
35	(SN-634)	AP		1000				145.00			AP-102 02D	S	674.490	D153A	W-314/W-211 INTERFACE NE 241-AP	n/a
36	SN-635	AY		400				120.00		120.00	AY-102 02A	U12	674.490	D153A	AY-101 01A	U12
37	SN-636	AN		1000				2,151.00			AN-104 04A	D	664.360	D153A	W-314/W-211 INTERFACE NE 241-AP	n/a
38	(SN-636)	AP		1000				145.00			AP-102 02D	D	674.490	D153A	W-314/W-211 INTERFACE NE 241-AP	n/a
39	SN-637	AZ		1000				1,573.00			AZ VALVE PIT (NEW)	C	669.500	D153A	W-314/W-211 INTERFACE NE 241-AP	n/a
40	(SN-637)	INTERFACE		1490				2,555.00			W-314/W-211 INTERFACE NE 241-AP	n/a	674.490	D153A	WTP INTERFACE	n/a
41	SN-700/SN-701	AP		1490				2,738.00			AP-102 02D	700=V/701=U	674.490	D153A	WTP INTERFACE	n/a
42																
43																

44 **ASSUMPTIONS 12-2001:**

45

46 **Jumpers: Unless otherwise noted per information from design estimates based as follows:**
47 Central Pump Pit (CPP) Estimate 108' - if origin or termination
48 Central Pump Pit (CPP): 205' used as estimate for 0_A CPP Jumper Length when CPP is used as Transfer or Intermediate Pit.
49 From Source (CPP) through Single Pit to receiver tank estimate 108'
50 From Source Pit through both ANA and ANB estimate Jumper Length of 205'
51 Transfer Pit Estimate 205' Equivalent Length for Jumpers
52 AN Valve Pit Assume 108' for Jumpers
53 AW Valve Pit Assume 108' for Jumpers
54 Note: Equivalent Length for Jumpers is identified above if not within assumptions noted
55 AW 02A Assume jumper length 30' CS between SN-268 & SN-269 (Not 108'/205')
56 Tanks: 75' dia; 25' between tanks
57 All Farms configured to drain lines from Valve Pits to CPP.
58
59 AN: SS all pits
60 AP: CS Valve Pit; SS CPP: AP-A jumper CS
61 AW: SS all pits (CPP by W-521)
62 AY: SS all pits incl. 0A
63 AZ: SS all pits incl. 0A
64
65 Equivalent Lengths Verified w/Jim Collins FFS 12/05/2001:
66 All 3" SS pipe w. 3' radius Bends, no fittings (i.e. equivalent to straight pipe)
67 SN-630 =491'
68 SN-631 = 130'
69 SN-632 = 154'
70 SN-633 = 843'
71 SN-634 = 1558'
72 SN-635 = 120'
73 SN-636 = 2151'
74 SN-637 = 1573'
75
76 No Pit/No Jumpers @ W-314/W-211 Interface Point, NE of 241-AP
77
78 W-211: (SN-636); SN-637; SN-700/SN-701 (Mark Przybylski)
79 W-211 lengths represent difference due to changes from preliminary estimates to actual installed.
80 Changes required to remedy field issues discovered during construction.
81
82 Note: WTP elevation was +45' per BNFL now elevation estimate +63' per BHI.
83
84
85
86

SN-265	Jumpers: est 108 SS
SN-268:	Est 51' CS Equivalent Pipe Length / John G.
SN-268 AW:	Line length est. of 88' reported accurate. 124' length estimated by Bill Willis for earlier evaluation not used.
SN-610:	Originates in AP - 02A pit est. 205' for jumpers in AN-102 02A pit - SS jumpers for future use.
SN-612;	Eq Length SS Jumpers = approx. 100' per FFS. (02A will have new SS Jumpers - W-211)
	02A Jumper SS per W-211 AP-102 & AP-104 DD Docs. Length same as for AZ 0xA pits
SN-622	Eq Length est 55' SS per W-211.
	02D Jumpers Rte. Specific 60' if in SN-634 and out SN-622
	02D Jumpers Rte. Specific 90' if in SN-636 and out SN-622
SN-632	AZ 101 0XA Pit: Verified by W-211 SS Jumpers approx 100 ft.
	Total Equivalent Straight Pipe Length Of 3" Pipe For AZ-101 Pump Discharge Jumpers = approx. 100 ft.
	Per Paul Dorsi Temp - 200F
	Viscosity - 10 cp
	SG - 1.25
	Flow - 140 GPM
	Friction Factor 0.028
SN 633	SS Jumpers approx 100 ft. AY 02 pit will match AZ 02 pit (J. G. 12-11-01)
SN 635	Jumper Eq Length Est 120' SS per John G. 12-11-01.
SN-636	AN Farm from 0_A to AN valve Pits all CS: Jumpers SS
	AW Same
	AP Same
(SN-634)	W-314 to 02D is 145 SS per W-211 value.
	Assume ALL AP Farm jumpers are CS - May verify with AP System Engineer - call Tim Oten to determine SE
	SN-631, 632, 633, 634, 635 - Installed and pressure tested to 400 psi per Curt Rieck.
	Also, 3 lines (2 from 02D & 1 from W-314 Interface) have design Pressure of 1490 psi per Curt.
SN-611	SN-611 pipe is CARBON STEEL
	Eq Length: AutoCad PolyLine length (not Eq. Length) per Brian = 393.87'; Eq. Length = 413.87' CS
	Measured Square corner. Total 8 90° bends
	SN-611 to AP-01A; Jumpers = 205' in AP and 108' in other pits.
SN-616	Eq Length: AutoCad PolyLine length (not Eq. Length) per Brian = 323.14'; Eq. Length = 336.14' CS (est. 340')
	Measured Square corner. Total 6 90° bends
	Pg. A-29: K = r/d = 3/3" = 3/.25" = 12; K = 34 ft
Per CRANE Technical Paper #410:	Pg. 2-8: Eq. 2-4 K=(ft L/D): 34 ft = (ft L/D)
	L = 34D = 34 x 3" = 102"; 102"/12"per' = 8.5'
	L = 8.5' Equivalent Length for 3 in 90° bend with 3' radius
	(deduct 6 ft for ea bend from AutoCad PolyLine length and add 8.5' to arrive at total equivalent pipe length)
SN-263	AW-103 03A elevation confirmed H-2-70411, Sh. 1 as-build @ 683.565. Design on H-2-70411, Sh 2 & H-2-70429 show 683.55
	AW Pits 01A Thru 06A all use same design detail, as-build reflects field variations.

CASE 3S6D Transfer List - Tank-to-Tank

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
2	Transfer		Via Routing														Encasement Drainage Piping Size		
3	From Tank	To Tank	Start	End	Primary Pipe 3" Sch-40 Pipe (3.068" ID) Line ID #	Comment	Tank Farm Built (Yr)	Design Press (lbf/in²)	Carbon Steel Length (ft)	Stainless Steel Length (ft)	Elevation Start	Source Elevation	Elevation End	Source Elevation	Total Change in Elevation (ft)	Comments:	Low Point	High Point	Ref. Dwg.
4	AN-101	AN-106					80-81	275	442	626					-0.02				
5			AN-101 01A							108	664.36	Per D153A 11-2001							
6			AN-101 01A	AN-B	SN-261	Line # repeated in AW Farm		275	264		666.16	H-2-71989	664.38	H-2-71989		Nozzle elevation not shown on D153A	1.5 "		H-2-71998 s1
7			AN-B							205	666.38	Est per D153A 11-2001	666.45	Per D153A 11-2001					
8			AN-B	AN-A	SN-268	Line # repeated in AW Farm		275	51		666.45	Per D153A 11-2001	666.50	Per D153A 11-2001			1.5 "		H-2-71990 s1
9			AN-A							205	666.50	Per D153A 11-2001	665.30	Est Per D153A 11-2001					
10			AN-A	AN-106 06A	SN-266			275	127		665.30	Est Per D153A 11-2001	664.34	Est Per D153A		Nozzle elevation not shown on D153A	1.5"		H-2-71998 s1
11			AN-106 06A							108	664.34	Est Per D153A 11-2001							
12									442	626					-0.02				
13																			
14	AN-101	AP-103					93-86	400	942	2,830					10.98				
15			AN-101 01A							108	664.36	Per D153A 11-2001							
16			AN-101 01A	NEW AZ PIT	SN-630			400		491	664.36	Per D153A 11-2001	669.50	Per D153A 11-2001			2 "		H-2-71998 s1
17			NEW AZ PIT							205	668.55	Per D153A 11-2001	669.50	Per D153A 11-2001					
18			NEW AZ PIT	INTERFACE	SN-634	W-314/W-211 INTERFACE		400		1,558	669.50	Per D153A 11-2001	674.00	Per D153A 11-2001		SN-634 also Interface>AP102 1558 conf w/J. Collins	2 "		H-14-103263 s3
19			INTERFACE			No Pit - No Jumpers @ Interface				0	674.00	Per D153A 11-2001							
20			INTERFACE	AP-102-02D	(SN-634)	SN-634 also AZ>Interface		400		145	674.00	Per D153A 11-2001	674.40	Per D153A 11-2001					
21			AP-102-02D			JUMPERS IN 02D = 60 FT				60	674.40	Elev. Change in Pit/Jumper	675.89						
22			AP-102-02D	AP-102-02A	SN-622			400		55	675.89	Per D153A 11-2001	676.25	Per D153A 11-2001					
23			AP-102-02A							100	676.25	Elev. Change in Pit/Jumper	675.28						
24			AP-102-02A	AP Valve Pit	SN-612			400	431		675.28	Per H-2-90563	676.61	Per D153A 11-2001		Hand entry on D153 Rev C			
25			AP Valve Pit						205		676.61	Per D153A 11-2001							
26			AP Valve Pit	AP-103 03A	SN-613			400	306		676.61	Per D153A 11-2001	675.34	Est per D153A 11-2001		Nozzle elevation not shown on D153A	1.5 "		H-2-90563
27			AP-103 03A							108	675.34	Est per D153A 11-2001							
28									942	2,830					10.98				
29																			
30	AN-101	AP-107					83-86	400	1,059	2,830					10.98				
31			AN-101 01A							108	664.36	Per D153A 11-2001							
32			AN-101 01A	NEW AZ PIT	SN-630			400		491	664.36	Per D153A 11-2001	669.50	Per D153A 11-2001			2 "		H-2-71998 s1
33			NEW AZ PIT							205	669.50	Per D153A 11-2001	669.50	Per D153A 11-2001					
34			NEW AZ PIT	INTERFACE	SN-634	W-314/W-211 INTERFACE		400		1,558	669.50	Per D153A 11-2001	674.00	Per D153A 11-2001		SN-634 also Interface>AP102 1558 conf w/J. Collins	2 "		H-14-103263 s3
35			INTERFACE	AP-102-02D	(SN-634)	SN-634 also AZ>Interface		400		145	674.00	Per D153A 11-2001	674.40	Per D153A 11-2001					
36			AP-102-02D			JUMPERS IN 02D = 60 FT				60	674.40	Elev. Change in Pit/Jumper	675.89						
37			AP-102-02D	AP-102-02A	SN-622			400		55	675.89	Per D153A 11-2001	676.25	Per D153A 11-2001					
38			AP-102-02A							100	676.25	Elev. Change in Pit/Jumper	675.28						
39			AP-102-02A	AP Valve Pit	SN-612			400	431		675.28	Per H-2-90563	676.61	Per D153A 11-2001		Hand entry on D153 Rev C			
40			AP Valve Pit						205		676.61	Per D153A 11-2001							
41			AP Valve Pit	AP-107 07A	SN-617			400	423		676.61	Est per D153A 11-2001	675.34	Est per D153A 11-2001		Line SN-617/Pit 07A not on D153A	1.5 "		H-2-90563
42			AP-107 07A							108	675.34	Est Per D153A 11-2001							
43									1,059	2,830					10.98				
44																			
45	AN-101	WTP						400	0	6,102					61.08				
46			AN-101 01A							108	664.36	Per D153A 11-2001							
47			AN-101 01A	NEW AZ PIT	SN-630			400		491	664.36	Per D153A 11-2001	669.50	Per D153A 11-2001			2 "		H-2-71998 s1
48			NEW AZ PIT							205	669.50	Per D153A 11-2001	669.50	Per D153A 11-2001					
49			NEW AZ PIT	INTERFACE	SN-634	W-314/W-211 INTERFACE		400		1,558	669.50	Per D153A 11-2001	674.00	Per D153A 11-2001		SN-634 also Interface>AP102 1558 conf w/J. Collins	2 "		H-14-103263 s3
50			INTERFACE	AP-102-02D	(SN-634)	SN-634 also AZ>Interface		400		145	674.00	Per D153A 11-2001	674.40	Per D153A 11-2001					
51			AP-102-02D	WTP Interface	SN-700 or SN-701	Includes jumpers 02D		400		2,738	674.40	Per D153A 11-2001	662.44	Per D153A 11-2001		2738' Equivalent Length from Mark Przybylski, FFS			
52			WTP Interface							5,245	662.44	Per D153A 11-2001			-1.92				
53			WTP Interface	WTP (Vit Plant) internal equivalent pipe length and working height elevation						857	662.44	Per D153A 11-2001	725.44			Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
54			WTP Totals:							6,102	725.44				61.08	Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
55																			
56	AN-102	AP-107					83-86	275	1,464	3,240					11.00				
57			AN-102 02A							108	664.34	Est Per D153A 11-2001							
58			AN-102 02A	AN-B	SN-262	Line # repeated in AW Farm		275	141		664.38	Per H-2-72010	666.16	Per H-2-71989		Nozzle elevation not shown on D153A	2 "		H-2-71998 s1
59			AN-B							205	666.46	Est Per D153A 11-2001							
60			AN-B	AN-101 01A	SN-261	Line # repeated in AW Farm		275	264		666.16	H-2-71989	664.38	H-2-71989		Nozzle elevation not shown on D153A	1.5"		H-2-71998 s1
61			AN-101 01A							205	664.36	Per D153A 11-2001							
62			AN-101 01A	NEW AZ PIT	SN-630			400		491	664.36	Per D153A 11-2001	669.50	Per D153A 11-2001			2 "		H-2-71998 s1
63			NEW AZ PIT							205	669.50	Per D153A 11-2001		Per D153A 11-2001					
64			NEW AZ PIT	INTERFACE	SN-634	W-314/W-211 INTERFACE		400		1,558	669.50	Per D153A 11-2001	674.00	Per D153A 11-2001		SN-634 also Interface>AP102 1558 conf w/J. Collins	2 "		H-14-103263 s3
65			INTERFACE	AP-102-02D	(SN-634)	SN-634 also AZ>Interface		400		145	674.00	Per D153A 11-2001	674.40	Per D153A 11-2001					
66			AP-102-02D			JUMPERS IN 02D = 60 FT				60	674.40	Elev. Change in Pit/Jumper	676.17						
67			AP-102-02D	AP-102-02A	SN-622			400		55	675.89	Per D153A 11-2001	676.25	Per D153A 11-2001					
68			AP-102-02A							100	676.25	Elev. Change in Pit/Jumper	675.50						
69			AP-102-02A	AP Valve Pit	SN-612			400	431		675.28	Per H-2-90563	676.61	Per D153A 11-2001		Hand entry on D153 Rev C			
70			AP Valve Pit						205		676.61	Per D153A 11-2001							
71			AP Valve Pit	AP-107 07A	SN-617			400	423		676.61	Est per D153A 11-2001	675.34	Est per D153A 11-2001		Line SN-617/Pit 07A not on D153A	1.5 "		H-2-90563
72			AP-107 07A							108	675.34	Est Per D153A 11-2001							
73									1,464	3,240					11.00				
74																			

CASE 3S6D Transfer List - Tank-to-Tank

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
2	Transfer		Via Routing														Encasement Drainage Piping Size		
3	From Tank	To Tank	Start	End	Primary Pipe 3" Sch-40 Pipe (3.068" ID) Line ID #	Comment	Tank Farm Built (Yr)	Design Press (lb/in²)	Carbon Steel Length (ft)	Stainless Steel Length (ft)	Elevation Start	Source Elevation	Elevation End	Source Elevation	Total Change in Elevation (ft)	Comments:	Low Point	High Point	Ref. Dwg.
75	AN-102	WTP						275	405	6,512					61.07				
76			AN-102 02A							108	664.38	Per H-2-72010							
77			AN-102 02A	AN-B	SN-262	Line # repeated in AW Farm		275	141		664.38	Per H-2-72010	666.16	Per H-2-71989		Nozzle elevation not shown on D153A	2"		H-2-71998 s1
78			AN-B							205	666.16	Per H-2-71989							
79			AN-B	AN-101 01A	SN-261	Line # repeated in AW Farm		275	264		666.16	H-2-71989	664.38	H-2-71989		Nozzle elevation not shown on D153A	1.5"		H-2-71998 s1
80			AN-101 01A							205	664.38	H-2-71989	664.36	Per D153A 11-2001					
81			AN-101 01A	NEW AZ PIT	SN-630			400		491	664.36	Per D153A 11-2001	669.50	Per D153A 11-2001			2"		H-2-71998 s1
82			NEW AZ PIT							205	669.50	Per D153A 11-2001							
83			NEW AZ PIT	INTERFACE	SN-634	W-314/W-211 INTERFACE		400		1,558	669.50	Per D153A 11-2001	674.00	Per D153A 11-2001		SN-634 also Interface>AP102 1558 conf w/J. Collins	2"		H-14-103263 s3
84			INTERFACE	AP-102-02D	(SN-634)	SN-634 also AZ>Interface		400		145	674.00	Per D153A 11-2001	674.40	Per D153A 11-2001					
85			AP-102-02D	WTP Interface	SN-700 or SN-701	Includes jumpers 02D		400		2,738	674.40	Per D153A 11-2001	662.44	Per D153A 11-2001		2738' Equivalent Length from Mark Przybylski, FFS			
86			WTP Interface						405	5,655	662.44	Per D153A 11-2001			-1.93				
87			WTP Interface	WTP (Vit Plant) internal equivalent pipe length and working height elevation						857	662.44	Per D153A 11-2001	725.44			Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
88			WTP Totals:							6,512	725.44				61.07	Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
89																			
90	AN-103	AN-102					80-81	275	253	421					0.03				
91			AN-103 03A							108	664.34	Est Per D153A 11-2001							
92			AN-103 03A	AN-B	SN-263	Line # repeated in AW Farm		275	112		664.34	Est Per D153A 11-2001	666.46	Est per D153A 11-2001		Nozzle elevation not shown on D153A	2"		H-2-71998 s1
93			AN-B							205	666.46	Est per D153A 11-2001	666.16	Per H-2-71989					
94			AN-B	AN-102 02A	SN-262	Line # repeated in AW Farm		275	141		666.16	Per H-2-71989	664.38	Per H-2-72010		Nozzle elevation not shown on D153A	2"		H-2-71998 s1
95			AN-102 02A							108	664.38	Per H-2-72010			0.03				
96									253	421									
97																			
98	AN-103	WTP						275	376	6,512					61.10				
99			AN-103 03A							108	664.34	Per D153A 11-2001							
100			AN-103 03A	AN-B	SN-263	Line # repeated in AW Farm		275	112		664.34	Est Per D153A 11-2001	666.46	Est per D153A 11-2001		Nozzle elevation not shown on D153A	2"		H-2-71998 s1
101			AN-B							205	666.46	Est Per D153A 11-2001	666.16	H-2-71989					
102			AN-B	AN-101 01A	SN-261	Line # repeated in AW Farm		275	264		666.16	H-2-71989	664.38	H-2-71989		Nozzle elevation not shown on D153A	1.5"		H-2-71998 s1
103			AN-101 01A							205	664.38	H-2-71989	664.36	Per D153A 11-2001					
104			AN-101 01A	NEW AZ PIT	SN-630			400		491	664.36	Per D153A 11-2001	669.50	Per D153A 11-2001			2"		H-2-71998 s1
105			NEW AZ PIT							205	669.50	Per D153A 11-2001							
106			NEW AZ PIT	INTERFACE	SN-634	W-314/W-211 INTERFACE		400		1,558	669.50	Per D153A 11-2001	674.00	Per D153A 11-2001		SN-634 also Interface>AP102 1558 conf w/J. Collins	2"		H-14-103263 s3
107			INTERFACE	AP-102-02D	(SN-634)	SN-634 also AZ>Interface		400		145	674.00	Per D153A 11-2001	674.40	Per D153A 11-2001					
108			AP-102-02D	WTP Interface	SN-700 or SN-701	Includes jumpers 02D		400		2,738	674.40	Per D153A 11-2001	662.44	Per D153A 11-2001		2738' Equivalent Length from Mark Przybylski, FFS			
109			WTP Interface						376	5,655	662.44	Per D153A 11-2001			-1.90				
110			WTP Interface	WTP (Vit Plant) internal equivalent pipe length and working height elevation						857	662.44	Per D153A 11-2001	725.44			Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
111			WTP Totals:							6,512	725.44				61.10	Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
112																			
113	AN-104	AN-101					80-81	275	562	626					-3.00				
114			AN-104 04A							108	667.38	Per H-2-72010							
115			AN-104 04A	AN-A	SN-264	Line # repeated in AW Farm		275	247		667.38	Per H-2-72010	666.16	Per H-2-71989			2"		H-2-71998 s1
116			AN-A							205	666.16	Per H-2-71989	666.50	Per D153A 11-2001					
117			AN-A	AN-B	SN-268	Line # repeated in AW Farm		275	51		666.50	Per D153A 11-2001	666.45	Per D153A 11-2001			1.5"		H-2-71990 s1
118			AN-B							205	666.45	Est per D153A 11-2001	666.16	H-2-71989					
119			AN-B	AN-101 01A	SN-261	Line # repeated in AW Farm		275	264		666.16	H-2-71989	664.38	H-2-71989		Nozzle elevation not shown on D153A	1.5"		H-2-71998 s1
120			AN-101 01A							108	664.38	H-2-71989			-3.00				
121									562	626									
122																			
123	AN-104	AN-102					80-81	275	439	626					0.00				
124			AN-104 04A							108	664.38	H-2-71989							
125			AN-104 04A	AN-A	SN-264	Line # repeated in AW Farm		275	247		667.38	Per H-2-72010	666.16	Per H-2-71989			2"		H-2-71998 s1
126			AN-A							205	666.16	Per H-2-71989	666.50	Per D153A 11-2001					
127			AN-A	AN-B	SN-268	Line # repeated in AW Farm		275	51		666.50	Per D153A 11-2001	666.45	Per D153A 11-2001			1.5"		H-2-71990 s1
128			AN-B							205	666.45	Elev. Change in Pit/Jumper	666.16	Per H-2-71989					
129			AN-B	AN-102 02A	SN-262	Line # repeated in AW Farm		275	141		666.16	Per H-2-71989	664.38	Per H-2-72010		Nozzle elevation not shown on D153A	2"		H-2-71998 s1
130			AN-102 02A							108	664.38	Per H-2-72010			0.00				
131									439	626									
132																			
133	AN-104	AN-103					80-81	275	410	626					0.00				
134			AN-104 04A							108	664.34	Per D153A 11-2001							
135			AN-104 04A	AN-A	SN-264	Line # repeated in AW Farm		275	247		667.38	Per H-2-72010	666.16	Per H-2-71989			2"		H-2-71998 s1
136			AN-A							205	665.30	Elev. Change in Pit/Jumper	666.50	Per D153A 11-2001					
137			AN-A	AN-B	SN-268	Line # repeated in AW Farm		275	51		666.50	Per D153A 11-2001	666.45	Per D153A 11-2001			1.5"		H-2-71990 s1
138			AN-B							205	666.45	Elev. Change in Pit/Jumper	666.46	Est per D153A 11-2001					
139			AN-B	AN-103 03A	SN-263	Line # repeated in AW Farm		275	112		666.46	Est per D153A 11-2001	664.34	Est per D153A 11-2001		Nozzle elevation not shown on D153A	2"		H-2-71998 s1
140			AN-103 03A							108	664.34	Est Per D153A 11-2001			0.00				
141									410	626									
142																			
143	AN-104	AN-105					80-81	275	384	421					0.00				
144			AN-104 04A							108	664.34	Per D153A 11-2001							
145			AN-104 04A	AN-A	SN-264	Line # repeated in AW Farm		275	247		667.38	Per H-2-72010	666.16	Per H-2-71989			2"		H-2-71998 s1

CASE 3S6D Transfer List - Tank-to-Tank

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
2	Transfer		Via Routing														Encasement Drainage Piping Size		
3	From Tank	To Tank	Start	End	Primary Pipe 3" Sch-40 Pipe (3.068" ID) Line ID #	Comment	Tank Farm Built (Yr)	Design Press (lbf/in²)	Carbon Steel Length (ft)	Stainless Steel Length (ft)	Elevation Start	Source Elevation	Elevation End	Source Elevation	Total Change in Elevation (ft)	Comments:	Low Point	High Point	Ref. Dwg.
146			AN-A							205	665.30	Per D153A 11-2001		665.30 (D153A)					
147			AN-A	AN-105 05A	SN-265	Line # repeated in AW Farm		275	137		665.30	Per D153A 11-2001	664.34	Per D153A 11-2001		Nozzle elevation not shown on D153A	2"		H-2-71998 s1
148			AN-105 05A							108	664.34	Per D153A 11-2001			0.00				
149									384	421									
150																			
151	AN-104	AN-106					80-81	275	374	421					0.00				
152			AN-104 04A							108	664.34	Per D153A 11-2001							
153			AN-104 04A	AN-A	SN-264	Line # repeated in AW Farm		275	247		667.38	Per H-2-72010	666.16	Per H-2-71989			2"		H-2-71998 s1
154			AN-A							205	665.30	Per D153A 11-2001		665.30 (D153A)					
155			AN-A	AN-106 06A	SN-266	Line # repeated in AW Farm		275	127		665.30	Est Per D153A 11-2001	664.34	Est Per D153A		Nozzle elevation not shown on D153A	1.5"		H-2-71998 s1
156			AN-106 06A							108	664.34	Est Per D153A			0.00				
157									374	421									
158																			
159	AN-104	AN-107					80-81	275	489	421					-3.03				
160			AN-104 04A							108	667.38	Per H-2-72010							
161			AN-104 04A	AN-A	SN-264	Line # repeated in AW Farm		275	247		667.38	Per H-2-72010	666.16	Per H-2-71989			2"		H-2-71998 s1
162			AN-A							205	666.16	Per H-2-71989	666.50	Per D153A 11-2001					
163			AN-A	AN-107 07A	SN-267	Line # repeated in AW Farm		275	242		666.50	Est Per D153A 11-2001	664.34	Est Per D153A 11-2001		Nozzle elevation not shown on D153A	1.5"		H-2-71998s1
164			AN-107 07A							108	664.34				-3.03				
165									489	421									
166																			
167	AN-104	AP-101					83-86	400	1,050	2,757					10.98				
168			AN-104 04A							108	664.36	Per D153A 11-2001							
169			AN-104 04A	INTERFACE	SN-636	W-314/W-211 INTERFACE		400		2,151	664.36	Per D153A 11-2001	674.00	Per D153A 11-2001		2151' SS conf/w Jim Collins FFS 12/5/01 was 1560 CS	1.5"		H-2-71998 s1
170			INTERFACE	AP-102-02D	(SN-636)	SN-636 also AZ>Interface		400		145	674.00	Per D153A 11-2001	674.40	Per D153A 11-2001		145' Equivalent Length from Mark Przybylski, FFS			
171			AP-102-02D			JUMPERS IN 02D = 90 FT				90	674.40	Elev. Change in Pit/Jumper	675.89	Per D153A 11-2001					
172			AP-102-02D	AP-102-02A	SN-622			400		55	675.89	Per D153A 11-2001	676.25	Per D153A 11-2001					
173			AP-102-02A							100	676.25	Elev. Change in Pit/Jumper	675.28	Per H-2-90563					
174			AP-102-02A	AP Valve Pit	SN-612			400	431		675.28	Per H-2-90563	676.61	Per D153A 11-2001		Hand entry on D153 Rev C			
175			AP Valve Pit						205		676.61	Per D153A 11-2001							
176			AP Valve Pit	AP-101 01A	SN-611			400	413.87		676.61	Est. Per D153A 11-2001	675.34	Est per M/U of D153A		Line/nozzle not specifically identified on D153	1.5"		H-2-90563
177			AP-101 01A							108	675.34				10.98				
178									1,050	2,757									
179																			
180	AN-104	AP-102					83-86	400	0	2,549					11.89				
181			AN-104 04A							108	664.36	Per D153A 11-2001							
182			AN-104 04A	INTERFACE	SN-636	W-314/W-211 INTERFACE		400		2,151	664.36	Per D153A 11-2001	674.00	Per D153A 11-2001		2151' SS conf/w Jim Collins FFS 12/5/01 was 1560 CS	1.5"		H-2-71998 s1
183			INTERFACE	AP-102-02D	(SN-636)	SN-636 also AZ>Interface		400		145	674.00	Per D153A 11-2001	674.40	Per D153A 11-2001		145' Equivalent Length from Mark Przybylski, FFS			
184			AP-102-02D			JUMPERS IN 02D = 90 FT				90	674.40	Elev. Change in Pit/Jumper	675.89	Per D153A 11-2001					
185			AP-102-02D	AP-102-02A	SN-622			400		55	675.89	Per D153A 11-2001	676.25	Per D153A 11-2001					
186									0	2,549	676.25				11.89				
187																			
188	AN-104	AP-104					83-86	400	950	2,757					10.92				
189			AN-104 04A							108	664.36	Per D153A 11-2001							
190			AN-104 04A	INTERFACE	SN-636	W-314/W-211 INTERFACE		400		2,151	664.36	Per D153A 11-2001	674.00	Per D153A 11-2001		2151' SS conf/w Jim Collins FFS 12/5/01 was 1560 CS	1.5"		H-2-71998s1
191			INTERFACE	AP-102-02D	(SN-636)	SN-636 also AZ>Interface		400		145	674.00	Per D153A 11-2001	674.40	Per D153A 11-2001		145' Equivalent Length from Mark Przybylski, FFS			
192			AP-102-02D			JUMPERS IN 02D = 90 FT				90	674.40	Elev. Change in Pit/Jumper	675.89	Per D153A 11-2001					
193			AP-102-02D	AP-102-02A	SN-622			400		55	675.89	Per D153A 11-2001	676.25	Per D153A 11-2001					
194			AP-102-02A							100	676.25	Elev. Change in Pit/Jumper	675.28	Per H-2-90563					
195			AP-102-02A	AP Valve Pit	SN-612			400	431		675.28	Per H-2-90563	676.61	Per D153A 11-2001		Hand entry on D153 Rev C			
196			AP Valve Pit						205		676.61	Per D153A 11-2001							
197			AP Valve Pit	AP-104 04A	SN-614			400	314		676.61	Est Per D153A / H-14-104365	675.28	Est per D153A 11-2001		Hand entry on D153 Rev C	1.5"		H-2-90563
198			AP-104 04A							108	675.28	Est per D153A 11-2001			10.92				
199									950	2,757									
200																			
201	AN-104	AP-106					83-86	400	976	2,757					10.98				
202			AN-104 04A							108	664.36	Per D153A 11-2001							
203			AN-104 04A	INTERFACE	SN-636	W-314/W-211 INTERFACE		400		2,151	664.36	Per D153A 11-2001	674.00	Per D153A 11-2001		2151' SS conf/w Jim Collins FFS 12/5/01 was 1560 CS	1.5"		H-2-71998 s1
204			INTERFACE	AP-102-02D	(SN-636)	SN-636 also AZ>Interface		400		145	674.00	Per D153A 11-2001	674.40	Per D153A 11-2001		145' Equivalent Length from Mark Przybylski, FFS			
205			AP-102-02D			JUMPERS IN 02D = 90 FT				90	674.40	Elev. Change in Pit/Jumper	675.89	Per D153A 11-2001					
206			AP-102-02D	AP-102-02A	SN-622			400		55	675.89	Per D153A 11-2001	676.25	Per D153A 11-2001					
207			AP-102-02A							100	676.25	Elev. Change in Pit/Jumper	675.28	Per H-2-90563					
208			AP-102-02A	AP Valve Pit	SN-612			400	431		675.28	Per H-2-90563	676.61	Per D153A 11-2001		Hand entry on D153 Rev C			
209			AP Valve Pit						205		676.61	Per D153A 11-2001							
210			AP Valve Pit	AP-106 06A	SN-616			400	340		676.61	Est Per D153A 11-2001	675.34	Est Per D153A 11-2001			1.5"		H-2-90563
211			AP-106 06A							108	675.34				10.98				
212									976	2,757									
213																			
214																			
215	AN-104	AP-108					83-86	400	1,079	2,757					10.98				
216			AN-104 04A							108	664.36	Per D153A 11-2001							

CASE 3S6D Transfer List - Tank-to-Tank

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
2	Transfer		Via Routing														Encasement Drainage Piping Size		
3	From Tank	To Tank	Start	End	Primary Pipe 3" Sch-40 Pipe (3.068" ID) Line ID #	Comment	Tank Farm Built (Yr)	Design Press (lbf/in²)	Carbon Steel Length (ft)	Stainless Steel Length (ft)	Elevation Start	Source Elevation	Elevation End	Source Elevation	Total Change in Elevation (ft)	Comments:	Low Point	High Point	Ref. Dwg.
217			AN-104 04A	INTERFACE	SN-636	W-314/W-211 INTERFACE		400		2,151	664.36	Per D153A 11-2001	674.00	Per D153A 11-2001		2151' SS conf/w Jim Collins FFS 12/5/01 was 1560 CS	1.5"		H-2-71998 s1
218			INTERFACE	AP-102-02D	(SN-636)	SN-636 also AZ>Interface		400		145	674.00	Per D153A 11-2001	674.40	Per D153A 11-2001		145' Equivalent Length from Mark Przybylski, FFS			
219			AP-102-02D			JUMPERS IN 02D = 90 FT				90	674.40	Elev. Change in Pit/Jumper	675.89	Per D153A 11-2001					
220			AP-102-02D	AP-102-02A	SN-622			400		55	675.89	Per D153A 11-2001	676.25	Per D153A 11-2001					
221			AP-102-02A							100	676.25	Elev. Change in Pit/Jumper	675.28	Per H-2-90563					
222			AP-102-02A	AP Valve Pit	SN-612			400	431		675.28	Per H-2-90563	676.61	Per D153A 11-2001		Hand entry on D153 Rev C			
223			AP Valve Pit						205		676.61	Per D153A 11-2001							
224			AP Valve Pit	AP-108 08A	SN-618			400	443		676.61	Est Per D153A 11-2001	675.34	Est Per D153A 11-2001			1.5"		H-2-90563
225			AP-108 08A							108	675.34	Per D153A 11-2001			10.98				
226									1,079	2,757									
227																			
228	AN-104	AW-101					78-80	275	1,630	3,167					20.14				
229			AN-104 04A							108	664.36	Per D153A 11-2001							
230			AN-104 04A	INTERFACE	SN-636	W-314/W-211 INTERFACE		400		2,151	664.36	Per D153A 11-2001	674.00	Per D153A 11-2001		2151' SS conf/w Jim Collins FFS 12/5/01 was 1560 CS	1.5"		H-2-71998 s1
231			INTERFACE	AP-102-02D	(SN-636)	SN-636 also AZ>Interface		400		145	674.00	Per D153A 11-2001	674.40	Per D153A 11-2001		145' Equivalent Length from Mark Przybylski, FFS			
232			AP-102-02D			JUMPERS IN 02D = 90 FT				90	674.40	Elev. Change in Pit/Jumper	675.89	Per D153A 11-2001					
233			AP-102-02D	AP-102-02A	SN-622			400		55	675.89	Per D153A 11-2001	676.25	Per D153A 11-2001					
234			AP-102-02A							100	676.25	Elev. Change in Pit/Jumper	675.28	Per H-2-90563					
235			AP-102-02A	AP Valve Pit	SN-612			400	431		675.28	Per H-2-90563	676.61	Per D153A 11-2001		Hand entry on D153 Rev C			
236			AP Valve Pit						205		676.61	Per D153A 11-2001							
237			AP Valve pit	AW-102 02A	SN-609			400	761		676.61	Est per D153A 11-2001	684.11	Per H-2-70411		Nozzle elevation not shown on D153A	2"		H-2-90551s1
238			AW-102 02A							205	684.11	Per H-2-70411	683.61	Per H-2-70411					
239			AW-102 02A	AW-A V. Pit	SN-267	Line # repeated in AN Farm		275	124		683.61	Per H-2-70411	685.33	Est Per D153A 11-2001		Line # Not on D153A	1.5"		H-2-70411 s2
240			AW-A V. Pit							205	685.33	Est per D153 11-2001				Not on D153A			
241			AW-A V. Pit	AW-101 01A	SN-261	Line # repeated in AN Farm		275	109		685.33	Est per D153A 11-2001	684.50	Est per D153A 11-2001		Line # Not on D153A	1.5"		H-2-70411 s2
242			AW-101 01A							108	684.50	Est per D153A 11-2001			20.14	Not on D153A			
243									1,630	3,167									
244																			
245	AN-104	AW-103					78-80	275	1,648	3,167					19.21				
246			AN-104 04A							108	664.36	Per D153A 11-2001							
247			AN-104 04A	INTERFACE	SN-636	W-314/W-211 INTERFACE		400		2,151	664.36	Per D153A 11-2001	674.00	Per D153A 11-2001		2151' SS conf/w Jim Collins FFS 12/5/01 was 1560 CS	1.5"		H-2-71998 s1
248			INTERFACE	AP-102-02D	(SN-636)	SN-636 also AZ>Interface		400		145	674.00	Per D153A 11-2001	674.40	Per D153A 11-2001		145' Equivalent Length from Mark Przybylski, FFS			
249			AP-102-02D			JUMPERS IN 02D = 90 FT				90	674.40	Elev. Change in Pit/Jumper	675.89	Per D153A 11-2001					
250			AP-102-02D	AP-102-02A	SN-622			400		55	675.89	Per D153A 11-2001	676.25	Per D153A 11-2001					
251			AP-102-02A							100	676.25	Elev. Change in Pit/Jumper	675.28	Per H-2-90563					
252			AP-102-02A	AP Valve Pit	SN-612			400	431		675.28	Per H-2-90563	676.61	Per D153A 11-2001		Hand entry on D153 Rev C			
253			AP Valve Pit						205		676.61	Per D153A 11-2001							
254			AP Valve pit	AW-102 02A	SN-609			400	761		676.61	Est per D153A 11-2001	684.11	Per H-2-70411		Nozzle elevation not shown on D153A	2"		H-2-90551s1
255			AW-102 02A							205	684.11	Per H-2-70411	683.61	Per H-2-70411					
256			AW-102 02A	AW-A V. Pit	SN-267	Line # repeated in AN Farm		275	124		683.61	Per H-2-70411	685.33	Est Per D153A 11-2001		Line # Not on D153A	1.5"		H-2-70411 s2
257			AW-A V. Pit							205	685.33	Est per D153 11-2001							
258			AW-A V. Pit	AW-103 03A	SN-263	Line # repeated in AN Farm		275	127		685.33	Est per D153A 11-2001	683.57	per H-2-70411, sh 1		Line # Not on D153A	1.5"		H-2-70411 s2
259			AW-103 03A							108	683.57	per H-2-70411, sh 1			19.21				
260									1,648	3,167									
261																			
262	AN-104	AW-104					78-80	275	1,639	3,167					20.14				
263			AN-104 04A							108	664.36	Per D153A 11-2001							
264			AN-104 04A	INTERFACE	SN-636	W-314/W-211 INTERFACE		400		2,151	664.36	Per D153A 11-2001	674.00	Per D153A 11-2001		2151' SS conf/w Jim Collins FFS 12/5/01 was 1560 CS	1.5"		H-2-71998 s1
265			INTERFACE	AP-102-02D	(SN-636)	SN-636 also AZ>Interface		400		145	674.00	Per D153A 11-2001	674.40	Per D153A 11-2001		145' Equivalent Length from Mark Przybylski, FFS			
266			AP-102-02D			JUMPERS IN 02D = 90 FT				90	674.40	Elev. Change in Pit/Jumper	675.89	Per D153A 11-2001					
267			AP-102-02D	AP-102-02A	SN-622			400		55	675.89	Per D153A 11-2001	676.25	Per D153A 11-2001					
268			AP-102-02A							100	676.25	Elev. Change in Pit/Jumper	675.28	Per H-2-90563					
269			AP-102-02A	AP Valve Pit	SN-612			400	431		675.28	Per H-2-90563	676.61	Per D153A 11-2001		Hand entry on D153 Rev C			
270			AP Valve Pit						205		676.61	Per D153A 11-2001							
271			AP Valve Pit	AW-102 02A	SN-610			400	800		676.61	Est per D153A 11-2001	684.50	Est per D153A 11-2001		Nozzle elevation not shown on D153A			
272			AW-102 02A							205	684.50	Per D153A 11-2001							
273			AW-102 02A	AW-B	SN-268	Line # repeated in AN Farm		275	88		684.50	Est. Per D153A 11-2001	685.29	Est. Per D153A 11-2001			1.5"		H-2-71990s1
274			AW-B V. Pit							205	685.29	Per D153A 11-2001							
275			AW-B V. Pit	AW-104 04A	SN-264	Line # repeated in AN Farm		275	115		685.29	Per D153A 11-2001	684.50	Est per D153A 11-2001		Line # Not on D153A	2"		H-2-71998s1
276			AW-104 04A							108	684.50	Est per D153A 11-2001			20.14				
277									1,639	3,167									
278																			
279	AN-104	AW-105					78-80	275	1,761	3,167					20.14				
280			AN-104 04A							108	664.36	Per D153A 11-2001							
281			AN-104 04A	INTERFACE	SN-636	W-314/W211 INTERFACE		400		2,151	664.36	Per D153A 11-2001	674.00	Per D153A 11-2001		2151' SS conf/w Jim Collins FFS 12/5/01 was 1560 CS	1.5"		H-2-71998 s1
282			INTERFACE	AP-102-02D	(SN-636)	SN-636 also AZ>Interface		400		145	674.00	Per D153A 11-2001	674.40	Per D153A 11-2001		145' Equivalent Length from Mark Przybylski, FFS			
283			AP-102-02D			JUMPERS IN 02D = 90 FT				90	674.40	Elev. Change in Pit/Jumper	675.89	Per D153A 11-2001					
284			AP-102-02D	AP-102-02A	SN-622			400		55	675.89	Per D153A 11-2001	676.25	Per D153A 11-2001					
285			AP-102-02A							100	676.25	Elev. Change in Pit/Jumper	675.28	Per H-2-90563					
286			AP-102-02A	AP Valve Pit	SN-612			400	431		675.28	Per H-2-90563	676.61	Per D153A 11-2001		Hand entry on D153 Rev C			
287			AP Valve Pit						205		676.61	Per D153A 11-2001							

CASE 3S6D Transfer List - Tank-to-Tank

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
2	Transfer		Via Routing														Encasement Drainage Piping Size		
3	From Tank	To Tank	Start	End	Primary Pipe 3" Sch-40 Pipe (3.068" ID) Line ID #	Comment	Tank Farm Built (Yr)	Design Press (lbf/in²)	Carbon Steel Length (ft)	Stainless Steel Length (ft)	Elevation Start	Source Elevation	Elevation End	Source Elevation	Total Change in Elevation (ft)	Comments:	Low Point	High Point	Ref. Dwg.
288			AP Valve pit	AW-102 02A	SN-609			400	761		676.61	Est per D153A 11-2001	684.11	Per H-2-70411		Nozzle elevation not shown on D153A	2"		H-2-90551s1
289			AW-102 02A							205	684.11	Per H-2-70411	683.61	Per H-2-70411					
290			AW-102 02A	AW-A V. Pit	SN-267	Line # repeated in AN Farm		275	124		683.61	Per H-2-70411	685.33	Est Per D153A 11-2001		Line # Not on D153A	1.5"		H-2-71998s1
291			AW-A V. Pit							205	685.33	Est per D153 11-2001							
292			AW-A V. Pit	AW-105 05A	SN-265	Line # repeated in AN Farm		275	240		685.33	Est per D153A 11-2001	684.50	Est Per D153A		Line # Not on D153A	2"		H-2-71998s1
293			AW-105 05A							108	684.50	Est per D153A 11-2001			20.14				
294									1,761	3,167									
295																			
296	AN-104	AZ-101					71	275	562	1,673					1.16				
297			AN-104 04A							108	667.38	Per H-2-72010							
298			AN-104 04A	AN-A	SN-264	Line # repeated in AW Farm		275	247		667.38	Per H-2-72010	666.16	Per H-2-71989			2"		H-2-71998 s1
299			AN-A							205	666.16	Per H-2-71989	666.50	Per D153A 11-2001					
300			AN-A	AN-B	SN-268	Line # repeated in AW Farm		275	51		666.50	Per D153A 11-2001	666.45	Per D153A 11-2001			1.5"		H-2-71990 s1
301			AN-B							205	666.45	Elev. Change in Pit/Jumper	666.16	H-2-71989					
302			AN-B	AN-101 01A	SN-261	Line # repeated in AW Farm		275	264		666.16	H-2-71989	664.38	H-2-71989		Nozzle elevation not shown on D153A	1.5"		H-2-71998 s1
303			AN-101 01A							205	664.38	H-2-71989	664.36						
304			AN-101 01A	NEW AZ PIT	SN-630			400		491	664.36	H-2-71989	669.50	Per D153A 11-2001			2"		H-2-71998 s1
305			NEW AZ PIT							205	669.50	Elev. Change in Pit/Jumper	669.25						
306			NEW AZ PIT	AZ-101 01A	SN-632			400		154	669.25	Per D153A 11-2001	668.54	Per D153A 11-2001			1"		H-14-102695s1
307			AZ-101 01A							100	668.54	Per D153A 11-2001			1.16				
308									562	1,673									
309																			
310	AN-104	WTP						400	0	5,999					61.08				
311			AN-104 04A							108	664.36	Per D153A 11-2001							
312			AN-104 04A	INTERFACE	SN-636	W-314/W211 INTERFACE		400		2,151	664.36	Per D153A 11-2001	674.00	Per D153A 11-2001		2151' SS conf/w Jim Collins FFS 12/5/01 was 1560 CS	1.5"		H-2-71998 s1
313			INTERFACE	AP-102-02D	(SN-636)	SN-636 also AZ>Interface		400		145	674.00	Per D153A 11-2001	674.40	Per D153A 11-2001		145' Equivalent Length from Mark Przybylski, FFS			
314			AP-102-02D	WTP Interface	SN-700 or SN-701	Includes jumpers 02D		400		2,738	674.40	Per D153A 11-2001	662.44	Per D153A 11-2001		2738' Equivalent Length from Mark Przybylski, FFS			
315			WTP Interface							5,142	662.44	Per D153A 11-2001			-1.92				
316			WTP Interface	WTP (Vit Plant) internal equivalent pipe length and working height elevation						857	662.44	Per D153A 11-2001	725.44			Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
317			WTP Totals:							5,999	725.44				61.08	Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
318																			
319	AN-105	AN-102					80-81	275	329	626					0.03				
320			AN-105 05A							108	664.34	Per D153A 11-2001							
321			AN-105 05A	AN-A	SN-265	Line # repeated in AW Farm		275	137		664.34	Per D153A 11-2001	665.30	Per D153A 11-2001			2"		H-2-71998 s1
322			AN-A							205	665.30	Elev. Change in Pit/Jumper	666.50	Per D153A 11-2001					
323			AN-A	AN-B	SN-268	Line # repeated in AW Farm		275	51		666.50	Per D153A 11-2001	666.45	Per D153A 11-2001			1.5"		H-2-71990 s1
324			AN-B							205	666.45	Elev. Change in Pit/Jumper	666.16	Per H-2-71989					
325			AN-B	AN-102 02A	SN-262	Line # repeated in AW Farm		275	141		666.16	Per H-2-71989	664.38	Per H-2-72010		Nozzle elevation not shown on D153A	2"		H-2-71998 s1
326			AN-102 02A							108	664.38	Per H-2-72010			0.03				
327									329	626									
328																			
329	AN-105	WTP						275	452	6,717					61.10				
330			AN-105 05A							108	664.34	Per D153A 11-2001							
331			AN-105 05A	AN-A	SN-265	Line # repeated in AW Farm		275	137		664.34	Per D153A 11-2001	665.30	Per D153A 11-2001			2"		H-2-71998 s1
332			AN-A							205	665.30	Elev. Change in Pit/Jumper	666.50						
333			AN-A	AN-B	SN-268	Line # repeated in AW Farm		275	51		666.50	Per D153A 11-2001	666.45	Per D153A 11-2001			1.5"		H-2-71990 s1
334			AN-B							205	666.45	Elev. Change in Pit/Jumper	666.16	H-2-71989					
335			AN-B	AN-101 01A	SN-261	Line # repeated in AW Farm		275	264		666.16	H-2-71989	664.38	H-2-71989		Nozzle elevation not shown on D153A	1.5"		H-2-71998 s1
336			AN-101 01A							205	664.38	H-2-71989	664.36	Per D153A 11-2001					
337			AN-101 01A	NEW AZ PIT	SN-630			400		491	664.36	Per D153A 11-2001	669.50	Per D153A 11-2001			2"		H-2-71998 s1
338			NEW AZ PIT							205	669.50	Per D153A 11-2001							
339			NEW AZ PIT	INTERFACE	SN-634	W-314/W211 INTERFACE		400		1,558	669.50	Per D153A 11-2001	674.00	Per D153A 11-2001		SN-634 also Interface>AP102 1558 conf w/J. Collins	2"		H-14-103263 s3
340			INTERFACE	AP-102-02D	(SN-634)	SN-634 also AZ>Interface		400		145	674.00	Per D153A 11-2001	674.40	Per D153A 11-2001					
341			AP-102-02D	WTP Interface	SN-700 or SN-701	Includes jumpers 02D		400		2,738	674.40	Per D153A 11-2001	662.44	Per D153A 11-2001		2738' Equivalent Length from Mark Przybylski, FFS			
342			WTP Interface						452	5,860	662.44	Per D153A 11-2001			-1.90				
343			WTP Interface	WTP (Vit Plant) internal equivalent pipe length and working height elevation						857	662.44	Per D153A 11-2001	725.44			Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
344			WTP Totals:						452	6,717	725.44				61.10	Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
345																			
346	AN-106	AW-102					78-80	275	1,839	3,445					19.77				
347			AN-106 06A							108	664.34	Per D153A 11-2001							
348			AN-106 06A	AN-A	SN-266	Line # repeated in AW Farm		275	127		664.34	Per D153A 11-2001	665.30	Est Per D153A 11-2001		Nozzle elevation not shown on D153A	1.5"		H-2-71998 s1
349			AN-A							205	665.30	Elev. Change in Pit/Jumper	666.50	666.5 Per D153A					
350			AN-A	AN-B	SN-268	Line # repeated in AW Farm		275	51		666.50	Per D153A 11-2001	666.45	Per D153A 11-2001			1.5"		H-2-71990 s1
351			AN-B							205	666.45	Elev. Change in Pit/Jumper	666.16	H-2-71989					
352			AN-B	AN-101 01A	SN-261	Line # repeated in AW Farm		275	264		666.16	H-2-71989	664.38	H-2-71989		Nozzle elevation not shown on D153A	1.5"		H-2-71998 s1
353			AN-101 01A							205	664.38	H-2-71989	664.36	Per D153A 11-2001					
354			AN-101 01A	NEW AZ PIT	SN-630			400		491	664.36	Per D153A 11-2001	669.50	Per D153A 11-2001			2"		H-2-71998 s1
355			NEW AZ PIT							205	669.50	Per D153A 11-2001							
356			NEW AZ PIT	INTERFACE	SN-634	W-314/W211 INTERFACE		400		1,558	669.50	Per D153A 11-2001	674.00	Per D153A 11-2001		SN-634 also Interface>AP102 1558 conf w/J. Collins	2"		H-14-103263 s3
357			INTERFACE	AP-102-02D	(SN-634)	SN-634 also AZ>Interface		400		145	674.00	Per D153A 11-2001	674.40	Per D153A 11-2001					
358			AP-102-02D			JUMPERS IN 02D = 60 FT				60	674.40	Elev. Change in Pit/Jumper	675.89	Per D153A 11-2001					

CASE 3S6D Transfer List - Tank-to-Tank

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
2	Transfer		Via Routing														Encasement Drainage Piping Size		
3	From Tank	To Tank	Start	End	Primary Pipe 3" Sch-40 Pipe (3.068" ID) Line ID #	Comment	Tank Farm Built (Yr)	Design Press (lb/in²)	Carbon Steel Length (ft)	Stainless Steel Length (ft)	Elevation Start	Source Elevation	Elevation End	Source Elevation	Total Change in Elevation (ft)	Comments:	Low Point	High Point	Ref. Dwg.
359			AP-102-02D	AP-102-02A	SN-622			400		55	675.89	Per D153A 11-2001	676.25	Per D153A 11-2001					
360			AP-102-02A							100	676.25	Elev. Change in Pit/Jumper	675.28	Per H-2-90563					
361			AP-102-02A	AP Valve Pit	SN-612			400	431		675.28	Per H-2-90563	676.61	Per D153A 11-2001		Hand entry on D153 Rev C			
362			AP Valve Pit						205		676.61	Per D153A 11-2001							
363			AP Valve pit	AW-102 02A	SN-609			400	761		676.61	Est per D153A 11-2001	684.11	Per H-2-70411		Nozzle elevation not shown on D153A	2"		H-2-90551s1
364			AW-102 02A							108	684.11	Per H-2-70411			19.77				
365									1,839	3,445									
366																			
367	AN-106	WTP						275	442	6,717					61.10				
368			AN-106 06A							108	664.34	Per D153A 11-2001							
369			AN-106 06A	AN-A	SN-266	Line # repeated in AW Farm		275	127		664.34	Per D153A 11-2001	665.30	Est Per D153A 11-2001		Nozzle elevation not shown on D153A	1.5"		H-2-71998 s1
370			AN-A							205	665.30	Elev. Change in Pit/Jumper	666.50	666.5 Per D153A					
371			AN-A	AN-B	SN-268	Line # repeated in AW Farm		275	51		666.50	Per D153A 11-2001	666.45	Per D153A 11-2001			1.5"		H-2-71990 s1
372			AN-B							205	666.45	Elev. Change in Pit/Jumper	666.16	H-2-71989					
373			AN-B	AN-101 01A	SN-261	Line # repeated in AW Farm		275	264		666.16	H-2-71989	664.38	H-2-71989		Nozzle elevation not shown on D153A	1.5"		H-2-71998 s1
374			AN-101 01A							205	664.38	H-2-71989	664.36	Per D153A 11-2001					
375			AN-101 01A	NEW AZ PIT	SN-630			400		491	664.36	Per D153A 11-2001	669.50	Per D153A 11-2001			2 "		H-2-71998 s1
376			NEW AZ PIT							205	669.50	Per D153A 11-2001							
377			NEW AZ PIT	INTERFACE	SN-634	W-314/W211 INTERFACE		400		1,558	669.50	Per D153A 11-2001	674.00	Per D153A 11-2001		SN-634 also Interface>AP102 1558 conf w/J. Collins	2 "		H-14-103263 s3
378			INTERFACE	AP-102-02D	(SN-634)	SN-634 also AZ>Interface		400		145	674.00	Per D153A 11-2001	674.40	Per D153A 11-2001					
379			AP-102-02D	WTP Interface	SN-700 or SN-701	Includes jumpers 02D		400		2,738	674.40	Per D153A 11-2001	662.44	Per D153A 11-2001		2738' Equivalent Length from Mark Przybylski, FFS			
380			WTP Interface						442	5,860	662.44	Per D153A 11-2001			-1.90				
381			WTP Interface	WTP (Vit Plant) internal equivalent pipe length and working height elevation						857	662.44	Per D153A 11-2001	725.44						
382			WTP Totals:							6,717	725.44				61.10	Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
383																			
384	AN-107	WTP						275	557	6,814					61.10				
385			AN-107 07A							205	664.34	Est Per D153A 11-2001							
386			AN-107 07A	AN-A	SN-267	Line # repeated in AW Farm		275	242		664.34	Est Per D153A 11-2001	666.50	Est Per D153A 11-2001		Nozzle elevation not shown on D153A	1.5"		H-2-71998 s1
387			AN-A							205	666.50	Per D153A 11-2001		666.5 Per D153A					
388			AN-A	AN-B	SN-268	Line # repeated in AW Farm		275	51		666.50	Per D153A 11-2001	666.45	Per D153A 11-2001			1.5"		H-2-71990 s1
389			AN-B							205	666.45	Elev. Change in Pit/Jumper	666.16	H-2-71989					
390			AN-B	AN-101 01A	SN-261	Line # repeated in AW Farm		275	264		666.16	H-2-71989	664.38	H-2-71989		Nozzle elevation not shown on D153A	1.5"		H-2-71998 s1
391			AN-101 01A							205	664.38	H-2-71989	664.36	Per D153A 11-2001					
392			AN-101 01A	NEW AZ PIT	SN-630			400		491	664.36	Per D153A 11-2001	669.50	Per D153A 11-2001			2 "		H-2-71998 s1
393			NEW AZ PIT							205	669.50	Per D153A 11-2001							
394			NEW AZ PIT	INTERFACE	SN-634	W-314/W211 INTERFACE		400		1,558	669.50	Per D153A 11-2001	674.00	Per D153A 11-2001		SN-634 also Interface>AP102 1558 conf w/J. Collins	2 "		H-14-103263 s3
395			INTERFACE	AP-102-02D	(SN-634)	SN-634 also AZ>Interface		400		145	674.00	Per D153A 11-2001	674.40	Per D153A 11-2001					
396			AP-102-02D	WTP Interface	SN-700 or SN-701	Includes jumpers 02D		400		2,738	674.40	Per D153A 11-2001	662.44	Per D153A 11-2001		2738' Equivalent Length from Mark Przybylski, FFS			
397			WTP Interface						557	5,957	662.44	Per D153A 11-2001			-1.90				
398			WTP Interface	WTP (Vit Plant) internal equivalent pipe length and working height elevation						857	662.44	Per D153A 11-2001	725.44			Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
399			WTP Totals:							6,814	725.44				61.10	Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
400																			
401	AP-101	WTP						400	1,050	3,858					50.10				
402			AP-101 01A							108	675.34	Est per M/U of D153A							
403			AP-101 01A	AP Valve Pit	SN-611			400	413.87		675.34	Est per M/U of D153A	676.61	Est. Per D153A 11-2001		Line/nozzle not specifically identified on D153	1.5"		H-2-90563
404			AP Valve Pit						205		676.61	Per D153A 11-2001							
405			AP Valve Pit	AP-102-02A	SN-612			400	431		676.61	Per D153A 11-2001	675.28	Per H-2-90563		Hand entry on D153 Rev C			
406			AP-102-02A							100	675.28	Per H-2-90563	676.25						
407			AP-102-02A	AP-102-02D	SN-622			400		55	676.25	Per D153A 11-2001	675.89	Per D153A 11-2001					
408			AP-102-02D								675.89	Per D153A 11-2001	674.40						
409			AP-102-02D	WTP Interface	SN-700 or SN-701	Includes jumpers 02D		400		2,738	674.40	Per D153A 11-2001	662.44	Per D153A 11-2001		2738' Equivalent Length from Mark Przybylski, FFS			
410			WTP Interface						1,050	3,001	662.44	Per D153A 11-2001			-12.90				
411			WTP Interface	WTP (Vit Plant) internal equivalent pipe length and working height elevation						857	662.44	Per D153A 11-2001	725.44			Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
412			WTP Totals:							3,858	725.44				50.10	Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
413																			
414	AP-102	WTP						400	0	3,758					49.19				
415			AP-102 02A							108	676.25	Est per M/U of D153A							
416			AP-102-02A	AP-102-02D	SN-622			400		55	676.25	Per D153A 11-2001	675.89	Per D153A 11-2001			1.5"		H-2-90563
417			AP-102-02D								675.89	Per D153A 11-2001	674.40						
418			AP-102-02D	WTP Interface	SN-700 or SN-701	Includes jumpers 02D		400		2,738	674.40	Per D153A 11-2001	662.44	Per D153A 11-2001		2738' Equivalent Length from Mark Przybylski, FFS			
419			WTP Interface						0	2,901	662.44	Per D153A 11-2001			-13.81				
420			WTP Interface	WTP (Vit Plant) internal equivalent pipe length and working height elevation						857	662.44	Per D153A 11-2001	725.44			Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
421			WTP Totals:							3,758	725.44				49.19	Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
422																			
423	AP-104	AP-107					83-86	400	942	216					0.06				
424			AP-104 04A							108	675.28	Est per D153A 11-2001							
425			AP-104 04A	AP Valve Pit	SN-614			400	314		675.28	Est per D153A 11-2001	676.61	Est Per D153A / H-14-104365		Hand entry on D153 Rev C	1.5"		H-2-90563
426			AP Valve Pit						205		676.61	Est Per D153A / H-14-104365							
427			AP Valve Pit	AP-107 07A	SN-617			400	423		676.61	Est Per D153A / H-14-104365	675.34	Est per D153A 11-2001		Line SN-617/Pit 07A not on D153A	1.5"		H-2-90563
428			AP-107 07A							108	675.34	Est per M/U of D153A			0.06				
429									942	216									

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	CASE 3S6D Transfer List - Tank-to-Tank																		
2	Transfer		Via Routing														Encasement Drainage Piping Size		
3	From Tank	To Tank	Start	End	Primary Pipe 3" Sch-40 Pipe (3.068" ID) Line ID #	Comment	Tank Farm Built (Yr)	Design Press (lb/in²)	Carbon Steel Length (ft)	Stainless Steel Length (ft)	Elevation Start	Source Elevation	Elevation End	Source Elevation	Total Change in Elevation (ft)	Comments:	Low Point	High Point	Ref. Dwg.
430																			
431	AP-104	WTP						400	950	3,858					50.16				
432			AP-104 04A							108	675.28	Est per D153A 11-2001							
433			AP-104 04A	AP Valve Pit	SN-614			400	314		675.28	Est per D153A 11-2001	676.61	Est Per D153A / H-14-104365		Hand entry on D153 Rev C	1.5"		H-2-90563
434			AP Valve Pit						205		676.61	Est Per D153A / H-14-104365							
435			AP Valve Pit	AP-102-02A	SN-612			400	431		676.61	Est Per D153A / H-14-104365	675.28	Per H-2-90563		Hand entry on D153 Rev C			
436			AP-102-02A							100	675.28	Per H-2-90563	676.25						
437			AP-102-02A	AP-102-02D	SN-622			400		55	676.25	Per D153A 11-2001	675.89	Per D153A 11-2001					
438			AP-102-02D								675.89	Per D153A 11-2001	674.40						
439			AP-102-02D	WTP Interface	SN-700 or SN-701	Includes jumpers 02D		400		2,738	674.40	Per D153A 11-2001	662.44	Per D153A 11-2001		2738' Equivalent Length from Mark Przybylski, FFS			
440			WTP Interface						950	3,001	662.44	Per D153A 11-2001			-12.84				
441			WTP Interface	WTP (Vit Plant) internal equivalent pipe length and working height elevation						857	662.44	Per D153A 11-2001	725.44			Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
442			WTP Totals:							3,858	725.44				50.16	Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
443																			
444	AP-105	AP-104					83-86	400	821	216					-0.06				
445			AP-105 05A							108	675.34	Est per D153A 11-2001							
446			AP-105 05A	AP Valve Pit	SN-615			400	302		675.34	Est per D153A 11-2001	676.61	Est Per D153A / H-14-104365			1.5"		H-2-90563s1
447			AP Valve Pit						205		676.61	Est Per D153A / H-14-104365							
448			AP Valve Pit	AP-104 04A	SN-614			400	314		676.61	Est Per D153A / H-14-104365	675.28	Est per D153A 11-2001		Hand entry on D153 Rev C	1.5"		H-2-90563
449			AP-104 04A							108	675.28	Est per D153A 11-2001			-0.06				
450									821	216									
451																			
452	AP-105	WTP						400	938	3,858					50.10				
453			AP-105 05A							108	675.34	Est per D153A 11-2001							
454			AP-105 05A	AP Valve Pit	SN-615			400	302		675.34	Est per D153A 11-2001	676.61	Est per D153A 11-2001			1.5"		H-2-90563s1
455			AP Valve Pit						205		676.61	Est per D153A 11-2001							
456			AP Valve Pit	AP-102-02A	SN-612	W-314/W-211 INTERFACE		400	431		676.61	Per D153A 11-2001	675.28	Per H-2-90563		Hand entry on D153 Rev C			
457			AP-102-02A							100	675.28	Per H-2-90563	676.25						
458			AP-102-02A	AP-102-02D	SN-622			400		55	676.25	Per D153A 11-2001	675.89	Per D153A 11-2001					
459			AP-102-02D								675.89	Per D153A 11-2001	674.40						
460			AP-102-02D	WTP Interface	SN-700 or SN-701	Includes jumpers 02D		400		2,738	674.40	Per D153A 11-2001	662.44	Per D153A 11-2001		2738' Equivalent Length from Mark Przybylski, FFS			
461			WTP Interface						938	3,001	662.44	Per D153A 11-2001			-12.90				
462			WTP Interface	WTP (Vit Plant) internal equivalent pipe length and working height elevation						857	662.44	Per D153A 11-2001	725.44			Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
463			WTP Totals:							3,858	725.44				50.10	Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
464																			
465	AP-106	AN-102					80-81	275	1,381	3,240					-10.97				
466			AP-106 06A							108	675.34	Est per M/U of D153A							
467			AP-106 06A	AP Valve Pit	SN-616			400	340		675.34	Est Per D153A 11-2001	676.61	Est Per D153A 11-2001			1.5"		H-2-90563
468			AP Valve Pit						205		676.61	Per D153A 11-2001							
469			AP Valve Pit	AP-102-02A	SN-612			400	431		676.61	Per D153A 11-2001	675.28	Per H-2-90563		Hand entry on D153 Rev C			
470			AP-102-02A							100	675.28	Per H-2-90563	676.25						
471			AP-102-02A	AP-102-02D	SN-622			400		55	676.25	Per D153A 11-2001	675.89	Per D153A 11-2001					
472			AP-102-02D			JUMPERS IN 02D = 60 FT				60	675.89	Per D153A 11-2001	674.40						
473			AP-102-02D	INTERFACE	(SN-634)	W-314/W-211 INTERFACE		400		145	674.40	Per D153A 11-2001	674.00	Per D153A 11-2001					
474			INTERFACE	NEW AZ PIT	SN-634			400		1,558	674.00	Per D153A 11-2001	669.50	Per D153A 11-2001		SN-634 also Interface>AP102 1558 conf w/J. Collins	2"		H-14-103263 s3
475			NEW AZ PIT							205	669.50	Per D153A 11-2001							
476			NEW AZ PIT	AN-101 01A	SN-630			400		491	669.50	Per D153A 11-2001	664.36	Per D153A 11-2001		Nozzle elevation not shown on D153A	2"		H-2-71998 s1
477			AN-101 01A							205	664.36	Per D153A 11-2001	666.16	H-2-71989					
478			AN-101 01A	AN-B	SN-261	Line # repeated in AW Farm		275	264		666.16	H-2-71989	664.38	H-2-71989		Nozzle elevation not shown on D153A	1.5"		H-2-71990 s1
479			AN-B							205	664.38	H-2-71989	666.16	Per H-2-71989					
480			AN-B	AN-102 02A	SN-262	Line # repeated in AW Farm		275	141		666.16	Per H-2-71989	664.38	Per H-2-72010		Nozzle elevation not shown on D153A	2"		H-2-71998 s1
481			AN-102 02A							108	664.38	Per H-2-72010			-10.97				
482									1381	3,240									
483																			
484	AP-106	WTP						400	976	3,858					50.10				
485			AP-106 06A							108	675.34	Est per M/U of D153A					1.5"		H-2-90563
486			AP-106 06A	AP Valve Pit	SN-616			400	340		675.34	Est Per D153A 11-2001	676.61	Est Per D153A 11-2001					
487			AP Valve Pit						205		676.61	Per D153A 11-2001							
488			AP Valve Pit	AP-102-02A	SN-612			400	431		676.61	Per D153A 11-2001	675.28	Per H-2-90563		Hand entry on D153 Rev C			
489			AP-102-02A							100	675.28	Per H-2-90563	676.25						
490			AP-102-02A	AP-102-02D	SN-622			400		55	676.25	Per D153A 11-2001	675.89	Per D153A 11-2001					
491			AP-102-02D								675.89	Per D153A 11-2001	674.40						
492			AP-102-02D	WTP Interface	SN-700 or SN-701	Includes jumpers 02D		400		2,738	674.40	Per D153A 11-2001	662.44	Per D153A 11-2001		2738' Equivalent Length from Mark Przybylski, FFS			
493			WTP Interface						976	3,001	662.44	Per D153A 11-2001			-12.90				
494			WTP Interface	WTP (Vit Plant) internal equivalent pipe length and working height elevation						857	662.44	Per D153A 11-2001	725.44			Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
495			WTP Totals:							3,858	725.44				50.10	Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
496																			
497	AP-107	AW-102					78-80	400	1,428	216					9.16				
498			AP-107 07A							108	675.34	Est per M/U of D153A							
499			AP-107 07A	AP Valve Pit	SN-617			400	423		675.34	Est per D153A 11-2001	676.61	Est per D153A 11-2001		Line SN-617/Pit 07A not on D153A	1.5"		H-2-90563
500			AP Valve Pit						205		676.61	Per D153A 11-2001							

CASE 3S6D Transfer List - Tank-to-Tank

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
2	Transfer		Via Routing														Encasement Drainage Piping Size		
3	From Tank	To Tank	Start	End	Primary Pipe 3" Sch-40 Pipe (3.068" ID) Line ID #	Comment	Tank Farm Built (Yr)	Design Press (lb/in²)	Carbon Steel Length (ft)	Stainless Steel Length (ft)	Elevation Start	Source Elevation	Elevation End	Source Elevation	Total Change in Elevation (ft)	Comments:	Low Point	High Point	Ref. Dwg.
501			AP Valve Pit	AW-102 02A	SN-610			400	800		676.61	Est per D153A 11-2001	684.50	Est per D153A 11-2001		Nozzle elevation not shown on D153A			
502			AW-102 02A							108	684.50	Est per D153A 11-2001			9.16				
503									1,428	216									
504																			
505	AP-108	WTP						400	1,079	3,858					50.10				
506			AP-108 08A							108	675.34	Per D153A 11-2001							
507			AP-108 08A	AP Valve Pit	SN-618			400	443		675.34	Est Per D153A 11-2001	676.61	Est Per D153A 11-2001		Shown as 675.34 on D153A	1.5"		H-2-90563
508			AP Valve Pit						205		676.61	Per D153A 11-2001							
509			AP Valve Pit	AP-102-02A	SN-612			400	431		676.61	Per D153A 11-2001	675.28	Per H-2-90563		Hand entry on D153 Rev C			
510			AP-102-02A							100	675.28	Per H-2-90563	676.25						
511			AP-102-02A	AP-102-02D	SN-622			400		55	676.25	Per D153A 11-2001	675.89	Per D153A 11-2001					
512			AP-102-02D								675.89	Per D153A 11-2001	674.40						
513			AP-102-02D	WTP Interface	SN-700 or SN-701	Includes jumpers 02D		400		2,738	674.40	Per D153A 11-2001	662.44	Per D153A 11-2001		2738' Equivalent Length from Mark Przybylski, FFS			
514			WTP Interface						1,079	3,001	662.44	Per D153A 11-2001			-12.90				
515			WTP Interface	WTP (Vit Plant) internal equivalent pipe length and working height elevation						857	662.44	Per D153A 11-2001	725.44			Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
516			WTP Totals:							3,858	725.44				50.10	Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
517																			
518	AW-101	AN-105					80-81	275	2,082	3,855					-20.16				
519			AW-101 01A							108	684.50	Est per D153A 11-2001							
520			AW-101 01A	AW-A V. Pit	SN-261	Line # repeated in AN Farm		275	109		684.50	Est per D153A 11-2001	685.33	Est per D153A 11-2001		Line # Not on D153A	1.5"		H-2-70411s2
521			AW-A V. Pit							205	685.33	Est per D153A 11-2001							
522			AW-A V. Pit	AW-102 02A	SN-267	Line # repeated in AN Farm		275	124		685.33	Est per D153A 11-2001	683.61	Per H-2-70411		Line # Not on D153A	1.5"		H-2-70411s2
523			AW-102 02A							205	683.61	Per H-2-70411	684.11	Per H-2-70411					
524			AW-102 02A	AP Valve pit	SN-609			400	761		684.11	Per H-2-70411	676.61	Est per D153A 11-2001		Nozzle elevation not shown on D153A	2"		H-2-90551s1
525			AP Valve Pit						205		676.61	Per D153A 11-2001							
526			AP Valve Pit	AP-102-02A	SN-612			400	431		676.61	Per D153A 11-2001	675.28	Per H-2-90563		Hand entry on D153 Rev C			
527			AP-102-02A							100	675.28	Per H-2-90563	676.25	Per D153A 11-2001					
528			AP-102-02A	AP-102-02D	SN-622			400		55	676.25	Per D153A 11-2001	675.89	Per D153A 11-2001					
529			AP-102-02D			JUMPERS IN 02D = 60 FT				60	675.89	Per D153A 11-2001	674.40						
530			AP-102-02D	INTERFACE	(SN-634)	W-314/W-211 INTERFACE		400		145	674.40	Per D153A 11-2001	674.00	Per D153A 11-2001					
531			INTERFACE	NEW AZ PIT	SN-634			400		1,558	674.00	Per D153A 11-2001	669.50	Per D153A 11-2001		SN-634 also Interface>AP102 1558 cont w/J. Collins	2"		H-14-103263 s3
532			NEW AZ PIT							205	669.50	Per D153A 11-2001							
533			NEW AZ PIT	AN-101 01A	SN-630			400		491	669.50	Per D153A 11-2001	664.36	Per D153A 11-2001		Nozzle elevation not shown on D153A	2"		H-2-71998 s1
534			AN-101 01A							205	664.36	Per D153A 11-2001	666.16	H-2-71989					
535			AN-101 01A	AN-B	SN-261	Line # repeated in AW Farm		275	264		666.16	H-2-71989	664.38	H-2-71989		Nozzle elevation not shown on D153A	1.5"		H-2-71998 s1
536			AN-B							205	664.38	H-2-71989	666.45	666.45 (D153A)					
537			AN-B	AN-A	SN-268	Line # repeated in AW Farm		275	51		666.45	Per D153A 11-2001	666.50	Per D153A 11-2001			1.5"		H-2-71990 s1
538			AN-A							205	666.50	Elev. Change in Pit/Jumper	665.30	Per D153A 11-2001					
539			AN-A	AN-105 05A	SN-265	Line # repeated in AW Farm		275	137		665.30	Per D153A 11-2001	664.34	Per D153A 11-2001		Nozzle elevation not shown on D153A	2"		H-2-71998 s1
540			AN-105 05A							108	664.34	Per D153A 11-2001			-20.16				
541									2,082	3,855									
542																			
543	AW-101	WTP						275	1,630	4,268					40.94				
544			AW-101 01A							108	684.50	Est per D153A 11-2001							
545			AW-101 01A	AW-A V. Pit	SN-261	Line # repeated in AN Farm		275	109		684.50	Est Per D153A 11-2001	685.33	Est per D153A 11-2001		Line # Not on D153A	1.5"		H-2-70411s2
546			AW-A V. Pit							205	685.33	Est Per D153A 11-2001							
547			AW-A V. Pit	AW-102 02A	SN-267	Line # repeated in AN Farm		275	124		685.33	Est per D153A 11-2001	683.61	Per H-2-70411		Line # Not on D153A	1.5"		H-2-71998s1
548			AW-102 02A							205	683.61	Per H-2-70411	684.11	Per H-2-70411					
549			AW-102 02A	AP Valve pit	SN-609			400	761		684.11	Per H-2-70411	676.61	Est per D153A 11-2001		Nozzle elevation not shown on D153A	2"		H-2-90551s1
550			AP Valve Pit						205		676.61	Per D153A 11-2001							
551			AP Valve Pit	AP-102-02A	SN-612	W-314/W-211 INTERFACE		400	431		676.61	Per D153A 11-2001	675.28	Per H-2-90563		Hand entry on D153 Rev C			
552			AP-102-02A							100	675.28	Per H-2-90563	676.25						
553			AP-102-02A	AP-102-02D	SN-622			400		55	676.25	Per D153A 11-2001	675.89	Per D153A 11-2001					
554			AP-102-02D								675.89	Per D153A 11-2001	674.40	Per D153A 11-2001					
555			AP-102-02D	WTP Interface	SN-700 or SN-701	Includes jumpers 02D		400		2,738	674.40	Per D153A 11-2001	662.44	Per D153A 11-2001		2738' Equivalent Length from Mark Przybylski, FFS			
556			WTP Interface						1,630	3,411	662.44	Per D153A 11-2001			-22.06				
557			WTP Interface	WTP (Vit Plant) internal equivalent pipe length and working height elevation						857	662.44	Per D153A 11-2001	725.44			Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
558			WTP Totals:							4,268	725.44				40.94	Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
559																			
560	AW-102	AP-102					78-80	275	1,472	313					-7.75				
561			AW-102-02E							108	683.03	Est Per D153A 11-2001							
562			AW-102-02E	AW-102 02A	SN-272			275	75.00		683.03	Est Per D153A 11-2001	684.50	Est Per D153A 11-2001		Line # Not on D153A			
563			AW-102 02A							205	684.50	Est Per D153A 11-2001	684.11	Per H-2-70411					
564			AW-102 02A	AP Valve pit	SN-609			400	761		684.11	Per H-2-70411	676.61	Est per D153A 11-2001		Requires new jumpers/W-521 **			
565			AP Valve pit						205		676.61	Est per D153A 11-2001							
566			AP Valve pit	AP-102-02A	SN-612			400	431		676.61	Per D153A 11-2001	675.28	Per H-2-90563		Hand entry on D153 Rev C			
567			AP-102-02A							100	675.28	Per H-2-90563							
568									1,472	313					-7.75				
569																			
570	AW-102	AP-104					78-80	275	1,355	421					-7.75				
571			AW-102-02E							108	683.03	Est Per D153A 11-2001							

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	CASE 3S6D Transfer List - Tank-to-Tank																		
2	Transfer		Via Routing														Encasement Drainage Piping Size		
3	From Tank	To Tank	Start	End	Primary Pipe 3" Sch-40 Pipe (3.068" ID) Line ID #	Comment	Tank Farm Built (Yr)	Design Press (lb/in²)	Carbon Steel Length (ft)	Stainless Steel Length (ft)	Elevation Start	Source Elevation	Elevation End	Source Elevation	Total Change in Elevation (ft)	Comments:	Low Point	High Point	Ref. Dwg.
572			AW-102-02E	AW-102 02A	SN-272			275	75.00		683.03	Est Per D153A 11-2001	684.50	Est Per D153A 11-2001		Line # Not on D153A			
573			AW-102 02A							205	684.50		684.11	Per H-2-70411					
574			AW-102 02A	AP Valve pit	SN-609			400	761		684.11	Per H-2-70411	676.61	Est Per D153A / H-14-104365		Nozzle elevation not shown on D153A			
575			AP Valve pit						205		676.61	Est Per D153A / H-14-104365							
576			AP Valve pit	AP-104 04A	SN-614			400	314		676.61	Est Per D153A / H-14-104365	675.28	Est per D153A 11-2001		Hand entry on D153 Rev C			
577			AP-104 04A							108	675.28								
578									1,355	421					-7.75				
579																			
580	AW-102	AY-101					78-80	275	1,472	3,507					-9.03				
581			AW-102-02E							108	683.03	Est Per D153A 11-2001							
582			AW-102-02E	AW-102 02A	SN-272			275	75.00		683.03	Est Per D153A 11-2001	684.50	Est Per D153A 11-2001		Line # Not on D153A			
583			AW-102 02A							205	684.50		684.11	Per H-2-70411					
584			AW-102 02A	AP Valve pit	SN-609			400	761		684.11	Per H-2-70411	676.61	Est per D153A 11-2001		Nozzle elevation not shown on D153A			
585			AP Valve pit						205		676.61	Est Per D153A 11-2001							
586			AP Valve pit	AP-102-02A	SN-612			400	431		676.61	Per D153A 11-2001	675.28	Per H-2-90563		Hand entry on D153 Rev C			
587			AP-102-02A							100	675.28	Per H-2-90563	676.25						
588			AP-102-02A	AP-102-02D	SN-622			400		55	676.25	Per D153A 11-2001	675.89	Per D153A 11-2001					
589			AP-102-02D			JUMPERS IN 02D = 60 FT				60	675.89	Per D153A 11-2001	674.40						
590			AP-102-02D	INTERFACE	(SN-634)	W-314/W-211 INTERFACE		400		145	674.40	Per D153A 11-2001	674.00	Per D153A 11-2001					
591			INTERFACE	AZ Valve pit	SN-634			400		1,558	674.00	Per D153A 11-2001	669.50	Per D153A 11-2001		SN-634 also Interface>AP102 1558 conf w/J. Collins			
592			AZ Valve pit							205	669.50	Est Per D153A 11-2001							
593			NEW AZ PIT	AY-102 02A	SN-633			400		843	669.50	Per D153A 11-2001	675.01	Per D153A 11-2001					
594			AY-102-02A	AY-101-01A	SN-635			400		120	674.42	Per D153A 11-2001	674.00	Per D153A 11-2001		120'SS conf w Jim Collins 12/5/01 was 170'			
595			AY-101-01A							108	674.00								
596									1,472	3,507					-9.03				
597																			
598	AW-102	AY-102					78-80	275	1,472	3,524					-8.02				
599			AW-102-02E							108	683.03	Est Per D153A 11-2001							
600			AW-102-02E	AW-102 02A	SN-272			275	75.00		683.03	Est Per D153A 11-2001	684.50	Est Per D153A 11-2001		Line # Not on D153A			
601			AW-102 02A							205	684.50	Est Per D153A 11-2001	684.11	Per H-2-70411					
602			AW-102 02A	AP Valve pit	SN-609			400	761		684.11	Per H-2-70411	676.61	Est per D153A 11-2001		Nozzle elevation not shown on D153A			
603			AP Valve pit						205		676.61	Est Per D153A 11-2001							
604			AP Valve pit	AP-102-02A	SN-612			400	431		676.61	Per D153A 11-2001	675.28	Per H-2-90563		Hand entry on D153 Rev C			
605			AP-102-02A							100	675.28	Per H-2-90563	676.25	Per D153A 11-2001					
606			AP-102-02A	AP-102-02D	SN-622			400		55	676.25	Per D153A 11-2001	675.89	Per D153A 11-2001					
607			AP-102-02D							205	675.89	Per D153A 11-2001	674.40						
608			AP-102-02D	INTERFACE	(SN-634)	W-314/W-211 INTERFACE		400		145	674.40	Per D153A 11-2001	674.00	Per D153A 11-2001					
609			INTERFACE	AZ Valve pit	SN-634			400		1,558	674.00	Per D153A 11-2001	669.50	Per D153A 11-2001		SN-634 also Interface>AP102 1558 conf w/J. Collins			
610			AZ Valve pit							205	669.50	Est Per D153A 11-2001							
611			NEW AZ PIT	AY-102 02A	SN-633			400		843	669.50	Per D153A 11-2001	675.01	Per D153A 11-2001					
612			AY-102-02A							100	675.01	Est Per D153A 11-2001							
613									1,472	3,524					-8.02				
614																			
615	AW-102	WTP					78-80	275	1,472	4,063					-20.59				
616			AW-102-02E							108	683.03	Est Per D153A 11-2001							
617			AW-102-02E	AW-102 02A	SN-272			275	75.00		683.03	Est Per D153A 11-2001	684.50	Est Per D153A 11-2001		Line # Not on D153A			
618			AW-102 02A							205	684.50		684.11	Per H-2-70411					
619			AW-102 02A	AP Valve pit	SN-609			400	761		684.11	Per H-2-70411	676.61	Est per D153A 11-2001		Nozzle elevation not shown on D153A			
620			AP Valve pit						205		676.61	Est per D153A 11-2001							
621			AP Valve pit	AP-102-02A	SN-612			400	431		676.61	Per D153A 11-2001	675.28	Per H-2-90563		Hand entry on D153 Rev C			
622			AP-102-02A							100	675.28	Per H-2-90563	676.25	Per D153A 11-2001					
623			AP-102-02A	AP-102-02D	SN-622			400		55	676.25	Per D153A 11-2001	675.89	Per D153A 11-2001					
624			AP-102-02D								675.89	Per D153A 11-2001	674.40	Per D153A 11-2001					
625			AP-102-02D	WTP Interface	SN-700 or SN-701	Includes jumpers 02D		400		2,738	674.40	Per D153A 11-2001	662.44	Per D153A 11-2001		2738' Equivalent Length from Mark Przybylski, FFS			
626			WTP Interface						1,472	3,206	662.44				-20.59				
627			WTP Interface	WTP (Vit Plant) internal equivalent pipe length and working height elevation						857	662.44	Per D153A 11-2001	725.44			Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
628			WTP Totals:							4,063	725.44				42.41	Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
629																			
630	AW-103	AP-102					78-80	275	1,648	618					-8.29				
631			AW-103 03A							108	683.57	per H-2-70411, sh 1							
632			AW-103 03A	AW-A V. Pit	SN-263	Line # repeated in AN Farm		275	127		683.57	per H-2-70411, sh 1	685.33	Est per D153A 11-2001		Line # Not on D153A			
633			AW-A V. Pit							205	685.33	Est per D153A 11-2001							
634			AW-A V. Pit	AW-102 02A	SN-267	Line # repeated in AN Farm		275	124		685.33	Est per D153A 11-2001	683.61	Per H-2-70411		Line # Not on D153A			
635			AW-102 02A							205	683.61	Per H-2-70411	684.11	Per H-2-70411					
636			AW-102 02A	AP Valve pit	SN-609			400	761		684.11	Per H-2-70411	676.61	Est per D153A 11-2001		Nozzle elevation not shown on D153A			
637			AP Valve pit						205		676.61								
638			AP Valve pit	AP-102-02A	SN-612			400	431		676.61	Per D153A 11-2001	675.28	Per H-2-90563		Hand entry on D153 Rev C			
639			AP-102-02A							100	675.28	Per H-2-90563							
640									1,648	618					-8.29				
641																			
642	AW-103	AP-104					78-80	275	1,483	626					-9.22				

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	CASE 3S6D Transfer List - Tank-to-Tank																		
2	Transfer		Via Routing														Encasement Drainage Piping Size		
3	From Tank	To Tank	Start	End	Primary Pipe 3" Sch-40 Pipe (3.068" ID) Line ID #	Comment	Tank Farm Built (Yr)	Design Press (lb/in²)	Carbon Steel Length (ft)	Stainless Steel Length (ft)	Elevation Start	Source Elevation	Elevation End	Source Elevation	Total Change in Elevation (ft)	Comments:	Low Point	High Point	Ref. Dwg.
643			AW-104 04A							108	684.50	Est per D153A 11-2001							
644			AW-104 04A	AW-B	SN-264	Line # repeated in AN Farm		275	115		684.50	Est per D153A 11-2001	685.29	Per D153A 11-2001		Line # Not on D153A			
645			AW-B V. pit							205	685.29	Per D153A 11-2001							
646			AW-B V. Pit	AW-102 02A	SN-268	Line # repeated in AN Farm		275	88		685.29	Est. Per D153A 11-2001	684.50	Est. Per D153A 11-2001		Line # Not on D153A			
647			AW-102 02A							205	684.50	Est. Per D153A 11-2001	684.11	Per H-2-70411					
648			AW-102 02A	AP Valve pit	SN-609			400	761		684.11	Per H-2-70411	676.61	Est per D153A 11-2001		Nozzle elevation not shown on D153A			
649			AP Valve pit						205		676.61	Est per D153A 11-2001							
650			AP Valve pit	AP-104 04A	SN-614			400	314		676.61	Est Per D153A / H-14-104365	675.28	Est per D153A 11-2001		Hand entry on D153 Rev C			
651			AP-104 04A							108	675.28	Est per D153A 11-2001							
652									1,483	626					-9.22				
653																			
654	AW-103	AW-104					78-80	275	454	831					0.93				
655			AW-103 03A							108	683.57	per H-2-70411, sh 1							
656			AW-103 03A	AW-A V. Pit	SN-263	Line # repeated in AN Farm		275	127		683.57	per H-2-70411, sh 1	685.33	Est per D153A 11-2001		Line # Not on D153A	2"		H-2-71998s1
657			AW-A V. Pit							205	665.33	Est per D153A 11-2001							
658			AW-A V. Pit	AW-102 02A	SN-267	Line # repeated in AN Farm		275	124		685.33	Est per D153A 11-2001	683.61	Per H-2-70411		Line # Not on D153A	1.5"		H-2-70411s2
659			AW-102 02A							205	683.61	Per H-2-70411	684.50	Est. Per D153A 11-2001					
660			AW-102 02A	AW-B	SN-268	Line # repeated in AN Farm		275	88		684.50	Est. Per D153A 11-2001	685.29	Est. Per D153A 11-2001			1.5"		H-2-71990s1
661			AW-B V. Pit							205	685.29	Per D153A 11-2001							
662			AW-B V. Pit	AW-104 04A	SN-264	Line # repeated in AN Farm		275	115		685.29	Per D153A 11-2001	684.50	Est per D153A 11-2001		Line # Not on D153A	2"		H-2-71998s1
663			AW-104 04A							108	684.50	Est per D153A 11-2001			0.93				
664									454	831									
665																			
666	AW-103	AY-102					68-70	275	1,648	3,584					-8.56				
667			AW-103 03A							108	683.57	per H-2-70411, sh 1							
668			AW-103 03A	AW-A V. Pit	SN-263	Line # repeated in AN Farm		275	127		683.57	per H-2-70411, sh 1	685.33	Est per D153A 11-2001		Line # Not on D153A	2"		H-2-71998s1
669			AW-A V. Pit							205	665.33	Est per D153A 11-2001							
670			AW-A V. Pit	AW-102 02A	SN-267	Line # repeated in AN Farm		275	124		685.33	Est per D153A 11-2001	683.61	Per H-2-70411		Line # Not on D153A	1.5"		H-2-70411s2
671			AW-102 02A							205	683.61	Per H-2-70411	684.11	Per H-2-70411					
672			AW-102 02A	AP Valve pit	SN-609			400	761		684.11	Per H-2-70411	676.61	Est per D153A 11-2001		Nozzle elevation not shown on D153A	2"		H-2-90551s1
673			AP Valve Pit						205		676.61	Per D153A 11-2001							
674			AP Valve Pit	AP-102-02A	SN-612			400	431		676.61	Per D153A 11-2001	675.28	Per H-2-90563		Hand entry on D153 Rev C			
675			AP-102-02A							100	675.28	Per H-2-90563	676.25						
676			AP-102-02A	AP-102-02D	SN-622			400		55	676.25	Per D153A 11-2001	675.89	Per D153A 11-2001					
677			AP-102-02D			JUMPERS IN 02D = 60 FT				60	675.89	Per D153A 11-2001	674.40	Per D153A 11-2001					
678			AP-102-02D	INTERFACE	(SN-634)	W-314/W-211 INTERFACE		400		145	674.40	Per D153A 11-2001	674.00	Per D153A 11-2001			2"		H-14-103263s3
679			INTERFACE	NEW AZ PIT	SN-634			400		1,558	674.00	Per D153A 11-2001	669.50	Per D153A 11-2001		SN-634 also Interface>AP102 1558 conf w/J. Collins			
680			NEW AZ PIT							205	669.25	Per D153A 11-2001							
681			NEW AZ PIT	AY-102 02A	SN-633			400		843	669.50	Per D153A 11-2001	675.01	Per D153A 11-2001			2"		H-14-103263s3
682			AY-102-02A							100	675.01	Per D153A 11-2001			-8.56				
683									1,648	3,584									
684																			
685	AW-103	WTP						275	1,648	4,268					41.88				
686			AW-103 03A							108	683.57	per H-2-70411, sh 1							
687			AW-103 03A	AW-A V. Pit	SN-263	Line # repeated in AN Farm		275	127		683.57	per H-2-70411, sh 1	685.33	Est per D153A 11-2001		Line # Not on D153A	2"		H-2-71998s1
688			AW-A V. Pit							205	685.33	Est per D153 11-2001							
689			AW-A V. Pit	AW-102 02A	SN-267	Line # repeated in AN Farm		275	124		685.33	Est per D153A 11-2001	683.61	Per H-2-70411		Line # Not on D153A	1.5"		H-2-71998s1
690			AW-102 02A							205	683.61	Per H-2-70411	684.11	Per H-2-70411					
691			AW-102 02A	AP Valve pit	SN-609			400	761		684.11	Per H-2-70411	676.61	Est per D153A 11-2001		Nozzle elevation not shown on D153A	2"		H-2-90551s1
692			AP Valve Pit						205		676.61	Per D153A 11-2001							
693			AP Valve Pit	AP-102-02A	SN-612			400	431		676.61	Per D153A 11-2001	675.28	Per H-2-90563		Hand entry on D153 Rev C			
694			AP-102-02A							100	675.28	Per H-2-90563	676.25						
695			AP-102-02A	AP-102-02D	SN-622			400		55	676.25	Per D153A 11-2001	675.89	Per D153A 11-2001					
696			AP-102-02D	WTP Interface	SN-700 or SN-701	Includes jumpers 02D		400		2,738	675.89	Per D153A 11-2001	662.44	Per D153A 11-2001		2738' Equivalent Length from Mark Przybylski, FFS			
697			WTP Interface						1,648	3,411	662.44	Per D153A 11-2001			-21.13				
698			WTP Interface	WTP (Vit Plant) internal equivalent pipe length and working height elevation						857	662.44	Per D153A 11-2001	725.44			Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
699			WTP Totals:							4,268	725.44				41.88	Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
700																			
701	AW-104	AP-104					83-86	275	1,522	626					-9.22				
702			AW-104 04A							108	684.50	Est per D153A 11-2001							
703			AW-104 04A	AW-B	SN-264	Line # repeated in AN Farm		275	115		684.50	Est per D153A 11-2001	685.29	Per D153A 11-2001		Line # Not on D153A	2"		H-2-71998s1
704			AW-B V. Pit							205	685.29	Per D153A 11-2001							
705			AW-B V. Pit	AW-102 02A	SN-268	Line # repeated in AN Farm		275	88		685.29	Est. Per D153A 11-2001	684.50	Est. Per D153A 11-2001			1.5"		H-2-71990s1
706			AW-102 02A							205	684.50	684.50 Est per D153 11-2001							
707			AW-102 02A	AP Valve Pit	SN-610			400	800		684.50	Est per D153A 11-2001	676.61	Est Per D153A / H-14-104365		Nozzle elevation not shown on D153A			
708			AP Valve Pit						205		676.61	Est Per D153A / H-14-104365							
709			AP Valve Pit	AP-104 04A	SN-614			400	314		676.61	Est Per D153A / H-14-104365	675.28	Est per D153A 11-2001		Hand entry on D153 Rev C	1.5"		H-2-90563s1
710			AP-104 04A							108	675.28	Est per D153A 11-2001			-9.22				
711									1,522	626									
712																			
713	AW-104	AW-102					78-80	275	203	421					0.00				

CASE 3S6D Transfer List - Tank-to-Tank

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
2	Transfer		Via Routing														Encasement Drainage Piping Size		
3	From Tank	To Tank	Start	End	Primary Pipe 3" Sch-40 Pipe (3.068" ID) Line ID #	Comment	Tank Farm Built (Yr)	Design Press (lb/in²)	Carbon Steel Length (ft)	Stainless Steel Length (ft)	Elevation Start	Source Elevation	Elevation End	Source Elevation	Total Change in Elevation (ft)	Comments:	Low Point	High Point	Ref. Dwg.
714			AW-104 04A							108	684.50	Est per D153A 11-2001							
715			AW-104 04A	AW-B	SN-264	Line # repeated in AN Farm		275	115		684.50	Est per D153A 11-2001	685.29	Per D153A 11-2001		Line # Not on D153A	2"		H-2-71998s1
716			AW-B V. Pit							205	685.29	Per D153A 11-2001							
717			AW-B V. Pit	AW-102 02A	SN-268	Line # repeated in AN Farm		275	88		685.29	Est. Per D153A 11-2001	684.50	Est. Per D153A 11-2001			1.5"		H-2-71990s1
718			AW-102 02A							108	684.50	684.50 Est per D153 11-2001			0.00				
719									203	421									
720																			
721	AW-104	WTP						275	1,434	4,268					40.94				
722			AW-104 04A							108	684.50	Est per D153A 11-2001							
723			AW-104 04A	AW-B	SN-264	Line # repeated in AN Farm		275	115		684.50	Est per D153A 11-2001	685.29	Per D153A 11-2001		Line # Not on D153A	2"		H-2-71998s1
724			AW-B V. Pit							205	685.29	Per D153A 11-2001							
725			AW-B V. Pit	AW-102 02A	SN-268	Line # repeated in AN Farm		275	88		685.29	Est. Per D153A 11-2001	684.50	Est. Per D153A 11-2001			1.5"		H-2-71990s1
726			AW-102 02A							205	684.50	684.50 Est per D153 11-2001							
727			AW-102 02A	AP Valve Pit	SN-610			400	800		684.50	Est per D153A 11-2001	676.61	Est per D153A 11-2001		Nozzle elevation not shown on D153A			
728			AP Valve Pit	AP-102-02A	SN-612			400	431		676.61	Per D153A 11-2001	675.28	Per H-2-90563		Hand entry on D153 Rev C			
729			AP-102-02A							100	675.28	Per H-2-90563	676.25						
730			AP-102-02A	AP-102-02D	SN-622	W-314/W-211 INTERFACE		400		55	676.25	Per D153A 11-2001	675.89	Per D153A 11-2001					
731			AP-102-02D								675.89	Per D153A 11-2001	674.40						
732			AP-102-02D	WTP Interface	SN-700 or SN-701	Includes jumpers 02D		400		2,738	674.40	Per D153A 11-2001	662.44	Per D153A 11-2001		2738' Equivalent Length from Mark Przybylski, FFS			
733			WTP Interface						1,434	3,411	662.44	Per D153A 11-2001			-22.06				
734			WTP Interface	WTP (Vit Plant) internal equivalent pipe length and working height elevation						857	662.44	Per D153A 11-2001	725.44			Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
735			WTP Totals:							4,268	725.44				40.94	Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
736																			
737	AW-105	AP-102					78-80	275	1,800	618					-9.22				
738			AW-105 05A							108	684.5	Est per D153A 11-2001							
739			AW-105 05A	AW-A V. pit	SN-265	Line # repeated in AN Farm		275	240		684.5	Est per D153A 11-2001	685.33	Est per D153A 11-2001		Line # Not on D153A			
740			AW-A V. pit							205	685.33								
741			AW-A V. pit	AW-102 02A	SN-267	Line # repeated in AN Farm		275	124		685.33	Est per D153A 11-2001	683.61	Per H-2-70411		Line # Not on D153A			
742			AW-102 02A							205	683.61	Per H-2-70411							
743			AW-102 02A	AP Valve pit	SN-610			400	800		684.50	Est per D153A 11-2001	676.61	Est per D153A 11-2001		Nozzle elevation not shown on D153A			
744			AP Valve pit						205		676.61	Est per D153A 11-2001							
745			AP Valve pit	AP-102-02A	SN-612			400	431		676.61	Per D153A 11-2001	675.28	Per H-2-90563		Hand entry on D153 Rev C			
746			AP-102-02A							100	675.28	Per H-2-90563							
747									1,800	618					-9.22				
748																			
749	AW-105	AP-104					78-80	275	1,683	626					-9.16				
750			AW-105 05A							108	684.5	Est per D153A 11-2001							
751			AW-105 05A	AW-A V. pit	SN-265	Line # repeated in AN Farm		275	240		684.5	Est per D153A 11-2001	685.33	Est per D153A 11-2001		Line # Not on D153A			
752			AW-A V. pit							205	685.33	Est per D153A 11-2001							
753			AW-A V. pit	AW-102 02A	SN-267	Line # repeated in AN Farm		275	124		685.33	Est per D153A 11-2001	683.61	Per H-2-70411		Line # Not on D153A			
754			AW-102 02A							205	683.61	Per H-2-70411	684.50	Est per D153A 11-2001					
755			AW-102 02A	AP Valve pit	SN-610			400	800		684.50	Est per D153A 11-2001	676.61	Est Per D153A / H-14-104365		Nozzle elevation not shown on D153A			
756			AP Valve pit						205		676.61	Est Per D153A / H-14-104365							
757			AP Valve pit	AP-104 04A	SN-614			400	314		676.61	Est Per D153A / H-14-104365	675.28	Est per D153A 11-2001		Hand entry on D153 Rev C			
758			AP-104 04A							108	675.34	Est per D153A 11-2001							
759									1,683	626					-9.16				
760																			
761	AW-105	WTP						275	1,556	4,268					40.94				
762			AW-105 05A							108	684.5	Est per D153A 11-2001							
763			AW-105 05A	AW-A V. Pit	SN-265	Line # repeated in AN Farm		275	240		684.5	Est per D153A 11-2001	685.33	Est per D153A 11-2001		Line # Not on D153A	2"		H-2-71998s1
764			AW-A V. Pit							205	685.33	Est per D153A 11-2001							
765			AW-A V. Pit	AW-102 02A	SN-267	Line # repeated in AN Farm		275	124		685.33	Est per D153A 11-2001	683.61	Per H-2-70411		Line # Not on D153A	1.5"		H-2-70411 s2
766			AW-102 02A							205	683.61	Per H-2-70411	684.11	Per H-2-70411					
767			AW-102 02A	AP Valve pit	SN-609			400	761		684.11	Per H-2-70411	676.61	Est per D153A 11-2001		Nozzle elevation not shown on D153A	2"		H-2-90551s1
768			AP Valve Pit	AP-102-02A	SN-612	W-314/W-211 INTERFACE		400	431		676.61	Per D153A 11-2001	675.28	Per H-2-90563		Hand entry on D153 Rev C			
769			AP-102-02A							100	675.28	Per H-2-90563	676.25	Per D153A 11-2001					
770			AP-102-02A	AP-102-02D	SN-622			400		55	676.25	Per D153A 11-2001	675.89	Per D153A 11-2001					
771			AP-102-02D								675.89	Per D153A 11-2001	674.40						
772			AP-102-02D	WTP Interface	SN-700 or SN-701	Includes jumpers 02D		400		2,738	674.40	Per D153A 11-2001	662.44	Per D153A 11-2001		2738' Equivalent Length from Mark Przybylski, FFS			
773			WTP Interface						1,556	3,411	662.44	Per D153A 11-2001			-22.06				
774			WTP Interface	WTP (Vit Plant) internal equivalent pipe length and working height elevation						857	662.44	Per D153A 11-2001	725.44			Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
775			WTP Totals:							4,268	725.44				40.94	Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
776																			
777	AW-106	AP-105					83-86	275	1,621	626					-9.16				
778			AW-106 06A							108	684.5	Est per D153A 11-2001							
779			AW-106 06A	AW-B	SN-266	Line # repeated in AN Farm		275	226		684.5	Est per D153A 11-2001	685.29			Line # Not on D153A	1.5"		H-2-70411s2
780			AW-B V. Pit							205	685.29	Per D153A 11-2001							
781			AW-B V. Pit	AW-102 02A	SN-268	Line # repeated in AN Farm		275	88		685.29	Est. Per D153A 11-2001	684.50	Est. Per D153A 11-2001			1.5"		H-2-71990s1
782			AW-102 02A							205	684.50	Est per D153A 11-2001							
783			AW-102 02A	AP Valve Pit	SN-610			400	800		684.50	Est per D153A 11-2001	676.61	Est per D153A 11-2001		Nozzle elevation not shown on D153A			
784			AP Valve Pit						205		676.61	Per D153A 11-2001							

CASE 3S6D Transfer List - Tank-to-Tank

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
2	Transfer		Via Routing														Encasement Drainage Piping Size		
3	From Tank	To Tank	Start	End	Primary Pipe 3" Sch-40 Pipe (3.068" ID) Line ID #	Comment	Tank Farm Built (Yr)	Design Press (lb/in²)	Carbon Steel Length (ft)	Stainless Steel Length (ft)	Elevation Start	Source Elevation	Elevation End	Source Elevation	Total Change in Elevation (ft)	Comments:	Low Point	High Point	Ref. Dwg.
785			AP Valve Pit	AP-105 05A	SN-615			400	302		676.61	Est per D153A 11-2001	675.34	Est per D153A 11-2001			1.5"		H-2-90563s1
786			AP-105 05A							108	675.34	Est per D153A 11-2001			-9.16				
787									1,621	626									
788																			
789	AW-106	AP-106					83-86	275	1,767	518					-9.16				
790			AW-106 06A							108	684.5	Est per D153A 11-2001							
791			AW-106 06A	AW-B	SN-266	Line # repeated in AN Farm		275	226		684.5	Est per D153A 11-2001	685.29	Est per D153A 11-2001		Line # Not on D153A	1.5"		H-2-71998s1
792			AW-B V. Pit							205	685.29	Per D153A 11-2001							
793			AW-B V. Pit	AW-102 02A	SN-268	Line # repeated in AN Farm		275	88		685.29	Est. Per D153A 11-2001	684.50	Est. Per D153A 11-2001			1.5"		H-2-71990s1
794			AW-102 02A							205	684.50	Est per D153A 11-2001							
795			AW-102 02A	AP Valve Pit	SN-610			400	800		684.50	Est per D153A 11-2001	676.61	Est per D153A 11-2001		Nozzle elevation not shown on D153A			
796			AP Valve Pit						205		676.61	Est per D153A 11-2001							
797			AP Valve Pit	AP-106 06A	SN-616			400	340		676.61	Est Per D153A 11-2001	675.34	Est Per D153A 11-2001			1.5"		H-2-90563s1
798			AP-106 06A						108		675.34	Per D153A 11-2001			-9.16				
799									1,767	518									
800																			
801	AW-106	AP-108					83-86	275	1,762	626					-9.16				
802			AW-106 06A							108	684.5	Est per D153A 11-2001							
803			AW-106 06A	AW-B	SN-266	Line # repeated in AN Farm		275	226		684.5	Est per D153A 11-2001	685.29	Est per D153A 11-2001		Line # Not on D153A	1.5"		H-2-71998s1
804			AW-B V. Pit							205	685.29	Per D153A 11-2001							
805			AW-B V. Pit	AW-102 02A	SN-268	Line # repeated in AN Farm		275	88		685.29	Est. Per D153A 11-2001	684.50	Est. Per D153A 11-2001			1.5"		H-2-71990s1
806			AW-102 02A							205	684.50	Est per D153A 11-2001							
807			AW-102 02A	AP Valve Pit	SN-610			400	800		684.50	Est per D153A 11-2001	676.61	Est per D153A 11-2001		Nozzle elevation not shown on D153A			
808			AP Valve Pit						205		676.61	Per D153A 11-2001							
809			AP Valve Pit	AP-108 08A	SN-618			400	443		676.61	Est Per D153A 11-2001	675.34	Est Per D153A 11-2001		Shown as 675.34 on D153A	1.5"		H-2-90563s1
810			AP-108 08A							108	675.34	Per D153A 11-2001			-9.16				
811									1,762	626									
812																			
813	AW-106	AW-102					78-80	275	314	421					0.00				
814			AW-106 06A							108	684.5	Est per D153A 11-2001							
815			AW-106 06A	AW-B	SN-266	Line # repeated in AN Farm		275	226		684.5	Est per D153A 11-2001	685.29	Est per D153A 11-2001		Line # Not on D153A	1.5"		H-2-71998s1
816			AW-B V. Pit							205	685.29	Per D153A 11-2001							
817			AW-B V. Pit	AW-102 02A	SN-268	Line # repeated in AN Farm		275	88		685.29	Est. Per D153A 11-2001	684.50	Est. Per D153A 11-2001			1.5"		H-2-71990s1
818			AW-102 02A							108	684.50	684.50 Est per D153 11-2001			0.00				
819									314	421									
820																			
821	AW-106	AW-103					78-80	275	565	831					-0.93				
822			AW-106 06A							108	684.5	Est per D153A 11-2001							
823			AW-106 06A	AW-B	SN-266	Line # repeated in AN Farm		275	226		684.5	Est per D153A 11-2001	685.29	Est per D153A 11-2001		Line # Not on D153A	1.5"		H-2-71998s1
824			AW-B V. Pit							205	685.29	Per D153A 11-2001							
825			AW-B V. Pit	AW-102 02A	SN-268	Line # repeated in AN Farm		275	88		685.29	Est. Per D153A 11-2001	684.50	Est. Per D153A 11-2001			1.5"		H-2-71990s1
826			AW-102 02A							205	684.50	Est per D153A 11-2001	683.61	Per H-2-70411					
827			AW-102 02A	AW-A V. Pit	SN-267	Line # repeated in AN Farm		275	124		683.61	Per H-2-70411	685.33	Est per D153 11-2001		Line # Not on D153A	1.5"		H-2-71998s1
828			AW-A V. Pit							205	685.33	Est per D153A 11-2001							
829			AW-A V. Pit	AW-103 03A	SN-263	Line # repeated in AN Farm		275	127		685.33	Est per D153A 11-2001	683.57	per H-2-70411, sh 1		Line # Not on D153A	2"		H-2-71998s1
830			AW-103 03A							108	683.57	per H-2-70411, sh 1			-0.93				
831									565	831									
832																			
833	AW-106	AW-104					78-80	275	341	421					0.00				
834			AW-106 06A							108	684.5	Est per D153A 11-2001							
835			AW-106 06A	AW-B	SN-266	Line # repeated in AN Farm		275	226		684.5	Est per D153A 11-2001	685.29	Est per D153A 11-2001		Line # Not on D153A	1.5"		H-2-71998s1
836			AW-B V. Pit							205	685.29	Per D153A 11-2001							
837			AW-B V. Pit	AW-104 04A	SN-264	Line # repeated in AN Farm		275	115		685.29	Per D153A 11-2001	684.50	Est per D153A 11-2001		Line # Not on D153A	2"		H-2-71998s1
838			AW-104 04A							108	684.50	Est per D153A 11-2001			0.00				
839									341	421									
840																			
841	AW-106	AW-105					78-80	275	678	831					0.00				
842			AW-106 06A							108	684.5	Est per D153A 11-2001							
843			AW-106 06A	AW-B	SN-266	Line # repeated in AN Farm		275	226		684.5	Est per D153A 11-2001	685.29	Est per D153A 11-2001		Line # Not on D153A	1.5"		H-2-71998s1
844			AW-B V. Pit							205	685.29	Per D153A 11-2001							
845			AW-B V. Pit	AW-102 02A	SN-268	Line # repeated in AN Farm		275	88		685.29	Est. Per D153A 11-2001	684.50	Est. Per D153A 11-2001			1.5"		H-2-71990s1
846			AW-102 02A							205	684.50	Est per D153A 11-2001	683.61	Per H-2-70411					
847			AW-102 02A	AW-A V. Pit	SN-267	Line # repeated in AN Farm		275	124		683.61	Per H-2-70411	685.33	Est per D153 11-2001		Line # Not on D153A	1.5"		H-2-71998s1
848			AW-A V. Pit							205	685.33	Est per D153A 11-2001							
849			AW-A V. Pit	AW-105 05A	SN-265	Line # repeated in AN Farm		275	240		685.33	Est per D153A 11-2001	684.50	Est Per D153A		Line # Not on D153A	2"		H-2-71998s1
850			AW-105 05A							108	684.5	Est per D153A 11-2001			0.00				
851									678	831									
852																			
853	AY-101	WTP						400	0	6,674					51.44				
854			AY-101 01A							108	674.00	Per D153A 11-2001							
855			AY-101 01A	AY-102 02A	SN-635			400		120	674.00	Per D153A 11-2001	674.42	Per D153A 11-2001		120'SS conf w Jim Collins 12/5/01 was 170'	1"		H-14-102650 s1

CASE 3S6D Transfer List - Tank-to-Tank

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
2	Transfer		Via Routing														Encasement Drainage Piping Size		
3	From Tank	To Tank	Start	End	Primary Pipe 3" Sch-40 Pipe (3.068" ID) Line ID #	Comment	Tank Farm Built (Yr)	Design Press (lb/in²)	Carbon Steel Length (ft)	Stainless Steel Length (ft)	Elevation Start	Source Elevation	Elevation End	Source Elevation	Total Change in Elevation (ft)	Comments:	Low Point	High Point	Ref. Dwg.
856			AY-102-02A							100	674.42	Per D153A 11-2001	675.01						
857			AY-102-02A	NEW AZ PIT	SN-633			400		843	675.01	Per D153A 11-2001	669.50	Per D153A 11-2001			2"		H-14-103263 s3
858			NEW AZ PIT							205	669.50	Per D153A 11-2001							
859			NEW AZ PIT	INTERFACE	SN-634	W-314/W-211 INTERFACE		400		1,558	669.50	Per D153A 11-2001	674.00	Per D153A 11-2001		SN-634 also Interface>AP102 1558 conf w/J. Collins	2"		H-14-103263 s3
860			INTERFACE	AP-102-02D	(SN-634)	SN-634 also AZ>Interface		400		145	674.00	Per D153A 11-2001	674.40	Per D153A 11-2001					
861			AP-102-02D	WTP Interface	SN-700 or SN-701	Includes jumpers 02D		400		2,738	674.40	Per D153A 11-2001	662.44	Per D153A 11-2001		2738' Equivalent Length from Mark Przybylski, FFS			
862			WTP Interface						0	5,817	662.44	Per D153A 11-2001			-11.56				
863			WTP Interface	WTP (Vit Plant) internal equivalent pipe length and working height elevation						857	662.44	Per D153A 11-2001	725.44			Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
864			WTP Totals:							6,674	725.44				51.44	Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
865																			
866	AY-102	AN-103					80-81	275	376	2,044					-10.67				
867			AY-102-02A							100	675.01	Per D153A 11-2001							
868			AY-102-02A	NEW AZ PIT	SN-633			400		843	675.01	Per D153A 11-2001	669.50	Per D153A 11-2001			2"		H-14-103263 s3
869			NEW AZ PIT							205	669.50	Per D153A 11-2001							
870			NEW AZ PIT	AN-101 01A	SN-630			400		491	669.50	Per D153A 11-2001	664.36	Per D153A 11-2001		Nozzle elevation not shown on D153A	2"		H-2-71998s1
871			AN-101 01A							100	664.36	Per D153A 11-2001	666.16	H-2-71989					
872			AN-101 01A	AN-B	SN-261	Line # repeated in AW Farm		275	264		666.16	H-2-71989	664.38	H-2-71989		Nozzle elevation not shown on D153A	1.5"		H-2-71998s1
873			AN-B							205	664.38	H-2-71989	666.46	Est per D153A 11-2001					
874			AN-B	AN-103 03A	SN-263	Line # repeated in AW Farm		275	112		666.46	Est per D153A 11-2001	664.34	Est per D153A 11-2001		Nozzle elevation not shown on D153A	2"		H-2-71998s1
875			AN-103 03A							100	664.34	Est Per D153A 11-2001			-10.67				
876									376	2,044									
877																			
878	AY-102	AN-106					80-81	275	442	2,354					-10.67				
879			AY-102-02A							100	675.01	Per D153A 11-2001							
880			AY-102-02A	NEW AZ PIT	SN-633			400		843	675.01	Per D153A 11-2001	669.50	Per D153A 11-2001			2"		H-14-103263s3
881			NEW AZ PIT							205	669.50	Per D153A 11-2001							
882			NEW AZ PIT	AN-101 01A	SN-630			400		491	669.50	Per D153A 11-2001	664.36	Per D153A 11-2001		Nozzle elevation not shown on D153A	2"		H-2-71998s1
883			AN-101 01A							205	664.36	Per D153A 11-2001	666.16	H-2-71989					
884			AN-101 01A	AN-B	SN-261	Line # repeated in AW Farm		275	264		666.16	H-2-71989	664.38	H-2-71989		Nozzle elevation not shown on D153A	1.5"		H-2-71998s1
885			AN-B							205	664.38	H-2-71989	666.45	666.45 (D153A)					
886			AN-B	AN-A	SN-268	Line # repeated in AW Farm		275	51		666.45	Per D153A 11-2001	666.50	Per D153A 11-2001			1.5"		H-2-71990 s1
887			AN-A							205	666.50	Elev. Change in Pit/Jumper	665.30	666.5 Per D153A					
888			AN-A	AN-106 06A	SN-266	Line # repeated in AW Farm		275	127		665.30	Est Per D153A 11-2001	664.34	Est Per D153A		Nozzle elevation not shown on D153A	1.5"		H-2-71998s1
889			AN-106 06A							100	664.34				-10.67				
890									442	2,354									
891																			
892	AY-102	AP-102					83-86	400	0	3,066					1.24				
893			AY-102-02A							100	675.01	Per D153A 11-2001							
894			AY-102-02A	NEW AZ PIT	SN-633			400		843	675.01	Per D153A 11-2001	669.50	Per D153A 11-2001			2"		H-14-103263s3
895			NEW AZ PIT							205	669.50	Per D153A 11-2001							
896			NEW AZ PIT	INTERFACE	SN-634	W-314/W-211 INTERFACE		400		1,558	669.50	Per D153A 11-2001	674.00	Per D153A 11-2001		SN-634 also Interface>AP102 1558 conf w/J. Collins	2"		H-14-103263s3
897			INTERFACE	AP-102-02D	(SN-634)	SN-634 also AZ>Interface		400		145	674.00	Per D153A 11-2001	674.40	Per D153A 11-2001					
898			AP-102-02D			JUMPERS IN 02D = 60 FT				60	674.40	Elev. Change in Pit/Jumper	675.89	Per D153A 11-2001					
899			AP-102-02D	AP-102-02A	SN-622			400		55	675.89	Per D153A 11-2001	676.25	Per D153A 11-2001					
900			AP-102-02A							100	676.25								
901									0	3,066					1.24				
902																			
903	AY-102	WTP						400	0	6,133					50.43				
904			AY-102-02A							100	675.01	Per D153A 11-2001							
905			AY-102-02A	NEW AZ PIT	SN-633			400		843	675.01	Per D153A 11-2001	669.50	Per D153A 11-2001			2"		H-14-103263s3
906			NEW AZ PIT							205	669.50	Per D153A 11-2001							
907			NEW AZ PIT	INTERFACE	SN-637	W-314/W-211 INTERFACE		400		1,573	669.50	Per D153A 11-2001	674.00	Per D153A 11-2001		1573' SS conf/w Jim Collins FFS 12/5/01; was 1110' CS	2"		H-14-103263s1
908			INTERFACE	WTP Interface	(SN-637)	SN-637 also AZ>Interface		400		2,555	674.00	Per D153A 11-2001	662.44	Per D153A 11-2001		2555' Equivalent Length from Mark Przybylski, FFS			
909			WTP Interface							5,276	662.44	Per D153A 11-2001			-12.57				
910			WTP Interface	WTP (Vit Plant) internal equivalent pipe length and working height elevation						857	662.44	Per D153A 11-2001	725.44			Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
911			WTP Totals:						0	6,133	725.44				50.43	Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
912																			
913	AZ-101	WTP						400	0	5,444					56.90				
914			AZ-101 01A							100	668.54	Per D153A 11-2001							
915			AZ-101 01A	NEW AZ PIT	SN-632			400		154	668.54	Per D153A 11-2001	669.25	Per D153A 11-2001			1"		H-14-102695s1
916			NEW AZ PIT							205	669.25	Elev. Change in Pit/Jumper	669.50						
917			NEW AZ PIT	INTERFACE	SN-637	W-314/W-211 INTERFACE		400		1,573	669.50	Per D153A 11-2001	674.00	Per D153A 11-2001		1573' SS conf/w Jim Collins FFS 12/5/01; was 1110' CS	2"		H-14-103263 s3
918			INTERFACE	WTP Interface	(SN-637)	SN-637 also AZ>Interface		400		2,555	674.00	Per D153A 11-2001	662.44	Per D153A 11-2001		2555' Equivalent Length from Mark Przybylski, FFS			
919			WTP Interface							4,587	662.44	Per D153A 11-2001			-6.10				
920			WTP Interface	WTP (Vit Plant) internal equivalent pipe length and working height elevation						857	662.44	Per D153A 11-2001	725.44			Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
921			WTP Totals:							5,444	725.44				56.90	Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
922																			
923	AZ-102	WTP						400	0	5,674					54.94				
924			AZ-102 02A							100	670.50	Per D153A 11-2001							
925			AZ-102 02A	AZ-101 01A	SN-631			400		130	670.50	Per D153A 11-2001	668.54	Per D153A 11-2001			1"		H-14-102695 s2
926			AZ-101 01A							100	668.54	Per D153A 11-2001							

CASE 3S6D Transfer List - Tank-to-Tank

	Transfer		Via Routing															Encasement Drainage Piping Size		
	From Tank	To Tank	Start	End	Primary Pipe 3" Sch-40 Pipe (3.068" ID) Line ID #	Comment	Tank Farm Built (Yr)	Design Press (lbf/in²)	Carbon Steel Length (ft)	Stainless Steel Length (ft)	Elevation Start	Source Elevation	Elevation End	Source Elevation	Total Change in Elevation (ft)	Comments:	Low Point	High Point	Ref. Dwg.
927			AZ-101 01A	NEW AZ PIT	SN-632			400		154	668.54	Per D153A 11-2001	669.25	Per D153A 11-2001			1 "		H-14-102695 s1
928			NEW AZ PIT							205	669.25	Elev. Change in Pit/Jumper	669.50						
929			NEW AZ PIT	INTERFACE	SN-637	W-314/W-211 INTERFACE		400		1,573	669.50	Per D153A 11-2001	674.00	Per D153A 11-2001		1573' SS cont/w Jim Collins FFS 12/5/01; was 1110' CS	2 "		H-14-103263 s3
930			INTERFACE	WTP Interface	(SN-637)	SN-637 also AZ>Interface		400		2,555	674.00	Per D153A 11-2001	662.44	Per D153A 11-2001		2555' Equivalent Length from Mark Przybylski, FFS			
931			WTP Interface							4,817	662.44	Per D153A 11-2001			-8.06				
932			WTP Interface	WTP (Vit Plant) internal equivalent pipe length and working height elevation						857	662.44	Per D153A 11-2001	725.44			Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
933			WTP Totals:							5,674	725.44				54.94	Elev. 662.44' per D153A + 63' Internal WTP Elev per BNI			
934																			
935																			
936	WTP (Vit Plant) estimated internal equivalent pipe length and elevation from interface to receiving tank									857	662.44		725.44		63.00				

937 WTP estimated internal equivalent pipe lengt from CALC-W375PT-PR00199.

938 Note: W-314/W-211 INTERFACE - No Pit; No Jumpers! Lines: SN-634, (SN-634); SN-636, (SN-636); SN-637, (SN-637)

939

	Equivalent Length (HNF-2938)
	(ft)
Pump Pit	108
Valve Pit	205

940 **References**

941 HNF-2938, Evaluation of 241-AN Tank Farm Supporting Phase I Privatization Waste Feed Delivery, dated 1998.

942 BNFL CALC-W375PT-PR00199, Pressure Drop Calculation from DOE-BNFL Inc. Interface to HLW Receipt, dated January 6, 2000.

943 BNFL-5193-ID-20, Rev.4d.r6, Interface Control Document for High-Level Waste Feed, dated February 24, 2000.

944 Note: WTP elevation was +45' per BNFL now elevation estimate +63' per BHI.

945 **Elevation Reference Drawings**

	Farm	Dwg #s
946		
947	AN	H-2-71990, H-2-71998 s1. H-14-103263 s3, H-2-90551s1, H-14-102695s1, H-2-70411s2, H-2-90563
948	AP	H-2-90542 s1
949	AW	H-2-70402, H-2-7011s2, H-2-70411s2, H-2-71998s1. H-2-71990s1, H-2-90563s1, H-2-90551s1
950	AY	H-14-102650 s1-4, H-2-71990s1, H-2-71998s1, H-14-103263
951	AZ	H-14-102695 s1-2, H-14-103263 s1-4

952 **Elevation data based on 200E plant grid coordinates and vertical datum system**

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APPENDIX B-3

EQUIVALENT PIPELINE LENGTH AND ELEVATION CHANGE IN DOE FEED LINES FROM TFC TO THE DOE/WTP INTERFACE (PRELIMINARY)

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CALCULATION SHEET

PROJECT: RPP-WTP
JOB NO.: 24590
CALC NO.: 24590-PTF-M3C-FRP-00001
SHEET REV: A
SHEET NO.: 1

BY: John Richardson
DATE: Jan 23rd 2002

SUBJECT: Pressure Losses in DOE Feed Lines.

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1 Purpose 1
2 Scope 1
3 Methodology 1
4 Assumptions 2
5 Results 2
5.1 Calculation of Reynolds Number 2
5.2 Calculation of Equivalent Line Length 3
6 Conclusions 3
7 References 3
8 Attachments 4

1 Purpose

The purpose of these calculations is to provide CHG with "equivalent line length" and static head data from the DOE/WTP interface to the Feed Receipt Tanks within the Pretreatment Facility. CHG will use this data, and complete the transfer line calculations for the entire system from the Tank Farms to the (worst case) Feed Receipt Tank.

2 Scope

For all feeds, CHG's document Ref. RPP5346 identifies pressure losses in the feed lines from the TFC to the DOE/WTP interface.
Provisional results of these calculations were presented to CHG in ICD Team meeting Ref CCN 024712. During the ICD review, John Richardson, BNI Mechanical Systems, provided information that the equivalent line length from the interface point to the BNI receipt tanks will be 857 feet, and the lift height to the tanks will be 63 feet. Issue of this calculation closes out Action Item 4.3 assigned to Bek Posta in ICD Team Meeting Refs CCN 024712 dated 11/14/01, and CCN 024713 dated 11/16/01.

3 Methodology

The simple calculations were produced using empirical data, formulae, and charts within the Crane Technical Paper No. 410 "FLOW OF FLUIDS THROUGH VALVES, FITTINGS, AND PIPE".
Specific references to Crane are provided.

CALCULATION SHEET

PROJECT: RPP-WTP
JDB NO.: 24590
CALC NO.: 24590-PTF-M3C-FRP-00001
SHEET REV: A
SHEET NO.: 2

BY: John Richardson
DATE: Jan 23rd 2002

SUBJECT: Pressure Losses in DOE Feed Lines.

4 Assumptions

- Clean commercial steel pipe is used.
- No contingency is provided, all the values are net, and no allowances are made for future additional in-line components, e.g. strainers / filters etc.
- All pulled bends are 4 x the pipe diameter. Based on the current plant layout, the total number of bends is assumed to be 12.
- Based on current P&ID, number of valves assumed to be 2 between the DOE / WTP Interface and the Feed Receipt vessel. Valves assumed to be 3" Plug Valves.

5 Results

5.1 Calculation of Reynolds Number

Case	Pipe N.S. (in)	ID (in)	ID (ft)	Flowrate (gpm)	Flowrate (ft^3/sec)	Velocity (ft/sec)	Viscosity (cP)	Density (g/ml)	Density (lb/ft^3)	Reynolds $N^{o.}$
A	3	3.068 [Ref 1]	0.256	140 [Ref 2]	0.312	6.076	94 [Ref 3]	1.5 [Ref 4]	93.642	2,306
B	3	3.068 [Ref 1]	0.256	160 [Ref 5]	0.356	6.944	50 [Ref 6]	1.5 [Ref 4]	93.642	4,954

References

1 Crane Page B-16 (Sch 40 Pipe Sizes)
2 HLW Waste Feed ICD Doc Number 24590-WTP-ICD-MG-01-020 Table 2 (Lower Range Flowrate)
3 HLW Waste Feed ICD Doc Number 24590-WTP-ICD-MG-01-020 Table 2 (Higher Range Viscosity quoted as <94)
4 HLW Waste Feed ICD Doc Number 24590-WTP-ICD-MG-01-020 Table 2 (Density quoted as <1.5)
5 HLW Waste Feed ICD Doc Number 24590-WTP-ICD-MG-01-020 Table 2 (Higher Range Flowrate)
6 HLW Waste Feed ICD Doc Number 24590-WTP-ICD-MG-01-020 Table 2 (Lower Range Viscosity quoted as <50)

$$R_e = \frac{Dv\rho}{\mu_e} \text{ ..... Crane Eq. 3-3}$$

where:
R_e = Reynolds Number
D = Pipe I.D. (ft)
v = Velocity (ft/sec)
ρ = Density (lb/ft^3)
μ_e = Absolute Viscosity (lb/ft.sec). 1cP = .000672 lb/ft.sec

$$R_e = \frac{Dv\rho}{\mu_e} = \frac{0.256 \times 6.076 \times 93.642}{94 \times 0.000672} = 2{,}306 \text{ (Case A)}$$

$$R_e = \frac{Dv\rho}{\mu_e} = \frac{0.256 \times 6.944 \times 93.642}{50 \times 0.000672} = 4{,}954 \text{ (Case B)}$$

Gives R_e range between 2,306 to 4,954 for cases A and B, i.e. Turbulent flow in both cases.

CALCULATION SHEET

PROJECT: RPP-WTP
JOB NO.: 24590
CALC NO.: 24590-PTF-M3C-FRP-00001
SHEET REV: A
SHEET NO.: 3

BY: John Richardson
DATE: Jan 23rd 2002

SUBJECT: Pressure Losses in DOE Feed Lines.

5.2 Calculation of Equivalent Line Length

These calculations are for lines from DOE/WTP Interface to "Worst Case" Feed Receipt Vessel (P.I. No FRP-VSL-00002D).

Total length of 3" Sch. 40 piping = 361 + 100 + 162 + 18 + 75 + 15 + 38 + 25 = **794 ft** (Ref sketch on Sheet No. 4)

a) Equivalent length for 90°, 4xD bends, 12 in total (Ref sketch on Sheet No. 4)
r/d = 4
K_b = 0.32 (Ref Crane Fig. 2-16 attachment 1 of 3)
Gives L = 4.5 ft (Ref Crane Page A-30 attachment 2 of 3)

∴ Total equivalent length = 4.5 x 12 = **54 ft**

b) Equivalent length for 3" Sch. 40 Plug Valve, 2 in total (Ref sketch on Sheet No. 4)
Equivalent length pipe diameters = 18 (Ref Crane Page A-29 attachment 3 of 3)
Gives L = 4.5 ft (Ref Crane Page A-30 attachment 2 of 3)

∴ Total equivalent length = 4.5 x 2 = **9 ft**

∴ **Total equivalent length = 794 + 54 + 9 = 857 ft**

Total Lift Height (Static Head) = 25 + 38 = 63 ft

6 Conclusions

These calculations indicate turbulent flow can be expected under all conceivable conditions. Results show an equivalent piping length of 857ft from the DOE / WTP Interface to the "worst case" Feed Receipt Tank, i.e. P.I. No FRP-VSL-00002D, and a total lift height of 63ft.
Issue of this calculation closes out Action Item 4.3 assigned to Bek Posta in ICD Team Meeting Refs CCN 024712 dated 11/14/01, and CCN 024713 dated 11/16/01.

7 References

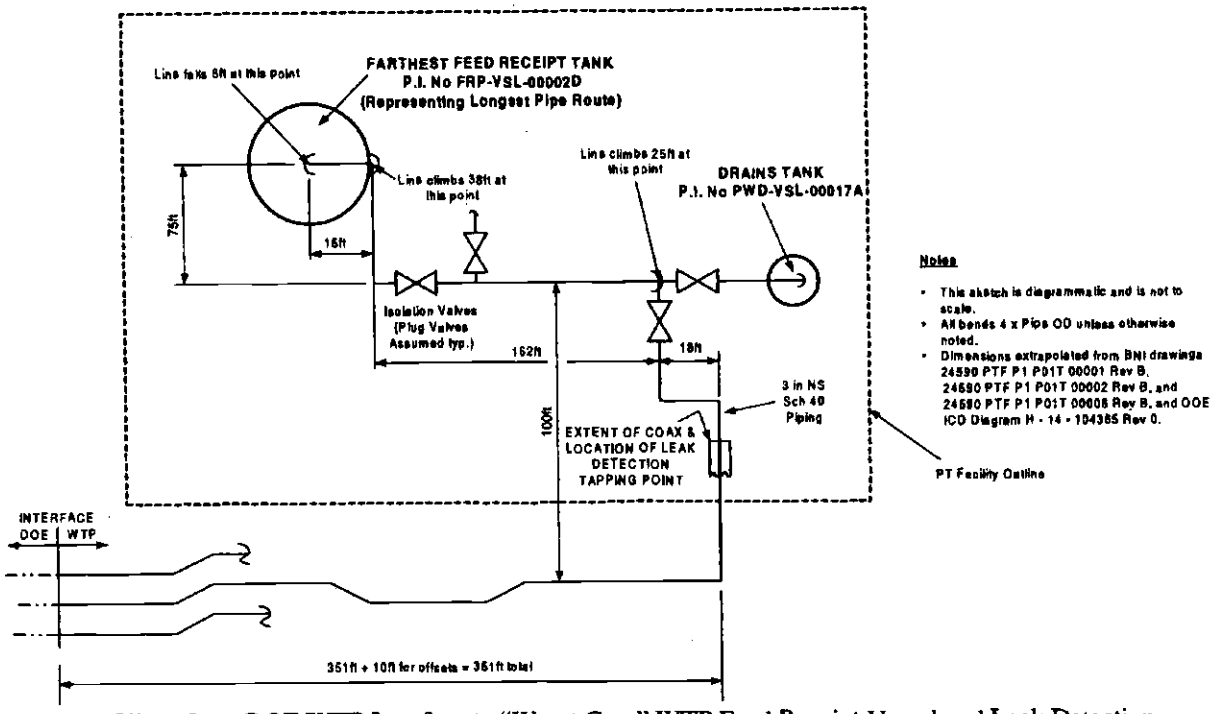
RPP-5346 Rev 1: Waste Feed Delivery Transfer System Analysis.
ICD Team Meeting Ref CCN 024712 dated 11/14/01.
ICD Team Meeting Ref CCN 024713 dated 11/16/01.
24590 PTF P1 P01T 00001 Rev B: PT Facility General Arr^{gt} Plan at 0' 0"
24590 PTF P1 P01T 00002 Rev B: PT Facility General Arr^{gt} Plan at 28' 0"
24590 PTF P1 P01T 00006 Rev B: PT Facility General Arr^{gt} Plan at -36' 0"
DOE ICD Diagram H - 14 - 104365 Rev 0
HLW Waste Feed ICD Doc Number 24590-WTP-ICD-MG-01-020 Rev B.
Crane Technical Paper No. 410 "FLOW OF FLUIDS THROUGH VALVES, FITTINGS, AND PIPE".

CALCULATION SHEET

PROJECT: RPP-WTP
JOB NO.: 24590
CALC NO.: 24590-PTF-M3C-FRP-00001
SHEET REV: A
SHEET NO.: 4

BY: John Richardson
DATE: Jan 23rd 2002

SUBJECT: Pressure Losses in DOE Feed Lines.



Sketch of lines from DOE/WTP Interface to "Worst Case" WTP Feed Receipt Vessel and Leak Detection Take-off Point

8 Attachments

1. Crane "Flow of Fluids", Fig 2-16
2. Crane "Flow of Fluids", Page A-30
3. Crane "Flow of Fluids", Page A-29

APPENDIX C

SURFACE ROUGHNESS OF CARBON STEEL AND STAINLESS STEEL WASTE TRANSFER LINES CAUSED BY CORROSION AND SCALING

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APPENDIX C

SURFACE ROUGHNESS OF CARBON STEEL AND STAINLESS STEEL WASTE TRANSFER LINES CAUSED BY CORROSION AND SCALING

November 5, 1999

Prepared By:

R. P. Anantatmula
And
J. R. Divine

LOCKHEED MARTIN HANFORD CORPORATION
for the
U.S. Department of Energy
Richland Operations Office

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SURFACE ROUGHNESS OF CARBON STEEL AND STAINLESS STEEL WASTE TRANSFER LINES CAUSED BY CORROSION AND SCALING

C1.0 INTRODUCTION

The waste transfer system in the 200 East Area of the Hanford Site operated by Lockheed Martin Hanford Corporation (LMHC) has several pipelines of carbon steel and stainless steel. The two materials are mixed in some pipelines while other lines are of one material only. The waste transfer system contains 1000 ft of 3 in. carbon steel pipe and 6000 ft of 3 in. stainless steel pipe believed to be AISI Type 304 or 304L. Much of the line has been used for up to fifteen years and plans are to use it for an additional 35 years. Both radioactive waste and "raw" water, essentially untreated Columbia River water, will be passed through the lines which will then be drained before being used again. Because pump requirements depend strongly on the pipe roughness, LMHC has requested information on changes in roughness due to corrosion and scaling. Surface roughness estimates were requested over a time period of 50 years for carbon steel and over a period of 40 years for stainless steel. This report discusses the contributions to surface roughness from corrosion and scaling.

C2.0 BACKGROUND

The waste transfer lines from Tank Farms to British Nuclear Fuel Limited, Inc. (BNFL) will be used more than three times annually, while the intertank pipelines will be used on an average once per year. The transfer piping is sloped in such a way that at the end of the waste transfer the waste water will drain into the tank in which the transfer is made with no possibility of stagnant water remaining in the pipe. Each waste transfer campaign is expected to last a total of ten days. The raw water will be heated in skid-mounted "boilers" and hot water will be used when it is deemed necessary. Corrosion inhibitors will be added to the water prior to its being pumped into the transfer lines. No heating, other than perhaps trace-heating to maintain the temperature, will be done on the line. There are two types of wastes that will be processed through the system: a high level waste (HLW) feed at 80°C containing 5 vol% solids and a low activity waste (LAW) feed at 45°C containing 2 vol% solids. The pH of the waste solutions is expected to be > 7. The waste solutions are generally expected to be $\geq$1M $NaNO_2$, $\geq$3M $NaNO_3$ and $\geq$3M NaOH. Between waste transfers, however, flush water containing raw water (Columbia River water) inhibited with 0.01M NaOH and 0.011M $NaNO_2$ will be used to flush the transfer lines after each transfer.

C3.0 CORROSION

C3.1 CORROSION BEHAVIOR OF CARBON AND STAINLESS STEELS

At the compositions quoted above, the waste solutions are benign toward carbon steel from a corrosion perspective (Anantatmula et al. 1994). Corrosion of stainless steel is expected to be negligible at the high pH and low temperature of the waste solutions containing low amounts of chloride. The inhibited flush water will not be aggressive toward carbon steel resulting in negligible corrosion. Raw water is usually corrosive to carbon steel unless it is inhibited or there is significant amounts of calcium and magnesium salts in the water that will form a protective scale. The Columbia River water, based on 1991 and 1994 analyses and the analysis in the scaling section of this report, has a Langelier index value of < 0 and Ryznar index value of > 6. Waters with Langelier index value of < 0 and Ryznar index value of > 6 tend not to form scales and be corrosive to steel (a discussion of Langelier and Ryznar indices is given in section 4.2). However, the addition of inhibitors to the raw water is expected to make the flush water benign towards steel. Therefore, only the carbon steel pipeline carrying the raw water to the inhibitor feed point will be subjected to a high general corrosion rate of ~ 4 mils per year (0.1 mm/y) [1mil = 0.001 in.] (Truitt and Wagner 1985). Stainless steel corrodes at a low general corrosion rate of < 0.1 mil per year (0.0025 mm/y) when exposed to fresh water at normal temperatures. The presence of inhibitors in the water is not expected to have any deleterious effects on the stainless steel, because the material has excellent resistance to general corrosion in solutions containing hydroxide, nitrate and nitrite. The chloride content and temperature of the raw water and waste solution is low enough to preclude pitting and stress corrosion cracking (SCC) of stainless steel pipe and preserve its integrity.

Corrosion of materials in aqueous systems is influenced by the following factors:

- Physical configuration of the system
- Water chemistry
- Presence of solids in the water
- Flow rate
- Temperature and
- Presence of microbes.

For the present surface roughness assessment, contribution to corrosion by microbes will be ignored since microbial corrosion primarily involves pitting corrosion. Depending on their abrasiveness, the presence of solids in the water is generally presumed to have a profound effect on corrosion if flow rates are high. However, studies performed by Pacific Northwest Laboratory (Smith and Elmore 1992) on simulated aging wastes at up to 15 ft/sec fluid velocity indicated that the corrosion products were not removed from the carbon steel surface in spite of an increase in corrosion rate. The increase in corrosion rate was attributed to the ease with which fresh reactants were brought to the corroded surface by flowing waste as a result of a thinner boundary layer.

C3.2 SURFACE ROUGHNESS ESTIMATES - CORROSION

C3.2.1 Carbon Steel

The millscale (produced during hot rolling and forging) on carbon steel consists of three superimposed layers of iron oxides, viz., ferrous oxide (FeO) on the inside, magnetite (Fe_3O_4) in the middle, and ferric oxide (Fe_2O_3) on the outside. The relative portions of the three oxides vary with rolling temperature. A typical millscale on 9.5 mm plate would be about 50 µm thick and contains approximately 70% FeO, 20% Fe_3O_4, and 10% Fe_2O_3. Therefore, the surface roughness of as-received carbon steel pipe is ~ 2 mils (0.05 mm).

The contribution to transfer pipe surface roughness from corrosion is primarily from general corrosion mechanism, although from structural integrity standpoint pitting and SCC are very important mechanisms. Because higher corrosion rates will be experienced by the least used carbon steel transfer lines, to retain conservatism, it will be assumed that the waste transfer system will be used on an average once per year. Furthermore, each campaign is expected to last ten days. Because the waste solutions are compliant with double-shell tank waste specifications and the flush water is inhibited, with the exception of the short length of carbon steel pipeline carrying raw water, the general corrosion of carbon steel pipelines will be minimal. The corrosion contribution to surface roughness primarily occurs during the long waiting periods between the waste transfers. Immediately after the waste transfer, the flush water is drained into the receiving tank. The presence of any stagnant water in the pipe is detrimental to carbon steel because the inhibition characteristics of the water will be lost by a reaction of carbon dioxide in the air in the pipe with the hydroxide in the water. This could lead to pitting of carbon steel in near neutral pHs and if the water contains small amounts of chloride, pitting of the stainless steel is possible. Moreover, raw water may contain sufficient sulfate reducing bacteria to cause microbiologically influenced corrosion (MIC) in the stainless steel line. Savannah River Site and others have had MIC penetrate a pipe from the inside in a matter of weeks.

Assuming the water drains into the receiving tank, a moist film of inhibited water will be left on the pipe surface. Some of the inhibition characteristics of the film will quickly be lost by a reaction of carbon dioxide in the air in the pipe with the hydroxide in the film. The effectiveness of the residual nitrite in the film as an inhibitor, however, is unknown. Because the pipe is open to the receiving tank, the interior of the pipe will be exposed to humid air conditions with a high relative humidity (RH).

Surface roughness of carbon steel under the humid air conditions described above can be estimated from the humid air corrosion models developed for carbon steel in the literature (Lee et al. 1996). The model, as modified by Anantatmula and Ohl (1996) was used for the estimates. The penetration by general corrosion is expressed as a function of time, RH and temperature as follows:

$$\ln D_g = a_0 + a_1 \ln (t) + a_2/RH + a_3/T$$

where D_g is corrosion depth in μm, t is time in years, T is temperature in °K, and a_0, a_1, a_2 and a_3 are constants with the following values:

$a_0 = 16.9865$
$a_1 = 0.6113$
$a_2 = -893.76$ and
$a_3 = -833.53$

The depth of penetration was calculated for times up to 50 years assuming 98% RH. An average temperature of 35°C was assumed although the temperature of waste solutions is expected to be in the range 45°-80°C. This is because the total waste transfer operation lasts for ten days and the pipe temperature is expected to drop to ambient temperature well before the next waste transfer.

Based on the above assumptions, the depth of penetration was calculated for carbon steel as a function of time from the model equation above. Depending on the availability of oxygen, the corrosion product on the inside surface of the carbon steel transfer lines could be either Fe_3O_4 or Fe_2O_3. Regardless of which oxide is assumed to be formed, the corrosion product thickness will be approximately twice that of the thickness of the metal lost. Using this information, conservative surface roughness estimates were made for the carbon steel pipe and are listed as a function of time in Table 1.

Table 1. Surface Roughness as a Function of Time for Carbon Steel.

Time (years)	Surface Roughness (mils)
15	70
20	85
25	100
30	110
35	120
40	130
45	140
50	150

The surface roughness values in the above table should be considered conservative because the tanks are ventilated resulting possibly in < 98% RH in the transfer pipes. In addition, at the present time, it is not known just how long the moist nitrite film will protect the carbon steel after each waste transfer. For the present calculations, it has been assumed that the nitrite film will not offer any protection. Based on a limited number of visual examinations, the roughness may be much less than estimated in Table 1.

C3.2.2 Stainless Steel

Unlike carbon steel, negligible amount of millscale is expected on as-received stainless steel pipe since the surface is normally protected by a chromium oxide film. Based on the foregoing, stainless steel corrodes at a low general corrosion rate of < 0.1 mpy (0.003 mm/y) when exposed to fresh water at normal temperatures including temperatures above 100°C. Assuming a maximum general corrosion rate of 0.1 mpy (0.003 mm/y), a surface roughness value of 8 mils (0.203 mm) is estimated for a 40-yr time period. Including the thickness of the millscale on the as-received pipe, a maximum surface roughness value of 10 mils (0.254 mm) is predicted for the stainless steel line through 40 years of waste transfer operations.

C4.0 SCALING

C4.1 SCALING PROCESSES

Scaling is the deposition of soluble products from the liquid. When a chemical species exceeds its solubility limit, it has a tendency to precipitate. This tendency is increased by the amount the solubility is exceeded and by the presence of deposition nuclei. Other factors will include temperature and liquid shear forces (Becker 1998; Lane 1993).

If the precipitation occurs in the bulk liquid and forms a slurry, then deposits will be loose and easily removed unless they agglomerate while on the surface. On the other hand, if the deposition nucleus is on the surface, then the deposit will occur there and be more firmly attached.

- Waste Composition

As mentioned earlier, the waste composition is very benign from a corrosion standpoint. It is known that if the temperature of the waste stream is too low, some waste components will precipitate. In discussions with Mr D. A. Reynolds, LMHC, it was determined that flushing with hot water will remove such precipitates.

- Water Composition

The composition of the river water varies with the season and exact location of the sampling as well as uses of the river and surrounding lands change. Table 2 shows a composition measured in 1994.

Table 2. Columbia River Water Composition.

Component	Concentration
Calcium, as $CaCO_3$	47.50 ppm (mg/l)
Magnesium, as equivalent $CaCO_3$	18.50
Bicarbonate, as equivalent $CaCO_3$	67.6
Chloride	1.00
Nitrate	<1.00
Sulfate	9.00
Silica, as SiO_2	6.20
Total Dissolved Solids, TDS	71.1
Methyl Orange alkalinity, as $CaCO_3$	55.4
pH	7.90

Laboratory Analysis 94-08393, ID 260170072, Collected 05/15/94, 200E Raw Water. Analyzed by WR Grace & Co., Lake Zurich, IL 60047.

- Solubility Effects

The solubility of most compounds increases with increasing temperature. $CaSO_4$ solubility, however, increases to about 40°C and then decreases with increasing temperature (Latimer and Hildebrand 1951); the solubility is about the same at both 25 and 60°C. Above about 63.5°C, the solubility decreases rapidly. At 25°C, the solubilities of $CaSO_4$ and $CaCO_3$ are given in Table 3. The solubility product of $Fe(OH)_3$ is also listed.

Table 3. Solubility Products.

Compound	Solubility Product[1]
$CaSO_4$	4.93×10^{-5}
$CaCO_3$	2.8×10^{-9}
$Fe(OH)_3$	2.79×10^{-39}

[1]Dean 1999

The solubility of Ca^{+2}, given in Table 2 is expressed in terms of $CaCO_3$. Expressing it as Ca^{+2}, the concentration is about 19 mg/l or 4.8×10^{-7} mol/l. Sulfate, $SO_4^{=}$, is 9 mg/l or about 9.4×10^{-8} mol/l. Thus the product of the calcium and sulfate concentrations is 4.5×10^{-14} which is much less than the solubility product for $CaSO_4$ given in Table 3. Consequently no $CaSO_4$ is expected to precipitate from the Hanford Raw Water.

In a similar calculation, $Fe(OH)_3$ is expected to be effectively totally insoluble. With a pH of 7.9, the OH^- concentration will be about 8×10^{-7} mol/l. As a result, the concentration of Fe^{+3} will not exceed about 5×10^{-21} mol/l which, effectively, is zero. Thus the iron that corrodes

will react with excess oxygen and precipitate in the immediate location of the corrosion site and form scale.

C4.2 DISCUSSION OF SCALING

Based on information from the various sources, it is not believed that scaling from the waste will be a problem because it is feasible to re-dissolve the material with hot water.

Langelier developed an empirical relationship to predict the potential for scaling. It considers carbonate solubility, pH, conductivity, and temperature. It is a crude estimate because other factors such as other salts are ignored. Ryznar modified the relationship for use in flowing streams. There are also modifications for use when the total dissolved salts exceed about 7,000 ppm.

These empirical relationships are called the Langelier Index and the Ryznar Index and provide very crude estimates. When using them it is best to err on the conservative side so that only if the prediction is strongly in favor of scaling should it be assumed to occur. Calculating the Langelier (stagnant or low flow rate water) and the Ryznar (flowing water) Indices (Kemmer 1998) for the raw water, the following were obtained, Table 4.

Table 4. Scaling Indices.

Temperature	Langelier	Ryznar
10°C	-.7	9.3
50°C	0.12	8.4
90°C	0.7	7.4

If the Langelier Index is negative, the water is considered non-scaling and corrosive. If the Ryznar Index is >6.0, the water is considered non-scaling and corrosive.

Because the water and the pipe will be hot only when the water is flowing, the conclusion is that the water will be somewhat corrosive (towards carbon steel) and non-scaling.

Consequently, most of the scaling due to carbonates would be expected to occur in the "boiler".

C5.0 CONCLUSIONS AND RECOMMENDATIONS

The surface roughness from corrosion for carbon steel is conservatively estimated as 150 mils for 50 years of waste transfer operations, while the corresponding value for stainless steel is expected to be a maximum of 10 mils. Scaling due to deposition from fluids in the pipe will not be a serious concern in the piping.

Based on the above estimates, the majority of the pressure drop will occur as a result of flow through the carbon steel part of the transfer pipeline. In order to check the validity of the estimates for carbon steel, it is recommended to inspect the inside surfaces of the carbon steel pipes that have been in operation for a known time period. Air drying of the pipes between waste transfers is recommended to reduce the surface roughness of the carbon steel pipes. The short section of carbon steel pipe carrying the raw water should also be checked periodically for its integrity. It is recommended to not let stagnant water remain in the transfer pipes, especially the stainless steel lines. Finally, if pressure drop must be minimized by minimizing the surface roughness of the transfer pipes, it is recommended to replace the carbon steel portion of the transfer line with stainless steel.

C6.0 REFERENCES

Anantatmula, R. P., M. J. Danielson and E. B. Schwenk, 1994, *Characterization of the Corrosion Behavior of the Carbon Steel Liner in Hanford Site Single-Shell Tanks*, WHC-EP-0772, Rev. 0, Westinghouse Hanford Company, Richland, Washington.

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ATTACHMENT C-1

SUMMARY OF SEARCH FOR TRANSFER LINE SOLIDS BUILDUP/SCALING INFORMATION

OCTOBER 1999

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Summary of Search for Transfer Line Solids Buildup/Scaling Information, October 1999

Because of the long length of the transfer route, the pipe internal roughness is a major factor in determining the pump and piping design. For new lines, a significant increase in surface roughness with time in operation will significantly increase the pressure drop and must be accounted for in the design specification. Since there is no readily available information about the change in pipe roughness with time for a caustic waste transfer line, a brief and focused effort was made to find such information. The change in pipe roughness due to corrosion is investigated in a separate report.

Several sources of information were investigated and the results are included in the attached pages.

- Expert opinion and experience were collected from personnel at Hanford, Savannah River, and Idaho Falls.
- Hanford transfer line failure studies were reviewed
- Savannah River transfer line failure studies were discussed
- Hanford internal video inspections of transfer lines (no videos made available)

No quantitative information was found. However, there was also no event reported of chronic scale buildup.

To continue this effort to provide quantitative information, the following are recommended:

1. Review video inspections of Hanford transfer lines for evidence of adherent solids.
2. Evaluate two-phase transport of food products (sugars, salts, etc.) and problems/solutions to transport mechanisms.
3. Evaluate crystal formation, crystal size, adherence and solubility of waste salts.
4. Evaluate chemical production in high percent solids liquors and resultant production concerns (i.e., electro-chemical chlorine production in ½ NaCl, ½ NaOH solution).
5. Evaluate pipe linings and resistance to abrasion (in high percent solids), temperature, and thermal cycling and solids adherence after prolonged periods of non-use.
6. Evaluate available pipe interior finishes for weldments and general piping including mechanical and acid etching as a means to reduce solids adherence.
7. Evaluate stainless steel 300 series as the piping material of choice providing definitive data on its performance to: a) chloride attack in neutral or low pH solutions, b) scaling/solids build-up as related to increase in flow resistance, and c) solids build-up after long periods of non-use and dissolution of solids in water rinses.

HANFORD TRANSFER LINE PIPE ROUGHNESS AND SCALING ADHERENCE PROPERTIES AFFECTING PUMPING EQUIPMENT AND LINE SELECTION

CONTACTS LISTING (October 1999):

David Lini, SAIC 509/373-9102

Darrel Duncan, NHC 509/372-1013

Jim Divine, ChemMet Ltd 509/967-2309

Richard W. Johnson, INEEL 208/526-0955

Richard Rice, INEEL 208/526-1992

R. P. (Mo) Anantatmula, LMHC 509/373-0785

Bruce Wiersma, SRS 803/725-5439

Earl Schwenk, COGEMA Engineering 509/943-4438

Charles Jenkins, SRS 803/725-1699

Daniel Reynolds, LMHC 509/373-3115

John Keve, COGEMA Engineering 509/376-8061

Wesley Nelson, COGEMA Engineering 509/376-5403

Fred Reich, COGEMA Engineering 509/371-8046

Scott Werry, LMHC 509/373-1831

Jim Field, LMHC 509/376-3753

Jeff Doeler, LMHC 509/373-6024

Jim Douglas, COGEMA Engineering 509/372-0989

Bill Morris, LMHC 509/372-3724

HANFORD TRANSFER LINE PIPE ROUGHNESS AND SCALING ADHERENCE PROPERTIES AFFECTING PUMPING EQUIPMENT AND LINE SELECTION

TELEPHONE CONFERENCE WITH:

Charles Jenkins, SRS 803/725-1699

Finally got through to Chuck on October 13, 1999 to discuss Savannah River's transfer line scaling, related to roughness and line type. Chuck indicated that cross-site or inter-area transfer lines are 304L stainless steel. A few intra-tank farm transfer lines are carbon steel. Stainless steel, by its nature, will not allow scaling buildup at the temperatures waste will be transferred under. If the temperature were 800° C, where oxidation could occur, scaling would be a significant problem.

Three stainless steel transfer lines have failed over the years, while no carbon steel lines have failed. The first SST line failure was due to chloride stress corrosion cracking. The transfer line was hydro-tested and the water was drained but the line was never dried, as called for in procedures. The pipe passed testing and set unused for years. The line was poorly sloped and was near the surface in 60 to 70 °F soil. Retesting of the line prior to use showed the line had failed. The results of the inspection indicated chloride stress corrosion cracking caused the transfer pipe failure. The second incident of stainless steel transfer pipe failure was a result of a steam leak. A steam line leak had occurred near a transfer pipe and heated the surrounding soil for some time. The heating and evaporation of water from within and outside the transfer line caused failure. The failure was most probably due to continued chloride attack over several months and the resultant stress corrosion cracking. (This failure is most likely the same as reported in the Wiersma write-up.) The third failure of a stainless steel transfer line was caused by thermal fatigue from continued pipe expansion and subsequent contraction. Waste transfers at SRS are conducted using a steam-lift principle. Steam is injected into the waste and the resultant vacuum lifts the liquid waste. Therefore, steam becomes part of the liquid waste stream. The continued expansion and contraction of transfer piping lead to the thermal failure. The cause of this failure, transfer lines too rigidly attached, has since been corrected at SRS.

Chuck also provided some general information: (1) inspected transfer lines at SRS have appeared clean and clear of build-up, (2) SRS always flushes lines after transfers with several volumes of water, (3) SRS would never consider installation of anything other than a stainless steel for a waste transfer line, (4) certain pipe lines that will see high levels of chloride will be fabricated from Hastelloy C or other high Ni alloys, (5) no scaling on stainless steel lines has been observed and (6) for caustic waste transfers use a 300 series, 304L, stainless steel pipe.

HANFORD TRANSFER LINE PIPE ROUGHNESS AND SCALING ADHERENCE PROPERTIES AFFECTING PUMPING EQUIPMENT AND LINE SELECTION

TELEPHONE CONFERENCE WITH:

Bruce Wiersma, SRS 803/725-5439

Finally got with Bruce on October 12, 1999 to discuss any knowledge he has on waste transfer line scaling buildup as it relates to pipe roughness and adherence properties. Bruce indicated he is aware of only two instances of transfer pipe plugging or failure at SRS. The first instance concerned the plugging of a stainless steel gravity drain line from the evaporator. (Bruce noted that waste transfer lines at SRS are stainless steel.) An inspection using an in-line viewing camera was conducted of the plugged line and concluded the evaporator clean out liquor was drained into the line where it cooled rapidly and crystallized, plugging the line. The internal surfaces of the pipe did not show any damage and in fact appeared quite smooth and clean.

The second waste transfer pipe mishap occurred when a steam line broke and caused a thermal failure in the pipe. An adjacent steam line that heated the stainless steel waste transfer line failed. The steam line heated the ground around the pipe and caused evaporation of the water flush in the transfer pipe. The high chloride attacked the piping welds causing stress corrosion cracking and failure of the pipe. The waste transfer pipe was made of 304L stainless steel. A write-up of the pipe failure and inspection is contained in the SRS internal report WSRC-TR-960356.

HANFORD TRANSFER LINE PIPE ROUGHNESS AND SCALING ADHERENCE PROPERTIES AFFECTING PUMPING EQUIPMENT AND LINE SELECTION

TELEPHONE CONFERENCE WITH:

Scott Werry, LMHC, Richland, WA 509/373-1831

I had called Dave Smet to inquire about videos of waste transfer lines. Dave indicated that I should speak with Scott Werry concerning any video work. I finally spoke with Scott on October 12, 1999 about any videos he may have of tank transfer line inspections or in-line inspections. Scott indicated his database consists of tank and pit inspections and does not contain any transfer line inspections. We spoke of the SL-119 work and he again indicated that video work is not in his database. He indicated that if any NDE inspection equipment was put in transfer lines it would have to pass the flammable gas controls and the line would have to be purged, which would go through Scott. Also the Flammable Gas Board would review and approve the work and most probably a USQ would have been conducted. Scott recalls no such actions ever being conducted. Scott indicated that several years ago, under Westinghouse, he was in the process of assembling the entire video library of tank farm work. After the site contract change, that effort was split and now no central group possess all the videos or even knows of their whereabouts. Scott suggested I call Mike Sumsion (376-4643) for additional 200 East Area videos and Joe Gonzalez (373-3056) for 200 West Area videos.

Scott called back and indicated there was a document that had "TEEM" in the title by EJ Walter that was done in the early 1990s that may be of some help. (The document was WHC-SD-WM-TEEM-001, *Pressure Testing of Underground Transfer Piping for Single-Shell Tank Salt Well.*) He also indicated that another document, HNF-SD-WM-ER-623, Rev 0 may have some data in a table at the end of the document. Scott again called and said I might also call Dan Pfluger (376-6164) as a source for additional information.

HANFORD TRANSFER LINE PIPE ROUGHNESS AND SCALING ADHERENCE PROPERTIES AFFECTING PUMPING EQUIPMENT AND LINE SELECTION

TELEPHONE CONFERENCE WITH:

Earl Schwenk, COGEMA Engineering, Richland, WA 943-4438

Talked with Earl on October 12,1999 and he indicated that he had conducted a failure analysis of a stainless steel transfer line about 20 years ago and the line was smooth other than the pitting. The analysis did not involve evaluation of pipe scaling, pipe roughness and associated adherence or pipe plugging but was a corrosion assessment. Earl provided an assessment of conditions that needed to be met, both materials and conditions, to assure successful transfer in waste piping. He first pointed out that stainless steel should be the pipe material of choice. Stainless steel will show very little general corrosion attack over time and therefore should provide no surface anomalies for scaling or solids build-up. No carbon steel should be used as it will pit and corrode too badly. A 300 series (304L or 316) stainless steel may not be the best choice of stainless if high chloride and neutral pH conditions may occur. A stainless steel that is higher in Ni or Cr may be needed to combat these conditions. The pH must be maintained well above 8.0. Even pH in the neutral range (6.0 -7.0) can cause chloride stress corrosion cracking and pitting, degradation of welds, and pipe failure. Suspended solids at 30 wt% will require turbulent flow for transfer. If waste streams with this amount of solids are transferred in laminar flow the solids will undoubtedly settle out or collect. Special piping, such Teflon-lined, would undoubtedly suffer from abrasion with the solids and Earl has no quantitative date on how such lined piping would hold up in this condition. It was agreed that a smooth surface of the piping would be essential for transfer of the tank wastes. Earl indicated Jim Divine would know much more concerning tank waste transfer line attack by chloride and corrosion cracking in neutral pH conditions and I should contact Jim for more on that subject. Earl also suggested I contact previous Grout Project engineers to ascertain what wt% solids and what specific conditions of the waste or equipment bounded grout waste transfers. Earl indicated I should also contact other industries to obtain two-phase material transfer data.

HANFORD TRANSFER LINE PIPE ROUGHNESS AND SCALING ADHERENCE PROPERTIES AFFECTING PUMPING EQUIPMENT AND LINE SELECTION

TELEPHONE CONFERENCE WITH:

Richard W. Johnson, INEEL 208/526-0955

A phone conversation was held with Richard on October 6, 1999 to discuss pipe roughness and adherence properties that may be in the *Handbook Of Fluid Dynamics* he had recently edited. (Richard's name was given to me by Jim Divine, ChemMet LTD, as a possible contact that may have information on caustic waste transport issues.) Richard indicated no such material is contained in the edition and he has no knowledge or working experience with caustic waste transport, pipe roughness or piping adherence properties. Richard did indicate that I might check with Dick Rice, INEEL, (208/526-1992) who has worked in the field of two-phase transport and may have some information that may be of help to me.

HANFORD TRANSFER LINE PIPE ROUGHNESS AND SCALING ADHERENCE PROPERTIES AFFECTING PUMPING EQUIPMENT AND LINE SELECTION

TELEPHONE CONFERENCE WITH:

Fred Reich, COGEMA Engineering, Richland, WA 509/371-8046

I talked with Fred on October 12, 1999 about any past experience he may have had with NDE testing of waste transfer lines and results he obtained concerning detection of corrosion, scaling products, etc. Fred indicated his only experience has been in the petrol-chemical field detecting corrosion in iron piping. A pipe crawler using pulse-echo ultrasonics was used in petroleum cross-site transfer lines to detect pitting and general corrosion. No work was ever done for the detection of corrosion products or scaling buildup. In petroleum lines "sour crude" contained sulfur that would react with the iron creating corrosion. The crawler was designed to operate in 18-inch, or larger lines, while oil, gasoline, or diesel were running in the lines. Fred indicated no work was done with stainless steel pipe lines. Fred has had no experience with external NDE of waste transfer lines and does not know of anyone who has had such experience.

HANFORD TRANSFER LINE PIPE ROUGHNESS AND SCALING ADHERENCE PROPERTIES AFFECTING PUMPING EQUIPMENT AND LINE SELECTION

TELEPHONE CONFERENCE WITH:

Dick Rice, INEEL, Idaho Falls, ID 208/526-1992

On October 6, 1999 I left a message for Dick to call me on his two-phase transport work as it may relate to caustic waste transfer. On October 7, Tish Stoots (208/526-1764) returned my call to obtain more information for Dick. Tish indicated she would get back to me with any information on the subject. On October 12, I again called Tish to inquire of any progress on the subject. She indicated she had spoken with Dick and he had no quantitative data on two-phase transport that would support Hanford high-level waste transport.

HANFORD TRANSFER LINE PIPE ROUGHNESS AND SCALING ADHERENCE PROPERTIES AFFECTING PUMPING EQUIPMENT AND LINE SELECTION

TELEPHONE CONFERENCE WITH:

James Divine, ChemMet Ltd, West Richland, WA 509/967-2309

On October 4, 1999 I spoke with Jim Divine concerning his knowledge of scaling products deposition in tank transfer lines and associated roughness and adherence properties. Jim indicated that that no PNL studies were done in the past to evaluate the type of corrosion and resultant deposition. He indicated that if the transfer piping were to be made of stainless steel there would be no pitting corrosion only deposit accumulation. A carbon steel transfer line would exhibit pitting corrosion over time. Jim has had experience in the 300 Area with 6 and 8-inch water lines that have closed to 2-inch with deposition but nothing akin to tank wastes. Jim indicated that I should call Richard W. Johnson at INEEL since he had either written or edited a *Handbook of Fluid Dynamics* and may have some information.

On October 5, 1999 Jim called back to state he didn't know of other contacts at any other DOE sites that would have any quantitative data concerning this subject. Jim did suggest that some simple experiments could be proposed that would produce data on pipe roughness and scale adherence affects on pump pressure output. But these data would be nothing different than calculations found in standard publications on momentum transfer.

Jim was very confident that no quantitative data exists on tank waste transfer lines scaling and adherence properties and was not aware of any specific work on adherence to stainless steel.

HANFORD TRANSFER LINE PIPE ROUGHNESS AND SCALING ADHERENCE PROPERTIES AFFECTING PUMPING EQUIPMENT AND LINE SELECTION

TELEPHONE CONFERENCE WITH:

Darrel Duncan, NHC, Richland, WA 509/372-1013

On October 4, 1999 I spoke with Darrel Duncan concerning his Hanford corrosion history and any knowledge he may have concerning tank transfer line corrosion product buildup or assessments done on removed piping. Darrel's pre-Hanford experience was in the petrol-chemical industry determining pipeline corrosion and weld longevity. At Hanford his corrosion work has centered on materials, container integrity and longevity and has not involved any work with tank transfer lines. He indicated that any scaling data from removed piping would be suspect because of the many flushes required to reduce the dose so that the material could be examined. These repeated flushes would undoubtedly remove much of the scale buildup rendering results questionable.

We spoke of previous NDE work and came to the conclusion that it was doubtful that any inline transfer data gathered could be quantitative. He indicated I should still speak with the NDE group in the 306 Building.

HANFORD TRANSFER LINE PIPE ROUGHNESS AND SCALING ADHERENCE PROPERTIES AFFECTING PUMPING EQUIPMENT AND LINE SELECTION

TELEPHONE CONFERENCE WITH:

David Lini, SAIC, Richland, WA 509/373-9102

On October 5, 1999 Dave returned my call to discuss his 1975 document *"Compilation of Hanford Corrosion Studies"*, ARH-ST-111. Dave indicated the corrosion assessment in the document was centered on finding data to support either the "leave in place option" or the "retrieval option" for wastes contained in the high-level waste tanks. These two options were on the forefront at Hanford since deactivation of the 149 single-shell tanks was underway and future storage of high-level liquid wastes was designated for double-shell tanks. The document focused on tank integrity assessments in an attempt to determine tank longevity. As Dave remembers, there is no information on tank transfer lines or any assessment of transfer line corrosion, product buildup and subsequent line plugging, or transfer line failure within the document. Dave did not know of any work done with caustic waste transfer lines concerning scaling buildup or transfer line pipe roughness assessments nor did he know of anyone on site that had such information.

HANFORD TRANSFER LINE PIPE ROUGHNESS AND SCALING ADHERENCE PROPERTIES AFFECTING PUMPING EQUIPMENT AND LINE SELECTION

TELEPHONE CONFERENCE WITH:

Wesley Nelson (509/376-5403) and John Keve (509/376-8061), COGEMA Engineering Corporation, Richland, WA

On October 6, 1999 I spoke with John and Wes concerning their work experience concerning any non-destructive examinations of removed or in-place tank transfer line piping. Neither had any experience conducting such examinations and stated that the 306 NDE shop had never done this type of work for tank transfer piping.

HANFORD TRANSFER LINE PIPE ROUGHNESS AND SCALING ADHERENCE PROPERTIES AFFECTING PUMPING EQUIPMENT AND LINE SELECTION

TELEPHONE CONFERENCE WITH:

Daniel Reynolds, LMHC, Richland, WA 509/373-3115

Finally caught up with Dan on October 13, 1999. Dan indicated that almost all waste transfers in the last several years have been evaporator feed that contain very little solids. Volume % solids have not been traditionally reported in waste transfers. In approximately the last five years compatibility assessments of the transfer and receiving tanks are to be done. The assessment may contain SPG but claim no solids. A grab sample may be taken but is not necessarily representative since mixer pumps do not have to run for any period of time. Tank 101-SY solution transfer will utilize bulk density versus solution density to determine volume % suspended solids. Inline dilution instrumentation will be utilized to maintain the slurry <25 vol% solids. It is assumed that 60% of the solids in 101-SY, mainly NaNO3 and NaNO2, will dissolve as water is added. Tank C106 will be monitored for % solids as it is sluiced out. The same vol% solids measuring system will be used as 101-SY. However, the solids will be maintained at <15 vol% during the transfer of the C106 slurry.

HANFORD TRANSFER LINE PIPE ROUGHNESS AND SCALING ADHERENCE PROPERTIES AFFECTING PUMPING EQUIPMENT AND LINE SELECTION

TELEPHONE CONFERENCE WITH:

Jim Douglas, COGEMA Engineering, Richland, WA 509/372-0989

I spoke with Jim on October 7, 1999 to find out what data was provided concerning waste tank transfers. The data Jim has been provided as he has compiled tank waste characterization documentation are:

- Total alpha
- Sodium (Na)
- Aluminum (Al)
- Nitrate (NO3)
- Nitrite (NO2)
- Hydroxide (OH)
- Specific gravity
- Sulfate (SO4)
- Phosphate (PO4)

Jim believes the average temperature for waste being transferred is approximately 75 °C. He indicated I should contact Jim Field of LMHC to double check the data provided with waste transfers. Jim indicated he has never seen a wt% solids value in any of the waste transfer data.

HANFORD TRANSFER LINE PIPE ROUGHNESS AND SCALING ADHERENCE PROPERTIES AFFECTING PUMPING EQUIPMENT AND LINE SELECTION

TELEPHONE CONFERENCE WITH:

Jim Field, LMHC, Richland, WA 509/376-3753

Talked with Jim on October 13, 1999 concerning data available concerning waste transfers. Jim supported Jim Douglas's conversation in the constituents reported in waste transfers. Jim did indicate that grab samples were conducted to determine % solids. He also indicated that following waste transfers, three pipe volumes of water are used to flush the line(s). Flush volumes are being contested in lines that are of great length. Jim also stated that recommendations are continually made to turn on transfer line trace heaters to match the temperature of the tank the transfer is coming from. Average transfer temperature is something hard to quantify. The range of transfer liquids can vary by almost 150 °F as line length, trace heater condition/settings, initial waste temperature, water added to waste prior to transfer and other parameters can affect delivery temperature.

HANFORD TRANSFER LINE PIPE ROUGHNESS AND SCALING ADHERENCE PROPERTIES AFFECTING PUMPING EQUIPMENT AND LINE SELECTION

TELEPHONE CONFERENCE WITH:

Bill Morris, LMHC, Richland, WA 509/372-3724

Bill called on October 13, 1999 and indicated Joe Gonzalez had no knowledge of transfer line videos but he did. Bill is the camera group lead and recalls videos of the east-west transfer line video and the AY Tank Farm transfer line video inspection with a boroscope. He recalls that the videos were taken in the early 1990s. Bill will review his video records on transfer line inspections this afternoon and call me back with information concerning the videos.

LIST OF DOCUMENTS CONCERNING INSPECTIONS OR TESTING OF UNDERGROUND WASTE TRANSFER LINES

1. WHC-SD-WM-ANAL-014, 1994, *S Tank Farm SL-119 Saltwell Piping Failure Analysis Report*, Rev. 0, Westinghouse Hanford Company, Richland, Washington.

2. WHC-SD-WM-ES-259, 1993, *Single-Shell Saltwell Transfer Piping Evaluation*, Rev. 0, Westinghouse Hanford Company, Richland, Washington.

3. WHC-SD-WM-TEEM-001, 1992, *Pressure Testing of Underground Transfer Piping for Single-Shell Tank Saltwell*, Rev. 0, Westinghouse Hanford Company, Richland, Washington.

4. HNF-SD-WM-ER-623, 1997, *DST Waste Transfer Piping and Pit System Integrity Assessment Report*, Rev. 0, Westinghouse Hanford Company, Richland, Washington.

5. WSRC-TR-96-0356, 1996, *Materials Degradation Evaluation of High Level Waste Transfer Line System (U)*, Westinghouse Savannah River Company, Aiken, South Carolina.

APPENDIX D

CRITICAL VELOCITY AND PRESSURE LOSS EVALUATION RESULTS FOR DOUBLE-SHELL TANK TRANSFER PIPING IN 200 EAST AREA FOR TANK-TO-TANK AND TANK-TO-WASTE TREATMENT PLANT TRANSFERS BASED ON HANFORD TANK WASTE OPERATION SIMULATOR DISTINCT TRANSFER ROUTE IDENTIFICATION FOR PROPOSED PHASE 1 WASTE FEED DELIVERY TRANSFERS

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TABLES

D-1. Summary of Parametric Cases – Waste Properties. D-1
D-2. Case 1 ..... D-3
D-3. Case 2 ..... D-5
D-4. Case 3 ..... D-7
D-5. Case 4 ..... D-9
D-6. Case 5 ..... D-11
D-7. Case 6 ..... D-13

CONVERSIONS

ft	feet = 0.3048 meter (m)
in.	inch = 2.54 centimeters (cm)
lbf/in^2	pounds per square inch = 0.006895 megapascals (MPa)
mils	0.001 in. = 0.0254 millimeter (mm)
gpm	0.0631 liter/second (L/s)
cP	centipose = 0.001 kilogram/meter-second (kg/m-s)

APPENDIX D

CRITICAL VELOCITY AND PRESSURE LOSS EVALUATION RESULTS FOR DOUBLE-SHELL TANK TRANSFER PIPING IN 200 EAST AREA FOR TANK-TO-TANK AND TANK-TO-WASTE TREATMENT PLANT TRANSFERS BASED ON HANFORD TANK WASTE OPERATION SIMULATOR DISTINCT TRANSFER ROUTE IDENTIFICATION FOR PROPOSED PHASE 1 WASTE FEED DELIVERY TRANSFERS

Table D-1. Summary of Parametric Cases – Waste Properties.

Case	Liquid Density (kg/L)	Solids Concentration (vol%)	Solids Density (kg/L)	Minimally Agitated PSD	Median Particle Size (μm)	Viscosity	Waste Type
1	1.1, 1.2, 1.3	10	2.9	Mean	7.5	Best-Estimate	HLW
2		10	2.9	95/95TL	22	Best-Estimate	HLW
3		10	2.9	Mean	7.5	Bounding	HLW
4	1.2, 1.3, 1.4	2	2.9	Mean	7.5	Best-Estimate	LAW
5	1.1, 1.2, 1.3	10	2.2	Mean	7.5	Best-Estimate	HLW*
6		5	2.9	Mean	7.5	Best-Estimate	HLW/LAW

* Agglomerate estimated solids density case.

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Case 1

Input Data

- Solid Particle Density (kg/L): Mean 2.9
- Viscosity Relation: Best-est
- Particle Size Distribution: Minimally Agitated, Mean
- Median Particle Size (µm): 7.5
- vol% Solids: 10
- Liquid Density (kg/L): 1.1 (wt% Solids 22.7); 1.2 (wt% Solids 21.2); 1.3 (wt% Solids 19.9)
- Bulk Density (kg/L): 1.28; 1.37; 1.46

Project W211 Prototype Transfer Pump (3x6A VCM 6 Stage, Curve No. 61412)

n_{max}= 3560 rpm

3-in.Sch. 40 Pipe (3.068 in. inside dia.)

Row	From (A)	To (B)	Specified System Design Pressure (lbf/in²) (C)	Carbon Steel Length (ft) (D)	Stainless Steel Length (ft) (E)	Total Change in Elevation (ft) (F)
18	AN-101	AN-106	275	442	626	0.0
19	AN-101	AP-103	400	942	2,830	11.0
20	AN-101	AP-107	400	1,059	2,830	11.0
21	AN-101	WTP	400	0	6,102	61.1
22	AN-102	AP-107	275	1,464	3,240	11.0
23	AN-102	WTP	275	405	6,512	61.1
24	AN-103	AN-102	275	253	421	0.0
25	AN-103	WTP	275	376	6,512	61.1
26	AN-104	AN-101	275	562	626	-3.0
27	AN-104	AN-102	275	439	626	0.0
28	AN-104	AN-103	275	410	626	0.0
29	AN-104	AN-105	275	384	421	0.0
30	AN-104	AN-106	275	374	421	0.0
31	AN-104	AN-107	275	489	421	-3.0
32	AN-104	AP-101	400	1,050	2,757	11.0
33	AN-104	AP-102	400	0	2,549	11.9
34	AN-104	AP-104	400	950	2,757	10.9
35	AN-104	AP-106	400	976	2,757	11.0
36	AN-104	AP-108	400	1,079	2,757	11.0
37	AN-104	AW-101	275	1,630	3,167	20.1
38	AN-104	AW-103	275	1,648	3,167	19.2
39	AN-104	AW-104	275	1,639	3,167	20.1
40	AN-104	AW-105	275	1,761	3,167	20.1
41	AN-104	AZ-101	275	562	1,673	1.2
42	AN-104*	WTP	400	0	5,999	61.1
43	AN-105	AN-102	275	329	626	0.0
44	AN-105	WTP	275	452	6,717	61.1
45	AN-106	AW-102	275	1,839	3,445	19.8
46	AN-106	WTP	275	442	5,717	61.1
47	AN-107	WTP	275	557	6,814	61.1
48	AP-101	WTP	400	1,050	3,858	50.1
49	AP-102	WTP	400	0	3,758	49.2
50	AP-104	AP-107	400	942	216	0.1
51	AP-104	WTP	400	950	3,858	50.2
52	AP-105	AP-104	400	821	216	-0.1
53	AP-105	WTP	400	938	3,858	50.1
54	AP-106	AN-102	275	1,381	3,240	-11.0
55	AP-106	WTP	400	976	3,858	50.1
56	AP-107	AW-102	400	1,428	216	9.2
57	AP-108	WTP	400	1,079	3,858	50.1
58	AW-101	AN-105	275	2,082	3,855	-20.2
59	AW-101	WTP	275	1,630	4,268	40.9
60	AW-102	AP-102	275	1,472	313	-7.8
61	AW-102	AP-104	275	1,355	421	-7.8
62	AW-102	AY-101	275	1,472	3,507	-9.0
63	AW-102	AY-102	275	1,472	3,524	-8.0
64	AW-102	WTP	275	1,472	4,063	42.4
65	AW-103	AP-102	275	1,646	618	-8.3
66	AW-103	AP-104	275	1,483	626	-9.2
67	AW-103	AW-104	275	454	831	0.9
68	AW-103	AY-102	275	1,648	3,584	-8.6
69	AW-103**	WTP	275	1,648	4,268	41.9
70	AW-104	AP-104	275	1,522	626	-9.2
71	AW-104	AW-102	275	203	421	0.0
72	AW-104**	WTP	275	1,434	4,268	40.9
73	AW-105	AP-102	275	1,800	618	-9.2
74	AW-105	AP-104	275	1,683	626	-9.2

Liquid Density 1.1 kg/L; Bulk Density 1.28 kg/L; wt% Solids 22.7

Critical Velocity: Wasp-OT — Velocity 2.6 ft/s, Flow Rate 60 gal/min, Viscosity 11 cP; OT — 3.4 ft/s, 79 gal/min, 1.5 cP. Target — 6.1 ft/s, 140 gal/min, 10 cP. System Design Pressure Control: Controlled Maximum Operating Condition to Prevent System Over Pressure at Pump Dead Head.

Row	From	To	Wasp-OT Total Pressure Drop (lbf/in²) BOL (G)	Wasp-OT EOL (H)	OT Total Pressure Drop (lbf/in²) BOL (I)	OT EOL (J)	Target Total Pressure Drop (lbf/in²) BOL (K)	Target EOL (L)	Min. of Design and Pump Dead Head Pressure (lbf/in²) (M)	Pump Speed (rpm) (N)	Allowable Maximum Flow Rate (gal/min) BOL (O)	EOL (P)	Total Pressure Drop (lbf/in²) BOL (Q)	EOL (R)
18	AN-101	AN-106	11	14	18	23	51	66	275	3,171	223	209	124	142
19	AN-101	AP-103	42	49	64	76	168	207	347	3,560	174	159	249	263
20	AN-101	AP-107	44	51	67	80	176	218	347	3,560	171	156	252	266
21	AN-101	WTP	84	90	113	123	246	283	347	3,560	149	139	271	279
22	AN-102	AP-107	53	62	82	98	217	272	275	3,171	138	125	211	220
23	AN-102	WTP	93	101	128	142	288	337	275	3,171	119	110	224	229
24	AN-103	AN-102	7	8	11	14	32	40	275	3,171	246	234	91	109
25	AN-103	WTP	93	100	127	141	286	334	275	3,171	119	111	224	229
26	AN-104	AN-101	11	14	19	25	58	75	275	3,171	216	201	134	152
27	AN-104	AN-102	11	14	18	22	51	65	275	3,171	223	209	124	142
28	AN-104	AN-103	11	13	17	22	49	63	275	3,171	225	211	121	139
29	AN-104	AN-105	9	11	14	18	40	52	275	3,171	235	221	108	127
30	AN-104	AN-106	9	11	14	18	40	51	275	3,171	235	222	107	125
31	AN-104	AN-107	9	11	15	19	46	60	275	3,171	227	213	118	138
32	AN-104	AP-101	43	50	66	78	173	214	347	3,560	172	157	251	265
33	AN-104	AP-102	28	30	40	44	95	111	347	3,560	218	204	202	218
34	AN-104	AP-104	42	49	64	75	166	205	347	3,560	175	160	248	262
35	AN-104	AP-106	42	49	64	76	168	207	347	3,560	174	159	249	263
36	AN-104	AP-108	44	51	67	79	175	217	347	3,560	172	156	252	265
37	AN-104	AW-101	60	70	90	107	231	289	275	3,171	134	121	214	223
38	AN-104	AW-103	60	70	89	107	232	290	275	3,171	134	121	214	223
39	AN-104	AW-104	60	70	90	107	232	290	275	3,171	134	121	214	223
40	AN-104	AW-105	62	72	92	111	240	301	275	3,171	132	119	216	224
41	AN-104	AZ-101	22	26	35	42	97	120	275	3,171	188	174	166	181
42	AN-104*	WTP	83	89	112	122	243	279	347	3,560	150	140	270	278
43	AN-105	AN-102	10	12	16	19	44	55	275	3,171	231	218	113	131
44	AN-105	WTP	96	104	132	146	298	349	275	3,171	117	108	226	231
45	AN-106	AW-102	65	76	98	117	255	319	275	3,171	128	116	218	226
46	AN-106	WTP	95	103	132	146	298	348	275	3,171	117	109	225	231
47	AN-107	WTP	98	106	135	151	309	363	275	3,171	115	106	227	232
48	AP-101	WTP	74	82	102	116	233	281	347	3,560	153	139	268	278
49	AP-102	WTP	58	62	76	82	158	181	347	3,560	184	172	240	251
50	AP-104	AP-107	15	19	24	32	71	94	347	3,560	230	210	186	211
51	AP-104	WTP	72	80	100	113	226	272	347	3,560	155	142	266	277
52	AP-105	AP-104	13	17	21	28	63	83	347	3,560	238	219	175	200
53	AP-105	WTP	73	80	99	113	225	271	347	3,560	155	142	266	277
54	AP-106	AN-102	40	49	68	83	200	252	275	3,171	143	130	207	217
55	AP-106	WTP	73	81	100	114	226	274	347	3,560	154	141	267	277
56	AP-107	AW-102	27	33	40	52	109	144	347	3,560	203	183	219	240
57	AP-108	WTP	75	83	103	117	235	283	347	3,560	152	139	269	279
58	AW-101	AN-105	49	62	86	108	263	336	275	3,171	127	115	219	227
59	AW-101	WTP	80	91	115	135	281	345	275	3,171	122	111	222	229
60	AW-102	AP-102	19	25	33	45	106	142	275	3,171	180	162	175	191
61	AW-102	AP-104	18	24	32	43	101	136	275	3,171	183	165	172	189
62	AW-102	AY-101	44	54	74	91	216	272	275	3,171	138	125	211	220
63	AW-102	AY-102	45	55	75	92	217	273	275	3,171	138	125	211	220
64	AW-102	WTP	77	87	110	128	264	323	275	3,171	125	114	220	227
65	AW-103	AP-102	23	31	41	54	128	170	275	3,171	169	152	185	200
66	AW-103	AP-104	21	28	37	49	116	155	275	3,171	174	157	180	196
67	AW-103	AW-104	14	16	22	26	60	76	275	3,171	216	201	134	152
68	AW-103	AY-102	48	58	79	98	231	291	275	3,171	134	122	214	222
69	AW-103**	WTP	81	92	116	136	283	347	275	3,171	121	110	223	230
70	AW-104	AP-104	21	28	38	50	119	159	275	3,171	175	156	181	197
71	AW-104	AW-102	6	8	10	12	28	36	275	3,171	250	240	84	100
72	AW-104**	WTP	78	88	111	129	268	327	275	3,171	125	113	221	228
73	AW-105	AP-102	25	33	44	58	137	184	275	3,171	165	147	189	204
74	AW-105	AP-104	23	31	41	55	130	173	275	3,171	168	151	186	201

Liquid Density 1.2 kg/L; Bulk Density 1.37 kg/L; wt% Solids 21.2

Critical Velocity: Wasp-OT — Velocity 2.4 ft/s, Flow Rate 56 gal/min, Viscosity 11 cP; OT — 3.2 ft/s, 74 gal/min, 1.5 cP. Target — 6.1 ft/s, 140 gal/min, 10 cP. System Design Pressure Control: Controlled Maximum Operating Condition to Prevent System Over Pressure at Pump Dead Head.

Row	From	To	Wasp-OT Total Pressure Drop (lbf/in²) BOL (S)	Wasp-OT EOL (T)	OT Total Pressure Drop (lbf/in²) BOL (U)	OT EOL (V)	Target Total Pressure Drop (lbf/in²) BOL (W)	Target EOL (X)	Min. of Design and Pump Dead Head Pressure (lbf/in²) (Y)	Pump Speed (rpm) (Z)	Allowable Maximum Flow Rate (gal/min) BOL (AA)	EOL (AB)	Total Pressure Drop (lbf/in²) BOL (AC)	EOL (AD)
18	AN-101	AN-106	11	13	17	21	55	70	275	3,065	216	202	124	142
19	AN-101	AP-103	41	47	61	72	178	221	371	3,560	175	159	266	281
20	AN-101	AP-107	42	49	63	75	186	232	371	3,560	172	156	269	284
21	AN-101	WTP	84	89	110	120	260	301	371	3,560	150	139	289	298
22	AN-102	AP-107	51	60	77	92	231	289	275	3,065	133	121	211	220
23	AN-102	WTP	92	100	124	137	304	358	275	3,065	115	106	224	230
24	AN-103	AN-102	7	8	10	13	34	43	275	3,065	237	226	91	108
25	AN-103	WTP	92	99	123	136	302	355	275	3,065	115	107	224	229
26	AN-104	AN-101	10	13	18	23	62	80	275	3,065	209	194	133	152
27	AN-104	AN-102	11	13	17	21	54	70	275	3,065	216	202	124	142
28	AN-104	AN-103	10	12	16	20	52	67	275	3,065	218	204	121	139
29	AN-104	AN-105	8	10	13	17	43	56	275	3,065	227	214	108	126
30	AN-104	AN-106	8	10	13	16	42	55	275	3,065	228	215	107	125
31	AN-104	AN-107	8	10	14	18	49	64	275	3,065	220	206	118	137
32	AN-104	AP-101	42	48	62	74	183	228	371	3,560	173	157	268	283
33	AN-104	AP-102	27	29	38	42	101	117	371	3,560	218	205	215	232
34	AN-104	AP-104	40	47	60	71	176	218	371	3,560	176	160	265	280
35	AN-104	AP-106	41	47	61	72	178	221	371	3,560	175	159	266	281
36	AN-104	AP-108	42	49	63	75	185	231	371	3,560	172	156	269	284
37	AN-104	AW-101	58	67	85	101	245	307	275	3,065	130	117	214	223
38	AN-104	AW-103	58	67	85	101	246	309	275	3,065	129	117	214	223
39	AN-104	AW-104	58	68	85	101	246	308	275	3,065	129	117	214	223
40	AN-104	AW-105	60	70	88	105	255	320	275	3,065	127	115	216	224
41	AN-104	AZ-101	21	25	33	39	102	128	275	3,065	183	168	166	181
42	AN-104*	WTP	83	88	109	118	257	296	371	3,560	151	140	288	297
43	AN-105	AN-102	9	11	15	18	47	59	275	3,065	224	211	112	130
44	AN-105	WTP	95	102	127	141	315	371	275	3,065	113	104	226	231
45	AN-106	AW-102	63	73	92	111	270	339	275	3,065	124	112	218	226
46	AN-106	WTP	94	102	127	141	315	370	275	3,065	113	105	226	231
47	AN-107	WTP	97	105	131	145	326	385	275	3,065	111	102	227	232
48	AP-101	WTP	74	81	99	112	247	299	371	3,560	153	140	286	298
49	AP-102	WTP	59	62	75	81	167	192	371	3,560	185	172	256	269
50	AP-104	AP-107	14	18	23	30	76	101	371	3,560	230	211	198	225
51	AP-104	WTP	72	79	97	109	240	289	371	3,560	156	142	284	296
52	AP-105	AP-104	12	16	20	26	67	89	371	3,560	238	219	167	214
53	AP-105	WTP	72	79	96	109	239	288	371	3,560	156	142	284	296
54	AP-106	AN-102	37	45	62	77	212	268	275	3,065	138	126	207	217
55	AP-106	WTP	73	80	97	110	241	292	371	3,560	155	141	285	296
56	AP-107	AW-102	26	32	38	49	116	153	371	3,560	203	183	234	257
57	AP-108	WTP	74	82	99	113	249	302	371	3,560	153	139	287	298
58	AW-101	AN-105	45	57	79	99	279	357	275	3,065	125	111	218	227
59	AW-101	WTP	79	89	111	129	298	367	275	3,065	118	107	223	229
60	AW-102	AP-102	17	23	30	41	112	152	275	3,065	174	157	174	191
61	AW-102	AP-104	16	22	29	39	108	145	275	3,065	177	150	172	189
62	AW-102	AY-101	41	50	68	84	229	289	275	3,065	134	122	211	220
63	AW-102	AY-102	42	51	69	85	230	291	275	3,065	134	121	211	220
64	AW-102	WTP	76	86	106	122	280	344	275	3,065	121	110	220	227
65	AW-103	AP-102	21	29	37	50	136	182	275	3,065	164	147	185	200
66	AW-103	AP-104	19	25	33	45	124	166	275	3,065	169	152	180	196
67	AW-103	AW-104	13	16	20	25	64	81	275	3,065	208	195	134	152
68	AW-103	AY-102	44	54	73	90	245	310	275	3,065	130	118	213	222
69	AW-103**	WTP	80	90	112	130	300	370	275	3,065	117	106	223	230
70	AW-104	AP-104	19	26	34	46	127	169	275	3,065	168	151	181	197
71	AW-104	AW-102	6	7	9	11	30	38	275	3,065	242	232	84	100
72	AW-104**	WTP	76	86	106	123	284	348	275	3,065	120	109	221	228
73	AW-105	AP-102	23	31	40	54	146	196	275	3,065	159	143	189	204
74	AW-105	AP-104	21	29	38	51	138	185	275	3,065	163	146	186	201

Liquid Density 1.3 kg/L; Bulk Density 1.46 kg/L; wt% Solids 19.9

Critical Velocity: Wasp-OT — Velocity 2.3 ft/s, Flow Rate 53 gal/min, Viscosity 11 cP; OT — 3.0 ft/s, 69 gal/min, 1.5 cP. Target — 6.1 ft/s, 140 gal/min, 10 cP. System Design Pressure Control: Controlled Maximum Operating Condition to Prevent System Over Pressure at Pump Dead Head.

Row	From	To	Wasp-OT Total Pressure Drop (lbf/in²) BOL (AE)	Wasp-OT EOL (AF)	OT Total Pressure Drop (lbf/in²) BOL (AG)	OT EOL (AH)	Target Total Pressure Drop (lbf/in²) BOL (AI)	Target EOL (AJ)	Min. of Design and Pump Dead Head Pressure (lbf/in²) (AK)	Pump Speed (rpm) (AL)	Allowable Maximum Flow Rate (gal/min) BOL (AM)	EOL (AN)	Total Pressure Drop (lbf/in²) BOL (AO)	EOL (AP)
18	AN-101	AN-106	10	12	16	20	58	74	275	2,969	209	196	124	142
19	AN-101	AP-103	39	45	57	68	188	234	395	3,560	176	160	283	299
20	AN-101	AP-107	41	47	60	71	197	246	395	3,560	172	156	286	302
21	AN-101	WTP	83	88	108	116	274	318	395	3,560	151	140	308	317
22	AN-102	AP-107	49	57	72	86	244	306	275	2,969	129	117	211	220
23	AN-102	WTP	91	98	120	132	321	378	275	2,969	111	103	225	230
24	AN-103	AN-102	6	8	10	12	36	45	275	2,969	230	219	91	108
25	AN-103	WTP	91	98	120	131	319	375	275	2,969	111	103	224	230
26	AN-104	AN-101	10	12	16	21	65	85	275	2,969	202	188	133	152
27	AN-104	AN-102	10	12	16	19	58	74	275	2,969	209	196	123	142
28	AN-104	AN-103	10	12	15	19	55	71	275	2,969	211	198	121	139
29	AN-104	AN-105	8	10	12	15	46	59	275	2,969	220	207	108	126
30	AN-104	AN-106	8	9	12	15	45	58	275	2,969	221	208	106	125
31	AN-104	AN-107	7	9	12	16	52	68	275	2,969	213	199	118	137
32	AN-104	AP-101	40	46	59	69	193	242	395	3,560	173	158	285	301
33	AN-104	AP-102	26	28	36	40	106	124	395	3,560	219	205	228	247
34	AN-104	AP-104	39	45	57	67	186	231	395	3,560	176	160	282	298
35	AN-104	AP-106	39	45	57	68	188	234	395	3,560	176	160	283	299
36	AN-104	AP-108	40	47	59	70	196	245	395	3,560	173	157	286	302
37	AN-104	AW-101	56	65	81	96	259	326	275	2,969	126	114	214	223
38	AN-104	AW-103	56	65	80	96	260	327	275	2,969	125	113	214	223
39	AN-104	AW-104	56	65	81	96	260	327	275	2,969	125	113	214	223
40	AN-104	AW-105	58	67	83	99	269	340	275	2,969	123	112	216	224
41	AN-104	AZ-101	20	23	31	37	108	135	275	2,969	176	163	166	181
42	AN-104*	WTP	83	87	106	115	270	313	395	3,560	152	141	306	316
43	AN-105	AN-102	9	10	14	17	49	63	275	2,969	217	204	112	130
44	AN-105	WTP	94	101	123	136	333	393	275	2,969	109	101	226	231
45	AN-106	AW-102	60	70	88	104	286	360	275	2,969	120	109	218	226
46	AN-106	WTP	93	100	123	136	332	392	275	2,969	109	101	226	231
47	AN-107	WTP	96	103	127	140	344	408	275	2,969	107	99	227	232
48	AP-101	WTP	73	80	96	108	261	317	395	3,560	154	140	305	317
49	AP-102	WTP	59	62	74	79	176	203	395	3,560	186	173	271	286
50	AP-104	AP-107	13	17	21	27	80	107	395	3,560	230	211	211	240
51	AP-104	WTP	72	78	94	106	253	306	395	3,560	156	142	302	315
52	AP-105	AP-104	12	15	19	24	71	95	395	3,560	238	219	199	228
53	AP-105	WTP	72	78	94	105	252	305	395	3,560	156	143	302	315
54	AP-106	AN-102	34	42	57	70	223	284	275	2,969	134	122	207	217
55	AP-106	WTP	72	79	94	106	255	309	395	3,560	156	142	303	316
56	AP-107	AW-102	25	31	36	46	123	163	395	3,560	204	183	249	274
57	AP-108	WTP	73	81	97	109	263	320	395	3,560	153	139	305	317
58	AW-101	AN-105	41	52	72	91	295	379	275	2,969	120	108	218	226
59	AW-101	WTP	77	87	106	123	315	390	275	2,969	114	103	223	230
60	AW-102	AP-102	15	21	28	38	119	161	275	2,969	169	152	174	191
61	AW-102	AP-104	15	20	26	36	115	154	275	2,969	171	155	172	189
62	AW-102	AY-101	38	47	63	77	242	307	275	2,969	130	118	210	220
63	AW-102	AY-102	39	47	64	78	243	308	275	2,969	130	118	211	220
64	AW-102	WTP	75	84	102	117	296	365	275	2,969	117	106	220	228
65	AW-103	AP-102	20	26	34	46	144	193	275	2,969	159	142	185	200
66	AW-103	AP-104	17	23	30	41	131	176	275	2,969	164	148	180	196
67	AW-103	AW-104	12	15	19	23	67	86	275	2,969	202	189	134	151
68	AW-103	AY-102	41	50	67	83	259	329	275	2,969	127	114	213	222
69	AW-103**	WTP	78	88	107	124	317	392	275	2,969	113	103	223	230
70	AW-104	AP-104	17	24	31	42	134	180	275	2,969	163	146	181	197
71	AW-104	AW-102	6	7	9	11	32	40	275	2,969	234	224	84	100
72	AW-104**	WTP	75	84	102	118	300	369	275	2,969	116	106	221	228
73	AW-105	AP-102	21	28	37	49	155	208	275	2,969	155	138	189	204
74	AW-105	AP-104	19	26	34	46	147	197	275	2,969	158	141	186	201

Case 1 (Input Data)

Project W211 Prototype Transfer Pump (3x6A VCM 6 Stage, Curve No. 61412)

n_{max} = 3560 rpm

Transfer: 3-in.Sch. 40 Pipe (3.068 in. inside dia.)

	Solid Particle Density (kg/L)	Mean	Minimally Agitated	Particle Size Distribution	wt% Solids	Liquid Density (kg/L)	Bulk Density (kg/L)
Case 1		2.9	7.5	Median Particle Size (μm)	22.7	1.1	1.28
	Viscosity Relation	Best-est	10	vol% Solids			
Case 2					21.2	1.2	1.37
Case 3					19.9	1.3	1.46

Case	Critical Velocity Velocity (ft/s)	Critical Velocity Flow Rate (gal/min)	Critical Velocity Viscosity (cP)	Critical Velocity Wasp-OT	Critical Velocity OT	Target Velocity (ft/s)	Target Flow Rate (gal/min)	Target Viscosity (cP)	Target Wasp-OT	Target OT
Case 1	2.6	60	11	3.4	79	1.5	6.1	140	10	
Case 2	2.4	56	11	3.2	74	1.5	6.1	140	10	
Case 3	2.3	53	11	3.0	69	1.5	6.1	140	10	

System Design Pressure Control: Controlled Maximum Operating Condition to Prevent System Over Pressure at Pump Dead Head

	From	To	Specified System Design Pressure (lbf/in²)	Carbon Steel Length (ft)	Stainless Steel Length (ft)	Total Change in Elevation (ft)	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL	Min. of Design and Pump Dead Head Pressure (lbf/in²)	Pump Speed (rpm)	Allowable Maximum Flow Rate (gal/min) BOL	Allowable Maximum Flow Rate (gal/min) EOL	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL
75	AW-105	WTP	275	1,556	4,268	40.9	79	90	114	132	276	338	275	3,171	123	112	222	229
76	AW-106	AP-105	275	1,621	626	-9.2	22	30	40	53	126	168	275	3,171	170	153	185	200
77	AW-106	AP-106	275	1,767	518	-9.2	24	32	42	56	132	177	275	3,171	167	150	187	202
78	AW-106	AP-108	275	1,762	626	-9.2	24	33	43	57	135	181	275	3,171	166	148	189	203
79	AW-106	AW-102	275	314	421	0.0	8	10	13	16	36	46	275	3,171	240	228	99	117
80	AW-106	AW-103	275	565	831	-0.9	14	17	23	29	66	85	275	3,171	209	194	142	160
81	AW-106	AW-104	275	341	421	0.0	8	10	13	17	38	48	275	3,171	238	225	103	121
82	AW-106	AW-105	275	678	831	0.0	16	20	26	33	75	96	275	3,171	203	187	150	167
83	AY-101*	WTP	400	0	6,674	51.4	84	90	116	126	261	301	347	3,560	145	135	274	282
84	AY-102	AN-103	275	376	2,044	-10.7	16	20	29	35	91	112	275	3,171	191	177	164	178
85	AY-102	AN-106	275	442	2,354	-10.7	20	24	35	42	106	130	275	3,171	181	168	173	186
86	AY-102	AP-102	400	0	3,066	1.2	26	29	41	46	107	126	347	3,560	207	194	215	230
87	AY-102*	WTP	400	0	6,133	50.4	79	84	108	118	242	278	347	3,560	150	140	270	278
88	AZ-101*	WTP	400	0	5,444	56.9	77	81	103	111	221	254	347	3,560	157	146	264	273
89	AZ-102*	WTP	400	0	5,674	54.9	77	82	104	114	228	262	347	3,560	155	144	266	275
90	Interface	WTP	400	0	857	63.0	42	43	46	47	65	70						

	From	To	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL	Min. of Design and Pump Dead Head Pressure (lbf/in²)	Pump Speed (rpm)	Allowable Maximum Flow Rate (gal/min) BOL	Allowable Maximum Flow Rate (gal/min) EOL	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL
75	AW-105	WTP	78	88	109	126	293	360	275	3,065	119	108	222	229
76	AW-106	AP-105	21	28	36	49	134	179	275	3,065	164	148	184	200
77	AW-106	AP-106	22	29	38	51	140	189	275	3,065	162	145	187	202
78	AW-106	AP-108	22	30	39	53	144	193	275	3,065	160	144	188	203
79	AW-106	AW-102	7	9	12	15	38	49	275	3,065	232	220	99	117
80	AW-106	AW-103	13	16	21	27	70	90	275	3,065	202	188	142	160
81	AW-106	AW-104	8	9	12	15	40	51	275	3,065	230	218	103	121
82	AW-106	AW-105	15	19	24	30	79	102	275	3,065	196	181	150	167
83	AY-101*	WTP	83	88	112	122	276	320	371	3,560	145	135	293	301
84	AY-102	AN-103	15	18	26	32	96	119	275	3,065	185	171	163	177
85	AY-102	AN-106	18	22	32	38	112	139	275	3,065	176	163	173	186
86	AY-102	AP-102	25	27	38	43	113	133	371	3,560	208	194	229	245
87	AY-102*	WTP	78	83	104	114	255	296	371	3,560	151	140	288	297
88	AZ-101*	WTP	76	81	100	108	234	270	371	3,560	158	147	282	292
89	AZ-102*	WTP	77	82	102	110	241	278	371	3,560	156	145	284	294
90	Interface	WTP	44	45	48	49	69	74						

	From	To	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL	Min. of Design and Pump Dead Head Pressure (lbf/in²)	Pump Speed (rpm)	Allowable Maximum Flow Rate (gal/min) BOL	Allowable Maximum Flow Rate (gal/min) EOL	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL
75	AW-105	WTP	76	86	105	121	309	382	275	2,969	115	104	222	229
76	AW-106	AP-105	19	25	33	45	142	190	275	2,969	159	143	184	199
77	AW-106	AP-106	20	27	35	47	149	200	275	2,969	157	140	187	202
78	AW-106	AP-108	20	28	36	48	153	205	275	2,969	155	139	188	203
79	AW-106	AW-102	7	8	11	14	40	52	275	2,969	225	213	99	117
80	AW-106	AW-103	12	15	20	25	75	96	275	2,969	196	182	142	159
81	AW-106	AW-104	7	9	11	14	42	54	275	2,969	223	211	102	121
82	AW-106	AW-105	14	18	23	28	84	108	275	2,969	190	175	150	167
83	AY-101*	WTP	82	87	108	117	290	338	395	3,560	146	136	311	321
84	AY-102	AN-103	13	16	24	29	101	126	275	2,969	179	166	163	177
85	AY-102	AN-106	16	20	29	35	118	147	275	2,969	171	158	172	186
86	AY-102	AP-102	23	26	35	40	119	141	395	3,560	209	195	243	261
87	AY-102*	WTP	77	82	101	110	269	313	395	3,560	152	141	306	316
88	AZ-101*	WTP	76	80	98	105	246	285	395	3,560	159	147	300	310
89	AZ-102*	WTP	76	81	99	107	254	294	395	3,560	157	145	302	313
90	Interface	WTP	46	47	49	51	73	79						

To convert pressure to feet of slurry multiply pressure by	1.802	1.684	1.58
To convert pressure to feet of water multiply pressure by	2.307	2.307	2.307

Notes

Pressure		Flow Rate
Exceeds Specified System Design Pressure	276	139 Flow rate less than target 140 gal/min
Exceeds 400 lbf/in²	431	No solution

BOL = beginning of life for transfers. Pipeline maximum expected pipe roughness of 70 mils (0.070 inches) for existing (20 year old) carbon steel lines and 2 mils (0.002 inches) for new stainless steel lines.

EOL = pipeline at end of life (50 years for carbon steel line, 40 years for stainless steel line) with pipe roughness due to corrosion estimated at 150 mils for carbon steel and 10 mils for stainless steel.

Unit weight of water= 62.416 lbf/ft³ at 48 °F reference temperature

* HLW Phase I (transfers before year 2018) transfer route to WTP.

** Special one time only HLW Balance of Mission (transfers after year 2018) transfer route to WTP.

Critical velocity

OT = 1.3 times best-estimate prediction of critical velocity using Oroskar and Turian (1980) empirical correlation.

Wasp-OT = 1.3 times best-estimate prediction of critical velocity using Oroskar and Turian (1980) empirical correlation with modified liquid density and viscosity based on Wasp "vehicle" concept for given particle size distribution (PSD). Although this method appears to be a logical extension of the Wasp method, it is provided here for comparison only because it has not been validated experimentally.

Pressure drop

Best estimate prediction using Wasp et al. (1977) method.

Case 2 — Input Data

Solid Particle Density (kg/L): Mean 2.9; Best-est.
Viscosity Relation: Minimally Agitated 9595TL
Particle Size Distribution: Median Particle Size (μm) 21.6; vol% Solids 10; wt% Solids 22.7
Liquid Density (kg/L): 1.1
Bulk Density (kg/L): 1.28

Project W211 Prototype Transfer Pump (3x6A VCM 6 Stage, Curve No. 61412)
n_{max}= 3560 rpm

	Critical Velocity		Target	System Design Pressure Control
Velocity (ft/s)	3.9	4.1	6.1	Controlled Maximum Operating Condition to Prevent System Over Pressure at Pump Dead Head
Flow Rate (gal/min)	90 (Wasp-OT)	95 (OT)	140	
Viscosity (cP)	11	1.5	10	

Transfer: 3-in.Sch. 40 Pipe (3.068 in. inside dia.)

From	To	Specified System Design Pressure (lbf/in²)	Carbon Steel Length (ft)	Stainless Steel Length (ft)	Total Change in Elevation (ft)	Critical Velocity Total Pressure Drop (lbf/in²) BOL	Critical Velocity Total Pressure Drop (lbf/in²) EOL	Critical Velocity Total Pressure Drop (lbf/in²) BOL	Critical Velocity Total Pressure Drop (lbf/in²) EOL	Target Total Pressure Drop (lbf/in²) BOL	Target Total Pressure Drop (lbf/in²) EOL	Min. of Design and Pump Dead Head Pressure (lbf/in²)	Pump Speed (rpm)	Allowable Maximum Flow Rate (gal/min) BOL	Allowable Maximum Flow Rate (gal/min) EOL	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL
AN-101	AN-106	275	442	626	0.0	28	35	30	38	53	68	275	3,171	224	209	123	142
AN-101	AP-103	400	942	2,830	11.0	94	115	99	122	171	214	347	3,560	175	158	248	263
AN-101	AP-107	400	1,059	2,830	11.0	98	120	104	128	179	225	347	3,560	171	155	252	266
AN-101	WTP	400	0	6,102	61.1	149	170	156	178	247	290	347	3,560	150	137	271	280
AN-102	AP-107	275	1,464	3,240	11.0	121	149	128	159	221	281	275	3,171	136	121	212	223
AN-102	WTP	275	405	6,512	61.1	172	199	180	209	289	345	275	3,171	116	105	226	233
AN-103	AN-102	275	253	421	0.0	17	22	18	23	32	42	275	3,171	246	234	90	108
AN-103	WTP	275	376	6,512	61.1	171	197	179	208	287	343	275	3,171	117	105	226	233
AN-104	AN-101	275	562	626	-3.0	31	39	33	42	59	78	275	3,171	216	201	133	152
AN-104	AN-102	275	439	626	0.0	28	35	30	38	53	68	275	3,171	224	209	123	142
AN-104	AN-103	275	410	626	0.0	27	34	28	36	51	65	275	3,171	226	212	120	139
AN-104	AN-105	275	384	421	0.0	22	28	23	30	42	54	275	3,171	235	221	107	126
AN-104	AN-106	275	374	421	0.0	22	27	23	29	41	53	275	3,171	236	222	106	125
AN-104	AN-107	275	489	421	-3.0	24	31	26	34	47	62	275	3,171	228	213	118	137
AN-104	AP-101	400	1,050	2,757	11.0	96	118	102	126	176	221	347	3,560	173	156	250	265
AN-104	AP-102	400	0	2,549	11.9	55	63	58	67	95	113	347	3,560	220	205	199	217
AN-104	AP-104	400	950	2,757	10.9	93	113	98	120	169	212	347	3,560	176	159	248	263
AN-104	AP-106	400	976	2,757	11.0	94	115	99	122	170	214	347	3,560	175	158	248	264
AN-104	AP-108	400	1,079	2,757	11.0	97	120	103	127	178	224	347	3,560	172	155	251	266
AN-104	AW-101	275	1,630	3,167	20.1	130	161	138	170	236	299	275	3,171	132	117	215	225
AN-104	AW-103	275	1,648	3,167	19.2	130	161	138	171	236	300	275	3,171	132	117	215	226
AN-104	AW-104	275	1,639	3,167	20.1	131	161	138	171	236	300	275	3,171	132	117	215	226
AN-104	AW-105	275	1,761	3,167	20.1	135	167	143	177	245	311	275	3,171	130	114	217	227
AN-104	AZ-101	275	562	1,673	1.2	53	65	56	69	98	124	275	3,171	189	173	166	181
AN-104*	WTP	400	0	5,999	61.1	147	168	154	176	243	285	347	3,560	151	138	270	279
AN-105	AN-102	275	329	626	0.0	24	30	25	32	45	58	275	3,171	232	219	112	130
AN-105	WTP	275	452	6,717	61.1	177	205	186	216	300	358	275	3,171	114	102	227	234
AN-106	AW-102	275	1,839	3,445	19.8	143	177	151	188	260	330	275	3,171	126	111	220	229
AN-106	WTP	275	442	6,717	61.1	177	205	186	216	299	357	275	3,171	114	102	227	234
AN-107	WTP	275	557	6,814	61.1	183	213	192	224	310	372	275	3,171	111	99	229	236
AP-101	WTP	400	1,050	3,858	50.1	139	165	146	173	236	289	347	3,560	153	137	268	280
AP-102	WTP	400	0	3,758	49.2	98	111	103	116	158	185	347	3,560	186	172	238	251
AP-104	AP-107	400	942	216	0.1	38	50	41	54	74	99	347	3,560	230	210	186	210
AP-104	WTP	400	950	3,858	50.2	135	160	142	168	229	280	347	3,560	155	139	266	278
AP-105	AP-104	400	821	216	-0.1	34	45	36	48	65	87	347	3,560	238	219	175	200
AP-105	WTP	400	938	3,858	50.1	135	159	142	168	228	279	347	3,560	155	140	266	278
AP-106	AN-102	275	1,381	3,240	-11.0	105	133	112	142	203	261	275	3,171	142	126	208	219
AP-106	WTP	400	976	3,858	50.1	136	161	143	170	231	282	347	3,560	154	139	267	279
AP-107	AW-102	400	1,428	216	9.2	61	79	65	84	113	150	347	3,560	203	182	219	241
AP-108	WTP	400	1,079	3,858	50.1	140	166	147	175	238	292	347	3,560	152	136	269	281
AW-101	AN-105	275	2,082	3,855	-20.2	137	175	147	188	269	348	275	3,171	124	109	221	230
AW-101	WTP	275	1,630	4,268	40.9	163	197	172	208	286	357	275	3,171	118	104	225	233
AW-102	AP-102	275	1,472	313	-7.8	55	74	59	79	110	149	275	3,171	180	161	175	192
AW-102	AP-104	275	1,355	421	-7.8	53	71	57	76	105	142	275	3,171	182	164	173	190
AW-102	AY-101	275	1,472	3,507	-9.0	115	144	122	154	220	282	275	3,171	137	122	212	222
AW-102	AY-102	275	1,472	3,524	-8.0	116	145	123	155	221	283	275	3,171	137	121	212	223
AW-102	WTP	275	1,472	4,063	42.4	154	185	162	196	268	334	275	3,171	123	109	222	231
AW-103	AP-102	275	1,648	618	-8.3	67	89	72	95	132	178	275	3,171	168	150	186	202
AW-103	AP-104	275	1,483	626	-9.2	61	81	65	86	121	162	275	3,171	174	156	181	197
AW-103	AW-104	275	454	831	0.9	33	41	35	44	61	79	275	3,171	216	201	133	151
AW-103	AY-102	275	1,648	3,584	-8.6	123	155	131	165	236	302	275	3,171	133	117	215	225
AW-103**	WTP	275	1,648	4,268	41.9	164	198	173	210	287	359	275	3,171	118	104	225	233
AW-104	AP-104	275	1,522	626	-9.2	62	82	66	88	123	166	275	3,171	173	155	182	198
AW-104	AW-102	275	203	421	0.0	15	19	16	20	29	37	275	3,171	251	240	83	100
AW-104**	WTP	275	1,434	4,268	40.9	156	187	164	198	272	338	275	3,171	122	108	222	231
AW-105	AP-102	275	1,800	618	-9.2	72	96	77	103	142	192	275	3,171	164	145	190	206
AW-105	AP-104	275	1,683	626	-9.2	68	90	73	97	135	181	275	3,171	167	149	187	203

Wt% Solids 21.2; Liquid Density (kg/L): 1.2; Bulk Density (kg/L): 1.37

	Critical Velocity		Target	System Design Pressure Control
Velocity (ft/s)	3.7	3.8	6.1	Controlled Maximum Operating Condition to Prevent System Over Pressure at Pump Dead Head
Flow Rate (gal/min)	85 (Wasp-OT)	88 (OT)	140	
Viscosity (cP)	11	1.5	10	

From	To	Critical Velocity Total Pressure Drop (lbf/in²) BOL	Critical Velocity Total Pressure Drop (lbf/in²) EOL	Critical Velocity Total Pressure Drop (lbf/in²) BOL	Critical Velocity Total Pressure Drop (lbf/in²) EOL	Target Total Pressure Drop (lbf/in²) BOL	Target Total Pressure Drop (lbf/in²) EOL	Min. of Design and Pump Dead Head Pressure (lbf/in²)	Pump Speed (rpm)	Allowable Maximum Flow Rate (gal/min) BOL	Allowable Maximum Flow Rate (gal/min) EOL	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL
AN-101	AN-106	26	33	28	35	56	72	275	3,065	216	202	123	142
AN-101	AP-103	89	109	94	115	179	226	371	3,560	176	159	265	281
AN-101	AP-107	94	115	98	121	188	238	371	3,560	172	155	269	285
AN-101	WTP	145	165	151	172	259	305	371	3,560	151	138	288	299
AN-102	AP-107	115	142	121	149	233	297	275	3,065	132	118	212	222
AN-102	WTP	167	192	173	200	304	364	275	3,065	113	101	226	233
AN-103	AN-102	16	20	17	22	34	44	275	3,065	238	227	90	108
AN-103	WTP	166	191	172	199	302	361	275	3,065	113	102	225	232
AN-104	AN-101	29	37	30	39	63	82	275	3,065	209	194	133	152
AN-104	AN-102	26	33	28	35	55	72	275	3,065	216	202	123	142
AN-104	AN-103	25	32	27	34	53	69	275	3,065	218	205	120	139
AN-104	AN-105	21	26	22	28	44	57	275	3,065	227	214	107	126
AN-104	AN-106	20	26	21	27	43	56	275	3,065	228	215	106	125
AN-104	AN-107	23	29	24	31	50	66	275	3,065	220	206	117	137
AN-104	AP-101	92	113	96	119	185	234	371	3,560	174	157	267	283
AN-104	AP-102	53	61	55	64	100	119	371	3,560	221	206	212	231
AN-104	AP-104	88	108	93	114	177	224	371	3,560	177	160	264	281
AN-104	AP-106	89	109	94	115	179	226	371	3,560	176	159	265	281
AN-104	AP-108	93	114	98	120	187	237	371	3,560	173	156	268	284
AN-104	AW-101	125	153	131	161	248	315	275	3,065	128	113	215	225
AN-104	AW-103	125	153	131	161	249	317	275	3,065	128	113	215	225
AN-104	AW-104	125	154	131	162	249	316	275	3,065	128	113	215	225
AN-104	AW-105	129	159	135	167	258	329	275	3,065	126	111	217	227
AN-104	AZ-101	50	62	53	65	103	131	275	3,065	183	168	165	181
AN-104*	WTP	144	163	149	169	255	301	371	3,560	152	139	287	298
AN-105	AN-102	23	28	24	30	47	61	275	3,065	224	211	112	130
AN-105	WTP	172	198	179	207	315	378	275	3,065	110	99	227	234
AN-106	AW-102	137	168	143	177	274	348	275	3,065	122	107	220	229
AN-106	WTP	172	198	179	207	314	377	275	3,065	110	99	227	234
AN-107	WTP	177	205	185	214	326	393	275	3,065	108	96	229	236
AP-101	WTP	135	159	140	166	248	305	371	3,560	154	138	286	299
AP-102	WTP	96	108	100	113	166	195	371	3,560	187	172	254	268
AP-104	AP-107	36	48	38	50	78	104	371	3,560	230	211	198	225
AP-104	WTP	131	154	137	161	241	295	371	3,560	156	141	284	297
AP-105	AP-104	32	42	34	45	69	92	371	3,560	238	219	187	214
AP-105	WTP	131	154	136	161	240	294	371	3,560	156	141	284	297
AP-106	AN-102	99	125	105	132	214	275	275	3,065	138	123	208	219
AP-106	WTP	132	156	138	163	243	298	371	3,560	155	140	285	298
AP-107	AW-102	58	75	61	79	119	159	371	3,560	203	183	234	259
AP-108	WTP	136	160	141	168	250	308	371	3,560	153	137	287	299
AW-101	AN-105	128	164	136	174	283	367	275	3,065	121	107	220	230
AW-101	WTP	157	189	164	198	301	376	275	3,065	115	101	224	233
AW-102	AP-102	52	69	55	74	116	157	275	3,065	174	156	175	192
AW-102	AP-104	49	66	52	70	111	150	275	3,065	176	159	172	190
AW-102	AY-101	108	136	114	144	232	297	275	3,065	133	118	211	222
AW-102	AY-102	109	137	115	145	233	299	275	3,065	133	118	212	222
AW-102	WTP	148	178	155	187	282	352	275	3,065	119	105	222	230
AW-103	AP-102	63	83	67	89	140	188	275	3,065	163	145	186	202
AW-103	AP-104	57	76	60	80	127	171	275	3,065	168	151	180	197
AW-103	AW-104	31	39	33	41	64	83	275	3,065	209	194	133	152
AW-103	AY-102	116	146	122	154	248	319	275	3,065	129	114	215	225
AW-103**	WTP	158	190	165	199	303	379	275	3,065	114	101	225	233
AW-104	AP-104	58	77	62	82	130	175	275	3,065	167	150	182	198
AW-104	AW-102	15	18	15	19	30	39	275	3,065	242	232	83	100
AW-104**	WTP	150	180	157	188	286	367	275	3,065	118	105	222	231
AW-105	AP-102	67	90	71	95	150	203	275	3,065	159	141	190	205
AW-105	AP-104	64	85	67	90	142	191	275	3,065	162	144	187	202

Wt% Solids 19.9; Liquid Density (kg/L): 1.3; Bulk Density (kg/L): 1.46

	Critical Velocity		Target	System Design Pressure Control
Velocity (ft/s)	3.4	3.6	6.1	Controlled Maximum Operating Condition to Prevent System Over Pressure at Pump Dead Head
Flow Rate (gal/min)	79 (Wasp-OT)	83 (OT)	140	
Viscosity (cP)	11	1.5	10	

From	To	Critical Velocity Total Pressure Drop (lbf/in²) BOL	Critical Velocity Total Pressure Drop (lbf/in²) EOL	Critical Velocity Total Pressure Drop (lbf/in²) BOL	Critical Velocity Total Pressure Drop (lbf/in²) EOL	Target Total Pressure Drop (lbf/in²) BOL	Target Total Pressure Drop (lbf/in²) EOL	Min. of Design and Pump Dead Head Pressure (lbf/in²)	Pump Speed (rpm)	Allowable Maximum Flow Rate (gal/min) BOL	Allowable Maximum Flow Rate (gal/min) EOL	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL
AN-101	AN-106	25	31	26	33	58	76	275	2,969	210	196	123	142
AN-101	AP-103	85	104	89	108	188	238	395	3,560	176	159	282	299
AN-101	AP-107	89	109	93	113	198	250	395	3,560	173	156	285	303
AN-101	WTP	141	160	146	165	271	321	395	3,560	152	139	306	318
AN-102	AP-107	109	134	114	140	245	312	275	2,969	126	114	212	222
AN-102	WTP	161	185	167	192	319	383	275	2,969	109	98	226	233
AN-103	AN-102	15	19	16	20	36	46	275	2,969	231	220	90	108
AN-103	WTP	160	184	166	191	316	380	275	2,969	110	99	225	232
AN-104	AN-101	27	35	28	36	66	87	275	2,969	203	188	133	152
AN-104	AN-102	25	31	26	33	58	76	275	2,969	210	196	123	142
AN-104	AN-103	24	30	25	32	56	72	275	2,969	212	198	120	139
AN-104	AN-105	19	25	20	26	46	60	275	2,969	220	207	107	126
AN-104	AN-106	19	24	20	26	45	59	275	2,969	221	208	106	125
AN-104	AN-107	21	27	22	29	52	69	275	2,969	213	199	117	137
AN-104	AP-101	87	107	91	112	194	246	395	3,560	174	157	284	304
AN-104	AP-102	50	58	52	60	105	125	395	3,560	221	206	225	246
AN-104	AP-104	84	102	88	107	186	235	395	3,560	177	160	281	299
AN-104	AP-106	85	104	88	108	188	238	395	3,560	176	159	282	299
AN-104	AP-108	88	108	92	113	196	249	395	3,560	173	156	285	302
AN-104	AW-101	119	146	124	152	261	332	275	2,969	124	110	215	225
AN-104	AW-103	119	146	124	152	262	334	275	2,969	124	110	215	225
AN-104	AW-104	119	146	124	152	262	333	275	2,969	124	110	215	225
AN-104	AW-105	123	151	128	158	271	346	275	2,969	122	108	217	227
AN-104	AZ-101	47	58	49	61	108	138	275	2,969	177	163	165	181
AN-104*	WTP	140	158	144	163	267	316	395	3,560	153	140	305	317
AN-105	AN-102	21	27	22	28	50	64	275	2,969	217	205	111	130
AN-105	WTP	166	191	172	198	330	397	275	2,969	107	96	227	234
AN-106	AW-102	130	160	135	167	288	367	275	2,969	119	105	219	229
AN-106	WTP	166	191	172	198	329	396	275	2,969	107	96	227	234
AN-107	WTP	171	198	177	205	342	412	275	2,969	105	94	229	235
AP-101	WTP	131	153	135	159	261	322	395	3,560	154	139	304	318
AP-102	WTP	94	106	97	109	174	205	395	3,560	188	173	269	285
AP-104	AP-107	34	45	36	47	82	110	395	3,560	230	211	211	240
AP-104	WTP	127	149	132	155	253	311	395	3,560	157	141	302	316
AP-105	AP-104	30	40	32	42	72	97	395	3,560	238	219	199	228
AP-105	WTP	127	149	131	154	252	310	395	3,560	157	142	302	315
AP-106	AN-102	92	117	97	123	224	289	275	2,969	134	120	207	218
AP-106	WTP	128	150	133	156	255	314	395	3,560	156	141	302	316
AP-107	AW-102	56	72	58	75	126	167	395	3,560	204	183	249	274
AP-108	WTP	131	155	136	160	263	325	395	3,560	154	138	305	318
AW-101	AN-105	119	153	126	161	297	386	275	2,969	118	104	219	229
AW-101	WTP	150	181	156	188	316	398	275	2,969	111	98	224	233
AW-102	AP-102	48	65	50	68	122	166	275	2,969	169	151	175	192
AW-102	AP-104	46	62	48	65	117	158	275	2,969	171	154	172	190
AW-102	AY-101	101	127	106	133	243	313	275	2,969	129	115	211	222
AW-102	AY-102	102	128	107	134	244	314	275	2,969	129	115	211	222
AW-102	WTP	143	171	148	178	297	371	275	2,969	115	102	222	230
AW-103	AP-102	58	78	61	82	147	198	275	2,969	158	141	185	201
AW-103	AP-104	53	70	55	74	134	181	275	2,969	163	147	180	196
AW-103	AW-104	29	37	31	38	68	87	275	2,969	203	189	133	151
AW-103	AY-102	108	137	113	143	260	335	275	2,969	125	111	214	224
AW-103**	WTP	152	182	157	189	318	399	275	2,969	111	98	225	233
AW-104	AP-104	54	72	57	76	137	185	275	2,969	162	145	181	198
AW-104	AW-102	14	17	14	18	32	41	275	2,969	235	225	83	100
AW-104**	WTP	144	172	150	179	301	378	275	2,969	114	102	222	231
AW-105	AP-102	63	84	66	88	158	214	275	2,969	154	137	190	205
AW-105	AP-104	59	79	62	83	150	202	275	2,969	157	140	186	202

Case 2

Input Data

	Mean	Best-est.
Solid Particle Density (kg/L)	2.9	
Viscosity Relation		

Minimally Agitated	Particle Size Distribution
9595TL	
21.6	Median Particle Size (μm)
10	vol% Solids

wt% Solids	22.7	wt% Solids	21.2
wt% Solids	19.9		

Liquid Density (kg/L)	1.1	1.2	1.3
Bulk Density (kg/L)	1.28	1.37	1.46

Project W211 Prototype Transfer Pump (3x6A VCM 6 Stage, Curve No. 61412)

n_{max}= 3560 rpm

	Critical Velocity				Target	System Design Pressure Control
Velocity (ft/s)	3.9	Wasp-OT	4.1	OT	6.1	Controlled Maximum Operating Condition to Prevent System Over Pressure at Pump Dead Head
Flow Rate (gal/min)	90		95		140	
Viscosity (cP)	11		1.5		10	

	Critical Velocity				Target	System Design Pressure Control
Velocity (ft/s)	3.7	Wasp-OT	3.8	OT	6.1	Controlled Maximum Operating Condition to Prevent System Over Pressure at Pump Dead Head
Flow Rate (gal/min)	85		88		140	
Viscosity (cP)	11		1.5		10	

	Critical Velocity				Target	System Design Pressure Control
Velocity (ft/s)	3.4	Wasp-OT	3.6	OT	6.1	Controlled Maximum Operating Condition to Prevent System Over Pressure at Pump Dead Head
Flow Rate (gal/min)	79		83		140	
Viscosity (cP)	11		1.5		10	

Transfer: 3-in.Sch. 40 Pipe (3.068 in. inside dia.)

From	To	Specified System Design Pressure (lbf/in²)	Carbon Steel Length (ft)	Stainless Steel Length (ft)	Total Change in Elevation (ft)	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL	Min. of Design and Pump Dead Head Pressure (lbf/in²)	Pump Speed (rpm)	Allowable Maximum Flow Rate (gal/min) BOL	Allowable Maximum Flow Rate (gal/min) EOL	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL
AW-105	WTP	275	1,556	4,268	40.9	160	193	169	204	280	350	275	3,171	120	106	224	232
AW-106	AP-105	275	1,621	626	-9.2	66	87	70	94	130	175	275	3,171	169	151	185	201
AW-106	AP-106	275	1,767	518	-9.2	69	92	74	99	137	185	275	3,171	166	148	186	204
AW-106	AP-108	275	1,762	626	-9.2	71	94	76	101	140	189	275	3,171	165	146	189	205
AW-106	AW-102	275	314	421	0.0	19	25	21	26	37	47	275	3,171	241	228	99	117
AW-106	AW-103	275	565	831	-0.9	36	45	38	48	68	88	275	3,171	210	194	141	160
AW-106	AW-104	275	341	421	0.0	20	26	22	28	39	50	275	3,171	238	225	102	121
AW-106	AW-105	275	678	831	0.0	40	51	43	55	76	99	275	3,171	203	187	149	168
AY-101*	WTP	400	0	6,674	51.4	155	177	163	187	261	308	347	3,560	145	132	274	284
AY-102	AN-103	275	376	2,044	-10.7	46	58	50	62	92	115	275	3,171	192	177	162	178
AY-102	AN-106	275	442	2,354	-10.7	55	68	58	73	107	135	275	3,171	182	168	172	187
AY-102	AP-102	400	0	3,066	1.2	59	69	62	73	108	129	347	3,560	209	194	212	229
AY-102*	WTP	400	0	6,133	50.4	144	165	151	173	242	285	347	3,560	151	138	269	279
AZ-101*	WTP	400	0	5,444	56.9	135	153	141	161	221	260	347	3,560	158	145	263	274
AZ-102*	WTP	400	0	5,674	54.9	138	157	144	165	228	268	347	3,560	156	143	266	276
Interface	WTP	400	0	857	63.0	51	54	52	55	65	71						

From	To	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL	Min. of Design and Pump Dead Head Pressure (lbf/in²)	Pump Speed (rpm)	Allowable Maximum Flow Rate (gal/min) BOL	Allowable Maximum Flow Rate (gal/min) EOL	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL
AW-105	WTP	154	185	161	194	295	369	275	3,065	116	102	224	232
AW-106	AP-105	61	82	65	87	137	185	275	3,065	164	147	185	201
AW-106	AP-106	65	86	68	92	144	195	275	3,065	161	143	188	203
AW-106	AP-108	66	88	70	94	148	199	275	3,065	160	142	189	204
AW-106	AW-102	18	23	19	25	39	50	275	3,065	233	221	99	117
AW-106	AW-103	34	43	36	45	72	93	275	3,065	203	188	141	160
AW-106	AW-104	19	24	20	26	41	53	275	3,065	231	218	102	121
AW-106	AW-105	38	49	40	51	81	105	275	3,065	196	181	149	168
AY-101*	WTP	150	171	156	179	274	325	371	3,560	146	134	292	302
AY-102	AN-103	43	54	46	57	96	122	275	3,065	186	171	162	177
AY-102	AN-106	51	63	54	67	112	142	275	3,065	177	162	172	186
AY-102	AP-102	56	65	58	69	113	136	371	3,560	210	195	226	244
AY-102*	WTP	140	159	145	166	254	300	371	3,560	152	139	287	298
AZ-101*	WTP	131	148	136	155	232	274	371	3,560	159	147	281	294
AZ-102*	WTP	134	152	139	159	240	283	371	3,560	157	144	283	294
Interface	WTP	53	55	53	56	69	75						

From	To	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL	Min. of Design and Pump Dead Head Pressure (lbf/in²)	Pump Speed (rpm)	Allowable Maximum Flow Rate (gal/min) BOL	Allowable Maximum Flow Rate (gal/min) EOL	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL
AW-105	WTP	148	177	154	185	310	388	275	2,969	112	100	223	232
AW-106	AP-105	57	76	60	80	145	195	275	2,969	159	142	185	200
AW-106	AP-106	60	81	63	85	152	206	275	2,969	156	139	187	203
AW-106	AP-108	62	82	65	87	156	210	275	2,969	155	138	189	204
AW-106	AW-102	17	22	18	23	41	53	275	2,969	226	214	98	117
AW-106	AW-103	32	40	33	42	75	98	275	2,969	197	182	141	160
AW-106	AW-104	18	23	19	24	43	56	275	2,969	223	211	102	121
AW-106	AW-105	36	46	38	48	85	110	275	2,969	190	175	149	167
AY-101*	WTP	145	165	150	171	287	341	395	3,560	147	135	310	321
AY-102	AN-103	40	50	42	53	101	128	275	2,969	180	166	161	177
AY-102	AN-106	47	59	50	62	118	149	275	2,969	172	158	171	186
AY-102	AP-102	52	62	55	64	118	143	395	3,560	211	195	240	260
AY-102*	WTP	135	153	140	159	266	315	395	3,560	153	140	305	317
AZ-101*	WTP	128	144	132	149	244	288	395	3,560	161	147	298	311
AZ-102*	WTP	130	147	134	152	251	297	395	3,560	158	145	301	313
Interface	WTP	54	57	55	58	72	79						

To convert pressure to feet of slurry multiply pressure by	1.802		1.684
To convert pressure to feet of water multiply pressure by	2.307		2.307

To convert pressure to feet of slurry multiply pressure by	1.58		
To convert pressure to feet of water multiply pressure by	2.307		

Notes

Pressure		Flow Rate	
Exceeds Specified System Design Pressure	276	139	Flow rate less than target 140 gal/min
Exceeds 400 lbf/in²	401		No solution

BOL = beginning of life for transfers. Pipeline maximum expected pipe roughness of 70 mils (0.070 inches) for existing (20 year old) carbon steel lines and 2 mils (0.002 inches) for new stainless steel lines.

EOL = pipeline at end of life (50 years for carbon steel line, 40 years for stainless steel line) with pipe roughness due to corrosion estimated at 150 mils for carbon steel and 10 mils for stainless steel.

Unit weight of water= 62.416 lbf/ft³ at 48 °F reference temperature

* HLW Phase I (transfers before year 2018) transfer route to WTP.

** Special one time only HLW Balance of Mission (transfers after year 2018) transfer route to WTP.

Critical velocity

OT = 1.3 times best-estimate prediction of critical velocity using Oroskar and Turian (1980) empirical correlation.

Wasp-OT = 1.3 times best-estimate prediction of critical velocity using Oroskar and Turian (1980) empirical correlation with modified liquid density and viscosity based on Wasp "vehicle" concept for given particle size distribution (PSD).

Pressure drop

Best estimate prediction using Wasp et al. (1977) method.

Case 3

Input Data

Solid Particle Density (kg/L): Mean 2.9; Upper Bound

Viscosity Relation

Minimally Agitated: Mean 7.5; 10

Particle Size Distribution: Median Particle Size (μm); vol% Solids

wt% Solids 22.7 | wt% Solids 21.2 | wt% Solids 19.9

Liquid Density (kg/L): 1.1 | 1.2 | 1.3

Bulk Density (kg/L): 1.28 | 1.37 | 1.46

Project W211 Prototype Transfer Pump (3x6A VCM 6 Stage, Curve No. 61412)

n_{max}= 3560 rpm

Transfer: 3-in.Sch. 40 Pipe (3.068 in. inside dia.)

	Critical Velocity				Target		System Design Pressure Control
Velocity (ft/s)	4.6	Wasp-OT	3.4	OT	6.1		Controlled Maximum Operating Condition to Prevent System Over Pressure at Pump Dead Head
Flow Rate (gal/min)	107		79		140		
Viscosity (cP)	40		1.6		32		

	Critical Velocity				Target		System Design Pressure Control
Velocity (ft/s)	4.5	Wasp-OT	3.2	OT	6.1		Controlled Maximum Operating Condition to Prevent System Over Pressure at Pump Dead Head
Flow Rate (gal/min)	103		73		140		
Viscosity (cP)	41		1.6		32		

	Critical Velocity				Target		System Design Pressure Control
Velocity (ft/s)	4.3	Wasp-OT	3.0	OT	6.1		Controlled Maximum Operating Condition to Prevent System Over Pressure at Pump Dead Head
Flow Rate (gal/min)	99		69		140		
Viscosity (cP)	42		1.6		32		

	From	To	Specified System Design Pressure (lbf/in²)	Carbon Steel Length (ft)	Stainless Steel Length (ft)	Total Change in Elevation (ft)	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL	Min. of Design and Pump Dead Head Pressure (lbf/in²)	Pump Speed (rpm)	Allowable Maximum Flow Rate (gal/min) BOL	Allowable Maximum Flow Rate (gal/min) EOL	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL
18	AN-101	AN-106	275	442	626	0.0	39	43	13	13	61	74	275	3,171	218	205	131	147
19	AN-101	AP-103	400	942	2,830	11.0	135	147	52	52	206	239	347	3,560	162	151	260	270
20	AN-101	AP-107	400	1,059	2,830	11.0	140	153	53	53	214	250	347	3,560	159	147	263	272
21	AN-101	WTP	400	0	6,102	61.1	223	235	107	108	317	341	347	3,560	129	124	286	289
22	AN-102	AP-107	275	1,464	3,240	11.0	170	186	63	63	263	309	275	3,171	125	116	220	226
23	AN-102	WTP	275	405	6,512	61.1	253	269	117	117	365	401	275	3,171	101	99	235	236
24	AN-103	AN-102	275	253	421	0.0	24	27	8	8	38	45	275	3,171	242	232	97	112
25	AN-103	WTP	275	376	6,512	61.1	252	267	117	117	363	398	275	3,171	102	99	235	236
26	AN-104	AN-101	275	562	626	-3.0	42	47	13	13	68	84	275	3,171	211	197	140	156
27	AN-104	AN-102	275	439	626	0.0	38	43	13	13	61	74	275	3,171	218	205	131	147
28	AN-104	AN-103	275	410	626	0.0	37	41	13	13	59	71	275	3,171	220	208	128	144
29	AN-104	AN-105	275	384	421	0.0	30	33	10	10	48	58	275	3,171	231	218	113	130
30	AN-104	AN-106	275	374	421	0.0	29	33	10	10	47	57	275	3,171	232	219	112	129
31	AN-104	AN-107	275	489	421	-3.0	33	37	9	9	54	66	275	3,171	223	210	124	141
32	AN-104	AP-101	400	1,050	2,757	11.0	137	150	52	52	210	245	347	3,560	160	149	261	271
33	AN-104	AP-102	400	0	2,549	11.9	86	91	37	37	125	135	347	3,560	204	195	218	228
34	AN-104	AP-104	400	950	2,757	10.9	133	145	51	51	203	236	347	3,560	163	151	259	269
35	AN-104	AP-106	400	976	2,757	11.0	134	146	51	51	205	238	347	3,560	162	151	260	270
36	AN-104	AP-108	400	1,079	2,757	11.0	138	151	52	53	213	248	347	3,560	160	148	262	272
37	AN-104	AW-101	275	1,630	3,167	20.1	180	197	69	69	277	327	275	3,171	122	114	222	228
38	AN-104	AW-103	275	1,648	3,167	19.2	180	198	69	69	278	328	275	3,171	121	113	223	228
39	AN-104	AW-104	275	1,639	3,167	20.1	180	198	69	69	278	327	275	3,171	121	113	223	228
40	AN-104	AW-105	275	1,761	3,167	20.1	186	204	71	71	286	339	275	3,171	120	112	224	229
41	AN-104	AZ-101	275	562	1,673	1.2	77	84	28	28	119	139	275	3,171	178	167	176	187
42	AN-104*	WTP	400	0	5,999	61.1	220	231	106	106	312	336	347	3,560	131	125	285	288
43	AN-105	AN-102	275	329	626	0.0	34	37	12	12	53	63	275	3,171	226	215	120	135
44	AN-105	WTP	275	452	6,717	61.1	262	278	120	120	378	418	275	3,171	100	98	236	237
45	AN-106	AW-102	275	1,839	3,445	19.8	197	217	75	75	305	360	275	3,171	116	109	226	230
46	AN-106	WTP	275	442	6,717	61.1	261	277	120	120	377	417	275	3,171	100	98	236	236
47	AN-107	WTP	275	557	6,814	61.1	269	286	123	123	390	431	275	3,171	98	97	236	237
48	AP-101	WTP	400	1,050	3,858	50.1	193	208	87	87	283	323	347	3,560	139	129	279	286
49	AP-102	WTP	400	0	3,758	49.2	144	151	73	73	201	217	347	3,560	167	160	255	262
50	AP-104	AP-107	400	942	216	0.1	48	55	14	14	79	101	347	3,560	227	208	190	213
51	AP-104	WTP	400	950	3,858	50.2	188	203	86	86	276	313	347	3,560	141	131	278	284
52	AP-105	AP-104	400	821	216	-0.1	42	48	13	13	70	89	347	3,560	235	217	179	203
53	AP-105	WTP	400	938	3,858	50.1	188	202	86	86	275	312	347	3,560	141	132	277	284
54	AP-106	AN-102	275	1,381	3,240	-11.0	154	170	50	50	245	289	275	3,171	130	121	217	223
55	AP-106	WTP	400	976	3,858	50.1	190	204	86	86	278	316	347	3,560	140	131	278	285
56	AP-107	AW-102	400	1,428	216	9.2	74	84	25	25	119	152	347	3,560	200	181	223	243
57	AP-108	WTP	400	1,079	3,858	50.1	194	209	87	88	285	325	347	3,560	138	129	279	286
58	AW-101	AN-105	275	2,082	3,855	-20.2	198	220	60	61	319	382	275	3,171	115	104	227	231
59	AW-101	WTP	275	1,630	4,268	40.9	226	245	94	94	339	394	275	3,171	108	104	231	233
60	AW-102	AP-102	275	1,472	313	-7.8	69	80	17	17	118	152	275	3,171	176	159	179	194
61	AW-102	AP-104	275	1,355	421	-7.8	67	78	17	17	114	146	275	3,171	178	161	177	192
62	AW-102	AY-101	275	1,472	3,507	-9.0	167	184	55	55	265	312	275	3,171	125	117	220	226
63	AW-102	AY-102	275	1,472	3,524	-8.0	168	186	56	56	266	314	275	3,171	125	116	220	226
64	AW-102	WTP	275	1,472	4,063	42.4	213	231	90	91	319	369	275	3,171	112	107	229	232
65	AW-103	AP-102	275	1,648	618	-8.3	86	99	23	23	144	184	275	3,171	163	148	191	204
66	AW-103	AP-104	275	1,483	626	-9.2	79	90	20	21	132	168	275	3,171	169	153	186	199
67	AW-103	AW-104	275	454	831	0.9	46	51	16	16	72	86	275	3,171	209	197	142	157
68	AW-103	AY-102	275	1,648	3,584	-8.6	178	196	58	59	282	333	275	3,171	121	113	223	228
69	AW-103**	WTP	275	1,648	4,268	41.9	227	247	95	95	341	396	275	3,171	108	104	231	233
70	AW-104	AP-104	275	1,522	626	-9.2	80	92	21	21	135	172	275	3,171	167	152	187	200
71	AW-104	AW-102	275	203	421	0.0	22	24	8	8	34	41	275	3,171	247	237	90	104
72	AW-104**	WTP	275	1,434	4,268	40.9	217	235	92	92	325	375	275	3,171	110	106	229	232
73	AW-105	AP-102	275	1,800	618	-9.2	92	106	24	24	155	198	275	3,171	159	143	195	207
74	AW-105	AP-104	275	1,683	626	-9.2	87	100	23	23	147	187	275	3,171	162	147	192	205

	Critical Velocity BOL	Critical Velocity EOL	Critical Velocity BOL	Critical Velocity EOL	Target BOL	Target EOL	Min. of Design and Pump Dead Head Pressure (lbf/in²)	Pump Speed (rpm)	Allowable Maximum Flow Rate (gal/min) BOL	Allowable Maximum Flow Rate (gal/min) EOL	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL
18	38	42	13	13	65	78	275	3,065	211	198	131	147
19	134	146	51	51	217	253	371	3,560	163	151	277	288
20	139	152	52	52	226	265	371	3,560	160	148	280	291
21	224	236	108	108	333	360	371	3,560	131	125	305	309
22	169	185	62	62	278	328	275	3,065	121	113	220	226
23	254	269	118	118	385	423	275	3,065	97	95	235	236
24	24	26	8	8	40	48	275	3,065	234	224	97	112
25	252	268	117	117	382	420	275	3,065	98	96	235	236
26	42	47	12	12	72	89	275	3,065	204	190	140	156
27	38	42	13	13	64	78	275	3,065	211	199	130	146
28	37	41	12	12	62	75	275	3,065	213	201	128	144
29	29	33	9	10	50	61	275	3,065	223	211	113	130
30	29	32	9	9	49	60	275	3,065	224	212	112	129
31	32	36	9	9	57	70	275	3,065	216	203	123	141
32	136	149	51	51	222	260	371	3,560	161	149	279	290
33	85	90	37	37	131	142	371	3,560	206	196	231	243
34	132	144	50	50	214	250	371	3,560	164	152	276	287
35	133	145	50	51	216	252	371	3,560	163	151	277	288
36	138	150	52	52	224	263	371	3,560	161	149	280	290
37	179	197	68	69	292	346	275	3,065	117	110	223	228
38	180	197	68	68	293	347	275	3,065	117	109	223	228
39	180	197	69	69	293	347	275	3,065	117	109	223	228
40	185	203	70	70	303	360	275	3,065	115	108	224	229
41	76	83	27	27	126	147	275	3,065	172	161	176	187
42	221	232	107	107	328	355	371	3,560	132	127	304	308
43	33	37	11	11	56	67	275	3,065	219	208	119	135
44	262	278	121	121	398	439	275	3,065	96	94	236	237
45	197	216	74	74	322	382	275	3,065	112	105	226	230
46	262	276	120	121	397	438	275	3,065	96	94	236	237
47	270	287	123	123	411	455	275	3,065	95	93	237	237
48	193	208	88	88	299	342	371	3,560	140	130	298	305
49	145	152	73	73	212	229	371	3,560	169	161	272	279
50	47	54	14	14	84	107	371	3,560	227	208	203	228
51	189	203	86	87	291	331	371	3,560	142	132	296	304
52	42	48	12	12	74	95	371	3,560	235	217	191	217
53	189	203	86	86	290	330	371	3,560	142	132	296	303
54	152	168	48	48	258	306	275	3,065	126	117	217	223
55	190	204	87	87	293	334	371	3,560	141	132	297	304
56	73	84	25	25	127	162	371	3,560	200	181	238	260
57	195	210	88	88	301	345	371	3,560	139	129	298	306
58	196	218	58	58	337	408	275	3,065	111	105	227	231
59	225	245	94	94	358	417	275	3,065	104	101	231	233
60	68	79	17	17	125	162	275	3,065	170	154	179	194
61	67	77	16	16	121	156	275	3,065	172	156	177	192
62	166	183	53	53	279	331	275	3,065	121	113	220	226
63	167	184	54	54	281	332	275	3,065	121	113	220	226
64	213	231	90	91	337	391	275	3,065	107	103	229	232
65	85	98	22	22	153	196	275	3,065	158	143	190	204
66	78	89	19	20	140	179	275	3,065	163	148	185	199
67	46	50	16	16	76	91	275	3,065	202	190	142	157
68	176	194	57	57	297	353	275	3,065	118	110	222	228
69	227	246	95	95	360	418	275	3,065	104	100	231	233
70	79	91	20	20	143	183	275	3,065	162	147	187	200
71	22	24	7	7	36	43	275	3,065	238	229	90	104
72	217	235	91	92	343	397	275	3,065	106	102	230	232
73	91	105	23	23	164	211	275	3,065	154	139	194	207
74	86	99	22	22	156	199	275	3,065	157	142	191	204

	Critical Velocity BOL	Critical Velocity EOL	Critical Velocity BOL	Critical Velocity EOL	Target BOL	Target EOL	Min. of Design and Pump Dead Head Pressure (lbf/in²)	Pump Speed (rpm)	Allowable Maximum Flow Rate (gal/min) BOL	Allowable Maximum Flow Rate (gal/min) EOL	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop (lbf/in²) EOL
18	38	42	12	12	68	83	275	2,969	204	192	131	147
19	133	145	51	51	228	267	395	3,560	164	152	295	306
20	138	151	52	52	238	279	395	3,560	161	149	298	309
21	225	236	109	109	350	379	395	3,560	132	126	324	328
22	168	185	61	62	292	346	275	2,969	117	109	220	226
23	254	270	119	119	404	446	275	2,969	94	92	235	236
24	24	26	8	8	42	51	275	2,969	227	217	97	112
25	253	268	118	119	401	442	275	2,969	94	92	235	236
26	41	46	12	12	76	94	275	2,969	197	185	140	156
27	38	42	12	12	68	82	275	2,969	204	192	130	146
28	37	41	12	12	66	79	275	2,969	206	195	128	144
29	29	33	9	9	53	65	275	2,969	216	205	113	130
30	29	32	9	9	52	64	275	2,969	217	205	112	129
31	32	36	9	9	60	74	275	2,969	209	197	123	141
32	136	148	51	51	234	274	395	3,560	162	150	296	308
33	85	90	37	37	137	150	395	3,560	207	197	245	258
34	131	143	50	50	225	263	395	3,560	165	153	294	306
35	133	145	50	50	228	266	395	3,560	164	152	294	306
36	137	150	51	52	236	277	395	3,560	162	149	297	309
37	179	196	68	69	308	366	275	2,969	114	106	223	228
38	179	196	68	68	309	367	275	2,969	114	106	223	228
39	179	197	68	69	309	367	275	2,969	114	106	223	228
40	184	203	70	70	319	380	275	2,969	112	104	224	229
41	76	83	27	27	132	155	275	2,969	167	156	176	187
42	221	233	108	108	344	373	395	3,560	133	128	323	327
43	33	37	11	11	59	71	275	2,969	212	201	119	135
44	263	279	122	122	414	462	275	2,969	92	91	236	237
45	196	215	74	74	339	404	275	2,969	108	102	226	230
46	262	278	122	122	417	461	275	2,969	92	91	236	237
47	270	287	124	124	432	479	275	2,969	91	90	237	237
48	194	209	89	89	314	360	395	3,560	141	131	316	325
49	146	153	75	75	223	241	395	3,560	170	162	289	297
50	47	54	14	14	88	114	395	3,560	228	209	216	242
51	190	204	87	88	306	350	395	3,560	143	133	315	323
52	42	48	12	12	78	101	395	3,560	235	217	203	231
53	189	203	87	87	305	348	395	3,560	143	133	315	323
54	151	167	47	47	271	323	275	2,969	122	114	216	223
55	191	205	88	88	308	353	395	3,560	142	132	315	323
56	73	84	25	25	134	172	395	3,560	200	181	253	277
57	195	210	89	89	317	364	395	3,560	140	130	317	325
58	194	215	56	56	355	427	275	2,969	108	102	227	231
59	226	245	94	94	377	448	275	2,969	101	97	231	233
60	67	78	16	16	132	172	275	2,969	165	149	179	194
61	66	76	16	16	128	165	275	2,969	167	151	177	192
62	164	181	52	52	294	349	275	2,969	118	109	220	225
63	165	182	53	53	295	351	275	2,969	117	109	220	226
64	214	231	91	91	355	413	275	2,969	104	99	229	232
65	84	96	21	21	162	207	275	2,969	153	138	190	203
66	77	88	19	19	148	189	275	2,969	158	144	185	199
67	45	50	15	16	80	96	275	2,969	196	184	142	157
68	174	192	55	55	312	373	275	2,969	114	106	222	228
69	227	246	95	95	379	443	275	2,969	100	97	231	233
70	78	90	19	19	151	194	275	2,969	157	142	187	200
71	21	24	7	7	38	45	275	2,969	231	222	89	104
72	217	235	92	92	361	419	275	2,969	103	99	230	232
73	90	103	22	22	173	223	275	2,969	149	135	194	207
74	85	98	21	21	164	211	275	2,969	152	138	191	204

Case 3

Input Data

Solid Particle Density (kg/L): Mean 2.9

Viscosity Relation: Upper Bound

Minimally Agitated Particle Size Distribution: Mean

Median Particle Size (μm): 7.5

vol% Solids: 10

Project W211 Prototype Transfer Pump (3x6A VCM 6 Stage, Curve No. 61412)

n_{max}= 3560 rpm

Transfer: 3-in.Sch. 40 Pipe (3.068 in. inside dia.)

	Columns G–R	Columns S–AD	Columns AE–AP
wt% Solids	22.7	21.2	19.9
Liquid Density (kg/L)	1.1	1.2	1.3
Bulk Density (kg/L)	1.28	1.37	1.46
Critical Velocity, Wasp-OT: Velocity (ft/s)	4.6	4.5	4.3
Critical Velocity, Wasp-OT: Flow Rate (gal/min)	107	103	99
Critical Velocity, Wasp-OT: Viscosity (cP)	40	41	42
Critical Velocity, OT: Velocity (ft/s)	3.4	3.2	3.0
Critical Velocity, OT: Flow Rate (gal/min)	79	73	69
Critical Velocity, OT: Viscosity (cP)	1.6	1.6	1.6
Target: Velocity (ft/s)	6.1	6.1	6.1
Target: Flow Rate (gal/min)	140	140	140
Target: Viscosity (cP)	32	32	32
To convert pressure to feet of slurry multiply pressure by	1.802	1.684	1.58
To convert pressure to feet of water multiply pressure by	2.307	2.307	2.307

Transfer data (columns A–F)

Row	From	To	Specified System Design Pressure (lbf/in²)	Carbon Steel Length (ft)	Stainless Steel Length (ft)	Total Change in Elevation (ft)
75	AW-105	WTP	275	1,556	4,268	40.9
76	AW-106	AP-105	275	1,621	626	-9.2
77	AW-106	AP-106	275	1,767	518	-9.2
78	AW-106	AP-108	275	1,762	626	-9.2
79	AW-106	AW-102	275	314	421	0.0
80	AW-106	AW-103	275	565	831	-0.9
81	AW-106	AW-104	275	341	421	0.0
82	AW-106	AW-105	275	678	831	0.0
83	AY-101*	WTP	400	0	6,674	51.4
84	AY-102	AN-103	275	376	2,044	-10.7
85	AY-102	AN-106	275	442	2,354	-10.7
86	AY-102	AP-102	400	0	3,066	1.2
87	AY-102*	WTP	400	0	6,133	50.4
88	AZ-101*	WTP	400	0	5,444	56.9
89	AZ-102*	WTP	400	0	5,674	54.9
90	Interface	WTP	400	0	857	63.0

Columns G–R (wt% Solids 22.7)

Row	From	To	Wasp-OT Total Pressure Drop (lbf/in²) BOL	Wasp-OT EOL	OT Total Pressure Drop (lbf/in²) BOL	OT EOL	Target Total Pressure Drop (lbf/in²) BOL	Target EOL	Min. of Design and Pump Dead Head Pressure (lbf/in²)	Pump Speed (rpm)	Allowable Maximum Flow Rate (gal/min) BOL	Allowable EOL	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop EOL
75	AW-105	WTP	222	241	93	93	334	387	275	3,171	109	105	230	233
76	AW-106	AP-105	85	97	22	22	142	181	275	3,171	164	149	190	203
77	AW-106	AP-106	88	101	23	23	148	190	275	3,171	162	146	192	205
78	AW-106	AP-108	91	104	24	24	153	195	275	3,171	160	144	194	206
79	AW-106	AW-102	27	30	9	9	42	51	275	3,171	237	225	105	121
80	AW-106	AW-103	50	55	16	16	79	95	275	3,171	203	190	150	165
81	AW-106	AW-104	28	31	9	9	44	54	275	3,171	234	223	108	125
82	AW-106	AW-105	55	61	18	18	88	107	275	3,171	196	183	157	172
83	AY-101*	WTP	235	248	109	109	338	365	347	3,560	125	120	289	292
84	AY-102	AN-103	74	80	23	23	116	133	275	3,171	179	169	175	185
85	AY-102	AN-106	86	94	28	28	135	155	275	3,171	169	159	185	194
86	AY-102	AP-102	96	102	38	38	143	155	347	3,560	192	183	231	240
87	AY-102*	WTP	218	230	102	102	312	337	347	3,560	131	126	285	288
88	AZ-101*	WTP	200	211	97	97	284	306	347	3,560	138	133	279	283
89	AZ-102*	WTP	206	217	99	99	293	316	347	3,560	136	130	281	285
90	Interface	WTP	61	63	45	45	75	78						

Columns S–AD (wt% Solids 21.2)

Row	From	To	Wasp-OT Total Pressure Drop (lbf/in²) BOL	Wasp-OT EOL	OT Total Pressure Drop (lbf/in²) BOL	OT EOL	Target Total Pressure Drop (lbf/in²) BOL	Target EOL	Min. of Design and Pump Dead Head Pressure (lbf/in²)	Pump Speed (rpm)	Allowable Maximum Flow Rate (gal/min) BOL	Allowable EOL	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop EOL
75	AW-105	WTP	222	241	93	93	353	409	275	3,065	105	101	231	233
76	AW-106	AP-105	83	96	21	21	151	193	275	3,065	159	144	190	203
77	AW-106	AP-106	86	100	22	22	157	202	275	3,065	156	141	192	205
78	AW-106	AP-108	90	103	23	23	162	207	275	3,065	155	140	194	206
79	AW-106	AW-102	26	29	9	9	45	54	275	3,065	229	218	105	121
80	AW-106	AW-103	49	55	16	16	84	101	275	3,065	196	183	149	164
81	AW-106	AW-104	28	31	9	9	47	57	275	3,065	227	215	108	125
82	AW-106	AW-105	55	61	18	18	93	113	275	3,065	190	177	157	172
83	AY-101*	WTP	236	248	109	109	355	385	371	3,560	126	121	308	312
84	AY-102	AN-103	73	79	22	22	122	141	275	3,065	174	164	175	185
85	AY-102	AN-106	85	93	27	27	142	164	275	3,065	164	154	185	194
86	AY-102	AP-102	95	101	37	37	150	164	371	3,560	193	184	246	256
87	AY-102*	WTP	218	230	102	102	328	356	371	3,560	132	127	304	308
88	AZ-101*	WTP	201	212	98	98	299	323	371	3,560	140	134	298	302
89	AZ-102*	WTP	207	218	99	99	309	334	371	3,560	137	131	300	304
90	Interface	WTP	64	65	47	47	79	83						

Columns AE–AP (wt% Solids 19.9)

Row	From	To	Wasp-OT Total Pressure Drop (lbf/in²) BOL	Wasp-OT EOL	OT Total Pressure Drop (lbf/in²) BOL	OT EOL	Target Total Pressure Drop (lbf/in²) BOL	Target EOL	Min. of Design and Pump Dead Head Pressure (lbf/in²)	Pump Speed (rpm)	Allowable Maximum Flow Rate (gal/min) BOL	Allowable EOL	Total Pressure Drop (lbf/in²) BOL	Total Pressure Drop EOL
75	AW-105	WTP	222	241	93	94	371	442	275	2,969	101	98	231	233
76	AW-106	AP-105	82	95	20	20	159	204	275	2,969	154	139	190	203
77	AW-106	AP-106	85	99	21	21	166	214	275	2,969	152	137	192	205
78	AW-106	AP-108	89	102	22	22	171	220	275	2,969	150	135	193	206
79	AW-106	AW-102	26	29	9	9	47	57	275	2,969	222	211	105	121
80	AW-106	AW-103	49	54	16	16	88	107	275	2,969	190	178	149	164
81	AW-106	AW-104	27	31	9	9	49	60	275	2,969	219	208	108	125
82	AW-106	AW-105	54	61	18	18	98	120	275	2,969	184	171	157	172
83	AY-101*	WTP	236	249	110	110	373	405	395	3,560	127	122	327	331
84	AY-102	AN-103	72	78	21	21	128	148	275	2,969	168	159	175	185
85	AY-102	AN-106	84	91	26	26	149	172	275	2,969	159	150	185	194
86	AY-102	AP-102	94	100	36	36	157	172	395	3,560	195	185	261	272
87	AY-102*	WTP	219	231	103	103	344	374	395	3,560	133	128	322	327
88	AZ-101*	WTP	202	212	99	99	313	340	395	3,560	141	135	316	321
89	AZ-102*	WTP	208	219	100	101	324	351	395	3,560	138	132	318	324
90	Interface	WTP	66	68	50	50	83	88						

Notes

Pressure		Flow Rate	
Exceeds Specified System Design Pressure	276	139	Flow rate less than target 140 gal/min
Exceeds 400 lbf/in²	401		No solution

BOL = beginning of life for transfers. Pipeline maximum expected pipe roughness of 70 mils (0.070 inches) for existing (20 year old) carbon steel lines and 2 mils (0.002 inches) for new stainless steel lines.

EOL = pipeline at end of life (50 years for carbon steel line, 40 years for stainless steel line) with pipe roughness due to corrosion estimated at 150 mils for carbon steel and 10 mils for stainless steel.

Unit weight of water= 62.416 lbf/ft³ at 48 °F reference temperature

* HLW Phase I (transfers before year 2018) transfer route to WTP.

** Special one time only HLW Balance of Mission (transfers after year 2018) transfer route to WTP.

Critical velocity

OT = 1.3 times best-estimate prediction of critical velocity using Oroskar and Turian (1980) empirical correlation.

Wasp-OT = 1.3 times best-estimate prediction of critical velocity using Oroskar and Turian (1980) empirical correlation with modified liquid density and viscosity based on Wasp "vehicle" concept for given particle size distribution (PSD).

Pressure drop

Best estimate prediction using Wasp et al. (1977) method.

Case 4 — Input Data

Project W211 Prototype Transfer Pump (3x6A VCM 6 Stage, Curve No. 61412); n_{max}= 3560 rpm

Solid Particle Density (kg/L): Mean 2.9 | Minimally Agitated Particle Size Distribution: Mean
Viscosity Relation: Best-est. | Median Particle Size (µm): 7.5
vol% Solids: 2

Liquid Density (kg/L): 1.2 (wt% Solids 4.7) | 1.3 (wt% Solids 4.4) | 1.4 (wt% Solids 4.1)
Bulk Density (kg/L): 1.234 | 1.332 | 1.43

Transfer: 3-in. Sch. 40 Pipe (3.068 in. inside dia.)

Critical Velocity / Target parameters (Velocity (ft/s), Flow Rate (gal/min), Viscosity (cP)):
- Density 1.2: Critical Velocity Wasp-OT 2.7 / 62 / 2; OT 2.6 / 59 / 1.5; Target 6.1 / 140 / 2
- Density 1.3: Critical Velocity Wasp-OT 2.5 / 58 / 2; OT 2.4 / 55 / 1.5; Target 6.1 / 140 / 2
- Density 1.4: Critical Velocity Wasp-OT 2.3 / 54 / 2; OT 2.2 / 52 / 1.5; Target 6.1 / 140 / 2

System Design Pressure Control: Controlled Maximum Operating Condition to Prevent System Over Pressure at Pump Dead Head

Row	A From	B To	C Specified System Design Pressure (lbf/in²)	D Carbon Steel Length (ft)	E Stainless Steel Length (ft)	F Total Change in Elevation (ft)	G Wasp-OT Total Pressure Drop (lbf/in²) BOL	H Wasp-OT EOL	I OT Total Pressure Drop (lbf/in²) BOL	J OT EOL	K Target Total Pressure Drop (lbf/in²) BOL	L Target EOL	M Min. of Design and Pump Dead Head Pressure (lbf/in²)	N Pump Speed (rpm)	O Allowable Maximum Flow Rate (gal/min) BOL	P EOL	Q Total Pressure Drop (lbf/in²) BOL	R EOL	S Wasp-OT Total Pressure Drop (lbf/in²) BOL	T EOL	U OT Total Pressure Drop (lbf/in²) BOL	V EOL	W Target Total Pressure Drop (lbf/in²) BOL	X EOL	Y Min. of Design and Pump Dead Head Pressure (lbf/in²)	Z Pump Speed (rpm)	AA Allowable Maximum Flow Rate (gal/min) BOL	AB EOL	AC Total Pressure Drop (lbf/in²) BOL	AD EOL	AE Wasp-OT Total Pressure Drop (lbf/in²) BOL	AF EOL	AG OT Total Pressure Drop (lbf/in²) BOL	AH EOL	AI Target Total Pressure Drop (lbf/in²) BOL	AJ EOL	AK Min. of Design and Pump Dead Head Pressure (lbf/in²)	AL Pump Speed (rpm)	AM Allowable Maximum Flow Rate (gal/min) BOL	AN EOL	AO Total Pressure Drop (lbf/in²) BOL	AP EOL
18	AN-101	AN-106	275	442	626	0.0	9	12	9	11	44	59	275	3,229	232	215	117	139	9	11	8	11	47	64	275	3,108	223	207	117	139	8	11	8	10	50	69	275	3,000	216	200	117	139
19	AN-101	AP-103	400	942	2,830	11.0	35	43	33	40	138	184	334	3,560	184	164	231	249	33	41	31	39	148	198	361	3,560	185	164	249	269	32	39	30	37	158	212	387	3,560	185	164	266	288
20	AN-101	AP-107	400	1,059	2,830	11.0	36	45	34	42	145	194	334	3,560	181	161	234	252	35	43	33	40	156	209	361	3,560	181	161	252	272	33	41	32	39	167	224	387	3,560	181	161	271	292
21	AN-101	WTP	400	0	6,102	61.1	69	77	66	74	191	242	334	3,560	165	147	248	263	69	77	67	74	205	260	361	3,560	166	147	267	283	70	77	68	74	218	279	387	3,560	166	147	287	304
22	AN-102	AP-107	275	1,464	3,240	11.0	44	55	41	51	181	243	275	3,229	149	132	205	217	42	52	39	49	195	261	275	3,108	144	127	205	217	40	50	38	47	208	280	275	3,000	139	123	205	217
23	AN-102	WTP	275	405	6,512	61.1	76	87	73	83	227	291	275	3,229	135	120	215	225	76	87	74	83	243	313	275	3,108	130	115	215	225	76	86	74	83	260	335	275	3,000	125	111	216	226
24	AN-103	AN-102	275	253	421	0.0	6	7	5	7	27	36	275	3,229	254	241	85	105	5	7	5	7	29	39	275	3,108	245	232	85	105	5	7	5	6	31	42	275	3,000	236	224	85	105
25	AN-103	WTP	275	376	6,512	61.1	76	87	73	83	225	288	275	3,229	136	121	215	224	76	86	73	83	241	310	275	3,108	130	116	215	225	76	86	73	82	258	332	275	3,000	125	111	215	225
26	AN-104	AN-101	275	562	626	-3.0	9	13	8	12	50	68	275	3,229	225	207	127	149	8	12	8	11	53	73	275	3,108	216	199	127	149	8	11	7	10	57	79	275	3,000	209	192	127	149
27	AN-104	AN-102	275	439	626	0.0	9	12	9	11	44	59	275	3,229	232	216	117	139	9	11	8	11	47	64	275	3,108	224	208	117	139	8	11	8	10	50	68	275	3,000	216	200	117	139
28	AN-104	AN-103	275	410	626	0.0	9	12	8	11	42	57	275	3,229	234	218	114	136	8	11	8	10	45	61	275	3,108	226	210	114	136	8	10	7	9	48	65	275	3,000	218	203	114	136
29	AN-104	AN-105	275	384	421	0.0	7	10	7	9	35	47	275	3,229	243	227	102	124	7	9	6	8	38	51	275	3,108	234	219	102	124	6	9	6	8	40	55	275	3,000	226	211	102	124
30	AN-104	AN-106	275	374	421	0.0	7	10	7	9	34	47	275	3,229	244	228	101	122	7	9	6	8	37	50	275	3,108	234	220	101	122	6	8	6	8	39	54	275	3,000	226	212	101	122
31	AN-104	AN-107	275	489	421	-3.0	7	10	6	9	40	55	275	3,229	235	219	113	135	6	9	6	8	43	59	275	3,108	227	211	113	135	6	8	5	7	46	63	275	3,000	219	203	113	135
32	AN-104	AP-101	400	1,050	2,757	11.0	36	44	33	41	143	190	334	3,560	182	162	233	251	34	42	32	40	153	205	361	3,560	182	162	251	271	33	41	31	38	164	220	387	3,560	183	162	269	291
33	AN-104	AP-102	400	0	2,549	11.9	21	25	20	24	73	94	334	3,560	232	211	177	202	21	24	20	23	78	101	361	3,560	232	212	190	218	21	24	20	23	83	108	387	3,560	232	212	204	233
34	AN-104	AP-104	400	950	2,757	10.9	34	42	32	40	137	182	334	3,560	185	165	230	248	33	41	31	38	147	196	361	3,560	185	165	248	268	32	39	30	37	157	210	387	3,560	186	165	266	288
35	AN-104	AP-106	400	976	2,757	11.0	35	43	33	40	138	184	334	3,560	184	164	231	249	33	41	31	39	149	198	361	3,560	185	164	249	269	32	39	30	37	159	212	387	3,560	185	164	267	288
36	AN-104	AP-108	400	1,079	2,757	11.0	36	45	34	42	145	193	334	3,560	181	161	234	252	35	43	33	40	155	208	361	3,560	181	161	252	272	33	41	31	38	166	223	387	3,560	182	161	270	292
37	AN-104	AW-101	275	1,630	3,167	20.1	50	62	47	58	195	259	275	3,229	145	128	208	220	49	60	46	56	209	279	275	3,108	140	123	208	220	47	58	45	54	224	299	275	3,000	135	119	208	220
38	AN-104	AW-103	275	1,648	3,167	19.2	50	62	47	58	195	260	275	3,229	145	128	208	220	48	60	46	56	210	280	275	3,108	139	123	208	220	47	57	44	54	224	300	275	3,000	134	119	208	220
39	AN-104	AW-104	275	1,639	3,167	20.1	50	62	48	58	195	260	275	3,229	145	128	208	220	49	60	46	56	210	280	275	3,108	139	123	208	220	47	58	45	54	224	300	275	3,000	134	119	208	220
40	AN-104	AW-105	275	1,761	3,167	20.1	52	64	49	60	203	270	275	3,229	143	126	210	221	50	62	48	58	218	291	275	3,108	137	121	210	221	49	60	46	56	233	312	275	3,000	132	117	210	221
41	AN-104	AZ-101	275	562	1,673	1.2	18	23	16	21	79	106	275	3,229	200	181	157	177	17	21	16	20	85	114	275	3,108	193	175	157	176	16	20	15	19	91	123	275	3,000	186	169	157	176
42	AN-104*	WTP	400	0	5,999	61.1	68	77	66	74	189	239	334	3,560	166	148	247	262	69	77	66	74	202	257	361	3,560	167	148	266	283	69	77	67	74	215	275	387	3,560	167	148	286	303
43	AN-105	AN-102	275	329	626	0.0	8	10	7	10	37	50	275	3,229	241	225	105	127	7	10	7	9	40	54	275	3,108	232	217	105	127	7	9	6	8	42	57	275	3,000	224	209	105	127
44	AN-105	WTP	275	452	6,717	61.1	78	90	75	86	235	302	275	3,229	133	118	217	226	78	89	75	85	252	325	275	3,108	127	113	217	226	78	88	75	84	269	348	275	3,000	122	109	217	227
45	AN-106	AW-102	275	1,839	3,445	19.8	54	67	51	63	215	286	275	3,229	139	123	212	223	53	65	50	61	231	309	275	3,108	134	118	212	223	51	62	48	59	247	331	275	3,000	129	114	212	223
46	AN-106	WTP	275	442	6,717	61.1	78	89	75	85	235	301	275	3,229	133	118	216	226	78	89	75	85	252	324	275	3,108	128	113	217	226	78	88	75	84	268	347	275	3,000	123	109	217	227
47	AN-107	WTP	275	557	6,814	61.1	80	92	77	88	244	314	275	3,229	130	116	218	227	80	91	77	87	262	338	275	3,108	125	111	219	228	80	90	77	86	280	362	275	3,000	120	106	219	228
48	AP-101	WTP	400	1,050	3,858	50.1	63	73	60	70	193	249	334	3,560	163	145	250	264	63	73	61	69	207	268	361	3,560	164	145	269	285	63	72	61	69	221	287	387	3,560	164	145	289	306
49	AP-102	WTP	400	0	3,758	49.2	49	54	47	52	124	155	334	3,560	199	179	215	235	49	54	48	52	133	167	361	3,560	200	180	232	254	50	55	49	53	142	179	387	3,560	200	180	248	272
50	AP-104	AP-107	400	942	216	0.1	13	18	12	17	64	88	334	3,560	233	212	176	201	12	17	12	16	69	95	361	3,560	233	212	189	217	12	16	11	15	74	102	387	3,560	233	212	203	233
51	AP-104	WTP	400	950	3,858	50.2	62	71	59	68	186	241	334	3,560	166	147	247	263	62	71	60	68	200	259	361	3,560	166	147	267	283	62	70	60	68	214	278	387	3,560	167	147	286	304
52	AP-105	AP-104	400	821	216	-0.1	12	16	11	15	57	78	334	3,560	240	220	165	191	11	15	10	14	61	84	361	3,560	240	220	178	206	10	14	9	13	66	90	387	3,560	240	220	191	222
53	AP-105	WTP	400	938	3,858	50.1	62	71	59	68	186	240	334	3,560	166	147	247	262	62	71	59	68	199	258	361	3,560	167	148	267	283	62	70	60	67	213	276	387	3,560	167	148	286	304
54	AP-106	AN-102	275	1,381	3,240	-11.0	31	42	28	38	164	224	275	3,229	155	137	200	214	28	38	26	35	176	241	275	3,108	149	132	200	214	26	35	23	32	189	258	275	3,000	144	127	200	214
55	AP-106	WTP	400	976	3,858	50.1	62	72	60	69	188	243	334	3,560	165	147	248	263	62	71	60	68	202	262	361	3,560	166	147	267	284	62	71	60	68	216	280	387	3,560	166	147	287	305
56	AP-107	AW-102	400	1,428	216	9.2	24	31	23	29	100	135	334	3,560	206	185	208	230	24	30	22	28	107	145	361	3,560	206	185	224	248	23	29	21	27	115	156	387	3,560	206	185	241	267
57	AP-108	WTP	400	1,079	3,858	50.1	63	74	61	70	194	252	334	3,560	163	144	250	265	63	73	61	70	209	271	361	3,560	163	144	270	286	63	72	61	69	223	290	387	3,560	163	144	289	307
58	AW-101	AN-105	275	2,082	3,855	-20.2	38	53	35	49	219	300	275	3,229	138	121	213	224	35	49	31	44	235	323	275	3,108	133	117	213	224	31	44	28	40	252	346	275	3,000	129	113	212	224
59	AW-101	WTP	275	1,630	4,268	40.9	68	81	65	77	234	308	275	3,229	134	118	216	226	67	79	64	75	252	332	275	3,108	128	113	216	226	66	78	63	74	269	356	275	3,000	123	109	217	227
60	AW-102	AP-102	275	1,472	313	-7.8	16	23	15	21	96	133	275	3,229	186	167	172	190	15	22	13	20	103	143	275	3,108	180	161	171	190	13	20	12	18	111	154	275	3,000	173	155	171	190
61	AW-102	AP-104	275	1,355	421	-7.8	15	22	14	20	91	126	275	3,229	189	170	169	187	14	20	13	19	98	136	275	3,108	182	164	169	187	13	18	11	17	105	146	275	3,000	176	158	168	187
62	AW-102	AY-101	275	1,472	3,507	-9.0	35	46	32	43	178	242	275	3,229	150	133	204	217	32	43	29	39	191	260	275	3,108	145	128	204	217	29	39	27	36	204	279	275	3,000	140	123	204	217
63	AW-102	AY-102	275	1,472	3,524	-8.0	35	47	32	43	179	243	275	3,229	150	132	204	217	33	44	30	40	192	261	275	3,108	144	128	204	217	30	40	27	37	205	280	275	3,000	140	123	204	217
64	AW-102	WTP	275	1,472	4,063	42.4	65	78	62	74	220	288	275	3,229	137	122	213	224	65	76	62	73	236	310	275	3,108	132	117	214	224	64	75	61	71	253	333	275	3,000	127	112	214	224
65	AW-103	AP-102	275	1,648	618	-8.3	20	28	18	26	114	158	275	3,229	176	157	182	199	18	26	17	24	123	170	275	3,108	169	151	182	199	16	24	15	22	132	183	275	3,000	164	146	182	198
66	AW-103	AP-104	275	1,483	626	-9.2	18	25	16	23	104	144	275	3,229	182	162	176	194	16	23	14	21	112	155	275	3,108	175	156	176	194	14	21	13	19	120	166	275	3,000	169	151	176	194
67	AW-103	AW-104	275	454	831	0.9	11	14	10	13	50	68	275	3,229	225	208	126	148	11	14	10	13	54	73	275	3,108	217	200	126	148	10	13	9	12	58	78	275	3,000	210	193	126	148
68	AW-103	AY-102	275	1,648	3,584	-8.6	38	50	35	46	191	260	275	3,229	146	129	207	219	35	46	32	43	205	280	275	3,108	141	124	207	219	32	43	29	39	219	300	275	3,000	136	120	207	219
69	AW-103**	WTP	275	1,648	4,268	41.9	69	82	65	78	236	310	275	3,229	133	117	216	226	68	80	65	76	254	334	275	3,108	128	113	217	227	67	79	64	75	271	358	275	3,000	123	108	217	227
70	AW-104	AP-104	275	1,522	626	-9.2	18	26	16	24	106	147	275	3,229	180	161	178	195	16	24	15	21	114	158	275	3,108	174	155	178	195	15	21	13	19	123	170	275	3,000	168	150	177	195
71	AW-104	AW-102	275	203	421	0.0	5	7	5	6	24	32	275	3,229	259	246	78	97	5	6	4	6	25	34	275	3,108	249	237	78	97	4	6	4	5	27	37	275	3,000	240	229	78	97
72	AW-104**	WTP	275	1,434	4,268	40.9	65	78	62	74	222	291	275	3,229	137	121	214	224	65	76	62	72	239	314	275	3,108	131	116	214	225	64	75	61	71	255	336	275	3,000	126	112	214	225
73	AW-105	AP-102	275	1,800	618	-9.2	21	31	20	28	123	171	275	3,229	171	152	186	202	20	28	18	26	133	184	275	3,108	165	147	186	202	18	26	16	23	142	197	275	3,000	159	142	186	202
74	AW-105	AP-104	275	1,683	626	-9.2	20	29	18	26	116	161	275	3,229	175	156	183	200	18	26	17	24	125	173	275	3,108	168	150	183	199	16	24	15	22	134	186	275	3,000	163	145	183	199

Case 4

Project W211 Prototype Transfer Pump (3x6A VCM 6 Stage, Curve No. 61412)

n_{max}= 3560 rpm

Input Data

Input	Value	
Solid Particle Density (kg/L)	Mean 2.9	
Viscosity Relation	Best-est	
Particle Size Distribution	Minimally Agitated	Mean
Median Particle Size (μm)	7.6	
vol% Solids	2	
Velocity (ft/s)		
Flow Rate (gal/min)		
Viscosity (cP)		

3-in.Sch. 40 Pipe (3.068 in. inside dia.)

Row	From	To	Specified System Design Pressure (lbf/in²)	Carbon Steel Length (ft)	Stainless Steel Length (ft)	Total Change in Elevation (ft)
75	AW-105	WTP	275	1,556	4,268	40.9
76	AW-106	AP-105	275	1,621	626	-9.2
77	AW-106	AP-106	275	1,767	518	-9.2
78	AW-106	AP-108	275	1,762	626	-9.2
79	AW-106	AW-102	275	314	421	0.0
80	AW-106	AW-103	275	565	831	-0.9
81	AW-106	AW-104	275	341	421	0.0
82	AW-106	AW-105	275	678	831	0.0
83	AY-101*	WTP	400	0	6,674	51.4
84	AY-102	AN-103	275	376	2,044	-10.7
85	AY-102	AN-106	275	442	2,354	-10.7
86	AY-102	AP-102	400	0	3,066	1.2
87	AY-102*	WTP	400	0	6,133	50.4
88	AZ-101*	WTP	400	0	5,444	56.9
89	AZ-102*	WTP	400	0	5,674	54.9
90	Interface	WTP	400	0	857	63.0

Liquid Density (kg/L) 1.2; Bulk Density (kg/L) 1.234; wt% Solids 4.7

	Critical Velocity: Wasp-OT		OT		Target		System Design Pressure Control: Controlled Maximum Operating Condition to Prevent System Over Pressure at Pump Dead Head					
Velocity (ft/s)	2.7		2.6		6.1							
Flow Rate (gal/min)	62		59		140							
Viscosity (cP)	2		1.5		2							
	Total Pressure Drop (lbf/in²)		Total Pressure Drop (lbf/in²)		Total Pressure Drop (lbf/in²)		Min. of Design and Pump Dead Head Pressure (lbf/in²)	Pump Speed (rpm)	Allowable Maximum Flow Rate (gal/min)		Total Pressure Drop (lbf/in²)	
Row	BOL	EOL	BOL	EOL	BOL	EOL			BOL	EOL	BOL	EOL
75	67	80	64	76	230	302	275	3,229	135	119	215	226
76	19	28	18	25	112	155	275	3,229	177	158	181	198
77	21	29	19	27	119	164	275	3,229	174	154	184	201
78	21	30	19	27	121	168	275	3,229	172	153	185	201
79	6	8	6	8	31	41	275	3,229	249	234	94	114
80	12	15	11	14	56	76	275	3,229	219	201	135	156
81	7	9	6	8	32	44	275	3,229	246	232	97	118
82	14	18	13	16	64	87	275	3,229	212	193	143	164
83	67	76	64	73	201	257	334	3,560	161	143	252	266
84	11	16	10	14	71	97	275	3,229	204	186	152	172
85	14	19	13	17	83	113	275	3,229	195	177	162	181
86	19	23	18	22	80	106	334	3,560	222	201	190	214
87	63	72	61	69	186	238	334	3,560	166	148	247	262
88	63	70	61	67	172	217	334	3,560	173	155	241	257
89	63	71	61	68	177	224	334	3,560	171	152	243	259
90	39	40	38	39	56	63						

Liquid Density (kg/L) 1.3; Bulk Density (kg/L) 1.332; wt% Solids 4.4

	Critical Velocity: Wasp-OT		OT		Target		System Design Pressure Control: Controlled Maximum Operating Condition to Prevent System Over Pressure at Pump Dead Head					
Velocity (ft/s)	2.5		2.4		6.1							
Flow Rate (gal/min)	58		55		140							
Viscosity (cP)	2		1.5		2							
	Total Pressure Drop (lbf/in²)		Total Pressure Drop (lbf/in²)		Total Pressure Drop (lbf/in²)		Min. of Design and Pump Dead Head Pressure (lbf/in²)	Pump Speed (rpm)	Allowable Maximum Flow Rate (gal/min)		Total Pressure Drop (lbf/in²)	
Row	BOL	EOL	BOL	EOL	BOL	EOL			BOL	EOL	BOL	EOL
75	66	78	63	74	247	325	275	3,108	129	114	215	226
76	18	25	16	23	121	168	275	3,108	170	152	181	198
77	19	27	17	24	128	177	275	3,108	167	149	184	200
78	19	28	17	25	131	181	275	3,108	166	148	185	201
79	6	8	6	7	33	45	275	3,108	239	225	93	114
80	11	14	10	13	61	82	275	3,108	211	193	135	156
81	6	8	6	8	35	47	275	3,108	237	223	97	118
82	13	17	12	15	69	93	275	3,108	204	186	143	164
83	67	76	64	72	215	276	361	3,560	161	143	271	287
84	10	14	9	13	76	104	275	3,108	197	179	152	172
85	12	17	11	16	89	122	275	3,108	188	170	162	181
86	18	22	17	20	86	114	361	3,560	222	201	204	230
87	63	71	61	68	200	255	361	3,560	167	148	266	283
88	63	70	61	68	184	234	361	3,560	174	155	260	277
89	63	71	61	68	189	241	361	3,560	171	153	262	279
90	41	42	41	42	60	68						

Liquid Density (kg/L) 1.4; Bulk Density (kg/L) 1.43; wt% Solids 4.1

	Critical Velocity: Wasp-OT		OT		Target		System Design Pressure Control: Controlled Maximum Operating Condition to Prevent System Over Pressure at Pump Dead Head					
Velocity (ft/s)	2.3		2.2		6.1							
Flow Rate (gal/min)	54		52		140							
Viscosity (cP)	2		1.5		2							
	Total Pressure Drop (lbf/in²)		Total Pressure Drop (lbf/in²)		Total Pressure Drop (lbf/in²)		Min. of Design and Pump Dead Head Pressure (lbf/in²)	Pump Speed (rpm)	Allowable Maximum Flow Rate (gal/min)		Total Pressure Drop (lbf/in²)	
Row	BOL	EOL	BOL	EOL	BOL	EOL			BOL	EOL	BOL	EOL
75	65	77	62	73	264	348	275	3,000	125	110	216	226
76	16	23	14	21	130	180	275	3,000	165	147	181	198
77	17	25	15	22	137	190	275	3,000	162	144	184	200
78	17	25	16	23	140	194	275	3,000	160	143	185	201
79	6	7	5	7	35	48	275	3,000	231	218	93	114
80	10	13	9	12	65	88	275	3,000	203	187	135	156
81	6	8	6	7	37	50	275	3,000	229	215	97	118
82	12	16	11	14	73	100	275	3,000	197	180	143	164
83	67	75	64	72	229	295	387	3,560	162	143	291	308
84	8	12	7	11	81	111	275	3,000	191	173	151	172
85	11	15	9	14	95	130	275	3,000	182	164	161	181
86	17	21	16	19	91	122	387	3,560	223	201	218	247
87	63	71	61	68	213	273	387	3,560	167	149	285	303
88	64	70	62	68	196	250	387	3,560	174	155	278	297
89	64	71	62	68	202	258	387	3,560	172	153	281	299
90	43	44	43	44	64	73						

	Liquid Density 1.2	Liquid Density 1.3	Liquid Density 1.4
To convert pressure to feet of slurry multiply pressure by	1.87	1.732	1.613
To convert pressure to feet of water multiply pressure by	2.307	2.307	2.307

Notes

Pressure		Flow Rate	
Exceeds Specified System Design Pressure	276	139	Flow rate less than target 140 gal/min
Exceeds 400 lbf/in²	401		No solution

BOL = beginning of life for transfers. Pipeline maximum expected pipe roughness of 70 mils (0.070 inches) for existing (20 year old) carbon steel lines and 2 mils (0.002 inches) for new stainless steel lines.

EOL = pipeline at end of life (50 years for carbon steel line, 40 years for stainless steel line) with pipe roughness due to corrosion estimated at 150 mils for carbon steel and 10 mils for stainless steel.

Unit weight of water= 62.416 lbf/ft³ at 48 °F reference temperature

* HLW Phase I (transfers before year 2018) transfer route to WTP.

** Special one time only HLW Balance of Mission (transfers after year 2018) transfer route to WTP.

Critical velocity

OT = 1.3 times best-estimate prediction of critical velocity using Oroskar and Turian (1980) empirical correlation.

Wasp-OT = 1.3 times best-estimate prediction of critical velocity using Oroskar and Turian (1980) empirical correlation with modified liquid density and viscosity based on Wasp "vehicle" concept for given particle size distribution (PSD).

Pressure drop

Best estimate prediction using Wasp et al. (1977) method.

Case 5 — Input Data

Parameter	Case (cols G–R)	Case (cols S–AD)	Case (cols AE–AP)
Solid Particle Density (kg/L)	Agglo. 2.2		
Viscosity Relation	Best-est		
Particle Size Distribution	Minimally Agitated, Mean		
Median Particle Size (µm)	7.5		
vol% Solids	10		
wt% Solids	18.2	16.9	15.8
Liquid Density (kg/L)	1.1	1.2	1.3
Bulk Density (kg/L)	1.21	1.3	1.39

Project W211 Prototype Transfer Pump (3x6A VCM 6 Stage, Curve No. 61412); n_{max}= 3560 rpm

3-in.Sch. 40 Pipe (3.068 in. inside dia.)

Parameter	Critical Velocity Wasp-OT (G,H)	Critical Velocity OT (I,J)	Target (K,L)	Critical Velocity Wasp-OT (S,T)	Critical Velocity OT (U,V)	Target (W,X)	Critical Velocity Wasp-OT (AE,AF)	Critical Velocity OT (AG,AH)	Target (AI,AJ)
Velocity (ft/s)	2.0	2.6	6.1	1.8	2.4	6.1	1.7	2.2	6.1
Flow Rate (gal/min)	46	61	140	42	55	140	38	50	140
Viscosity (cP)	11	1.5	10	11	1.5	10	11	1.5	10

System Design Pressure Control: Controlled Maximum Operating Condition to Prevent System Over Pressure at Pump Dead Head

Row	From (A)	To (B)	Specified System Design Pressure (lbf/in²) (C)	Carbon Steel Length (ft) (D)	Stainless Steel Length (ft) (E)	Total Change in Elevation (ft) (F)	Total Pressure Drop (lbf/in²) BOL (G)	EOL (H)	Total Pressure Drop (lbf/in²) BOL (I)	EOL (J)	Total Pressure Drop (lbf/in²) BOL (K)	EOL (L)	Min. of Design and Pump Dead Head Pressure (lbf/in²) (M)	Pump Speed (rpm) (N)	Allowable Maximum Flow Rate (gal/min) BOL (O)	EOL (P)	Total Pressure Drop (lbf/in²) BOL (Q)	EOL (R)	Total Pressure Drop (lbf/in²) BOL (S)	EOL (T)	Total Pressure Drop (lbf/in²) BOL (U)	EOL (V)	Total Pressure Drop (lbf/in²) BOL (W)	EOL (X)	Min. of Design and Pump Dead Head Pressure (lbf/in²) (Y)	Pump Speed (rpm) (Z)	Allowable Maximum Flow Rate (gal/min) BOL (AA)	EOL (AB)	Total Pressure Drop (lbf/in²) BOL (AC)	EOL (AD)	Total Pressure Drop (lbf/in²) BOL (AE)	EOL (AF)	Total Pressure Drop (lbf/in²) BOL (AG)	EOL (AH)	Total Pressure Drop (lbf/in²) BOL (AI)	EOL (AJ)	Min. of Design and Pump Dead Head Pressure (lbf/in²) (AK)	Pump Speed (rpm) (AL)	Allowable Maximum Flow Rate (gal/min) BOL (AM)	EOL (AN)	Total Pressure Drop (lbf/in²) BOL (AO)	EOL (AP)
18	AN-101	AN-106	275	442	626	0.0	6	8	11	13	49	62	275	3,261	229	215	124	143	6	7	9	12	52	67	275	3,146	221	207	124	142	5	6	8	10	55	71	275	3,043	214	200	124	142
19	AN-101	AP-103	400	942	2,830	11.0	27	30	40	46	160	197	328	3,560	174	159	236	249	25	29	37	42	170	210	352	3,560	174	159	253	267	24	27	34	39	180	223	376	3,560	175	159	270	285
20	AN-101	AP-107	400	1,059	2,830	11.0	28	32	41	48	168	207	328	3,560	170	155	239	251	26	30	38	44	178	221	352	3,560	171	156	256	270	25	28	35	41	189	235	376	3,560	172	156	273	288
21	AN-101	WTP	400	0	6,102	61.1	62	65	80	85	236	270	328	3,560	148	138	257	264	62	64	78	82	250	287	352	3,560	149	139	275	283	61	63	75	79	264	305	376	3,560	150	139	293	302
22	AN-102	AP-107	275	1,464	3,240	11.0	33	38	50	59	207	258	275	3,261	142	129	211	220	31	35	46	54	220	275	275	3,146	137	124	211	220	29	33	42	49	234	293	275	3,043	132	120	211	220
23	AN-102	WTP	275	405	6,512	61.1	67	71	88	95	275	320	275	3,261	123	114	224	229	66	70	85	91	282	341	275	3,146	118	110	224	229	66	68	82	87	309	362	275	3,043	114	106	224	230
24	AN-103	AN-102	275	253	421	0.0	4	5	7	8	30	38	275	3,261	252	241	91	109	4	4	6	7	32	41	275	3,146	244	232	91	109	3	4	5	6	34	43	275	3,043	236	225	91	108
25	AN-103	WTP	275	376	6,512	61.1	67	71	88	95	273	318	275	3,261	123	114	224	229	66	69	85	91	290	339	275	3,146	118	110	224	229	65	68	82	87	307	360	275	3,043	114	106	224	229
26	AN-104	AN-101	275	562	626	-3.0	6	7	11	13	55	71	275	3,261	222	206	134	152	5	6	9	12	59	76	275	3,146	214	199	134	152	4	5	8	10	62	81	275	3,043	207	193	133	152
27	AN-104	AN-102	275	439	626	0.0	6	8	11	13	49	62	275	3,261	229	215	124	142	6	7	9	12	52	66	275	3,146	222	207	124	142	5	6	8	10	55	71	275	3,043	214	201	124	142
28	AN-104	AN-103	275	410	626	0.0	6	7	10	12	47	60	275	3,261	232	217	121	139	6	7	9	11	50	64	275	3,146	224	210	121	139	5	6	8	10	53	68	275	3,043	216	203	121	139
29	AN-104	AN-105	275	384	421	0.0	5	6	8	10	38	49	275	3,261	241	227	108	127	5	6	7	9	41	53	275	3,146	233	219	108	127	4	5	7	8	44	56	275	3,043	225	212	108	126
30	AN-104	AN-106	275	374	421	0.0	5	6	8	10	38	49	275	3,261	242	228	107	125	5	5	7	9	40	52	275	3,146	234	220	107	125	4	5	6	8	43	55	275	3,043	226	213	107	125
31	AN-104	AN-107	275	489	421	-3.0	4	6	8	10	44	57	275	3,261	234	219	118	138	4	5	7	9	46	61	275	3,146	226	211	118	137	3	4	6	8	49	65	275	3,043	218	204	118	137
32	AN-104	AP-101	400	1,050	2,757	11.0	27	31	41	47	165	203	328	3,560	172	157	238	250	26	29	38	44	175	217	352	3,560	172	157	255	269	24	27	35	40	186	231	376	3,560	173	157	272	287
33	AN-104	AP-102	400	0	2,549	11.9	19	20	26	28	91	105	328	3,560	217	204	192	206	18	19	25	27	97	112	352	3,560	218	204	205	221	17	18	23	25	102	119	376	3,560	219	205	218	236
34	AN-104	AP-104	400	950	2,757	10.9	27	30	39	46	158	195	328	3,560	175	159	235	248	25	28	37	42	168	208	352	3,560	175	160	252	266	24	26	34	39	178	221	376	3,560	176	160	269	284
35	AN-104	AP-106	400	976	2,757	11.0	27	30	40	46	160	197	328	3,560	174	159	236	249	25	28	37	42	170	210	352	3,560	175	159	253	267	24	27	34	39	180	224	376	3,560	175	159	270	285
36	AN-104	AP-108	400	1,079	2,757	11.0	28	31	41	48	166	206	328	3,560	171	156	238	251	26	29	38	44	177	220	352	3,560	172	156	255	269	24	27	35	40	188	234	376	3,560	172	156	273	288
37	AN-104	AW-101	275	1,630	3,167	20.1	39	44	56	66	220	274	275	3,261	138	125	214	223	37	42	52	61	234	293	275	3,146	133	121	214	223	35	39	49	56	248	312	275	3,043	129	116	214	223
38	AN-104	AW-103	275	1,648	3,167	19.2	38	44	56	65	221	275	275	3,261	138	125	214	223	37	41	52	60	235	294	275	3,146	133	120	214	223	35	39	48	56	249	313	275	3,043	128	116	214	223
39	AN-104	AW-104	275	1,639	3,167	20.1	39	44	56	66	221	275	275	3,261	138	125	214	223	37	42	53	61	235	294	275	3,146	133	120	214	223	35	39	49	56	249	312	275	3,043	128	116	214	223
40	AN-104	AW-105	275	1,761	3,167	20.1	40	45	58	68	228	285	275	3,261	136	123	216	224	38	43	54	63	243	305	275	3,146	131	118	216	224	36	40	50	58	258	324	275	3,043	126	114	216	224
41	AN-104	AZ-101	275	562	1,673	1.2	13	15	21	25	92	114	275	3,261	193	179	167	181	12	14	19	22	98	122	275	3,146	187	172	166	181	11	13	17	20	104	129	275	3,043	181	167	166	181
42	AN-104*	WTP	400	0	5,999	61.1	62	64	79	84	232	266	328	3,560	149	139	256	263	61	64	77	81	246	283	352	3,560	150	140	274	282	61	63	75	78	260	300	376	3,560	151	140	292	301
43	AN-105	AN-102	275	329	626	0.0	6	7	9	11	42	53	275	3,261	238	224	113	131	5	6	8	10	45	56	275	3,146	229	217	113	130	5	5	7	9	47	60	275	3,043	222	209	112	130
44	AN-105	WTP	275	452	6,717	61.1	69	73	91	98	285	332	275	3,261	120	112	225	230	68	71	87	94	302	354	275	3,146	118	108	226	231	67	70	84	90	320	378	275	3,043	112	104	226	231
45	AN-106	AW-102	275	1,839	3,445	19.8	42	47	61	71	242	303	275	3,261	132	119	218	226	39	45	57	66	258	323	275	3,146	127	115	218	226	37	42	52	61	274	344	275	3,043	123	111	218	226
46	AN-106	WTP	275	442	6,717	61.1	69	72	90	98	284	332	275	3,261	121	112	225	230	68	71	87	93	302	353	275	3,146	116	108	226	231	67	70	84	89	319	375	275	3,043	112	104	226	231
47	AN-107	WTP	275	557	6,814	61.1	70	74	93	100	295	345	275	3,261	118	110	227	232	69	73	89	96	313	368	275	3,146	114	106	227	232	68	71	86	92	331	391	275	3,043	110	102	227	232
48	AP-101	WTP	400	1,050	3,858	50.1	53	58	70	77	222	267	328	3,560	152	139	254	263	53	57	68	74	236	285	352	3,560	153	139	272	283	52	56	65	71	250	303	376	3,560	153	140	290	302
49	AP-102	WTP	400	0	3,758	49.2	44	46	55	58	151	172	328	3,560	183	171	227	238	45	46	54	57	160	183	352	3,560	184	172	243	255	45	46	53	56	170	195	376	3,560	185	172	259	272
50	AP-104	AP-107	400	942	216	0.1	8	11	14	18	67	89	328	3,560	230	210	176	199	8	10	12	16	72	96	352	3,560	230	210	189	214	7	9	11	14	77	102	376	3,560	230	211	201	228
51	AP-104	WTP	400	950	3,858	50.2	53	57	69	76	216	258	328	3,560	154	141	252	262	52	56	66	73	229	276	352	3,560	155	142	270	281	52	55	64	70	243	293	376	3,560	156	142	288	300
52	AP-105	AP-104	400	821	216	-0.1	7	9	12	16	59	79	328	3,560	238	219	166	190	7	8	11	14	64	85	352	3,560	238	219	178	203	6	8	10	13	68	90	376	3,560	238	219	190	217
53	AP-105	WTP	400	938	3,858	50.1	53	56	69	76	215	257	328	3,560	154	141	252	262	52	56	66	72	228	274	352	3,560	155	142	270	281	52	55	64	70	242	292	376	3,560	156	142	288	300
54	AP-106	AN-102	275	1,381	3,240	-11.0	21	25	37	46	190	239	275	3,261	147	133	208	217	18	22	33	40	202	255	275	3,146	142	129	207	217	15	19	28	34	214	271	275	3,043	138	125	207	217
55	AP-106	WTP	400	976	3,858	50.1	53	57	69	76	217	260	328	3,560	154	141	253	262	52	56	67	73	231	278	352	3,560	154	141	271	281	52	55	65	70	245	296	376	3,560	155	141	289	301
56	AP-107	AW-102	400	1,428	216	9.2	17	20	25	31	103	136	328	3,560	203	183	207	227	16	19	23	29	110	146	352	3,560	203	183	222	244	15	18	21	26	117	156	376	3,560	204	183	237	261
57	AP-108	WTP	400	1,079	3,858	50.1	54	58	70	78	224	269	328	3,560	151	138	254	264	53	57	68	75	238	287	352	3,560	152	139	273	283	52	56	66	72	252	306	376	3,560	153	139	291	303
58	AW-101	AN-105	275	2,082	3,855	-20.2	25	31	46	58	251	319	275	3,261	131	118	219	227	20	26	40	50	267	340	275	3,146	126	114	219	227	16	22	33	43	283	362	275	3,043	123	111	218	226
59	AW-101	WTP	275	1,630	4,268	40.9	55	61	76	86	268	328	275	3,261	125	114	222	229	54	59	72	81	285	350	275	3,146	121	110	222	229	52	57	68	76	302	372	275	3,043	117	106	223	229
60	AW-102	AP-102	275	1,472	313	-7.8	9	12	17	24	100	135	275	3,261	185	167	175	192	7	11	15	20	107	144	275	3,146	179	161	175	191	6	9	12	17	114	154	275	3,043	173	156	174	191
61	AW-102	AP-104	275	1,355	421	-7.8	8	12	17	23	96	129	275	3,261	188	169	172	189	7	10	14	19	103	138	275	3,146	181	164	172	189	6	8	12	17	109	147	275	3,043	175	158	172	189
62	AW-102	AY-101	275	1,472	3,507	-9.0	24	29	42	51	206	258	275	3,261	142	129	211	220	21	25	37	45	219	276	275	3,146	137	125	211	220	18	22	32	39	232	293	275	3,043	133	121	211	220
63	AW-102	AY-102	275	1,472	3,524	-8.0	25	29	42	51	207	260	275	3,261	142	129	211	220	22	26	37	45	220	277	275	3,146	137	124	211	220	19	22	32	39	233	295	275	3,043	133	120	211	220
64	AW-102	WTP	275	1,472	4,063	42.4	54	59	73	82	252	307	275	3,261	129	118	220	227	52	57	69	78	268	326	275	3,146	124	113	220	227	51	55	66	74	284	349	275	3,043	120	109	220	227
65	AW-103	AP-102	275	1,648	618	-8.3	11	16	22	29	121	161	275	3,261	174	156	186	201	10	13	19	25	129	173	275	3,146	168	151	185	200	8	11	16	22	138	184	275	3,043	162	146	185	200
66	AW-103	AP-104	275	1,483	626	-9.2	10	13	19	26	110	147	275	3,261	179	162	180	196	8	11	16	22	118	157	275	3,146	173	156	180	196	6	9	13	19	125	168	275	3,043	168	151	180	196
67	AW-103	AW-104	275	454	831	0.9	8	10	13	15	57	72	275	3,261	221	207	134	152	7	9	12	14	61	77	275	3,146	214	200	134	152	7	8	10	12	64	82	275	3,043	207	193	134	152
68	AW-103	AY-102	275	1,648	3,584	-8.6	26	31	45	54	220	277	275	3,261	138	125	214	222	23	28	39	48	234	296	275	3,146	133	121	214	222	20	24	34	42	248	314	275	3,043	129	117	213	222
69	AW-103**	WTP	275	1,648	4,268	41.9	56	61	77	87	269	330	275	3,261	125	114	223	229	54	59	73	82	287	352	275	3,146	120	109	223	230	53	57	69	77	304	375	275	3,043	116	106	223	230
70	AW-104	AP-104	275	1,522	626	-9.2	10	14	20	26	113	150	275	3,261	178	160	182	197	8	12	17	23	121	161	275	3,146	172	155	181	197	6	10	14	19	128	172	275	3,043	166	150	181	197
71	AW-104	AW-102	275	203	421	0.0	4	4	6	7	27	34	275	3,261	257	246	84	101	3	4	5	6	29	36	275	3,146	248	238	84	100	3	3	5	6	30	38	275	3,043	240	230	84	100
72	AW-104**	WTP	275	1,434	4,268	40.9	54	59	73	83	255	311	275	3,261	128	117	220	227	52	57	70	78	272	332	275	3,146	124	113	221	228	51	55	66	74	288	353	275	3,043	119	109	221	228
73	AW-105	AP-102	275	1,800	618	-9.2	12	17	23	31	130	174	275	3,261	169	152	190	204	10	14	20	27	139	186	275	3,146	163	146	189	204	8	12	17	23	148	199	275	3,043	158	142	189	204
74	AW-105	AP-104	275	1,683	626	-9.2	11	15	22	29	123	164	275	3,261	173	155	187	201	9	13	19	25	132	176	275	3,146	167	150	186	201	8	11	16	22	140	188	275	3,043	161	145	186	201

Case 5 (Input Data)

Solid Particle Density (kg/L): Agglo. 2.2; Best-est.; Minimally Agitated; Mean 7.5; 10

Viscosity Relation

Particle Size Distribution: Median Particle Size (μm); vol% Solids

Liquid Density (kg/L): 1.1 (wt% Solids 18.2); 1.2 (wt% Solids 16.9); 1.3 (wt% Solids 15.8)

Bulk Density (kg/L): 1.21; 1.3; 1.39

Project W211 Prototype Transfer Pump (3x6A VCM 6 Stage, Curve No. 61412)

n_{max}= 3560 rpm

	Critical Velocity				Target	System Design Pressure Control
		Wasp-OT		OT		
Velocity (ft/s)	2.0		2.6		6.1	Controlled Maximum Operating Condition to Prevent System Over Pressure at Pump Dead Head
Flow Rate (gal/min)	46		61		140	
Viscosity (cP)	11		1.5		10	

	Critical Velocity				Target	System Design Pressure Control
		Wasp-OT		OT		
Velocity (ft/s)	1.8		2.4		6.1	Controlled Maximum Operating Condition to Prevent System Over Pressure at Pump Dead Head
Flow Rate (gal/min)	42		55		140	
Viscosity (cP)	11		1.5		10	

	Critical Velocity				Target	System Design Pressure Control
		Wasp-OT		OT		
Velocity (ft/s)	1.7		2.2		6.1	Controlled Maximum Operating Condition to Prevent System Over Pressure at Pump Dead Head
Flow Rate (gal/min)	38		50		140	
Viscosity (cP)	11		1.5		10	

	Transfer		3-in.Sch. 40 Pipe (3.068 in. inside dia.)																																													
	From	To	Specified System Design Pressure (lbf/in²)	Carbon Steel Length (ft)	Stainless Steel Length (ft)	Total Change in Elevation (ft)	Total Pressure Drop (lbf/in²)		Total Pressure Drop (lbf/in²)		Total Pressure Drop (lbf/in²)		Min. of Design and Pump Dead Head Pressure (lbf/in²)	Pump Speed (rpm)	Allowable Maximum Flow Rate (gal/min)		Total Pressure Drop (lbf/in²)		Total Pressure Drop (lbf/in²)		Total Pressure Drop (lbf/in²)		Total Pressure Drop (lbf/in²)		Min. of Design and Pump Dead Head Pressure (lbf/in²)	Pump Speed (rpm)	Allowable Maximum Flow Rate (gal/min)		Total Pressure Drop (lbf/in²)		Total Pressure Drop (lbf/in²)		Total Pressure Drop (lbf/in²)		Min. of Design and Pump Dead Head Pressure (lbf/in²)	Pump Speed (rpm)	Allowable Maximum Flow Rate (gal/min)		Total Pressure Drop (lbf/in²)		Total Pressure Drop (lbf/in²)		Total Pressure Drop (lbf/in²)		Min. of Design and Pump Dead Head Pressure (lbf/in²)	Pump Speed (rpm)	Allowable Maximum Flow Rate (gal/min)		Total Pressure Drop (lbf/in²)	
							BOL	EOL	BOL	EOL	BOL	EOL			BOL	EOL	BOL	EOL	BOL	EOL	BOL	EOL	BOL	EOL			BOL	EOL	BOL	EOL	BOL	EOL	BOL	EOL	BOL	EOL			BOL	EOL	BOL	EOL	BOL	EOL	BOL	EOL			BOL	EOL	BOL	EOL
75	AW-105	WTP	275	1,556	4,268	40.9	55	60	75	85	263	221	275	3,261	126	115	222	229	53	58	71	80	280	343	275	3,146	122	111	222	229	52	56	67	75	297	365	275	3,043	118	107	222	229
76	AW-106	AP-105	275	1,621	626	-9.2	11	15	21	28	119	159	275	3,261	174	157	185	200	9	13	18	24	127	170	275	3,146	169	152	185	200	7	10	15	21	136	181	275	3,043	163	147	184	199
77	AW-106	AP-106	275	1,767	518	-9.2	11	16	22	30	125	167	275	3,261	172	154	187	202	10	13	19	26	134	179	275	3,146	166	149	187	202	8	11	16	22	142	191	275	3,043	161	144	187	202
78	AW-106	AP-108	275	1,762	626	-9.2	12	16	23	30	128	171	275	3,261	170	153	189	203	10	14	19	26	137	183	275	3,146	164	147	188	203	8	12	16	23	146	195	275	3,043	159	143	188	203
79	AW-106	AW-102	275	314	421	0.0	5	5	7	9	34	43	275	3,261	247	234	100	118	4	5	7	8	36	46	275	3,146	238	226	99	117	4	4	6	7	38	49	275	3,043	231	219	99	117
80	AW-106	AW-103	275	565	831	-0.9	8	10	13	16	63	80	275	3,261	215	199	142	160	7	9	12	15	67	86	275	3,146	208	193	142	160	6	8	10	13	71	92	275	3,043	201	186	142	160
81	AW-106	AW-104	275	341	421	0.0	5	6	8	9	36	46	275	3,261	245	232	103	121	4	5	7	8	38	49	275	3,146	236	223	103	121	4	5	6	8	40	52	275	3,043	228	216	103	121
82	AW-106	AW-105	275	678	831	0.0	9	11	15	19	71	91	275	3,261	208	192	150	167	8	10	14	17	76	97	275	3,146	201	186	150	167	8	9	12	15	80	103	275	3,043	195	180	150	167
83	AY-101*	WTP	400	0	6,674	51.4	60	63	79	85	250	287	328	3,560	144	134	260	267	59	61	76	81	265	305	352	3,560	145	135	279	286	58	60	73	77	279	324	376	3,560	146	135	297	306
84	AY-102	AN-103	275	376	2,044	-10.7	7	9	15	18	87	106	275	3,261	196	182	164	178	6	7	13	16	92	113	275	3,146	189	176	164	178	4	6	10	13	97	120	275	3,043	183	170	163	177
85	AY-102	AN-106	275	442	2,354	-10.7	9	11	19	22	101	124	275	3,261	186	172	174	187	8	9	16	19	107	132	275	3,146	180	167	173	186	6	7	13	16	113	140	275	3,043	174	161	173	186
86	AY-102	AP-102	400	0	3,066	1.2	16	17	25	27	103	120	328	3,560	206	193	204	218	14	16	22	25	109	128	352	3,560	207	194	218	233	13	14	20	22	115	135	376	3,560	208	194	232	249
87	AY-102*	WTP	400	0	6,133	50.4	57	59	75	79	231	265	328	3,560	149	139	256	263	56	58	72	76	245	282	352	3,560	150	140	274	282	55	57	69	73	259	299	376	3,560	151	141	292	301
88	AZ-101*	WTP	400	0	5,444	56.9	57	59	73	77	212	242	328	3,560	156	146	251	258	56	59	71	74	224	257	352	3,560	157	146	268	277	56	58	69	72	237	273	376	3,560	158	147	286	296
89	AZ-102*	WTP	400	0	5,674	54.9	57	59	73	78	218	250	328	3,560	154	144	253	260	56	59	71	75	231	266	352	3,560	155	144	270	279	56	58	69	72	244	282	376	3,560	156	145	288	298
90	Interface	WTP	400	0	857	63.0	37	38	40	40	62	66							39	40	41	42	66	71							41	42	43	44	70	75						

91	To convert pressure to feet of slurry multiply pressure by	1.907
92	To convert pressure to feet of water multiply pressure by	2.307

91	To convert pressure to feet of slurry multiply pressure by	1.775
92	To convert pressure to feet of water multiply pressure by	2.307

91	To convert pressure to feet of slurry multiply pressure by	1.66
92	To convert pressure to feet of water multiply pressure by	2.307

Notes

Pressure		Flow Rate	
Exceeds Specified System Design Pressure	276	139	Flow rate less than target 140 gal/min
Exceeds 400 lbf/in²	401		No solution

BOL = beginning of life for transfers. Pipeline maximum expected pipe roughness of 70 mils (0.070 inches) for existing (20 year old) carbon steel lines and 2 mils (0.002 inches) for new stainless steel lines.

EOL = pipeline at end of life (50 years for carbon steel line, 40 years for stainless steel line) with pipe roughness due to corrosion estimated at 150 mils for carbon steel and 10 mils for stainless steel.

Unit weight of water= 62.416 lbf/ft³ at 48 °F reference temperature

* HLW Phase I (transfers before year 2018) transfer route to WTP.

** Special one time only HLW Balance of Mission (transfers after year 2018) transfer route to WTP.

Critical velocity

OT = 1.3 times best-estimate prediction of critical velocity using Oroskar and Turian (1980) empirical correlation.

Wasp-OT = 1.3 times best-estimate prediction of critical velocity using Oroskar and Turian (1980) empirical correlation with modified liquid density and viscosity based on Wasp "vehicle" concept for given particle size distribution (PSD).

Pressure drop

Best estimate prediction using Wasp et al. (1977) method.

Agglo. = Agglomerate

APPENDIX E

SENSITIVITY ANALYSIS OF SELECTED TRANSFER ROUTES TO WASTE TREATMENT PLANT

Calculations contained herein were produced in Mathcad 2001 Professional (Mathcad is a registered trademark of MathSoft, Inc. of Cambridge, Massachusetts).

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FIGURES

E-1. Minimum Agitated (Least Battered) Mean – Cumulative and Probability Density Particle Size Distribution by Volume E-3

E-2a. Critical Velocity and Pressure Drop for AY-101 to WTP – Minimum Agitated (Least Battered) Mean Particle Size Distribution, ρ_L =1.1 kg/L, ρ_s = 2.9 kg/L, Best-Estimate Viscosity Case E-4

E-2b. Critical Velocity and Pressure Drop for AY-101 to WTP – Minimum Agitated (Least Battered) Mean Particle Size Distribution, ρ_L =1.3 kg/L, ρ_s = 2.9 kg/L, Best-Estimate Viscosity Case E-5

E-2c. Critical Velocity and Pressure Drop for AY-101 to WTP – Minimum Agitated (Least Battered) Mean Particle Size Distribution, ρ_L =1.3 kg/L, ρ_s = 2.9 kg/L, Upper-bound Viscosity Case E-6

E-3a. Critical Velocity and Pressure Drop for AZ-101 to WTP – Minimum Agitated (Least Battered) Mean Particle Size Distribution, ρ_L =1.1 kg/L, ρ_s = 2.9 kg/L, Best-Estimate Viscosity Case E-7

E-3b. Critical Velocity and Pressure Drop for AZ-101 to WTP – Minimum Agitated (Least Battered) Mean Particle Size Distribution, ρ_L =1.3 kg/L, ρ_s = 2.9 kg/L, Best-Estimate Viscosity Case E-8

E-3c. Critical Velocity and Pressure Drop for AY-101 to WTP – Minimum Agitated (Least Battered) Mean Particle Size Distribution, ρ_L =1.3 kg/L, ρ_s = 2.9 kg/L, Upper-bound Viscosity Case E-9

E-4a. Critical Velocity and Pressure Drop for AW-103 to WTP – Minimum Agitated (Least Battered) Mean Particle Size Distribution, ρ_L =1.1 kg/L, ρ_s = 2.9 kg/L, Best-Estimate Viscosity Case E-10

E-4b. Critical Velocity and Pressure Drop for AW-103 to WTP – Minimum Agitated (Least Battered) Mean Particle Size Distribution, ρ_L =1.3 kg/L, ρ_s = 2.9 kg/L, Best-Estimate Viscosity Case E-11

E-4c. Critical Velocity and Pressure Drop for AW-103 to WTP – Minimum Agitated (Least Battered) Mean Particle Size Distribution, ρ_L =1.3 kg/L, ρ_s = 2.9 kg/L, Upper-bound Viscosity Case E-12

E-5. Minimum Agitated (Least Battered) 95/95 TL – Cumulative and Probability Density Particle Size Distribution by Volume E-13

E-6a. Critical Velocity and Pressure Drop for AY-101 to WTP – Minimum Agitated (Least Battered) 95/95 TL Particle Size Distribution, ρ_L =1.1 kg/L, ρ_s = 2.9 kg/L, Best-Estimate Viscosity Case E-14

E-6b. Critical Velocity and Pressure Drop for AY-101 to WTP – Minimum Agitated (Least Battered) 95/95 TL Particle Size Distribution, ρ_L =1.3 kg/L, ρ_s = 2.9 kg/L, Best-Estimate Viscosity Case E-15

E-6c. Critical Velocity and Pressure Drop for AY-101 to WTP – Minimum Agitated (Least Battered) 95/95 TL Particle Size Distribution, ρ_L =1.3 kg/L, ρ_s = 2.9 kg/L, Upper-bound Viscosity Case E-16

E-7a. Critical Velocity and Pressure Drop for AZ-101 to WTP – Minimum Agitated (Least Battered) 95/95 TL Particle Size Distribution, ρ_L =1.1 kg/L, ρ_s = 2.9 kg/L, Best-Estimate Viscosity Case E-17

E-7b. Critical Velocity and Pressure Drop for AZ-101 to WTP – Minimum Agitated (Least Battered) 95/95 TL Particle Size Distribution, ρ_L =1.3 kg/L, ρ_s = 2.9 kg/L, Best-Estimate Viscosity Case E-18

E-7c. Critical Velocity and Pressure Drop for AY-101 to WTP – Minimum Agitated (Least Battered) 95/95 TL Particle Size Distribution, ρ_L =1.3 kg/L, ρ_s = 2.9 kg/L, Upper-bound Viscosity Case E-19

E-8a. Critical Velocity and Pressure Drop for AW-103 to WTP – Minimum Agitated (Least Battered) 95/95 TL Particle Size Distribution, ρ_L =1.1 kg/L, ρ_s = 2.9 kg/L, Best-Estimate Viscosity Case E-20

E-8b. Critical Velocity and Pressure Drop for AW-103 to WTP – Minimum Agitated (Least Battered) 95/95 TL Particle Size Distribution, ρ_L =1.3 kg/L, ρ_s = 2.9 kg/L, Best-Estimate Viscosity Case E-21

E-8c. Critical Velocity and Pressure Drop for AW-103 to WTP – Minimum Agitated (Least Battered) 95/95 TL Particle Size Distribution, ρ_L =1.3 kg/L, ρ_s = 2.9 kg/L, Upper-bound Viscosity Case E-22

CH2MHILL Hanford Group, Inc.
EVALUATION ANALYSIS

Calc. No. RPP-LJJ-002
Revision: 2
Page No. 1 of 22

Client: Numatec Hanford Corporation
WO/Job No. 500689/BA10
Subject: Critical Velocity and Pressure Drop Study in Support of Waste Tank Feed Transfer System
Date: 02/25/2002 By: L. J. Julyk
Checked: By: S.D. Estey
Location: 200 Area - Hanford Site, Richland, Washington
Revised: By:

SENSITIVITY ANALYSIS - HLW Transfer Routes to WTP

HLW Transfer to WTP Source Tank	Equivalent Pipe Length L_{CS} (ft)	L_{SS} (ft)	Change in Elev. (ft) H (ft)	Limiting System Pressure (lbf/in²)
Phase I				
AN-104	0	5,999	61.1	400
AY-101	0	6,674	51.4	400
AY-102	0	6,133	50.4	400
AZ-101	0	5,444	56.9	400
AZ-102	0	5,674	54.9	400
Balance of Mission (BOM)				
AW-103	1,648	4,268	41.9	275
AW-104	1,434	4,268	40.9	275

The following waste and pipe parameter were considered in the sensitivity analysis for HLW transfers to WTP from AY-101, AZ-101 and AW-103.

Internal pipe diameter (nominal)

$D_{pipe} = 3.068\,in$

Pipe roughness estimates (Anantatmula and Divine 1999), beginning-of-life (BOL) for WTP transfers and end-of-life (EOL) pipe conditions indicated by dashed and solid lines, respectively in following plots

$\varepsilon_{BOL\_CS} := 70 \cdot mil$ BOL for existing 20-yr old carbon steel pipe line

$\varepsilon_{BOL\_SS} := 2 \cdot mil$ BOL for new stainless steel pipe line

$\varepsilon_{EOL\_CS} = 150\,mil$ EOL for carbon steel pipe at end of 50-year service life

$\varepsilon_{EOL\_SS} = 10\,mil$ EOL for stainless steel pipe at end of 40-year service life

Waste parameters (Jewett et al. 2002)

ρ_L = 1.1 and 1.3 kg/L liquid "carrier" density range

ρ_s = 2.9 kg/L solids particle density based on conservative dry theoretical particle constituents

expected, potential batch-to-batch extreme, and bounding solids concentrations (vol%)

C_s = 0, 5 and 10% volume percent concentration of solids.

Particle size distribution (PSD - by volume) measurement data (Jewett et al. 2002)

Minimally Agitated (Least battered) *Mean* and *95/95 TL* PSD

Viscosity Correlation Selection Parameter

β_μ = 1 Best-estimate correlation (Jewett et al. 2002)
2 Bounding (C104) case (Jewett et al. 2002)

CH2MHILL Hanford Group, Inc.
EVALUATION ANALYSIS

Calc. No. RPP-LJJ-002
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Page No. 2 of 22

Client: Numatec Hanford Corporation WO/Job No. 500689/BA10
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Location: 200 Area - Hanford Site, Richland, Washington Revised: By:

$A_f(D_i) \equiv \frac{\pi}{4} \cdot D_i^2$ flow area of pipe

Primary transfer pipe, 3-in. schedule 40

$D_{Pipe} \equiv 3.068 \cdot in$ internal diameter)

$A_P \equiv A_f(D_{Pipe})$ $A_P = 7.393\,in^2$ flow area of pipe $Q_v(v) \equiv A_P \cdot v$ volume flow rate

Project W-211 Transfer Pump (Curve No. 61412 or 61413)
(3x6A VCM 6 Stage Sulzer Pump)

$rev := 2 \cdot \pi \cdot rad$ $rpm := \frac{rev}{min}$

$gpm = 1\,\frac{gal}{min}$

Flow (gpm)	Head (ft)
0	625
80	564
100	550
120	528
140	500
200	400
240	310

$n_{max} := 3560 \cdot rpm$

$i := 0..6$

$vQ_{W211TP_i} := H_{W211TP_i} :=$

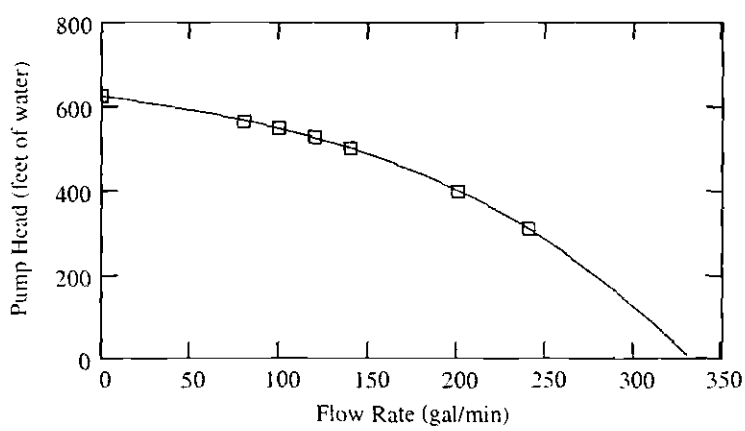
$cH_{W211TP} := regress(vQ_{W211TP}, vH_{W211TP}, 3)$

$H_{pump}(Q,n) := interp\left(cH_{W211TP}, vQ_{W211TP}, vH_{W211TP}, \frac{Q}{gpm} \cdot \frac{n_{max}}{n}\right) \cdot ft \cdot \left(\frac{n}{n_{max}}\right)^2$

$p_{pump}(Q,n,\rho) := H_{pump}(Q,n) \cdot \rho \cdot g$ $Q_{runout} := root(H_{pump}(Q, n_{max}), Q)$

$Q_{runout} = 332\,gpm$ run-out flow rate at n_{max}

$\frac{Q_{runout}}{A_P} = 14.408\,\frac{ft}{sec}$



Sensitivity.mcd

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EVALUATION ANALYSIS

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Client: Numatec Hanford Corporation
Subject: Critical Velocity and Pressure Drop Study in Support of Waste Tank Feed Transfer System
Location: 200 Area - Hanford Site, Richland, Washington

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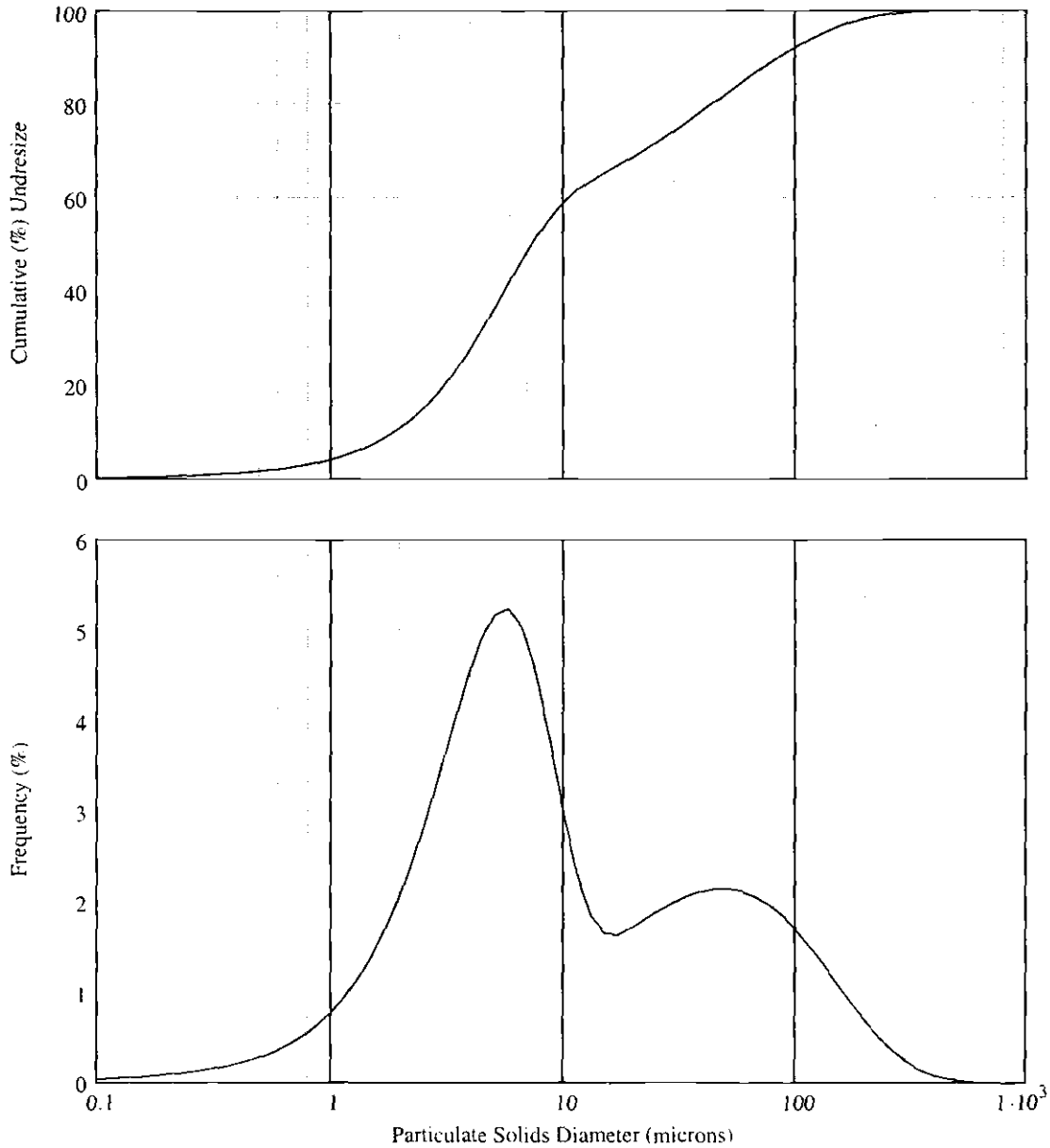
Checked: By: S.D. Estey
Revised: By:

Figure E-1. Minimum Agitated (Least Battered) *Mean* - Cumulative and Probability Density Particle Size Distribution by Volume.

$d_{pRR} := d_{LB\_M}$ $j_R := j_{LB\_M}$ $\phi_{RR} := PDF_{LB\_M}$ $\phi_{RRc} := CDF_{LB\_M}$ $d_{50} := D_\beta(d_{pRR}, \phi_{RRc}, 50\%)$

$d_{50} = 7.4\,\mu m$



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EVALUATION ANALYSIS

Calc. No. RPP-LJJ-002
Revision: 2
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Client: Numatec Hanford Corporation
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Checked: By: S.D. Estey
Location: 200 Area - Hanford Site, Richland, Washington
Revised: By:

Figure E-2a. Critical Velocity and Pressure Drop for AY-101 to WTP - Minimum Agitated (Least Battered) *Mean* Particle Size Distribution, ρ_L=1.1 kg/L, ρ_s=2.9 kg/L, Best-Estimate Viscosity Case.

	Carbon Steel	Stainless Steel
$D_{pipe} = 3.068\,in$	$L_{CS} := 0 \cdot ft$	$L_{SS} := 6674 \cdot ft$
$H := 51.4 \cdot ft$	$\varepsilon_{BOL\_CS} = 70\,mil$	$\varepsilon_{BOL\_SS} = 2\,mil$
	$\varepsilon_{EOL\_CS} = 150\,mil$	$\varepsilon_{EOL\_SS} = 10\,mil$

$d_{50} = 7.4\,\mu m$ median particle size

$\boxed{\beta_\mu := 1}$ select best-estimate viscosity

$\mu_l := \mu_c(\mu_L, \gamma_L, 0\%, \beta_\mu)$ $\mu_l = 1.5\,cP$ liquid viscosity

$\beta_{cv} := 1.2$ Oroskar and Turian (1980) critical velocity -empirical equation (1.3 times best-estimate)

$\kappa_{cv} := 1.30$

$\kappa_f := 1$ Best-estimate Wasp pressure drop relation

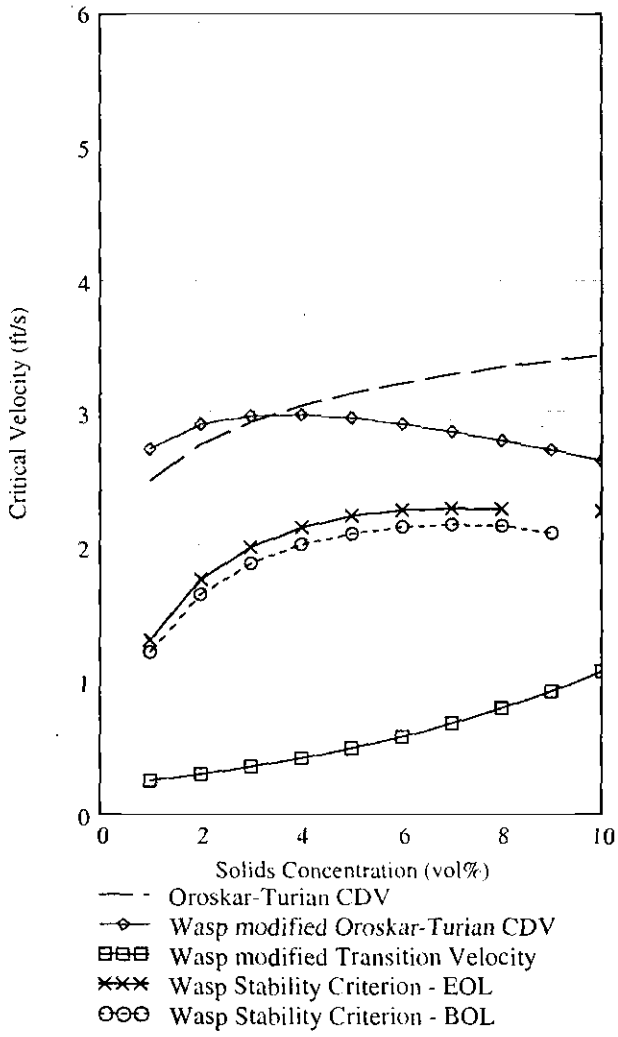
$K_D := 82$

$S := 5\%$ Wasp stability criterion parameter

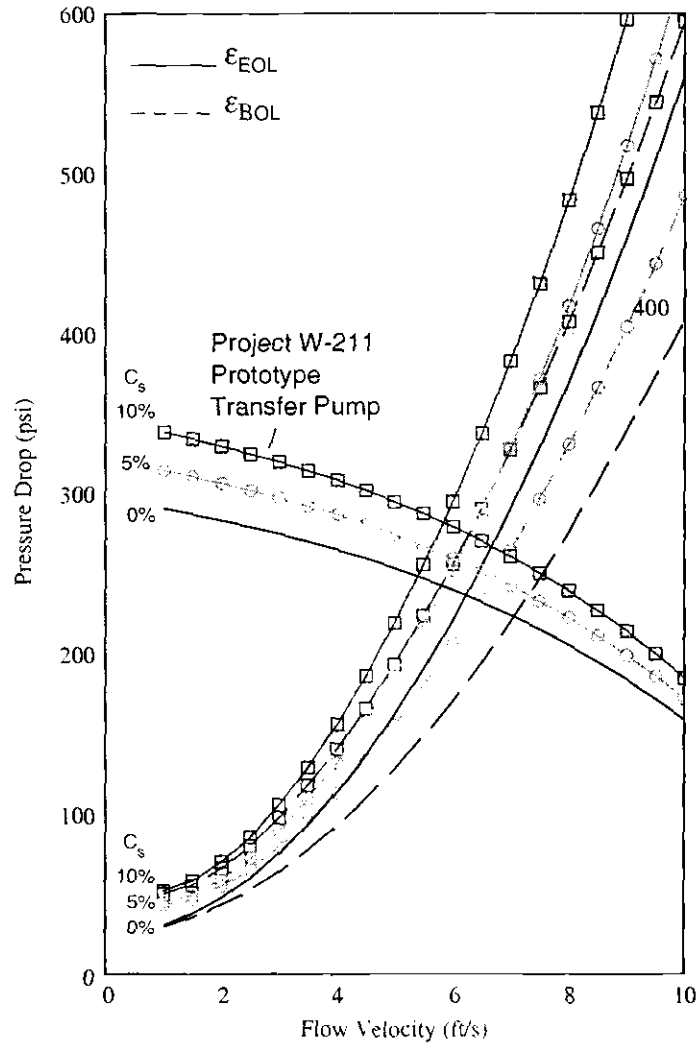
$\boxed{\rho_L := 1.1 \cdot kg \cdot liter^{-1}}$ liquid density

$\rho_s := 2.9 \cdot kg \cdot liter^{-1}$ solids density

Critical Velocity



Pressure Drop



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Subject: Critical Velocity and Pressure Drop Study in Support of Waste Tank Feed Transfer System
Date: 02/25/2002 By: L. J. Julyk
Checked: By: S.D. Estey
Location: 200 Area - Hanford Site, Richland, Washington
Revised: By:

Figure E-2b. Critical Velocity and Pressure Drop for AY-101 to WTP - Minimum Agitated (Least Battered) *Mean* Particle Size Distribution, ρ_L=1.3 kg/L, ρ_s=2.9 kg/L, Best-Estimate Viscosity Case.

	Carbon Steel	Stainless Steel
$D_{pipe} = 3.068\,in$	$L_{CS} = 0\,ft$	$L_{SS} = 6674\,ft$
$H = 51\,ft$	$\varepsilon_{BOL\_CS} = 70\,mil$	$\varepsilon_{BOL\_SS} = 2\,mil$
	$\varepsilon_{EOL\_CS} = 150\,mil$	$\varepsilon_{EOL\_SS} = 10\,mil$

$d_{50} = 7.4\,\mu m$ median particle size

$\beta_\mu := 1$ select best-estimate viscosity

$\mu_1 := \mu_c(\mu_L, \gamma_L, 0\%, \beta_\mu)$ $\mu_1 = 1.5\,cP$ liquid viscosity

$\beta_{cv} = 1.2$ Oroskar and Turian (1980) critical velocity -empirical equation (1.3 times best-estimate)

$\kappa_{cv} = 1.3$

$\kappa_f = 1$ Best-estimate Wasp pressure drop relation

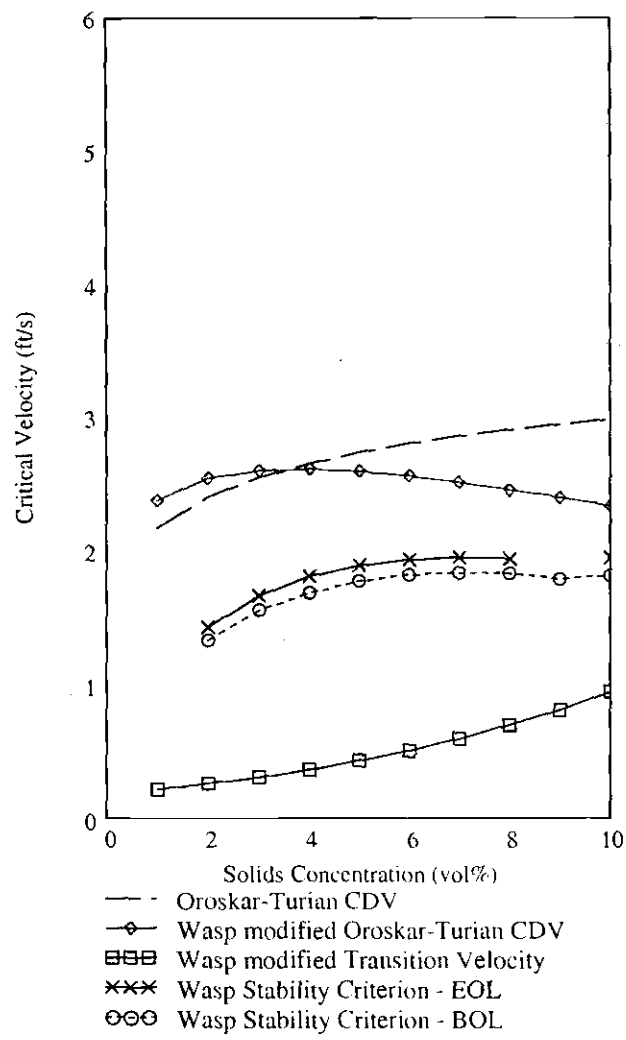
$K_D = 82$

$S = 5\,\%$ Wasp stability criterion parameter

$\rho_L := 1.3 \cdot kg \cdot liter^{-1}$ liquid density

$\rho_s = 2.9\,kg \cdot liter^{-1}$ solids density

Critical Velocity



Pressure Drop

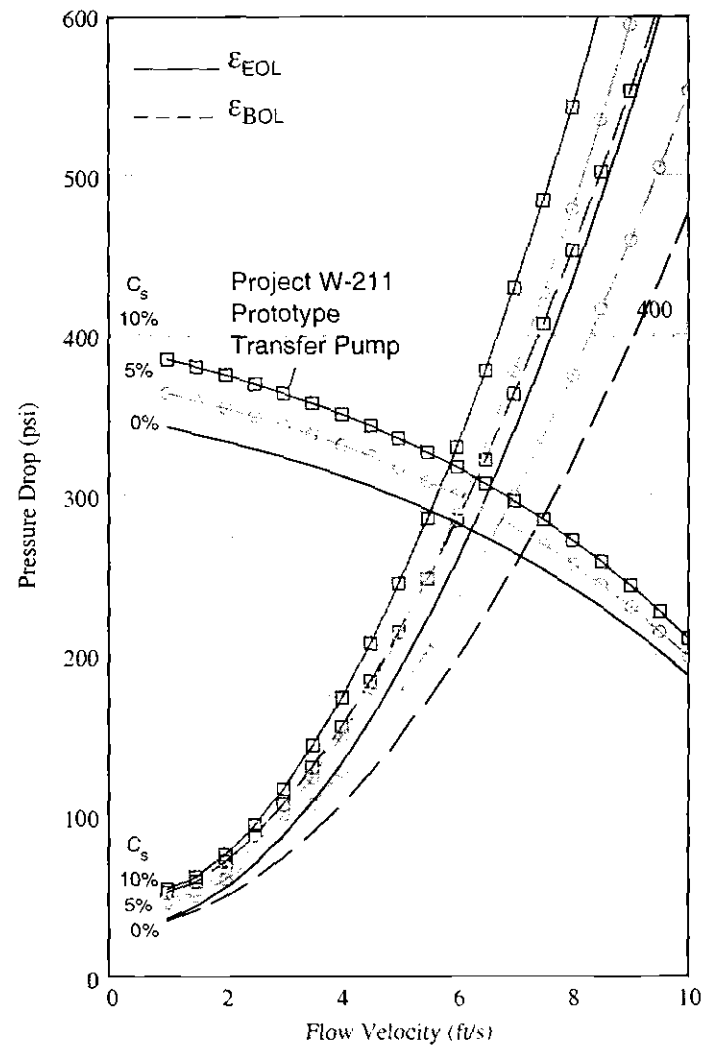


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Figure E-2c. Critical Velocity and Pressure Drop for AY-101 to WTP - Minimum Agitated (Least Battered) *Mean* Particle Size Distribution, ρ_L=1.3 kg/L, ρ_s=2.9 kg/L, Upper-bound Viscosity Case.

	Carbon Steel	Stainless Steel
$D_{pipe} = 3.068\,in$	$L_{CS} = 0\,ft$	$L_{SS} = 6674\,ft$
$H = 51\,ft$	$\varepsilon_{BOL\_CS} = 70\,mil$	$\varepsilon_{BOL\_SS} = 2\,mil$
	$\varepsilon_{EOL\_CS} = 150\,mil$	$\varepsilon_{EOL\_SS} = 10\,mil$

$\beta_{cv} = 1.2$, $\kappa_{cv} = 1.3$ — Oroskar and Turian (1980) critical velocity -empirical equation (1.3 times best-estimate)

$\kappa_f = 1$, $K_D = 82$ — Best-estimate Wasp pressure drop relation

$S = 5\,\%$ — Wasp stability criterion parameter

$d_{50} = 7.4\,\mu m$ — median particle size

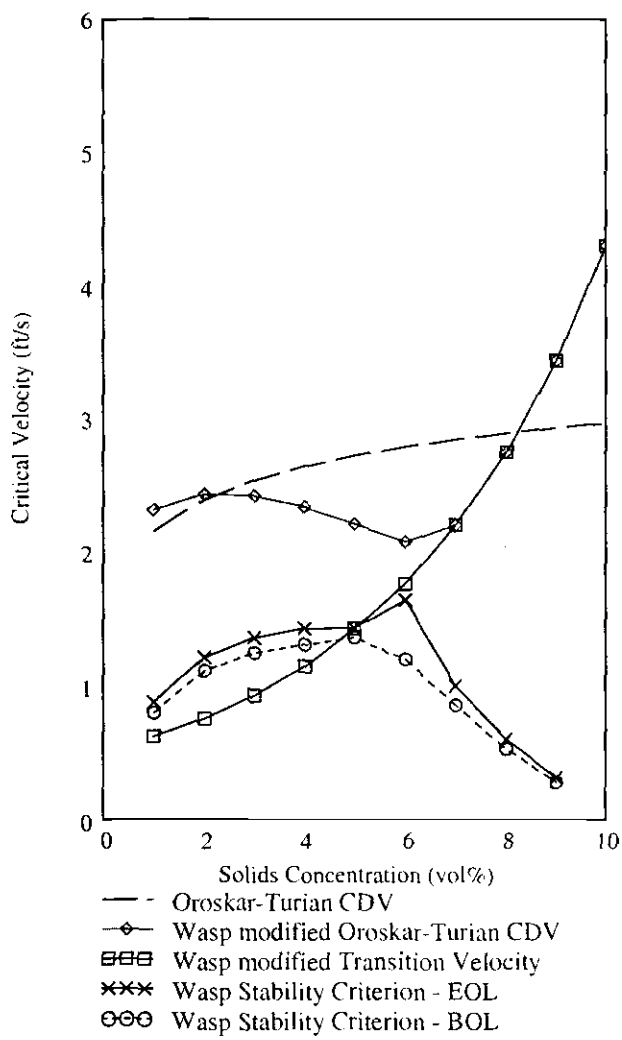
$\boxed{\beta_\mu := 2}$ — select bounding viscosity

$\mu_l := \mu_c(\mu_L, \gamma_L, 0\%, \beta_\mu)$ $\mu_l = 1.6\,cP$ — liquid viscosity

$\boxed{\rho_L := 1.3 \cdot kg \cdot liter^{-1}}$ — liquid density

$\rho_s = 2.9\,kg \cdot liter^{-1}$ — solids density

Critical Velocity



Pressure Drop

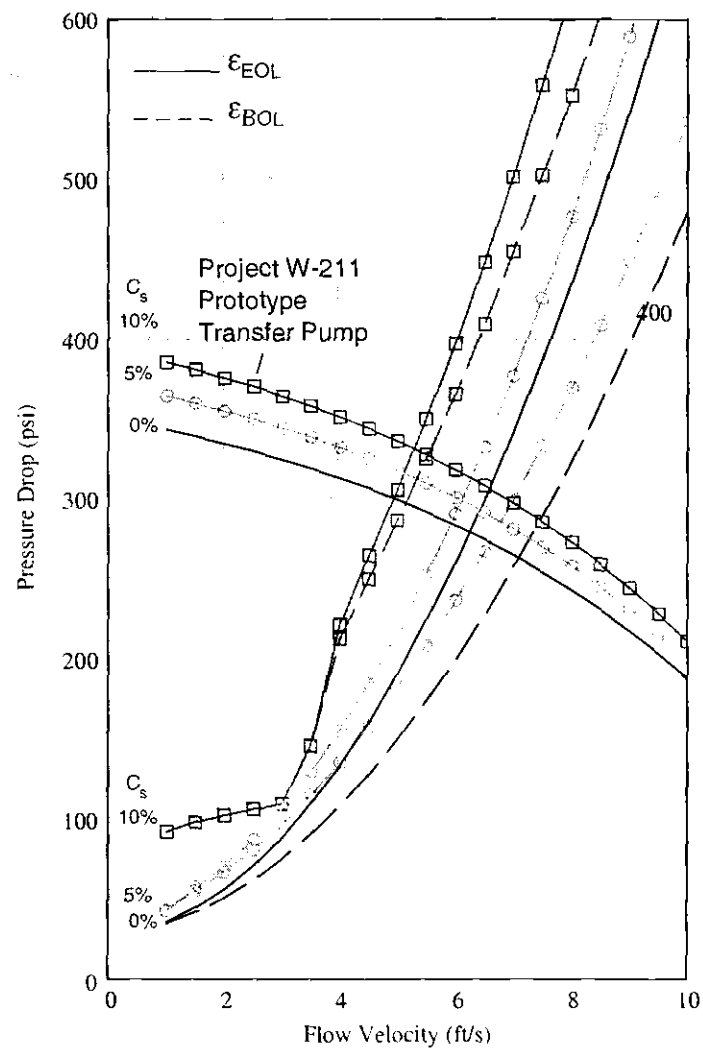


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Figure E-3a. Critical Velocity and Pressure Drop for AZ-101 to WTP - Minimum Agitated (Least Battered) *Mean* Particle Size Distribution, ρ_L=1.1 kg/L, ρ_s=2.9 kg/L, Best-Estimate Viscosity Case.

	Carbon Steel	Stainless Steel
$D_{pipe} = 3.068\,in$	$L_{CS} := 0 \cdot ft$	$L_{SS} := 5444 \cdot ft$
$H := 56.9 \cdot ft$	$\varepsilon_{BOL\_CS} = 70\,mil$	$\varepsilon_{BOL\_SS} = 2\,mil$
	$\varepsilon_{EOL\_CS} = 150\,mil$	$\varepsilon_{EOL\_SS} = 10\,mil$

$d_{50} = 7.4\,\mu m$ median particle size

$\beta_\mu := 1$ select best-estimate viscosity

$\mu_l := \mu_c(\mu_L, \gamma_L, 0\%, \beta_\mu)$ $\mu_l = 1.5\,cP$ liquid viscosity

$\beta_{cv} := 1.2$ Oroskar and Turian (1980) critical velocity -empirical equation (1.3 times best-estimate)

$\kappa_{cv} := 1.30$

$\kappa_f := 1$ Best-estimate Wasp pressure drop relation

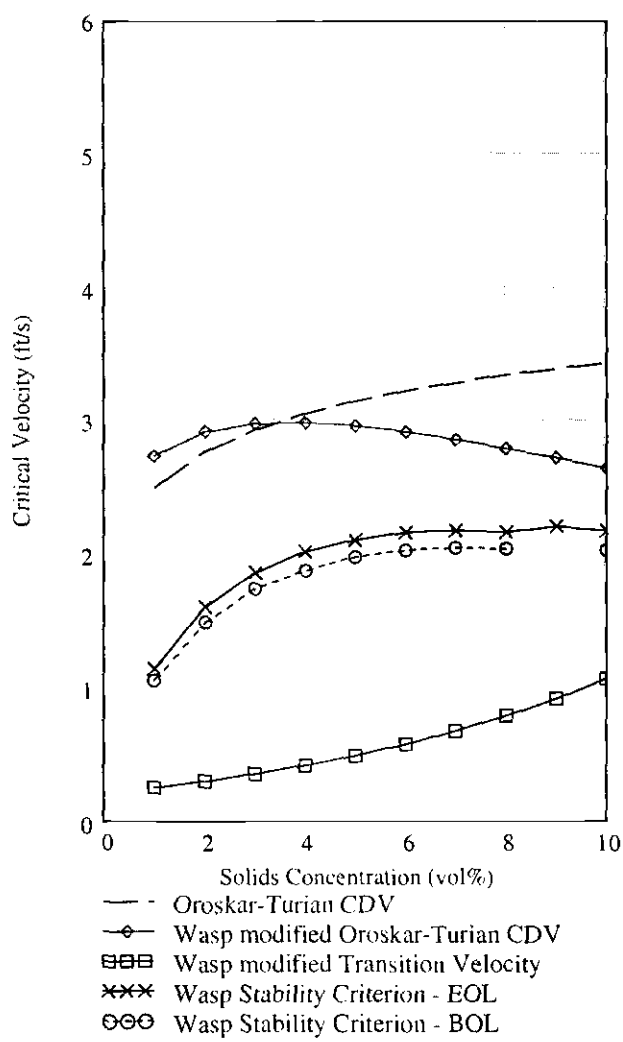
$K_D := 82$

$S := 5\%$ Wasp stability criterion parameter

$\rho_L := 1.1 \cdot kg \cdot liter^{-1}$ liquid density

$\rho_s := 2.9 \cdot kg \cdot liter^{-1}$ solids density

Critical Velocity



Pressure Drop

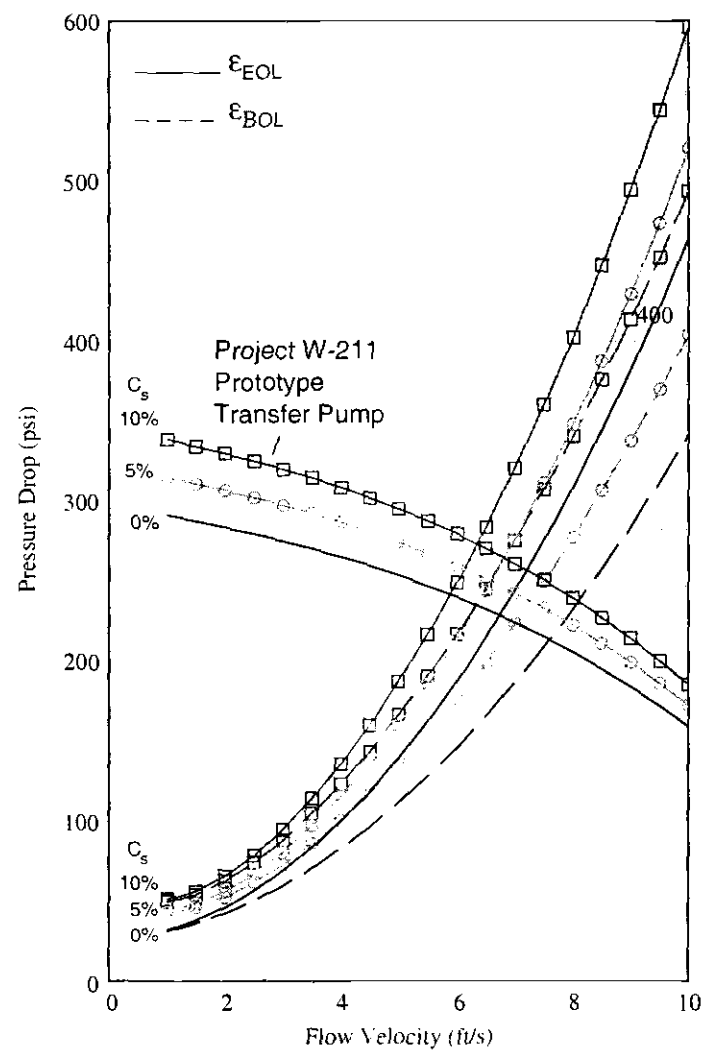


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Figure E-3b. Critical Velocity and Pressure Drop for AZ-101 to WTP - Minimum Agitated (Least Battered) *Mean* Particle Size Distribution, ρ_L=1.3 kg/L, ρ_s=2.9 kg/L, Best-Estimate Viscosity Case.

	Carbon Steel	Stainless Steel
$D_{pipe} = 3.068\,in$	$L_{CS} = 0\,ft$	$L_{SS} = 5444\,ft$
$H = 57\,ft$	$\varepsilon_{BOL\_CS} = 70\,mil$	$\varepsilon_{BOL\_SS} = 2\,mil$
	$\varepsilon_{EOL\_CS} = 150\,mil$	$\varepsilon_{EOL\_SS} = 10\,mil$

$\beta_{cv} = 1.2$ Oroskar and Turian (1980) critical velocity -empirical equation (1.3 times best-estimate)

$\kappa_{cv} = 1.3$

$\kappa_f = 1$ Best-estimate Wasp pressure drop relation

$K_D = 82$ $S = 5\,\%$ Wasp stability criterion parameter

$d_{50} = 7.4\,\mu m$ median particle size

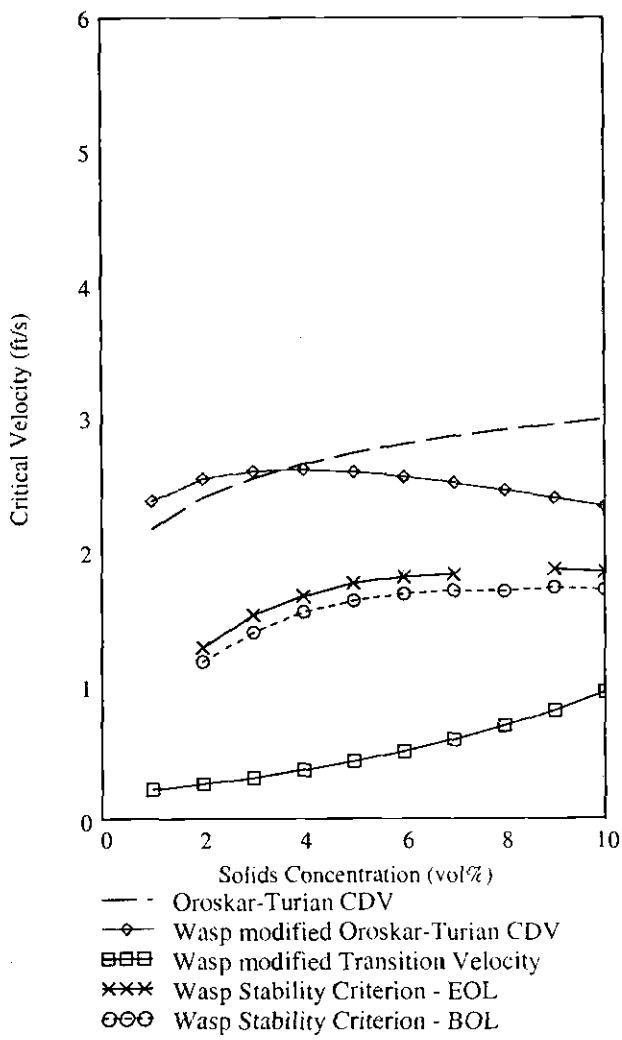
$\beta_\mu := 1$ select best-estimate viscosity

$\mu_l := \mu_c(\mu_L, \gamma_L, 0\%, \beta_\mu)$ $\mu_l = 1.5\,cP$ liquid viscosity

$\rho_L := 1.3 \cdot kg \cdot liter^{-1}$ liquid density

$\rho_s = 2.9\,kg \cdot liter^{-1}$ solids density

Critical Velocity



Pressure Drop

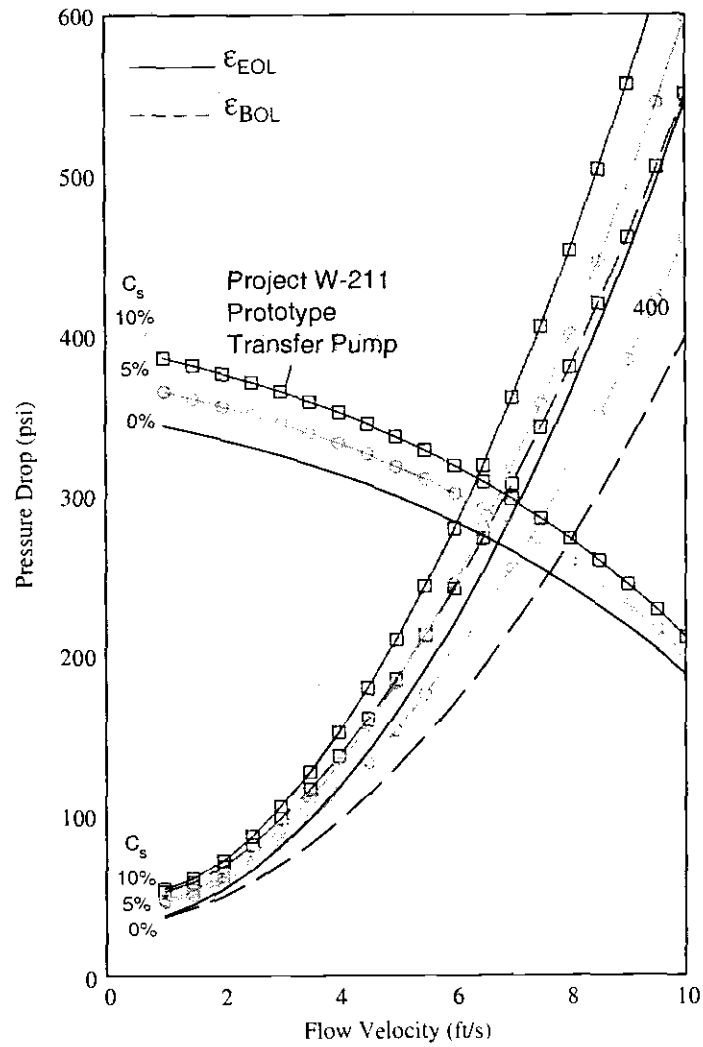


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Figure E-3c. Critical Velocity and Pressure Drop for AY-101 to WTP - Minimum Agitated (Least Battered) *Mean* Particle Size Distribution, ρ_L=1.3 kg/L, ρ_s=2.9 kg/L, Upper-bound Viscosity Case.

	Carbon Steel	Stainless Steel
$D_{pipe} = 3.068\,in$	$L_{CS} = 0\,ft$	$L_{SS} = 5444\,ft$
$H = 57\,ft$	$\varepsilon_{BOL\_CS} = 70\,mil$	$\varepsilon_{BOL\_SS} = 2\,mil$
	$\varepsilon_{EOL\_CS} = 150\,mil$	$\varepsilon_{EOL\_SS} = 10\,mil$

$\beta_{cv} = 1.2$ Oroskar and Turian (1980) critical velocity -empirical equation (1.3 times best-estimate)

$\kappa_{cv} = 1.3$

$\kappa_f = 1$ Best-estimate Wasp pressure drop relation

$K_D = 82$ $S = 5\,\%$ Wasp stability criterion parameter

$d_{50} = 7.4\,\mu m$ median particle size

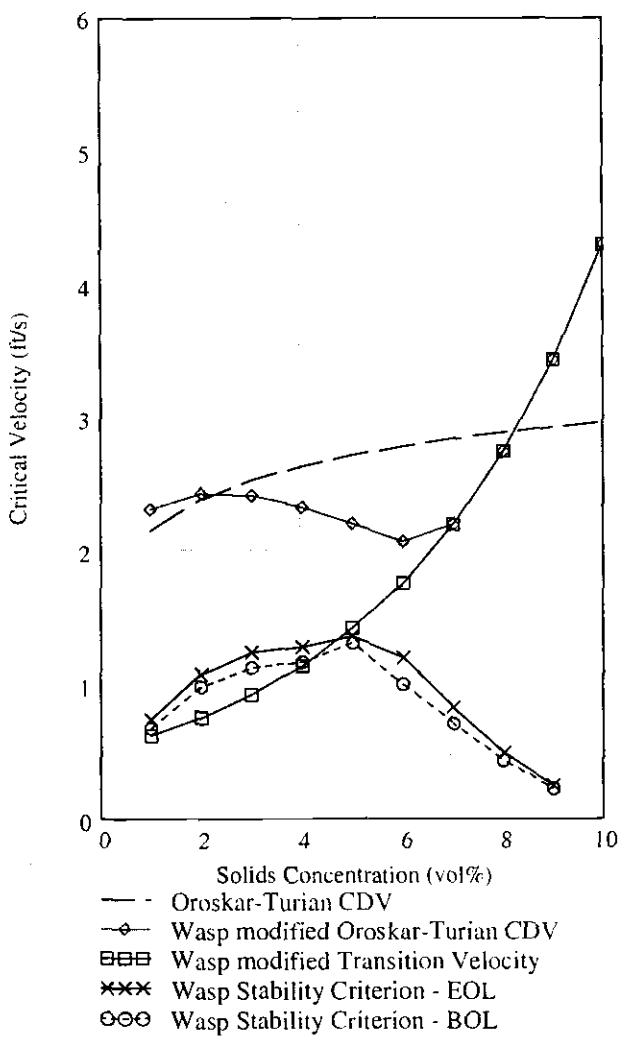
$\boxed{\beta_\mu := 2}$ select bounding viscosity

$\mu_l := \mu_c(\mu_L, \gamma_L, 0\%, \beta_\mu)$ $\mu_l = 1.6\,cP$ liquid viscosity

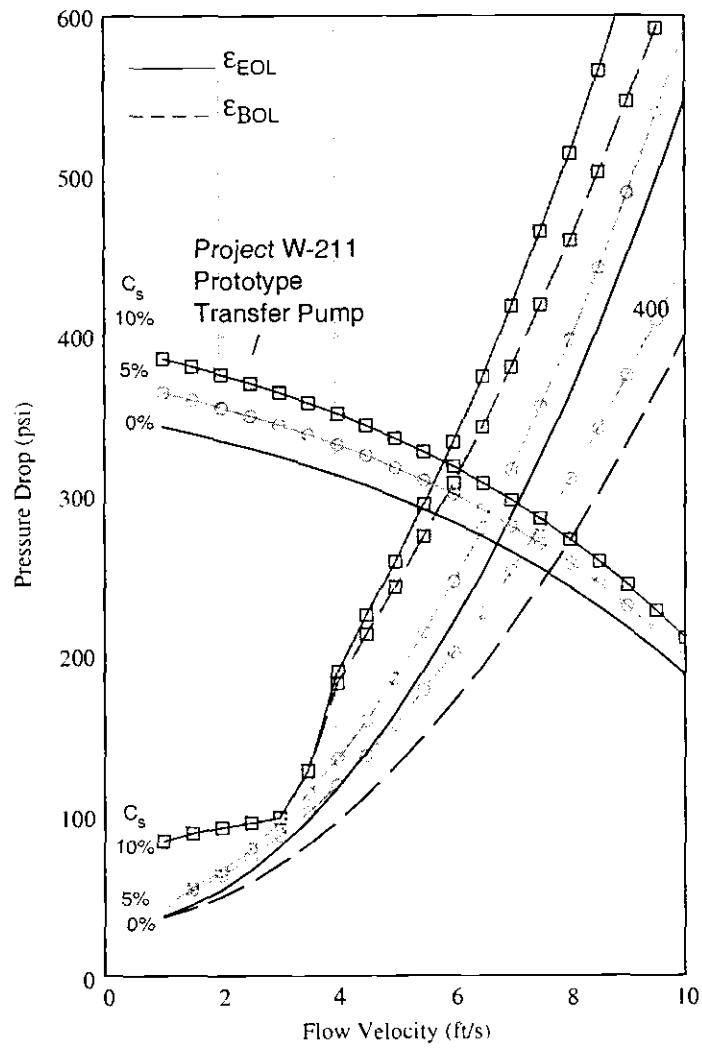
$\boxed{\rho_L := 1.3 \cdot kg \cdot liter^{-1}}$ liquid density

$\rho_s = 2.9\,kg \cdot liter^{-1}$ solids density

Critical Velocity



Pressure Drop



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Checked: By: S.D. Estey
Revised: By:

Figure E-4a. Critical Velocity and Pressure Drop for AW-103 to WTP - Minimum Agitated (Least Battered) *Mean* Particle Size Distribution, ρ_L=1.1 kg/L, ρ_s=2.9 kg/L, Best-Estimate Viscosity Case.

	Carbon Steel	Stainless Steel
$D_{pipe} = 3.068\,in$	$L_{CS} := 1648 \cdot ft$	$L_{SS} := 4268 \cdot ft$
$H := 41.9 \cdot ft$	$\varepsilon_{BOL\_CS} = 70\,mil$	$\varepsilon_{BOL\_SS} = 2\,mil$
	$\varepsilon_{EOL\_CS} = 150\,mil$	$\varepsilon_{EOL\_SS} = 10\,mil$

$d_{50} = 7.4\,\mu m$ median particle size

$\beta_\mu := 1$ select best-estimate viscosity

$\mu_1 := \mu_c(\mu_L, \gamma_L, 0\%, \beta_\mu)$ $\mu_1 = 1.5\,cP$ liquid viscosity

$\beta_{cv} := 1.2$ Oroskar and Turian (1980) critical velocity -empirical equation (1.3 times best-estimate)

$\kappa_{cv} := 1.30$

$\kappa_f := 1$ Best-estimate Wasp pressure drop relation

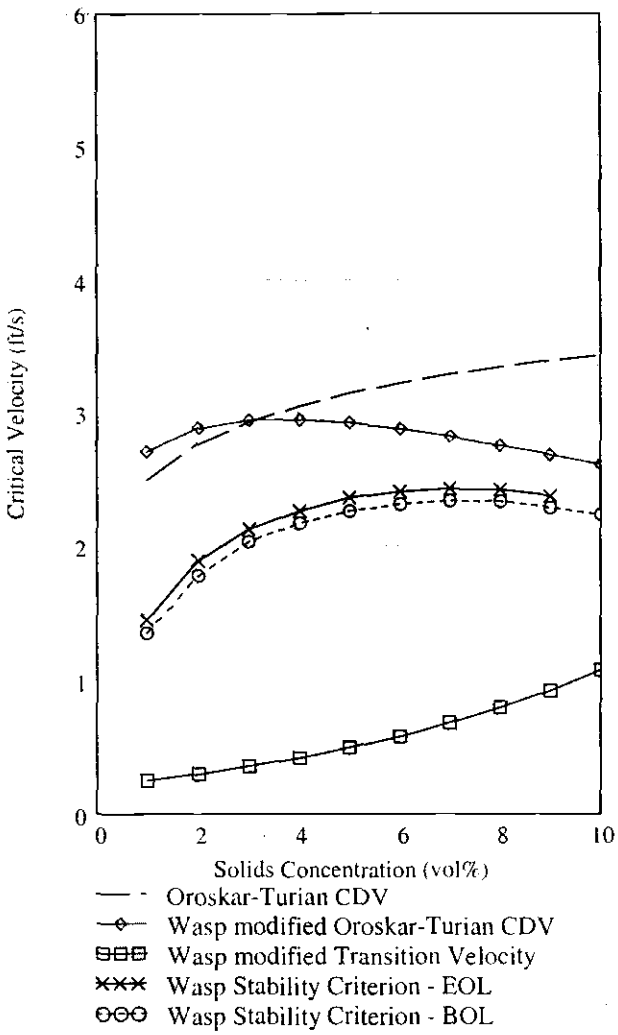
$K_D := 82$

$S := 5\%$ Wasp stability criterion parameter

$\rho_L := 1.1 \cdot kg \cdot liter^{-1}$ liquid density

$\rho_s := 2.9 \cdot kg \cdot liter^{-1}$ solids density

Critical Velocity



Pressure Drop

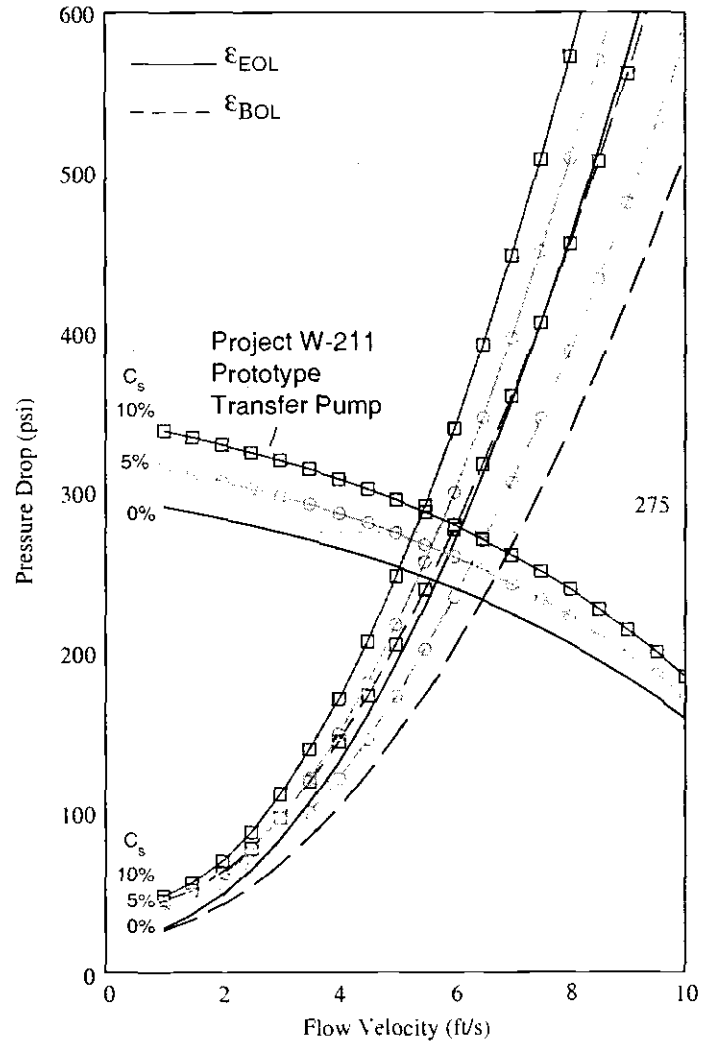


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Figure E-4b. Critical Velocity and Pressure Drop for AW-103 to WTP - Minimum Agitated (Least Battered) *Mean* Particle Size Distribution, ρ_L=1.3 kg/L, ρ_s=2.9 kg/L, Best-Estimate Viscosity Case.

	Carbon Steel	Stainless Steel
$D_{pipe} = 3.068\,in$	$L_{CS} = 1648\,ft$	$L_{SS} = 4268\,ft$
$H = 42\,ft$	$\varepsilon_{BOL\_CS} = 70\,mil$	$\varepsilon_{BOL\_SS} = 2\,mil$
	$\varepsilon_{EOL\_CS} = 150\,mil$	$\varepsilon_{EOL\_SS} = 10\,mil$

$\beta_{cv} = 1.2$ Oroskar and Turian (1980) critical velocity -empirical equation (1.3 times best-estimate)

$\kappa_{cv} = 1.3$

$\kappa_f = 1$ Best-estimate Wasp pressure drop relation

$K_D = 82$ $S = 5\,\%$ Wasp stability criterion parameter

$d_{50} = 7.4\,\mu m$ median particle size

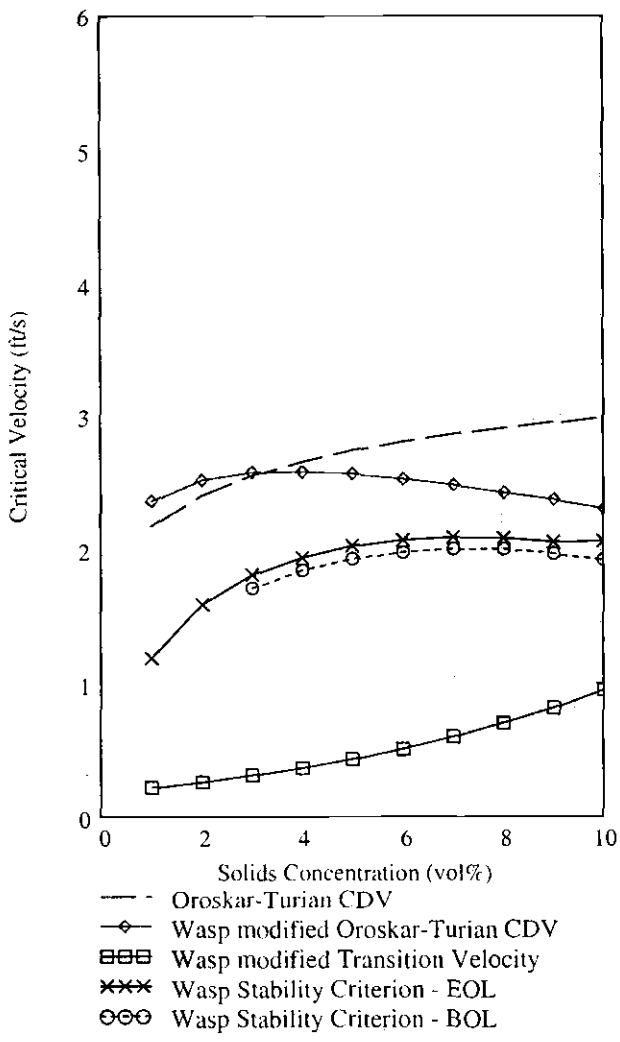
$\boxed{\rho_L := 1.3 \cdot kg \cdot liter^{-1}}$ liquid density

$\boxed{\beta_\mu := 1}$ select best-estimate viscosity

$\mu_l := \mu_c(\mu_L, \gamma_L, 0\%, \beta_\mu)$ $\mu_l = 1.5\,cP$ liquid viscosity

$\rho_S = 2.9\,kg \cdot liter^{-1}$ solids density

Critical Velocity



Pressure Drop

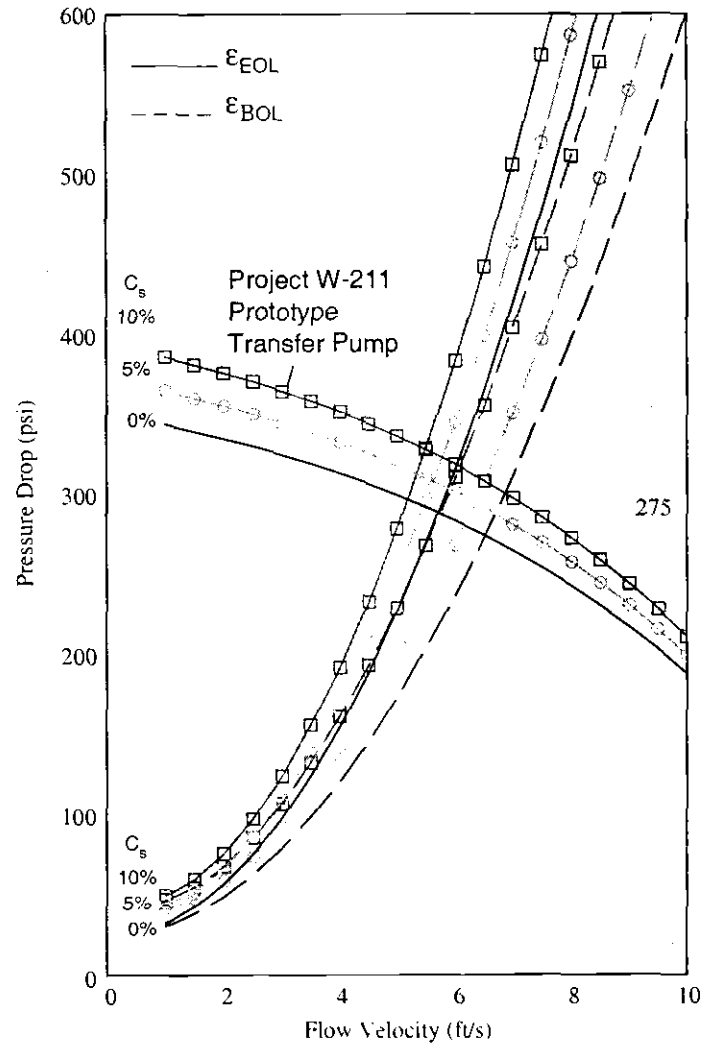


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Figure E-4c. Critical Velocity and Pressure Drop for AW-103 to WTP - Minimum Agitated (Least Battered) *Mean* Particle Size Distribution, ρ_L=1.3 kg/L, ρ_s=2.9 kg/L, Upper-bound Viscosity Case.

	Carbon Steel	Stainless Steel
$D_{pipe} = 3.068\,in$	$L_{CS} = 1648\,ft$	$L_{SS} = 4268\,ft$
$H = 42\,ft$	$\varepsilon_{BOL\_CS} = 70\,mil$	$\varepsilon_{BOL\_SS} = 2\,mil$
	$\varepsilon_{EOL\_CS} = 150\,mil$	$\varepsilon_{EOL\_SS} = 10\,mil$

$\beta_{cv} = 1.2$, $\kappa_{cv} = 1.3$ — Oroskar and Turian (1980) critical velocity -empirical equation (1.3 times best-estimate)

$\kappa_f = 1$, $K_D = 82$ — Best-estimate Wasp pressure drop relation

$S = 5\,\%$ — Wasp stability criterion parameter

$d_{50} = 7.4\,\mu m$ — median particle size

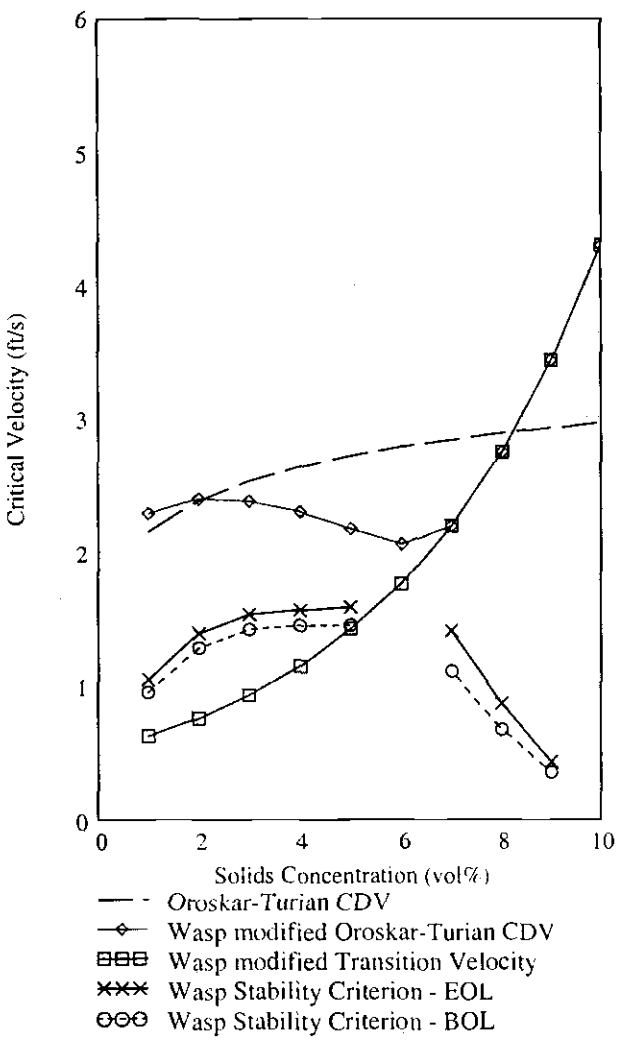
$\boxed{\beta_\mu := 2}$ — select bounding viscosity

$\mu_l := \mu_c(\mu_L, \gamma_L, 0\%, \beta_\mu)$ $\mu_l = 1.6\,cP$ — liquid viscosity

$\boxed{\rho_L := 1.3 \cdot kg \cdot liter^{-1}}$ — liquid density

$\rho_s = 2.9\,kg \cdot liter^{-1}$ — solids density

Critical Velocity



Pressure Drop

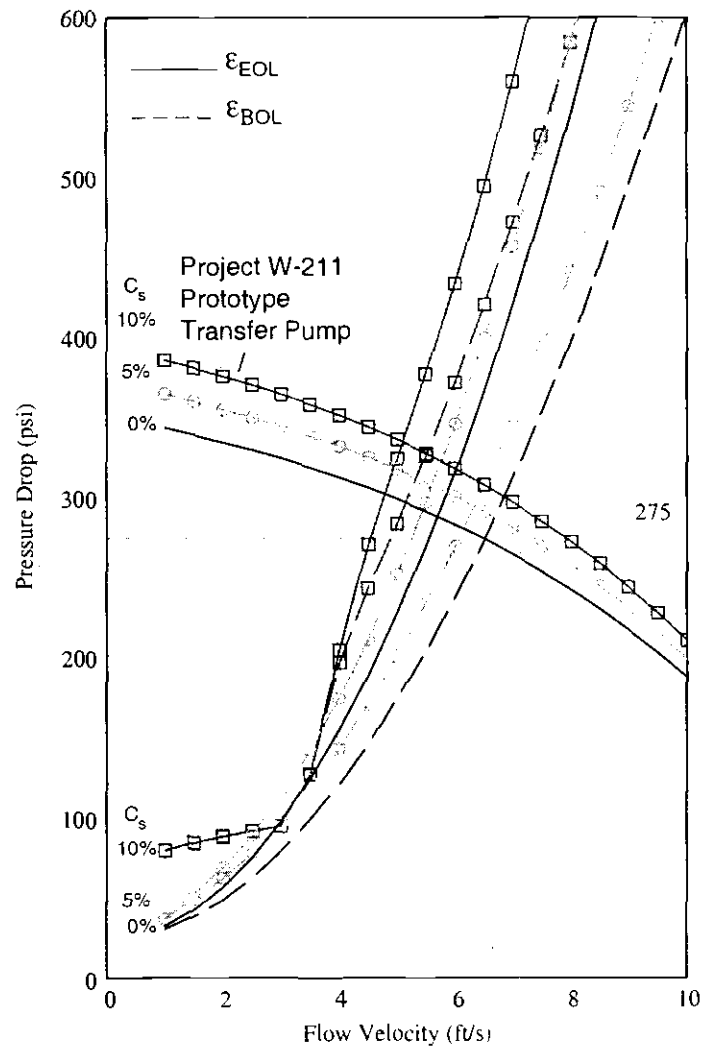


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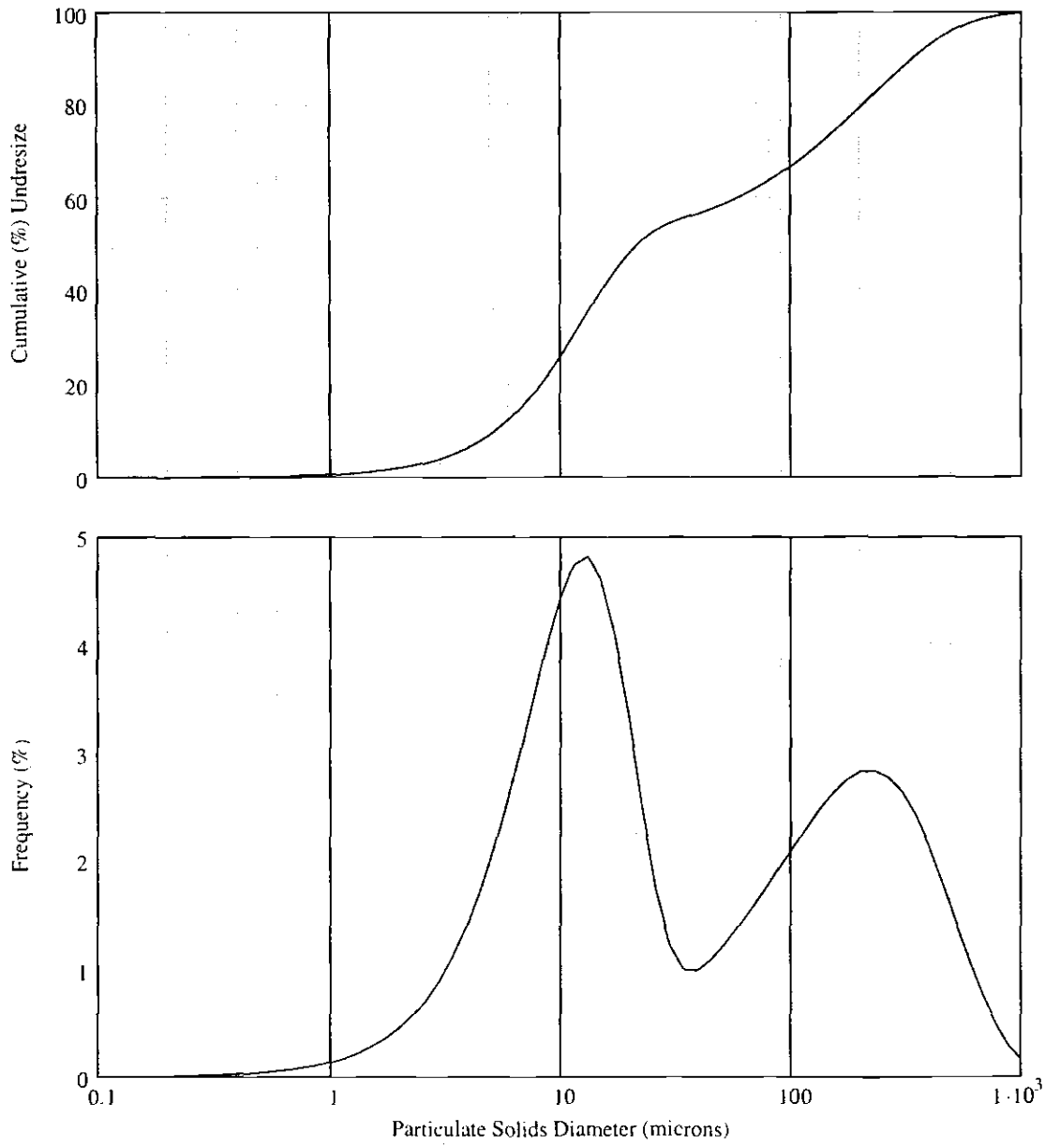
Figure E-5. Minimum Agitated (Least Battered) *95/95 TL* - Cumulative and Probability Density Particle Size Distribution by Volume.

$d_{pRR} := d_{LB\_9595TL}$ $j_R := j_{LB\_9595TL}$ $\phi_{RR} := PDF_{LB\_9595TL}$ $\phi_{RRc} := CDF_{LB\_9595TL}$ $d_{50} := D_\beta(d_{pRR}, \phi_{RRc}, 50\%)$

$d_{50} = 21.8\,\mu m$



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Revised: By:

Figure E-6a. Critical Velocity and Pressure Drop for AY-101 to WTP - Minimum Agitated (Least Battered) *95/95 TL* Particle Size Distribution, ρ_L=1.1 kg/L, ρ_s=2.9 kg/L, Best-Estimate Viscosity Case.

	Carbon Steel	Stainless Steel
$D_{pipe} = 3.068\,in$	$L_{CS} := 0 \cdot ft$	$L_{SS} := 6674 \cdot ft$
$H := 51.4 \cdot ft$	$\varepsilon_{BOL\_CS} = 70\,mil$	$\varepsilon_{BOL\_SS} = 2\,mil$
	$\varepsilon_{EOL\_CS} = 150\,mil$	$\varepsilon_{EOL\_SS} = 10\,mil$

$d_{50} = 21.8\,\mu m$ median particle size

$\beta_\mu := 1$ select best-estimate viscosity

$\mu_l := \mu_c(\mu_L, \gamma_L, 0\%, \beta_\mu)$ $\mu_l = 1.5\,cP$ liquid viscosity

$\beta_{cv} := 1.2$ Oroskar and Turian (1980) critical velocity -empirical equation (1.3 times best-estimate)

$\kappa_{cv} := 1.30$

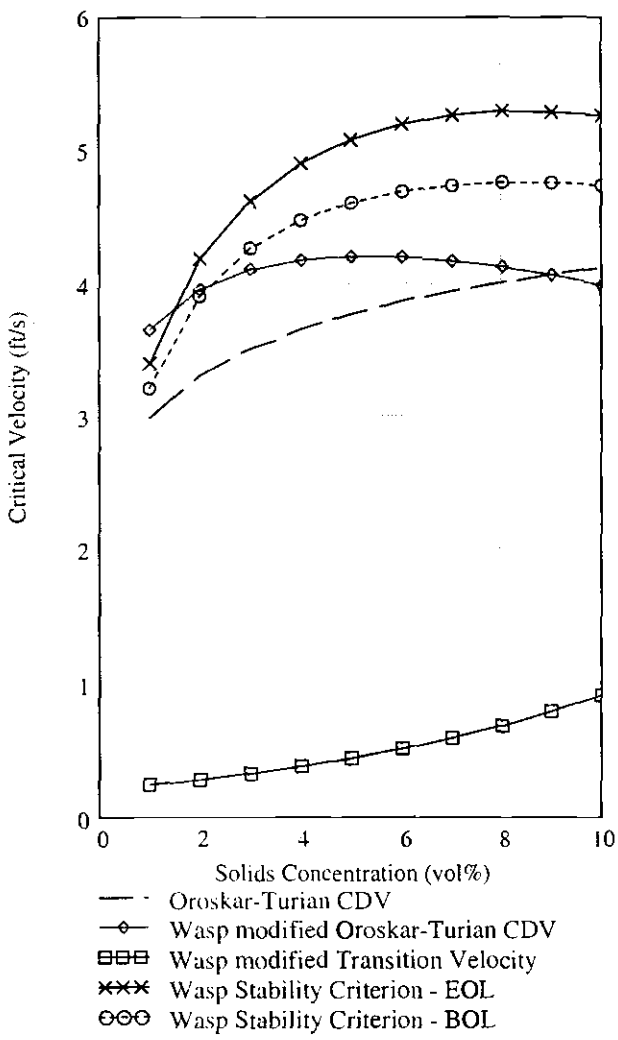
$\kappa_f := 1$ Best-estimate Wasp pressure drop relation

$K_D := 82$ $S := 5\%$ Wasp stability criterion parameter

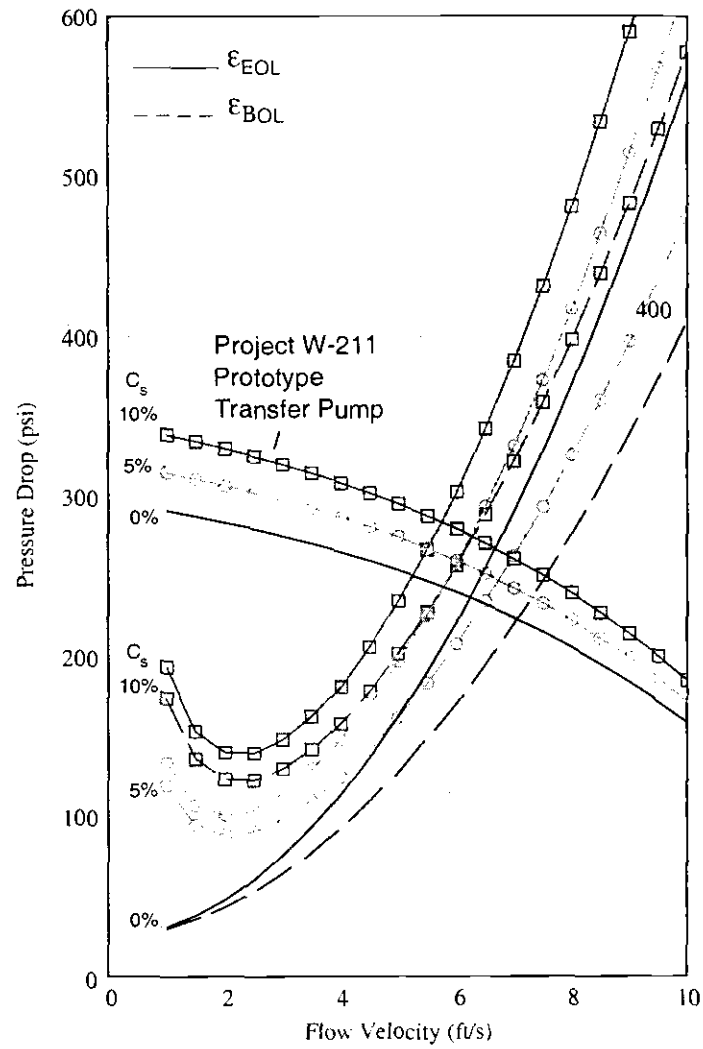
$\rho_L := 1.1 \cdot kg \cdot liter^{-1}$ liquid density

$\rho_s := 2.9 \cdot kg \cdot liter^{-1}$ solids density

Critical Velocity



Pressure Drop



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Subject: Critical Velocity and Pressure Drop Study in Support of Waste Tank Feed Transfer System
Location: 200 Area - Hanford Site, Richland, Washington

WO/Job No. 500689/BA10
Date: 02/25/2002 By: L. J. Julyk
Checked: By: S.D. Estey
Revised: By:

Figure E-6b. Critical Velocity and Pressure Drop for AY-101 to WTP - Minimum Agitated (Least Battered) *95/95 TL* Particle Size Distribution, ρ_L=1.3 kg/L, ρ_s=2.9 kg/L, Best-Estimate Viscosity Case.

	Carbon Steel	Stainless Steel
$D_{pipe} = 3.068\,in$	$L_{CS} = 0\,ft$	$L_{SS} = 6674\,ft$
$H = 51\,ft$	$\varepsilon_{BOL\_CS} = 70\,mil$	$\varepsilon_{BOL\_SS} = 2\,mil$
	$\varepsilon_{EOL\_CS} = 150\,mil$	$\varepsilon_{EOL\_SS} = 10\,mil$

$d_{50} = 21.8\,\mu m$ *median particle size*

$\beta_\mu := 1$ select best-estimate viscosity

$\mu_l := \mu_c(\mu_L, \gamma_L, 0\%, \beta_\mu)$ $\mu_l = 1.5\,cP$ liquid viscosity

$\beta_{cv} = 1.2$ Oroskar and Turian (1980) critical velocity -empirical equation (1.3 times best-estimate)

$\kappa_{cv} = 1.3$

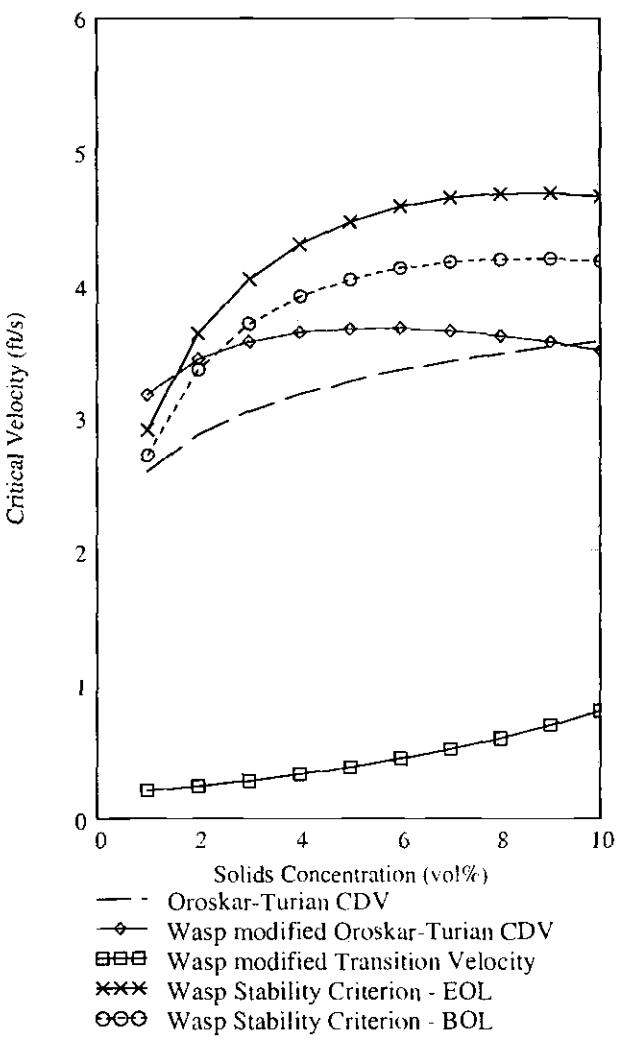
$\kappa_f = 1$ Best-estimate Wasp pressure drop relation

$K_D = 82$ $S = 5\,\%$ Wasp stability criterion parameter

$\rho_L := 1.3 \cdot kg \cdot liter^{-1}$ liquid density

$\rho_s = 2.9\,kg \cdot liter^{-1}$ solids density

Critical Velocity



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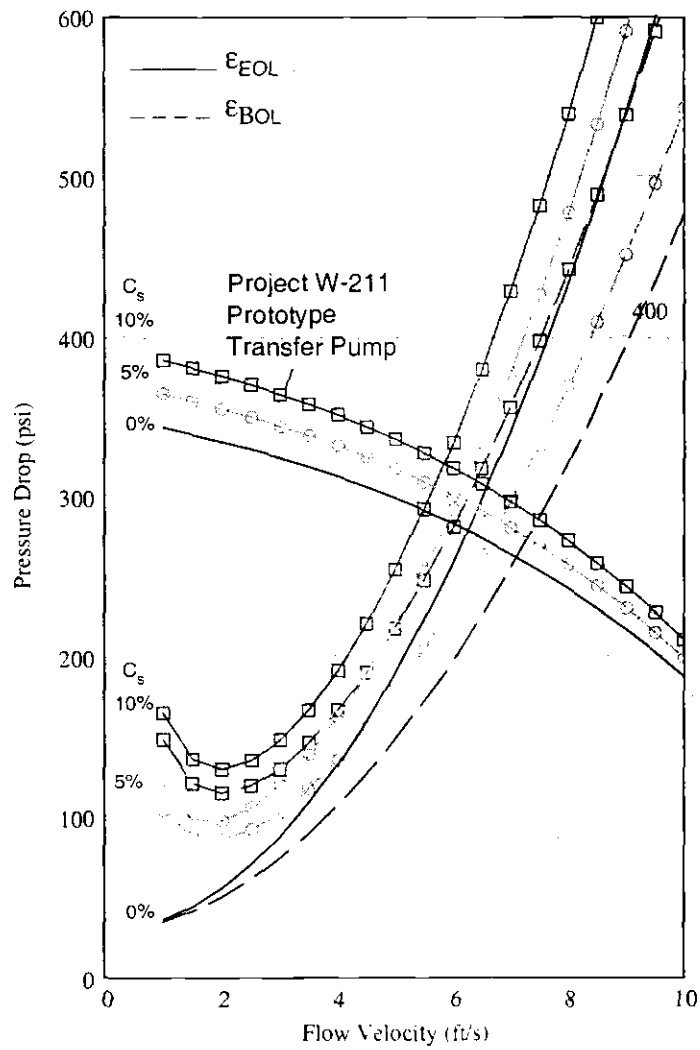

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Subject: Critical Velocity and Pressure Drop Study in Support of Waste Tank Feed Transfer System — Date: 02/25/2002 By: L. J. Julyk
Checked: By: S.D. Estey
Location: 200 Area - Hanford Site, Richland, Washington — Revised: By:

Figure E-6c. Critical Velocity and Pressure Drop for AY-101 to WTP - Minimum Agitated (Least Battered) *95/95 TL* Particle Size Distribution, ρ_L=1.3 kg/L, ρ_s=2.9 kg/L, Upper-bound Viscosity Case.

	Carbon Steel	Stainless Steel
$D_{pipe} = 3.068\,in$	$L_{CS} = 0\,ft$	$L_{SS} = 6674\,ft$
$H = 51\,ft$	$\varepsilon_{BOL\_CS} = 70\,mil$	$\varepsilon_{BOL\_SS} = 2\,mil$
	$\varepsilon_{EOL\_CS} = 150\,mil$	$\varepsilon_{EOL\_SS} = 10\,mil$

$\beta_{cv} = 1.2$, $\kappa_{cv} = 1.3$ — Oroskar and Turian (1980) critical velocity -empirical equation (1.3 times best-estimate)

$\kappa_f = 1$, $K_D = 82$ — Best-estimate Wasp pressure drop relation

$S = 5\,\%$ — Wasp stability criterion parameter

$d_{50} = 21.8\,\mu m$ — median particle size

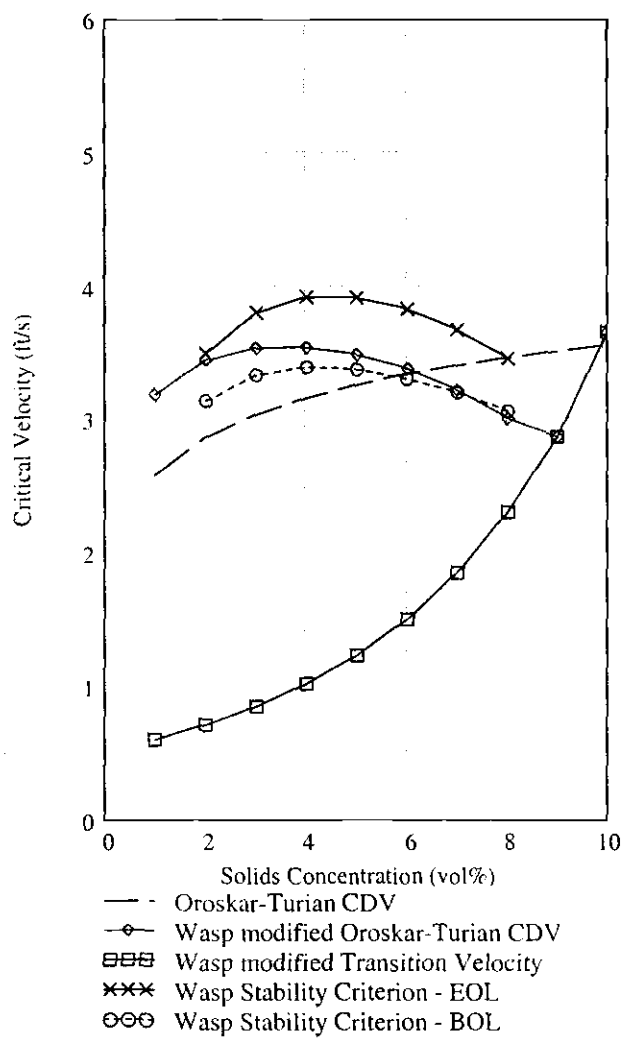
$\beta_\mu := 2$ — select bounding viscosity

$\mu_1 := \mu_c(\mu_L, \gamma_L, 0\%, \beta_\mu)$ $\mu_1 = 1.6\,cP$ — liquid viscosity

$\rho_L := 1.3 \cdot kg \cdot liter^{-1}$ — liquid density

$\rho_s = 2.9\,kg \cdot liter^{-1}$ — solids density

Critical Velocity



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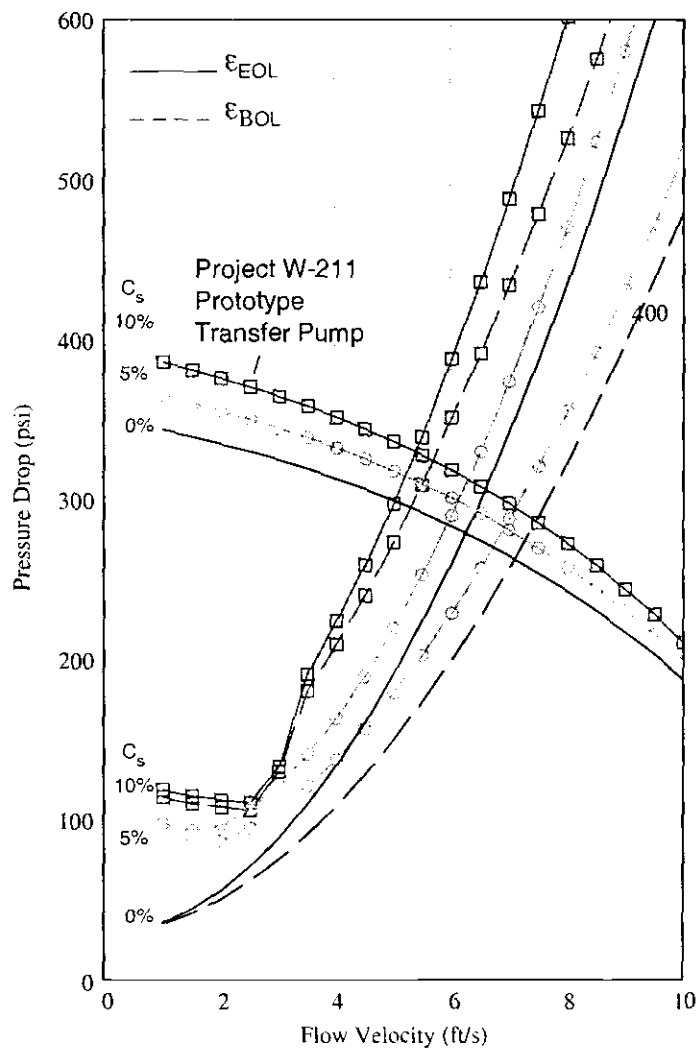

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Figure E-7a. Critical Velocity and Pressure Drop for AZ-101 to WTP - Minimum Agitated (Least Battered) *95/95 TL* Particle Size Distribution, ρ_L=1.1 kg/L, ρ_s=2.9 kg/L, Best-Estimate Viscosity Case.

	Carbon Steel	Stainless Steel
$D_{pipe} = 3.068\,in$	$L_{CS} := 0 \cdot ft$	$L_{SS} := 5444 \cdot ft$
$H := 56.9 \cdot ft$	$\varepsilon_{BOL\_CS} = 70\,mil$	$\varepsilon_{BOL\_SS} = 2\,mil$
	$\varepsilon_{EOL\_CS} = 150\,mil$	$\varepsilon_{EOL\_SS} = 10\,mil$

$\beta_{cv} := 1.2$ Oroskar and Turian (1980) critical velocity -empirical equation (1.3 times best-estimate)

$\kappa_{cv} := 1.30$

$\kappa_f := 1$ Best-estimate Wasp pressure drop relation

$K_D := 82$

$S := 5\%$ Wasp stability criterion parameter

$d_{50} = 21.8\,\mu m$ median particle size

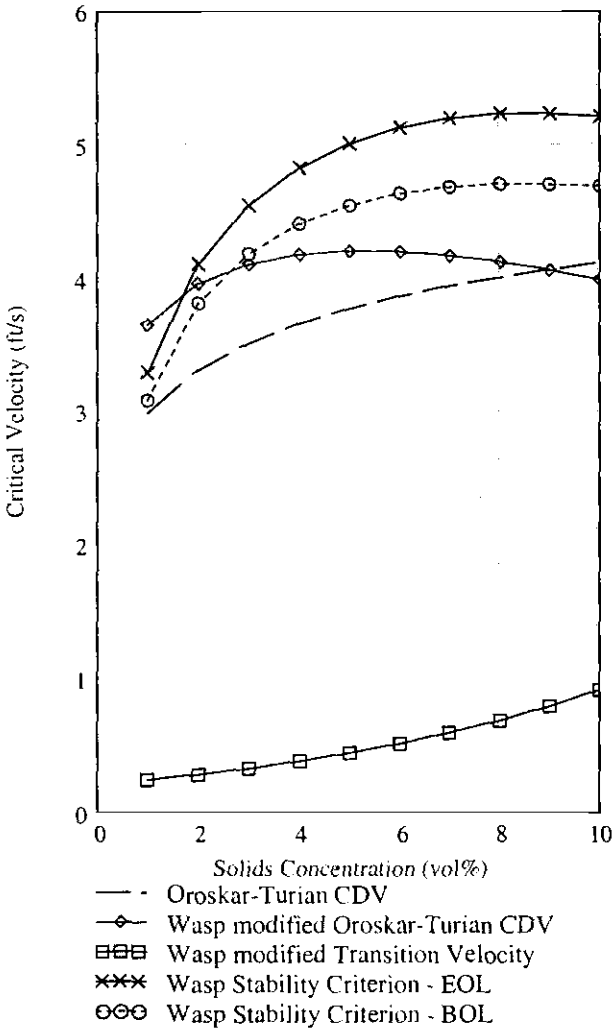
$\boxed{\beta_\mu := 1}$ select best-estimate viscosity

$\boxed{\rho_L := 1.1 \cdot kg \cdot liter^{-1}}$ liquid density

$\mu_l := \mu_c(\mu_L, \gamma_L, 0\%, \beta_\mu)$ $\mu_l = 1.5\,cP$ liquid viscosity

$\rho_s := 2.9 \cdot kg \cdot liter^{-1}$ solids density

Critical Velocity



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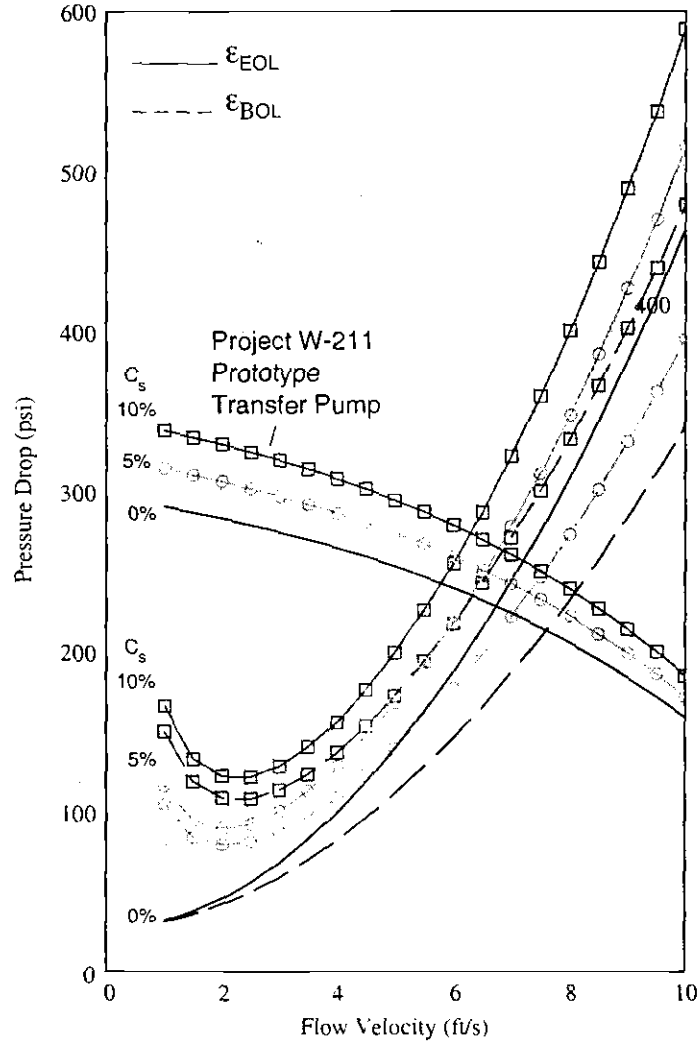

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Checked: By: S.D. Estey
Location: 200 Area - Hanford Site, Richland, Washington
Revised: By:

Figure E-7b. Critical Velocity and Pressure Drop for AZ-101 to WTP - Minimum Agitated (Least Battered) *95/95 TL* Particle Size Distribution, ρ_L=1.3 kg/L, ρ_s=2.9 kg/L, Best-Estimate Viscosity Case.

	Carbon Steel	Stainless Steel
$D_{pipe} = 3.068\,in$	$L_{CS} = 0\,ft$	$L_{SS} = 5444\,ft$
$H = 57\,ft$	$\varepsilon_{BOL\_CS} = 70\,mil$	$\varepsilon_{BOL\_SS} = 2\,mil$
	$\varepsilon_{EOL\_CS} = 150\,mil$	$\varepsilon_{EOL\_SS} = 10\,mil$

$\beta_{cv} = 1.2$ Oroskar and Turian (1980) critical velocity -empirical equation (1.3 times best-estimate)

$\kappa_{cv} = 1.3$

$\kappa_f = 1$ Best-estimate Wasp pressure drop relation

$K_D = 82$

$S = 5\,\%$ Wasp stability criterion parameter

$d_{50} = 21.8\,\mu m$ median particle size

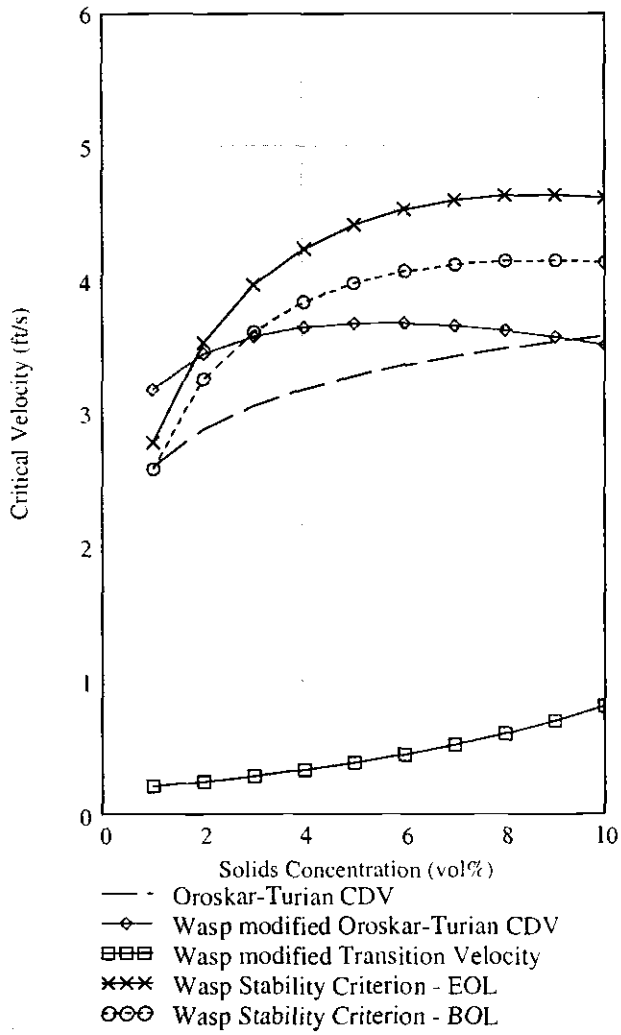
$\boxed{\beta_\mu := 1}$ select best-estimate viscosity

$\boxed{\rho_L := 1.3 \cdot kg \cdot liter^{-1}}$ liquid density

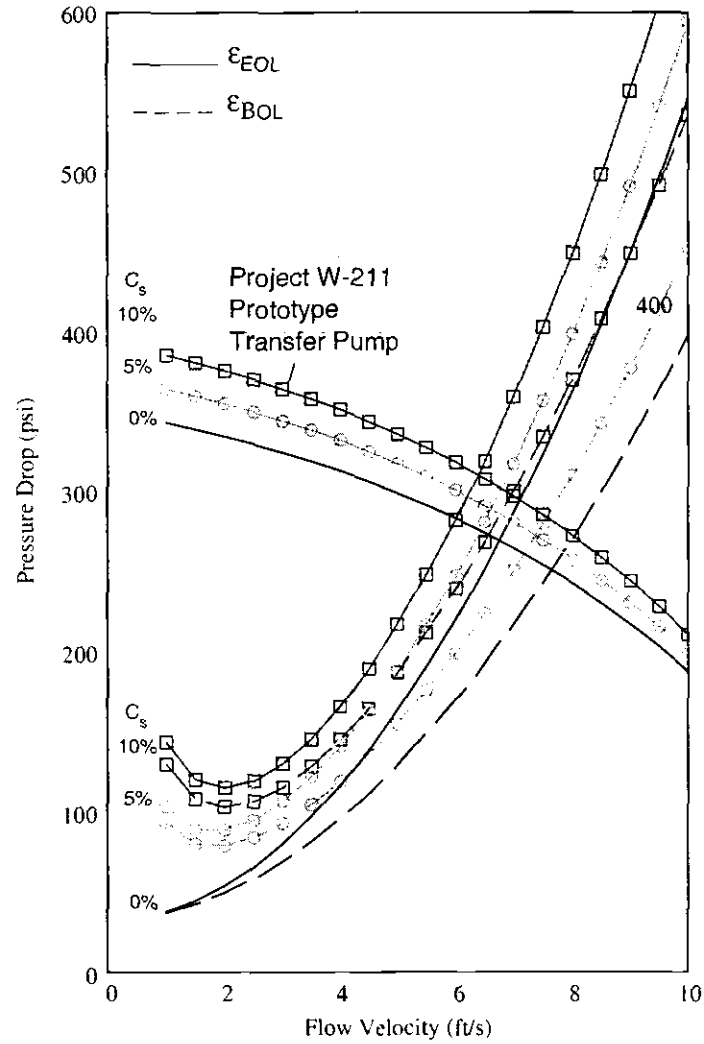
$\mu_l := \mu_c(\mu_L, \gamma_L, 0\%, \beta_\mu)$ $\mu_l = 1.5\,cP$ liquid viscosity

$\rho_s = 2.9\,kg \cdot liter^{-1}$ solids density

Critical Velocity



Pressure Drop



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Date: 02/25/2002 By: L. J. Julyk
Checked: By: S.D. Estey
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Figure E-7c. Critical Velocity and Pressure Drop for AY-101 to WTP - Minimum Agitated (Least Battered) *95/95 TL* Particle Size Distribution, ρ_L=1.3 kg/L, ρ_s=2.9 kg/L, Upper-bound Viscosity Case.

	Carbon Steel	Stainless Steel
$D_{pipe} = 3.068\,in$	$L_{CS} = 0\,ft$	$L_{SS} = 5444\,ft$
$H = 57\,ft$	$\varepsilon_{BOL\_CS} = 70\,mil$	$\varepsilon_{BOL\_SS} = 2\,mil$
	$\varepsilon_{EOL\_CS} = 150\,mil$	$\varepsilon_{EOL\_SS} = 10\,mil$

$\beta_{cv} = 1.2$ Oroskar and Turian (1980) critical velocity -empirical equation (1.3 times best-estimate)

$\kappa_{cv} = 1.3$

$\kappa_f = 1$ Best-estimate Wasp pressure drop relation

$K_D = 82$ $S = 5\,\%$ Wasp stability criterion parameter

$d_{50} = 21.8\,\mu m$ median particle size

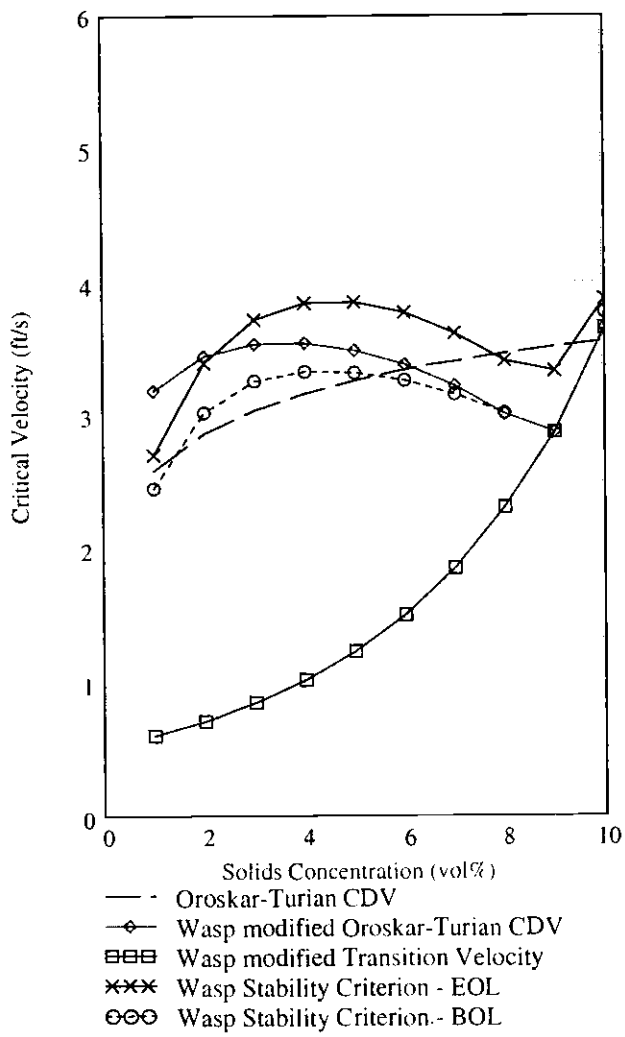
$\boxed{\beta_\mu := 2}$ select bounding viscosity

$\boxed{\rho_L := 1.3 \cdot kg \cdot liter^{-1}}$ liquid density

$\mu_l := \mu_c(\mu_L, \gamma_L, 0\%, \beta_\mu)$ $\mu_l = 1.6\,cP$ liquid viscosity

$\rho_s = 2.9\,kg \cdot liter^{-1}$ solids density

Critical Velocity



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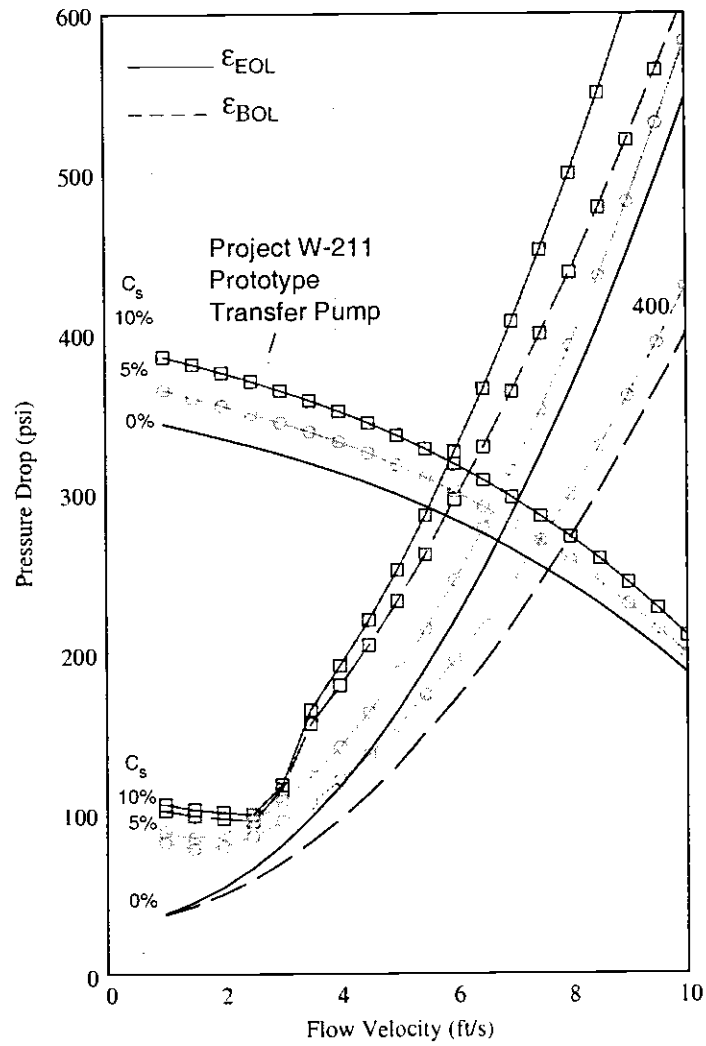

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Location: 200 Area - Hanford Site, Richland, Washington

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Checked: By: S.D. Estey
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Figure E-8a. Critical Velocity and Pressure Drop for AW-103 to WTP - Minimum Agitated (Least Battered) *95/95 TL* Particle Size Distribution, ρ_L=1.1 kg/L, ρ_s=2.9 kg/L, Best-Estimate Viscosity Case.

	Carbon Steel	Stainless Steel
$D_{pipe} = 3.068\,in$	$L_{CS} := 1648 \cdot ft$	$L_{SS} := 4268 \cdot ft$
$H := 41.9 \cdot ft$	$\varepsilon_{BOL\_CS} = 70\,mil$	$\varepsilon_{BOL\_SS} = 2\,mil$
	$\varepsilon_{EOL\_CS} = 150\,mil$	$\varepsilon_{EOL\_SS} = 10\,mil$

$d_{50} = 21.8\,\mu m$ median particle size

$\boxed{\beta_\mu := 1}$ select best-estimate viscosity

$\mu_1 := \mu_c(\mu_L, \gamma_L, 0\%, \beta_\mu)$ $\mu_1 = 1.5\,cP$ liquid viscosity

$\beta_{cv} := 1.2$ Oroskar and Turian (1980) critical velocity -empirical equation (1.3 times best-estimate)

$\kappa_{cv} := 1.30$

$\kappa_f := 1$ Best-estimate Wasp pressure drop relation

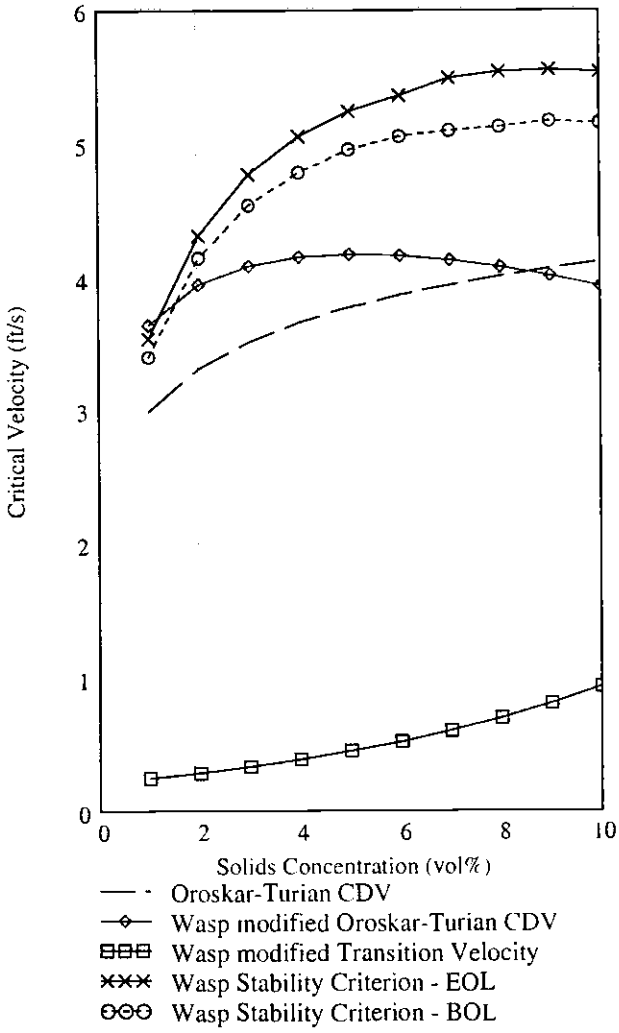
$K_D := 82$

$S := 5\%$ Wasp stability criterion parameter

$\boxed{\rho_L := 1.1 \cdot kg \cdot liter^{-1}}$ liquid density

$\rho_s := 2.9 \cdot kg \cdot liter^{-1}$ solids density

Critical Velocity



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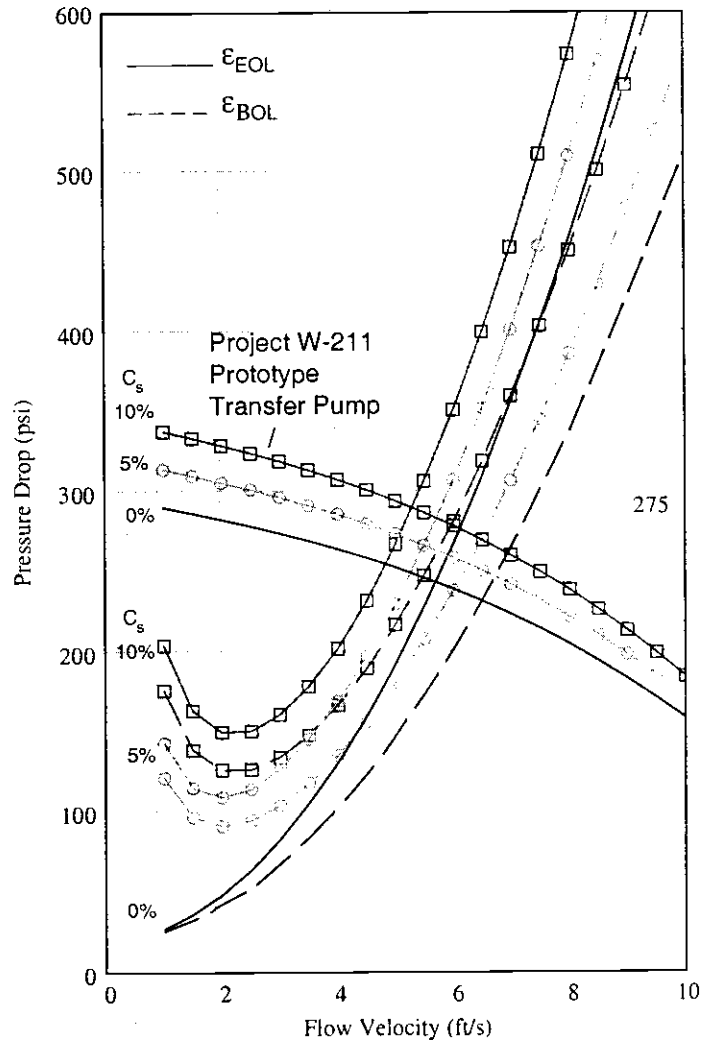

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Figure E-8b. Critical Velocity and Pressure Drop for AW-103 to WTP - Minimum Agitated (Least Battered) *95/95 TL* Particle Size Distribution, ρ_L=1.3 kg/L, ρ_s=2.9 kg/L, Best-Estimate Viscosity Case.

	Carbon Steel	Stainless Steel
$D_{pipe} = 3.068\,in$	$L_{CS} = 1648\,ft$	$L_{SS} = 4268\,ft$
$H = 42\,ft$	$\varepsilon_{BOL\_CS} = 70\,mil$	$\varepsilon_{BOL\_SS} = 2\,mil$
	$\varepsilon_{EOL\_CS} = 150\,mil$	$\varepsilon_{EOL\_SS} = 10\,mil$

$\beta_{cv} = 1.2$, $\kappa_{cv} = 1.3$ — Oroskar and Turian (1980) critical velocity -empirical equation (1.3 times best-estimate)

$\kappa_f = 1$, $K_D = 82$ — Best-estimate Wasp pressure drop relation

$S = 5\,\%$ — Wasp stability criterion parameter

$d_{50} = 21.8\,\mu m$ — median particle size

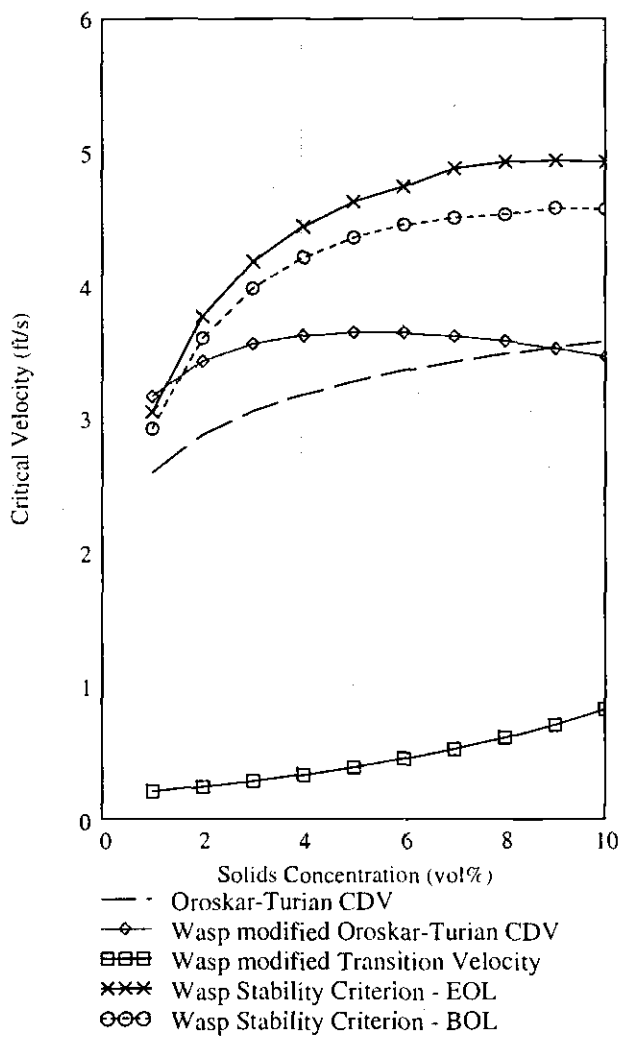
$\boxed{\beta_\mu := 1}$ — select best-estimate viscosity

$\mu_l := \mu_c(\mu_L, \gamma_L, 0\%, \beta_\mu)$ $\mu_l = 1.5\,cP$ — liquid viscosity

$\boxed{\rho_L := 1.3 \cdot kg \cdot liter^{-1}}$ — liquid density

$\rho_s = 2.9\,kg \cdot liter^{-1}$ — solids density

Critical Velocity



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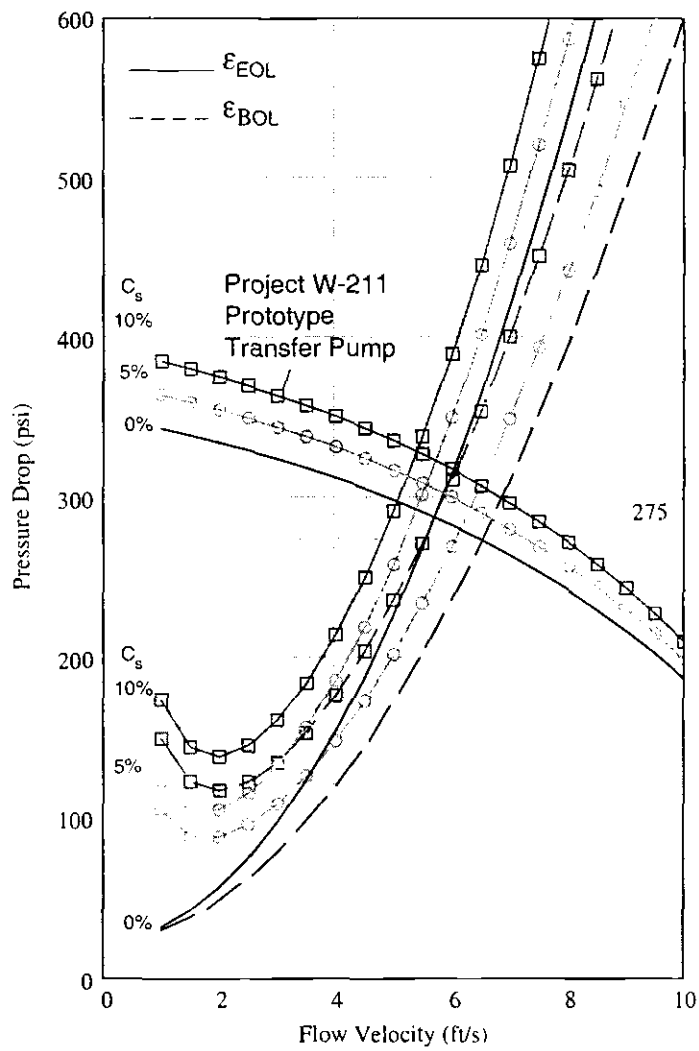

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Revised: By:

Figure E-8c. Critical Velocity and Pressure Drop for AW-103 to WTP - Minimum Agitated (Least Battered) *95/95 TL* Particle Size Distribution, ρ_L=1.3 kg/L, ρ_s=2.9 kg/L, Upper-bound Viscosity Case.

	Carbon Steel	Stainless Steel
$D_{pipe} = 3.068\,in$	$L_{CS} = 1648\,ft$	$L_{SS} = 4268\,ft$
$H = 42\,ft$	$\varepsilon_{BOL\_CS} = 70\,mil$	$\varepsilon_{BOL\_SS} = 2\,mil$
	$\varepsilon_{EOL\_CS} = 150\,mil$	$\varepsilon_{EOL\_SS} = 10\,mil$

$d_{50} = 21.8\,\mu m$ median particle size

$\beta_\mu := 2$ select bounding viscosity

$\mu_l := \mu_c(\mu_L, \gamma_L, 0\%, \beta_\mu)$ $\mu_l = 1.6\,cP$ *liquid viscosity*

$\beta_{cv} = 1.2$ *Oroskar and Turian (1980) critical velocity -empirical equation (1.3 times best-estimate)*

$\kappa_{cv} = 1.3$

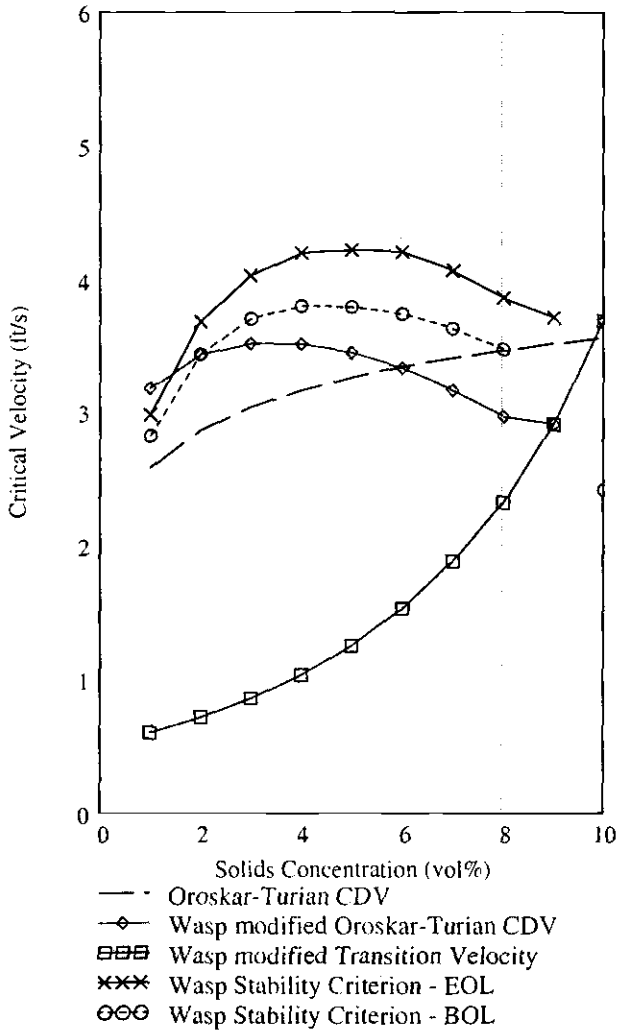
$\kappa_f = 1$ *Best-estimate Wasp pressure drop relation*

$K_D = 82$ $S = 5\,\%$ Wasp stability criterion parameter

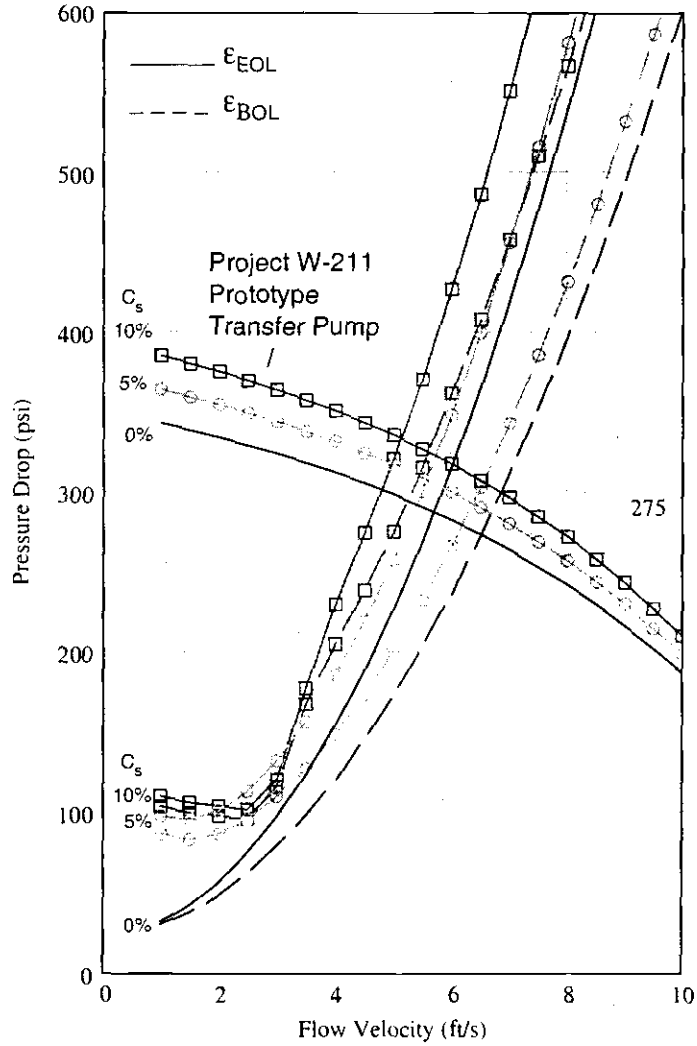
$\rho_L := 1.3 \cdot kg \cdot liter^{-1}$ liquid density

$\rho_s = 2.9\,kg \cdot liter^{-1}$ solids density

Critical Velocity



Pressure Drop



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APPENDIX F

CRITICAL VELOCITY AND PRESSURE DROP CORRELATION EQUATIONS

Calculations contained herein were produced in Mathcad 2001 Professional (Mathcad is a registered trademark of MathSoft, Inc. of Cambridge, Massachusetts).

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CH2MHILL Hanford Group, Inc.
EVALUATION ANALYSIS

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1.0 INTRODUCTION

The Hanford waste is transported through a three-inch diameter pipeline between tanks and to the Waste Treatment Plant (WTP). 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 dissolved sodium salts (primarily $NaNO_3$ and $NaNO_2$) with up to two weight percent (wt%) solids (less than one volume percent solids). In the case of the LAW feed the waste is mixed but is allowed to settle before the waste is decanted from the tank. Hence, the LAW feed can essentially be treated as a homogeneous liquid. The LAW feed is assumed to be adequately diluted to avoid precipitation of dissolved salts during transfer.

The HLW feed contains a greater concentration of solids, up to 200 grams of solids per liter of feed (Kirkbride et al. 2001). In addition, the HLW feed is extracted in batches during mixing of the waste tank. The solid particles in the Hanford HLW consists of multi-constituent undissolved solid particles that range in size from primary particles (nm to μm) to agglomerates (up to mm in size) forming a broad particle size distribution (PSD). Hence, the high-level transported waste is essentially a heterogeneous slurry comprised of coarser insoluble solid particles (agglomerates) transported in a homogeneous liquid mixture of very fine solid particles suspended in a dilute aqueous solution of dissolved salts and sodium hydroxide. Values of particle size, particle density, and slurry viscosity for HLW feed were applied based on recommendation by Jewett et al. (2002).

Note that this analysis does not address the potential for chemical precipitation / crystallization which is a function of the solubility characteristics of the dissolved multi-constituents of the waste feed, their chemical interaction, pH, and temperature. Nor does this analysis address the dynamic behavior of agglomerate formation and breakup during transfer or the resuspension of particles following a loss of flow for an extended period of time.

Current pressure ratings of existing and proposed additions to the tank-to-tank and tank-to-WTP, 3-inch diameter, Schedule-40, transfer pipelines for the double-shell tanks (DSTs) in the 200 East Area are 275 and 400 lbf/in^2. The 275 lbf/in^2 lines are carbon steel pipelines that were installed approximately 20 years ago. All new lines are to be stainless steel. Although some of the pipeline additions are rated at 450, 1,000, and 1,490 lbf/in^2, the PUREX jumper connectors are currently limited to 400 lbf/in^2, thus all pipelines are limited by either the minimum design pressure of the in-line piping in the transfer route or the design pressure of the PUREX jumper connectors.

Corrosion of in-place Hanford waste tank transfer pipelines could restrict proposed waste feed activities. Corrosion of the inner pipe surface reduces the effective wall thickness necessary to maintain pipe structural integrity and increases the effective roughness of the pipe causing increased frictional resistance or pressure loss. The increased pressure loss requires greater pump capacity to achieve required flow. The flow rate must be maintained above a minimum flow rate to assure that solid particles in the waste stream do not settle in the pipeline, leading to line plugging. The maximum flow rate is restricted by the design pressure rating of the pipeline system.

Hence, increased corrosion leads to a reduction in the effective operating flow range of the pump and pipe system. An investigation of the proposed transfer conditions, pipeline configurations, and potential corrosion is necessary to evaluate pump requirements and adequacy of existing pipeline pressure ratings, as well as, requirements for any pipe additions.

2.0 APPROACH

For HLW feeds, the minimum flow rate (critical velocity) to maintain particle suspension is estimated based on empirical correlations. Estey and Hu (1998) and Liddell and Burnett (2000) compared various critical velocity correlations available in the literature. Although no correlations were found that were directly applicable to the multi-constituent broad-particle-size distributions typical of the Hanford HLW, the Oroskar and Turian (1980) correlation was recommended by Estey and Hu (1998) as the most likely candidate. Liddell and Burnett (2000) recommended the Oroskar and Turian (1980) and Gillies and Shook (1991) correlations as the most likely candidates for use in the WFD analysis. Both of these correlation, as well as other correlations, are evaluated herein. However, the Oroskar and Turian (1980) correlation and a modified version that applied the Wasp method, to account for change in the liquid density and viscosity due to the finer particles in the PSD, were selected.

The pipeline pressure drop correlation for slurry flow developed by Wasp et al. (1977) is applied to obtain pressure drop estimates for each of the proposed transfer routes and waste conditions. Beginning-of-life (BOL) and end-of-life (EOL) pipe roughness values for carbon and stainless steel pipe were applied from estimates given by Anantatmula and Divine (1999) to envelop the pressure drop predictions.

For maximum flexibility in the use of the waste feed delivery (WFD) system, Phase I tank-to-tank and tank-to-WTP transfer pipeline routes were evaluated for both LAW and HLW feeds.

3.0 SUMMARY RESULTS

Although alternate critical velocity and pressure drop correlations were investigated, the Oroskar and Turian (1980) critical velocity and Wasp et al. (1977) pressure drop correlations were selected as being the most appropriate based on current limited knowledge of the waste physical properties for proposed transfers. Previous estimated waste physical property data provided in Estey (2000) and Jewett and Jensen (2000) for the in situ Hanford waste were reassessed by Jewett et al. (2002) along with recent PSD data (Bechtold et al. 2002) which resulted in revised recommended waste physical properties for the WFD analysis. The range of waste and transfer pipe physical properties of interest are identified in Section 5.0 of this appendix.

The recommended particle size distribution for the solid particles is based on a statistical analysis of the measured particle size distributions (by volume) from seven tanks (AW-103, AY-101, AY-102, AZ-102, C-104, C-107, and SY-102) representing Phase I HLW tank feeds. The "mean" PSD for the "minimally agitated" samples of the measured PSDs for each waste tank was recommended as a conservative basis PSD for the WFD analysis. An upper limit of the one-sided 95% confidence interval on the mean (UL 95) and an upper limit to a one-sided 95/95 tolerance limit (95/95 TL) were also statically determined for additional information.

Although these upper limit PSDs are used for sensitivity analysis, the mean PSD under conditions of minimal agitation (7.5 μm median particle size) is considered to be a conservative PSD for WFD analysis because in-tank mixing and pumping of the HLW feed is expected to breakup the larger agglomerated particles. This was observed in lab test under strong agitation by sonication of samples. However, the extent of agglomeration breakup during transfer could not be reliably established from the sonicated sample data. Hence, the more conservative non-sonicated sample data was used to establish the recommended PSD for the WFD analysis. The resulting statically based cumulative PSDs were curve fit to a two-mode Rosin-Rammler distribution function (Shook and Roco 1991) which provided the best curve fit to the recommended cumulative PSDs.

The recommended particle density of 2.9 kg/L is based on conservative mean of theoretical dry-basis densities of the solids. This conservatively neglects the expected reduced densities of agglomerated particles. The density of agglomerated particle were estimated to approach 2.2 kg/L but no direct measurements were available. Strain-rate dependent best-estimate and upper bound viscosity relations as function of solids concentration were also recommended. However, there was an apparent large variation in viscosity data for the relatively small number of tanks for which measurements were available.

Appendix D provides a tabular listing of the critical velocity, pressure drop at critical velocity, pressure drop at the target flow rate of 140 gal/min, and the maximum operating flow rate and corresponding pressure drop which would not exceed the pipeline system design pressure limit at the pump dead head condition. In some 275 lbf/in^2 limited pipeline transfer routes this required a reduced limit on the pump speed below the maximum pump speed for the Project W-211 transfer pump (3x6A VCM 6 stage SULZER proposed pump curve number 61412). No such restrictions were required for the 400 lbf/in^2 limited pipeline transfer routes. In addition, in all cases some 275 lbf/in^2 limited pipeline transfer routes might exceed the pipeline system design pressure at the target flow rate of 140 gal/min.

Case 1 is the base case using the conservative PSD (7.5 μm median particle size) based on mean of minimally agitated PSD data from seven tanks, particle density of 2.9 kg/L based on conservative mean of theoretical dry-basis densities of the solids, best-estimate viscosity relation as function of solids concentration, and maximum of 10 vol% solids with liquid densities of 1.1, 1.2 and 1.3 kg/L. The pressure drop at the critical velocities (maximum 3.4 ft/s) for all transfer routes was less than the pipeline system design pressure.

Case 2 is the same as Case 1 but uses the 95/95 TL of the minimally agitated PSD data. The pressure drop at the critical velocities (maximum 4.1 ft/s) for all transfer routes was less than the pipeline system design pressure. Some 275 lbf/in^2 limited pipeline transfer routes were predicted to be at greater risk to exceeding the pipeline system design pressure at the target flow rate of 140 gal/min.

Case 3 is the same as Case 1 but uses the upper bound viscosity relation.

Case 4 is the same as Case 1 but at 2 vol% solids to bound LAW feed with liquid densities of 1.2, 1.3, and 1.4 kg/L.

Case 5 is the same as Case 1 but uses the less conservative particle density of 2.2 kg/L to assess the potential effect of agglomerated particles.

Case 6 is the same as Case 1 but at a less conservative solids concentration of 5 vol%.

Appendix E provides the results of a "sensitivity" analysis on selected HLW transfer routes for the range of waste transfer properties considered. See main body of this report for a discussion of the detail results. Appendix G provides results of Wasp model verification.

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5.0 HANFORD WASTE AND TRANSFER PIPE PHYSICAL PROPERTIES

$TOL = 1 \times 10^{-5}$

Development of the expressions for the critical velocity and pressure drop correlations require knowledge of the following transfer pipe and waste physical property parameters.

Transfer Pipeline Parameters

D_{pipe} inside diameter of transfer pipeline $D_{pipe} := 3.068 \cdot in$

The pipeline for each transfer route is made up of new (stainless) and old (carbon) pipeline segments and various components (pipe bends, PUREX connectors, etc.). The equivalent pipe lengths for each pipe segment and the total elevation change for each transfer route was determined and is given in Appendix B. For each transfer route the equivalent pipe length for the carbon steel (CS) and stainless steel (SS) pipeline segments within the transfer route and the total elevation change are denoted by

L_{CS}	equivalent pipe length of carbon steel segment of pipeline transfer route (ft)	$0 \le L_{CS} \le 2100$
L_{SS}	equivalent pipe length of stainless steel segment of pipeline transfer route (ft)	$210 \le L_{CS} \le 6820$
H	total elevation change for transfer route (ft)	$-20 \le H \le 61$

The existing older carbon steel pipeline segments are limited to 275 lbf/in^2 while the existing or newer stainless steel pipeline segments are limited to 400 lbf/in^2 (due to current PUREX connector limitations) although the pipe design pressure is 400, 450, 1,000, or 1490 lbf/in^2. Hence, a given transfer pipeline route is limited to the minimum design pressure of the pipe components within the pipe transfer route.

$p_{pipe\_design} := 400 \cdot \frac{lbf}{in^2}$ or $275 \cdot \frac{lbf}{in^2}$ pipe design pressure **(F-1)**

Pipe roughness estimates (Anantatmula and Divine 1999), beginning-of-life (BOL) for WTP transfers and end-of-life (EOL) pipe conditions indicated by dashed and solid lines, respectively in plots

$mil := 10^{-3} \cdot in$

		corresponding relative roughness values for D_{pipe}
$\varepsilon_{BOL\_CS} := 70 \cdot mil$	BOL for existing 20-yr old carbon steel pipeline segments	$\varepsilon_{BOL\_CS} \cdot D_{pipe}^{-1} = 0.023$
$\varepsilon_{BOL\_SS} := 2 \cdot mil$	BOL for new stainless steel pipe line	$\varepsilon_{BOL\_SS} \cdot D_{pipe}^{-1} = 0.00065$
$\varepsilon_{EOL\_CS} := 150 \cdot mil$	EOL for carbon steel pipe at end of 50-year service life	$\varepsilon_{EOL\_CS} \cdot D_{pipe}^{-1} = 0.049$
$\varepsilon_{EOL\_SS} := 10 \cdot mil$	EOL for stainless steel pipe at end of 40-year service life	$\varepsilon_{EOL\_SS} \cdot D_{pipe}^{-1} = 0.00326$

(F-2)

Waste Transfer Parameters

Proper characterization of the physical properties of the transported waste slurries as a function of temperature, solids concentration, and agitation or shear is essential to any prediction of minimum flow rate requirement and associated pressure losses during transport. Of particular importance is the particle size distribution by volume, particle shape, the liquid and particle densities, and the liquid and slurry viscosity's, as well as the effect on each with increasing solids concentration. The effect of transport conditions must also be considered, such as temperature, dilution, and level of agitation from in-tank mixing, pumping operations, and pipe flow turbulence. Temperature and dilution affect the concentration of dissolved salts and the potential for precipitation of dissolved salts during transfer. Temperature also

affects the liquid and slurry viscosity. The level of agitation can affect the PSD due to breakup of agglomerated larger particles. The following waste feed parameters and physical properties for the Hanford HLW feed have been developed for the WFD analysis.

The contractual HLW feed may contain up to 200 grams of solids per liter of feed or up to approximately 6.9 volume percent (vol%) solids assuming a solids density of 2.9 kg/L (conservative mean of theoretical dry-basis densities per Jewett et al, 2002) and 9.1 vol% solids assuming a solids density of 2.2 kg/L (based on estimated agglomerated particle density per Jewett et al. 2002). In addition, because the HLW feed is extracted in batches during mixing of the waste feed tank, some variation in the batch-to-batch feed is expected when solids concentration of feed is determined on a whole tank basis. Hence, for the particulate solids *volume* fraction denoted by

α_d or C_s particulate solids *volume* fraction $0 < C_s \le 0.10$

The corresponding liquid volume fraction is denoted by

$\alpha_c(C_s) := (1 - C_s)$ carrier liquid *volume* fraction **(F-3)**

The median particle size by volume is denoted by

D_d or d_p or d_{50} particulate solid phase *median* particle size diameter (μm) of the particle size distribution (PSD) $1 \le d_{50} \le d_{50\_max}$ $\mu m \equiv 10^{-6} \cdot m$

The maximum value of the median particle size for Hanford HLW under pipe transport conditions has been an area of uncertainty along with the particle density and viscosity. In a preliminary assessment of available particle size data for Hanford HLW the mean, an upper limit of a one-sided 95% confidence interval on the mean (UL 95% CI), and upper limit to a one-sides 95/95 tolerance limit (95/95 TL) of the median particle size was estimated at 110, 140 and 275 μm, respectively (Jewett and Jensen 2000). The adequacy of the WFD transfer system piping was evaluated in Revision 1 of RPP-5346 (Julyk et al. 2000) for this preliminary estimate of the Hanford HLW PSD using the Oroskar and Turian (1980) critical velocity correlation and the Wasp et al. (1977) method to determine the pressure drop for each of the proposed tank-to-tank and tank-to-WTP transfer routes. The Thomas viscosity relation as a function of liquid viscosity and solids concentration was assumed in application of the Wasp method to determine the transfer route pressure drops.

However, the predicted pressure drop at the required minimum flow rate for a large number of the proposed transfer routes exceeded the design pressure of the transfer route pipeline system. In addition, as noted by Jewett and Jensen (2000), a number of uncertainties remained regarding the PSDs of Hanford HLW slurries, as well as, uncertainties in the solids particle density and slurry viscosity under transport conditions. This lead to a need for a more detailed reassessment of the Hanford waste physical properties at transport conditions. Previous estimated waste physical property data provided in Estey (2000) and Jewett and Jensen (2000) for the in situ Hanford waste were reassessed by Jewett et al. (2002) along with recent PSD data (Bechtold et al. 2002) which resulted in revised recommended waste physical properties for the WFD analysis.

The recommended particle size distribution for the solid particles is based on a statistical analysis of the measured particle size distributions (by volume) from seven tanks (AW-103, AY-101, AY-102, AZ-102, C-104, C-107, and SY-102) representing Phase I HLW tank feeds. The "mean" PSD for the "minimally agitated" samples of the measured PSDs for each waste tank was recommended as a conservative basis PSD for the WFD analysis. An upper limit of the one-sided 95% confidence interval on the mean (UL 95) and an upper limit to a one-sided 95/95 tolerance limit (95/95 TL) were also statically determined for additional information.

Although these upper limit PSDs are used for sensitivity analysis, the mean PSD under conditions of minimal agitation (7.5 μm median particle size) is considered to be a conservative PSD for WFD analysis because in-tank mixing and pumping of the HLW feed is expected to breakup the larger agglomerated particles. This was observed in lab test under strong agitation by sonication of waste samples. However, the extent of agglomeration breakup during transfer could not be reliably established from the sonicated waste sample data. Hence, the more conservative non-sonicated waste sample data was used to establish the recommended PSD for the WFD analysis. The resulting statically based cumulative PSDs were curve fit to a two-mode Rosin-Rammler distribution function (Shook and Roco 1991) which provided the best curve fit to the recommended cumulative PSDs (see Section 6.2.4 of Appendix F for details).

A reassessment of the particle density based on the theoretical dry-basis densities of seven tanks resulted in a mean value of 2.9 kg/L, with a 95% confidence interval of 2.6 to 3.2 kg/L, and a 95/95-tolerance limit of 3.9 kg/L. The recommended particle density of 2.9 kg/L is conservatively based on the mean of the weighted-average theoretical dry-basis densities of the solids contained in seven HLW tanks (AW-103, AY-101, AY-102, AZ-101, AZ-102, C-104, C-107, and SY-102). This conservatively neglects the expected reduced densities of expected larger agglomerated particles and flocs. The density of agglomerated particles were estimated to approach 2.2 kg/L but no direct measurements were available (Jewett et al. 2002). Hence,

ρ_d or ρ_s particulate solid phase density (kg/L) $2.2 \le \rho_s \le 3.9$ (Jewett et al. 2002)

A value 3.0 kg/L for the solids density was previously assumed in Revision 1 of RPP-5346 (Julyk et al. 2000) which is close to the recommended value of 2.9 kg/L.

The carrier liquid density is denoted by

ρ_L carrier liquid (no solids) phase density (kg/L) $\rho_{water} \le \rho_L \le 1.3$ (for HLW feed)

$\rho_{water} \le \rho_L \le 1.4$ (for LAW feed)

Fine particles (< 50 to 75 μm) of the PSD can join with the carrier liquid to form a homogeneous "vehicle" while the course particles are suspended as a heterogeneous "bed" within this homogeneous vehicle. The fine particles in the homogeneous "vehicle" liquid modify the effective liquid density and the rheology of the liquid. The modified homogeneous "vehicle" liquid density is given by

$$\rho_c(\rho_s, \rho_L, \Phi_v) := \rho_s \cdot \Phi_v + \rho_L \cdot (1 - \Phi_v)$$ effective density of the homogeneous "vehicle" liquid (liquid plus fine particles of PSD) **(F-4)**

where Φ_v is the concentration of fine particles joining with the carrier liquid. Note that ρ_c becomes the bulk density (ρ_b) when $\Phi_v = C_s$. In addition, the weight fraction of solids can be shown to be given by

$$C_W(\rho_L, \rho_s, C_s) := \frac{C_s \cdot \rho_s}{C_s \cdot \rho_s + (1 - C_s) \cdot \rho_L} = C_s \rho_s / \rho_b$$ (Wasp et al. 1977) **(F-5)**

The carrier liquid viscosity with no solids is denoted by

μ_L or μ_{cL} carrier liquid (no solids) phase viscosity (cP) $\mu_{water}(t_C) \le \mu_L \le 1.6$ $cP \equiv 10^{-2} \cdot poise$

and is approximated from the following relations given in Estey 2000. The density and viscosity of water as a function of temperature (°C) per Shook and Roco (1991) and Estey and Hu (1998) are given by

$$\rho_{water}(t_C) := \left[999.7 - 0.10512\cdot(t_C - 10) - 0.005121\cdot(t_C - 10)^2 + 0.00001329\cdot(t_C - 10)^3\right]\cdot\frac{kg}{m^3}$$ mass density of water (5 °C < t_C <100 °C) **(F-6)**

and

$$\mu_{water}(t_C) := \begin{cases} 100\cdot\exp\left[\ln(10)\cdot\left[\dfrac{1301}{998.333 + 8.1855\cdot(t_C - 20) + 0.00585\cdot(t_C - 20)^2} - 3.30233\right]\right]\cdot cP & \text{if } t_C \le 20 \\ (1.002)\cdot\exp\left[\ln(10)\cdot\left[\dfrac{\left[1.3272\cdot(20 - t_C) - 0.001053\cdot(t_C - 20)^2\right]}{t_C + 105}\right]\right]\cdot cP & \text{otherwise} \end{cases}$$ **(F-7)**

The viscosity of water based on the above correlation is plotted in Figure F-1a as a function of temperature. The above properties for water can be assumed for the pipeline flush condition as a function of the temperature of the flush water. These properties can vary if the flush water is treated.

The viscosity of the carrier liquid (water plus dissolved salts and caustic) is given in Estey 2000 by the following approximate relation:

$$\mu_{cL}(\rho_L, t_C, x_{salt}) := \mu_{water}(t_C)\cdot\left[x_{salt}\cdot\left[1 + 1.071\cdot\left(\frac{\rho_L}{\rho_{water}(t_C)} - 1\right)\right] + (1 - x_{salt})\cdot\exp\left[\left[7.143\cdot\left(\frac{\rho_L}{\rho_{water}(t_C)} - 1\right)\right]^{1.15}\right]\right]$$ **(F-8)**

where

ρ_L density of carrier liquid with *dissolved* solids

x_{salt} mass fraction of dissolved solids composed of sodium and other salts $= mass_{salt}/mass_{liquid}$

$x_{caustic}$ mass fraction of dissolved solids composed of sodium hydroxide $= mass_{caustic}/mass_{liquid} = 1 - x_{salt}$

This relation is shown in Figure F-1b vs. the density of the carrier liquid at selected temperatures and salt fractions.

The following temperature conversion functions may be used to convert between Fahrenheit and Celsius temperature scales.

$$T_F(t_C) := \frac{9}{5}\cdot t_C + 32 \qquad T_C(t_F) := \frac{5}{9}\cdot(t_F - 32)$$ **(F-9)**

Wasp et al. (1977) developed a method to estimate the pipe pressure loss for a combined homogeneous-heterogeneous flow with multiple particle sizes based on the concept of a "two-phase vehicle" (see Section 6.2 for details of Wasp method) Fine particles join with the carrier liquid to form a homogeneous "vehicle" while the course particles are suspended as a heterogeneous "bed" within this homogeneous vehicle. The fine particles in the vehicle modify the effective liquid density and rheology of the liquid. High concentrations (approaching 30% by volume) of "fine" particles (particle size diameters less than < 50 to 75 μm) can result in non-Newtonian viscosity characteristics. Various correlations have been considered in the literature to account for the change in viscosity with solids concentration of fine particles, such as the Thomas correlation given as

$$\mu_{cThomas}(\mu_L, \Phi_v) := \mu_L \cdot \left(1 + 2.5 \cdot \Phi_v + 10.05 \cdot \Phi_v^2 + 0.00273 \cdot \exp(16.6 \cdot \Phi_v)\right) \quad \text{Thomas correlation (Wasp et al. 1977)} \qquad \textbf{(F-10)}$$

where Φ_v is the concentration of fine particles joining with the carrier liquid as determined in the Wasp method.

Although other viscosity correlations are available in the literature, they require additional empirical parameters. The Thomas correlation was selected in Revision 1 of RPP-5346 (Julyk et al. 2000) as a first approximation due to the lack of data applicable to the Hanford waste at the time of the analysis. Plots of vehicle-to-carrier fluid density and viscosity (Thomas relation) are given in Figure F-1c.

Hanford waste viscosity behavior was reassessed by Jewett et al. (2002) which recommended the following "best-estimate" and "bounding" relations for the WFD analysis.

Best-Estimate viscosity correlation for HLW (Jewett et al. 2002)

$$\mu_{mBE}(\gamma, \Phi_v) := \begin{cases} 2 \cdot cP \cdot \left[1 + 2.5 \cdot \Phi_v + 10.05 \cdot \Phi_v^2 + 1.3 \cdot \left(e^{17 \cdot \Phi_v} - 1\right)\right] \cdot \left(\dfrac{\gamma}{sec^{-1}}\right)^{-0.06} & \text{if } \Phi_v > 0 \\ 1.5 \cdot cP & \text{otherwise} \end{cases} \qquad \textbf{(F-11)}$$

Bounding (based on tank C-104 waste data) viscosity correlation (Jewett et al. 2002)

$$\mu_{mC104}(\gamma, \Phi_v) := \begin{cases} 1.6 \cdot cP \cdot \left(1 + 2.5 \cdot \Phi_v + 10.05 \cdot \Phi_v^2 + 21 \cdot e^{39 \cdot \Phi_v}\right) \cdot \left(\dfrac{\gamma}{sec^{-1}}\right)^{-0.75} & \text{if } \Phi_v > 0 \\ 1.6 \cdot cP & \text{otherwise} \end{cases} \qquad \textbf{(F-12)}$$

where

$\gamma_r(v, D) := 8 \cdot \dfrac{v}{D}$ is the strain rate for pipe flow (Wasp et al. 1977) and v is the average pipe flow velocity and D is the internal pipe diameter. **(F-13)**

Note that the above "vehicle" viscosity relations are valid for 0% < Φ_v < 10% and 27 °C < t_C < 65 °C where Φ_v is the concentration of fine particles joining with the carrier liquid as determined in the Wasp method. Caution should be exercised in extrapolation beyond these limits. These relations were developed frrm limited data from three tanks (AY-102, AZ-101, and C-104). Although these relations were developed from viscosity data at temperatures from 27 to

65 °C, the effect of temperature did not appear to be significant within the range of experimental uncertainty. Thus, the regression analysis was independent of temperature. However, there was a shear-thinning strain rate effect (particularly for the C-104 tank data) which was included in the regression analysis.

The following relation is used to select the appropriate "vehicle" viscosity relation for analysis

$$\mu_c(\mu_L, \gamma_r, \Phi_v, \beta_\mu) := \begin{cases} \mu_{mBE}(\gamma_r, \Phi_v) & \text{if } \beta_\mu = 1 \\ \mu_{mC104}(\gamma_r, \Phi_v) & \text{if } \beta_\mu = 2 \\ \mu_{cThomas}(\mu_L, \Phi_v) & \text{otherwise} \end{cases} \qquad \textbf{(F-14)}$$

where

β_μ = 0 Thomas correlation (Wasp et al. 1977)
1 Best-estimate correlation (Jewett et al. 2002)
2 Bounding (C104) case (Jewett et al. 2002)

A comparison of the above three "vehicle" slurry viscosity relations is given in Figure F-1d.

As the concentrations of solids approaches zero in Equations F-11 and F-12, the corresponding liquid viscosity (based on the regression analysis) is given as 1.5 and 1.6 cP for the best-estimate and bounding viscosity relations, respectively. In the case of the Thomas relation (Equation F-10), the viscosity reduces to the carrier liquid viscosity (μ_L), which is given by Equation F-8, as the concentrations of solids approaches zero.

Proper usage of Equation F-14 is

$$\mu_c(\mu_{cL}(\rho_L, t_C, x_{salt}), \gamma_r(v, D_{pipe}), \Phi_v, \beta_\mu)$$

Note that only for $\beta_\mu = 0$ (Thomas relation selected) will this viscosity relation reduce to the liquid viscosity inputted as μ_L in Equation F-14 as the solids concentration of the fine solids in the PSD approaches zero. Details on the Hanford HLW PSD recommend in Jewett et al. (2002) for the WFD analysis are given in Section 6.2.

6.0 CRITICAL VELOCITY AND PRESSURE DROP CORRELATIONS

Empirical correlations for critical velocity (minimum slurry transport flow velocity to maintain suspension of solid particles) and pipeline friction pressure drop loss are available in the literature for various slurry types (homogeneous, heterogeneous, or compound homogeneous-heterogeneous) based on solid particle size and density, concentration of solids by weight or volume relative to total mass or volume of material being transported, carrier fluid density and viscosity, and pipe diameter and roughness. The slurry may exhibit Newtonian or non-Newtonian behavior. Non-Newtonian behavior is more likely at high concentrations (approaching 30% by volume) of fine particle solids (particle diameter less than approximately 100 microns). The slurry may be considered homogenous if the solid particles do not settle out independent of the flow velocity. In the following only heterogeneous and compound homogeneous-heterogeneous Newtonian flow conditions are addressed. This restriction appears to be appropriate for the Hanford WFD analysis based on physical properties of the limited Hanford waste sample data evaluated at this time.

6.1 HETEROGENEOUS FLOW

6.1.1 Critical Velocity

The flow should be maintained above a minimum flow rate (critical velocity) to prevent particles from settling in the pipe which could lead to pipe plugging and unstable operating conditions. Estey and Hu (1998) and Liddell and Burnett (2000) compared various critical velocity correlations available in the literature. Although no correlations were found that were directly applicable to the multi-constituent broad-particle-size distributions (PSD) typical of the Hanford HLW, the Oroskar and Turian (1980) correlation was recommended by Estey and Hu (1998) as the most likely candidate. Liddell and Burnett (2000) recommended the Oroskar and Turian (1980) and Gillies and Shook (1991) correlations as the most likely candidates for use in the WFD analysis. Both of these correlation, as well as other available alternate correlations, are provided below for comparison. Most available critical velocity correlations in the literature were developed from single constituent slurries (coal, sand, or gravel in water solution) for narrow PSDs with a median particle size greater than 100 μm as apposed to the Hanford HLW multi-constituent broad PSD.

Although the Oroskar and Turian (1980) correlation and a modified version that applied the Wasp method (attempt to account for changes in the liquid density and viscosity due to the finer particles in the PSD) were selected, none of the correlations have been validated experimentally for the Hanford waste properties at transfer conditions. The Oroskar and Turian (1980) critical velocity and alternate correlation's are given below. The Wasp modified Oroskar and Turian relation and the Gillies and Shook (1991) correlation are given in Section 6.2 of Appendix F where the recommend PSD is given along with the PSD used in Revision 1 of RPP-5346 for comparison.

The Oroskar and Turian (1980) critical velocity correlation is introduced first after the introduction some common relations: Reynolds Number, drag coefficient of settling particles, and the settling velocity relation for spherical particles, .The effect of particle shape while of some importance is not included because of the difficulty in characterizing the variation in the shape of the primary particles and their corresponding agglomerates and flocs.

The Reynolds Number for Newtonian flow is defined as

$$Re(D, v, \rho, \mu) := D \cdot v \cdot \frac{\rho}{\mu} \qquad \text{(F-15)}$$

where D is a characteristic length, v is the flow velocity, ρ is the fluid density, and μ is the fluid viscosity.

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The terminal settling velocity (v_∞) of a spherical particle settling in a stagnant unbound liquid is given by the following relations.

For Stokes flow ($Re < 0.1$) the drag coefficient of a spherical particle is given by

$$C_{DStokes}(D_d, v, \rho_L, \mu_L) := \frac{24}{Re(D_d, v, \rho_L, \mu_L)} \quad \textbf{(F-16)}$$

which leads the following explicit relation for v_∞

$$v_{\infty Stokes}(D_d, \rho_s, \rho_L, \mu_L) := g\cdot(\rho_s - \rho_L)\cdot(D_d)^2\cdot(18\cdot\mu_L)^{-1} \quad \textbf{(F-17)}$$

For Stokes and non-Stokes flow region, Turian (1971) gives the following correlation for C_D valid for $Re < 1.5\cdot 10^5$

$$C_D(D_d, v, \rho_L, \mu_L) := \left[\left(\frac{24}{Re(D_d, v, \rho_L, \mu_L)}\right)^{\frac{1}{2}} + 0.34035\cdot\left(Re(D_d, v, \rho_L, \mu_L)^{0.06071} \cdots + \frac{1}{1.72013 + 0.018\cdot Re(D_d, v, \rho_L, \mu_L)}\right)\right]^2 \quad \textbf{(F-18)}$$

and v_∞ is then given by

$$v_{\infty v}(D_d, \rho_s, \rho_L, \mu_L, v) := \sqrt{\frac{\frac{4}{3}\cdot D_d\cdot\left(\frac{\rho_s}{\rho_L} - 1\right)\cdot g}{C_D(D_d, v, \rho_L, \mu_L)}} \quad \textbf{(F-19)}$$

which is implicit in v_∞ but can be iteratively solved as follows.

The starting value for the iterative solution is obtained from the following approximate correlation for v_∞ with the introduction of the following non dimensional parameter (Turian 1971)

$$\Lambda(D_d, \rho_s, \rho_L, \mu_L) := \sqrt{\frac{4}{3}\cdot\frac{g\cdot D_d^3\cdot\rho_L\cdot(\rho_s - \rho_L)}{\mu_L^2}} \quad \textbf{(F-20)}$$

with

$$\lambda(\Lambda) := -1.38 + 1.94\cdot\log(\Lambda) - 8.6\cdot 10^{-2}\cdot\log(\Lambda)^2 - 2.52\cdot 10^{-2}\cdot\log(\Lambda)^3 + 9.19\cdot 10^{-4}\cdot\log(\Lambda)^4 + 5.35\cdot 10^{-4}\cdot\log(\Lambda)^5 \quad \textbf{(F-21)}$$

to give the approximate terminal settling velocity as

$$v_{\infty\_a}(D_d, \rho_s, \rho_L, \mu_L) := \frac{\mu_L}{D_d\cdot\rho_L}\cdot 10^{\lambda(\Lambda(D_d, \rho_s, \rho_L, \mu_L))} \quad \textbf{(F-22)}$$

Hence, the final value for the settling velocity is obtained from the iterative solution given by

$$v_\infty(D_d,\rho_s,\rho_L,\mu_L) := \begin{cases} v \leftarrow v_{\infty\_a}(D_d,\rho_s,\rho_L,\mu_L) & \text{initial guess} \\ \mathrm{root}(v - v_{\infty v}(D_d,\rho_s,\rho_L,\mu_L,v),v) & \text{iterative solution} \end{cases} \quad \textbf{(F-23)}$$

Reynolds Number for a settling spherical particle at terminal velocity is given by

$$Re_\infty(D_d,\rho_s,\rho_L,\mu_L) := Re(D_d, v_\infty(D_d,\rho_s,\rho_L,\mu_L),\rho_L,\mu_L) \quad \textbf{(F-24)}$$

The above drag coefficients correlations, as well as a third correlation referenced in Estey and Hu (1998), are compared in Figure F-2. Equations F-18 through F-23 are used herein for greater accuracy over a greater range of particle sizes.

In accordance with Oroskar and Turian (1980), the hindered settling velocity of a spherical particle is given by the following relations:

$$n = 4.65 - 2.32\cdot\frac{1}{\sqrt{0.5\cdot\pi}}\cdot\int_{-\infty}^{\infty}\exp\left(\frac{-\log(Re_\infty)^2}{0.5}\right)d\log(Re_\infty) \quad \textbf{(F-25)}$$

$$n(D_d,\rho_s,\rho_L,\mu_L) := (4.65 - 2.32\cdot pnorm(\log(Re_\infty(D_d,\rho_s,\rho_L,\mu_L)),0,0.5)) \quad \textbf{(F-26)}$$

$$v_{hindered}(D_d,\rho_s,C_s,\rho_L,\mu_L) := (\alpha_c(C_s))^{n(D_d,\rho_s,\rho_L,\mu_L)}\cdot v_\infty(D_d,\rho_s,\rho_L,\mu_L) \quad \text{hindered settling velocity} \quad \textbf{(F-27)}$$

Equations F-25 and F-26 were derived by Estey and Hu (1998) as an analytical approximation to the graphical relation given in Figure 5 of Oroskar and Turian (1980). A plot of the hindered settling velocity exponent (n), as defined by Equations F-25 and F-26, versus Reynolds Number is shown in Figure F-3 for comparison with Figure 5 given in Oroskar and Turian (1980).

The ratio of particle hindered settling velocity to the critical velocity is denoted by

$$\gamma_v = \frac{v_{hindered}}{v_{critical}} \quad \text{or} \quad \gamma_v(D_d,\rho_s,C_s,\rho_L,\mu_L,v) := \frac{v_{hindered}(D_d,\rho_s,C_s,\rho_L,\mu_L)}{v} \quad \textbf{(F-28)}$$

The fraction of the turbulent fluid eddies possessing a velocity larger than the particulate settling velocity is given (in corrected form derived from Equation 42 of Oroskar and Turian 1980) as

$$\chi(\gamma_v) := \frac{2}{\sqrt{\pi}}\cdot\left[\frac{2}{\sqrt{\pi}}\cdot\gamma_v\cdot\exp\left(\frac{-4}{\pi}\cdot\gamma_v^2\right) + \frac{\sqrt{\pi}}{2}\cdot\left(1 - \mathrm{erf}\left(\frac{2}{\sqrt{\pi}}\cdot\gamma_v\right)\right)\right] \quad \textbf{(F-29)}$$

χ versus γ_v is plotted in Figure F-4 for comparison with Figure 6 in Oroskar and Turian (1980).

The resulting Oroskar and Turian (1980) *semi-theoretical* correlation for the critical velocity (v_t) is given by:

$$v_d(D_d,\rho_s,\rho_L) := \sqrt{g\cdot D_d\cdot\left(\frac{\rho_s}{\rho_L}-1\right)}$$ characteristic velocity of a settling particle **(F-30)**

$$F_1(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,v) := \left[\frac{5\cdot(C_s)\cdot(\alpha_c(C_s))^{(2\cdot n(D_d,\rho_s,\rho_L,\mu_L)-1)}\cdot\left(\frac{D_{pipe}}{D_d}\right)\cdot\left(\frac{D_{pipe}\cdot\rho_L}{\mu_L}\cdot v_d(D_d,\rho_s,\rho_L)\right)^{\frac{1}{8}}}{\chi(\gamma_v(D_d,\rho_s,C_s,\rho_L,\mu_L,v))}\right]^{\frac{8}{15}}$$ **(F-31)**

$$v_{tv}(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,v) := v_d(D_d,\rho_s,\rho_L)\cdot F_1(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,v)$$ **(F-32)**

$$v_{crOTt}(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,\kappa_{cv}) := \kappa_{cv}\cdot root(v - v_{tv}(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,v),v)$$ semi-theoretical critical velocity correlation **(F-33)**

where D_{pipe} is the inside diameter of pipe and the other parameters are as defined above.

The Oroskar and Turian (1980) *empirical* correlation for the critical velocity (v_e) is given by:

$$F_2(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L) := 1.85\cdot(C_s)^{0.1536}\cdot(\alpha_c(C_s))^{0.3564}\cdot\left(\frac{D_{pipe}}{D_d}\right)^{0.378}\cdot\left(D_{pipe}\cdot\frac{\rho_L}{\mu_L}\cdot v_d(D_d,\rho_s,\rho_L)\right)^{0.09}$$ **(F-34)**

$$v_{ev}(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,v) := v_d(D_d,\rho_s,\rho_L)\cdot F_2(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L)\cdot\chi(\gamma_v(D_d,\rho_s,C_s,\rho_L,\mu_L,v))^{0.30}$$ **(F-35)**

$$v_{crOTe}(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,\kappa_{cv}) := \kappa_{cv}\cdot\left|\begin{array}{l} v \leftarrow v_{crOTt}(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,1) \\ root(v - v_{ev}(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,v),v)\end{array}\right.$$ empirical critical velocity correlation **(F-36)**

The Oroskar and Turian (1980) semi-theoretical and empirical equations given above were considered to do the best overall job of predicting the critical velocity. The overall percent rms deviation was 25.94 and 21.82, respectively compared to at least twice this for the other seven correlations considered.

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Estey and Hsu (1998) recommended that the slurry flow critical velocity be taken as the maximum value of the Oroskar and Turian (1980) semi-theoretical and empirical equations, i.e.,

$$v_{crOT}(D_{pipe}, D_d, \rho_s, C_s, \rho_L, \mu_L, \kappa_{cv}) := \frac{m}{sec} \cdot \left| \begin{array}{l} u_t \leftarrow v_{crOTt}(D_{pipe}, D_d, \rho_s, C_s, \rho_L, \mu_L, \kappa_{cv}) \cdot \left(\frac{m}{sec}\right)^{-1} \\ u_e \leftarrow v_{crOTe}(D_{pipe}, D_d, \rho_s, C_s, \rho_L, \mu_L, \kappa_{cv}) \cdot \left(\frac{m}{sec}\right)^{-1} \\ u_t \text{ if } u_t > u_e \\ u_e \text{ otherwise} \end{array} \right. \quad \textbf{(F-37)}$$

κ_{cv} is the uncertainty factor on the predicted critical velocity, set to 1 to obtain "best-estimate" value.

Turian, Hsu, and Ma (1987) compared 36 critical velocity correlations. Correlations proposed by Robinson and Graf (1972), Oroskar and Turian (1980), and by Wasp et al. (1977) were determined to do a better job of predicting the critical velocity than the other correlations considered. The relations by Robinson and Graf (1972) and Wasp et al. (1977) are given as

***Robinson and Graf* (1972)**

$$v_{crRG}(D_{pipe}, D_d, \rho_s, C_s, \rho_L, \mu_L, \kappa_{cv}) := \kappa_{cv} \cdot 0.901 \cdot C_s^{0.106} \cdot \sqrt{2 \cdot g \cdot D_{pipe} \cdot \left(\frac{\rho_s}{\rho_L} - 1\right)} \quad \textbf{(F-38)}$$

Wasp et al. (1977)

$$v_{crWasp}(D_{pipe}, D_d, \rho_s, C_s, \rho_L, \mu_L, \kappa_{cv}) := \kappa_{cv} \cdot 3.116 \cdot C_s^{0.186} \cdot \left(\frac{D_d}{D_{pipe}}\right)^{\frac{1}{6}} \cdot \sqrt{2 \cdot g \cdot D_{pipe} \cdot \left(\frac{\rho_s}{\rho_L} - 1\right)} \quad \textbf{(F-39)}$$

Also of interest are the following correlations.

Zandi and Govatos (1967) proposed a critical velocity relation developed from more than 1000 data points collected from 11 references. The critical velocity at transition from saltation to heterogeneous flow was given as

$$v_{crZG}(D_{pipe}, D_d, \rho_s, C_s, \rho_L, \mu_L, \kappa_{cv}) := \kappa_{cv} \cdot \sqrt{\frac{40 \cdot C_s \cdot g \cdot D_{pipe} \cdot \left(\frac{\rho_s}{\rho_L} - 1\right)}{\sqrt{C_D(D_d, v_\infty(D_d, \rho_s, \rho_L, \mu_L), \rho_L, \mu_L)}}} \quad \textbf{(F-40)}$$

Shook (1969) used the Durand's pressure loss correlation and determined the velocity corresponding to minimum pressure loss and proposed the following relation which is similar to the Zandi and Govatos (1967) relation.

$$v_{crShook}(D_{pipe}, D_d, \rho_s, C_s, \rho_L, \mu_L, \kappa_{cv}) := \kappa_{cv} \cdot 2.43 \cdot C_s^{\frac{1}{3}} \cdot \sqrt{\frac{2 \cdot g \cdot D_{pipe} \cdot \left(\frac{\rho_s}{\rho_L} - 1\right)}{\sqrt{C_D(D_d, v_\infty(D_d, \rho_s, \rho_L, \mu_L), \rho_L, \mu_L)}}} \quad \textbf{(F-41)}$$

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Gogus and Kokpinar (1999) developed the following empirical correlation based on experimental data for the ranges 230 μm < D_d < 5430 μm, 1.04 kg/liter < ρ_d < 2.68 kg/liter, 0.0254 m < D_{pipe} < 0.1524 m, and 0.0075 < α_d < 0.30

with particle settling velocity in slurry mixture (Thomas viscosity correlation is assumed herein) given by

$$v_{\infty m}(D_d,\rho_s,\rho_L,\mu_L,C_s) := v_\infty(D_d,\rho_s,\rho_c(\rho_s,\rho_L,C_s),\mu_{cThomas}(\mu_L,C_s)) \quad \text{resulting in} \qquad \textbf{(F-42)}$$

$$v'_{crGK}(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,\kappa_{cv}) := \kappa_{cv}\cdot 0.0548\cdot\left(\frac{D_d}{D_{pipe}}\right)^{-0.60}\cdot C_s^{0.27}\cdot\left(\frac{\rho_s}{\rho_L}-1\right)^{0.07}\cdot\left(\frac{\rho_L\cdot v_{\infty m}(D_d,\rho_s,\rho_L,\mu_L,C_s)\cdot D_d}{\mu_L}\right)^{0.30}$$

$$v_{crGK}(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,\kappa_{cv}) := v'_{crGK}(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,\kappa_{cv})\cdot\sqrt{g\cdot D_{pipe}} \qquad \textbf{(F-43)}$$

The authors claim only 15% average error in this prediction equation. However, application of Equation F-43 to Hanford HLW would require extrapolation beyond the experimental database, particularly with respect to the particle size,

Figure F-5 indicates that the Oroskar and Turian (1980) empirical equation generally predicts a higher critical velocity than the Oroskar and Turian (1980) semi-theoretical equation. The sensitivity of the Oroskar and Turian (1980) empirical equation to the liquid density, liquid viscosity, particle solids density, particle solids diameter, and solids volume fraction are shown in Figures F-6 through F-10 for solid-liquid flow in a 3-inch diameter pipe. Note that extrapolation is required for application to median particle sizes less than 100 μm which is outside the experimental database.

The following relation provides easy access to each of the above correlations and assures that the critical velocity returned is greater than the transition to turbulence velocity in the carrier liquid.

$$v_{cr}(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,\kappa_{cv},\beta_{cv}) := \frac{m}{sec}\cdot \left|\begin{array}{l}
v_T \leftarrow \dfrac{\kappa_{cv}\cdot 2300\cdot\mu_L}{D_{pipe}\cdot\rho_L} \quad \text{transition to turbulence velocity} \\
v_{crit} \leftarrow v_T \ \text{ if } C_s < 0.0001 \\
\text{otherwise} \\
\quad \left|\begin{array}{l}
v_{crit} \leftarrow v_{crOT}(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,\kappa_{cv}) \ \text{ if } \beta_{cv}=1 \\
v_{crit} \leftarrow v_{crOTt}(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,\kappa_{cv}) \ \text{ if } \beta_{cv}=1.1 \\
v_{crit} \leftarrow v_{crOTe}(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,\kappa_{cv}) \ \text{ if } \beta_{cv}=1.2 \\
v_{crit} \leftarrow v_{crWasp}(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,\kappa_{cv}) \ \text{ if } \beta_{cv}=2 \\
v_{crit} \leftarrow v_{crZG}(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,\kappa_{cv}) \ \text{ if } \beta_{cv}=3 \\
v_{crit} \leftarrow v_{crShook}(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,\kappa_{cv}) \ \text{ if } \beta_{cv}=4 \\
v_{crit} \leftarrow v_{crGK}(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,\kappa_{cv}) \ \text{ if } \beta_{cv}=5 \\
v_{crit} \leftarrow v_{crRG}(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,\kappa_{cv}) \ \text{ if } \beta_{cv}=6
\end{array}\right. \\
v_T \ \text{ if } v_T > v_{crit} \\
v_{crit} \ \text{ otherwise}
\end{array}\right. \qquad \textbf{(F-44)}$$

The critical velocity correlation selection key for equation F-44 is given as follows:

β_{cv} =
- 1 Oroskar and Turian (1980) maximum of semi-theoretical and empirical equation
- 1.1 Oroskar and Turian (1980) semi-theoretical equation
- 1.2 Oroskar and Turian (1980) empirical equation
- 2 Wasp et al. (1977)
- 3 Zandi and Govatos (1967)
- 4 Shook (1969)
- 5 Gogus and Kokpinar (1999)
- 6 Robinson and Graf (1972)

κ_{cv} is the uncertainty factor on the critical velocity, set to 1 to obtain the "best-estimate" prediction. In application of the various critical velocity correlations, the recommend value for κ_{cv} is at least 1.3 for an upper bound estimate to account for uncertainties in the empirical correlations and to include sufficient margin above the critical velocity to assure stable flow conditions.

Figures F-6 through F-10 show the sensitivity of the slurry parameters on the Oroskar and Turian (1980) empirical equation for the critical velocity best-estimate predication. The other correlations are compared to the Oroskar and Turian (1980) semi-theoretical and empirical equations in Figure F-15 along with the Turian, Hsu, and Ma (1987) regime transition correlation discussed in Section 6.1.2.2 below.

6.1.2 Friction Factors

In addition to pipe roughness, the friction factor for pipe flow is affected by the physical properties of the carrier liquid and the particles in suspension.

6.1.2.1 Friction Factor for Pipe Flow Due to Carrier Liquid

Slurry volume entirely liquid, $C_s = 0$.

Colebrook-White correlation for the Darcy or Moody friction factor (f) in the turbulent regime is given by

$$\frac{1}{\sqrt{f}} = -2\cdot\log\left(\frac{\eta}{3.7} + \frac{2.51}{Re\cdot\sqrt{f}}\right) \quad \text{strictly valid for } 4\cdot10^3 \le Re \le 10^8 \qquad \textbf{(F-45)}$$

where

$$f = \frac{h_L}{\frac{L}{D}\cdot\frac{v^2}{2\cdot g}} = \frac{\Delta p}{\left(\frac{L}{D}\cdot\frac{\rho\cdot v^2}{2}\right)} \qquad \textbf{(F-46)}$$

$$\eta = \frac{\varepsilon}{D_{pipe}} \quad \text{relative pipe roughness} \qquad \textbf{(F-47)}$$

ε roughness of pipe

This relation is implicit in the friction factor but Olujic (1981) obtained the following explicit approximation in the turbulent regime

$$f_t(Re,\eta) := \left[-2\cdot\log\left[\frac{\eta}{3.7} - \frac{5.02}{Re}\cdot\log\left[\frac{\eta}{3.7} + \left(\frac{14.5}{Re}\right)\right]\right]\right]^{-2}$$ turbulent regime, Re >4000 **(F-48)**

For the laminar regime, Re < 2100

$$f_l(Re) := \frac{64}{Re}$$ (independent of roughness) **(F-49)**

Olujic (1981) also reports the following approximation developed by Churchill in 1977 that includes the laminar and turbulent regimes as well as the transition regime between laminar and turbulent flow

$$f_c(Re,\eta) := \left| \begin{array}{l} A \leftarrow \left[2.457\cdot\ln\left[\dfrac{1}{\left(\dfrac{7}{Re}\right)^{0.9} + (0.27\cdot\eta)}\right]\right]^{16} \\ B \leftarrow \left(\dfrac{37530}{Re}\right)^{16} \\ 8\cdot\left[\left(\dfrac{8}{Re}\right)^{12} + \left(\dfrac{1}{A+B}\right)^{\frac{3}{2}}\right]^{\frac{1}{12}} \end{array} \right.$$

(Note that the transition regime is not well defined in practice but is approximated with a "smooth" transition curve for numerical convenience only. This approximation slightly over shoots the Colebrook-White friction factor correlation at the start of the turbulent regime.) **(F-50)**

or

$$f_c(D_{pipe}, v, \rho_L, \mu_L, \varepsilon) := f_c\left(Re(D_{pipe}, v, \rho_L, \mu_L), \frac{\varepsilon}{D_{pipe}}\right)$$ **(F-51)**

where v is average flow velocity of carrier liquid.

Figure 11 shows the resulting Darcy friction factor for pipe flow of Newtonian carrier fluid as a function of Reynolds Number and relative roughness ($\eta = \varepsilon / D_{pipe}$).

6.1.2.2 Friction Factor for Pipe Flow Due to Particles

A refined correlation of the particle contribution to the friction factor was given by Turian and Yuan (1977) and Turian, Hsu, and Ma (1987) as a function of flow regime based on the Fanning friction factor definition. The Darcy friction factor is equal to 4 times the Fanning friction factor. The corresponding results in terms of the Darcy friction factor definition become

Turian, Hsu, and Ma (1987)

$s =$	$K_s :=$	$\alpha_s :=$	$\beta_s :=$	$\gamma_s :=$	$\delta_s :=$	
0	12.127	0.7389	0.7717	−0.4054	−1.096	flow regime 0 (stationary bed)
1	107.09	1.018	1.046	−0.4213	−1.354	flow regime 1 (saltation)
2	30.115	0.8687	1.2	−0.1677	−0.6938	flow regime 2 (heterogeneous)
3	8.538	0.5024	1.428	0.1516	−0.3531	flow regime 3 (homogeneous)

Turian and Yuan (1977)

$K'_s :=$
0.4036
0.9857
0.5513
0.8444

(F-52)

$$f_{dm}(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, D_d, \rho_s, C_s, m, \beta_f) := 4 \cdot \frac{\mathrm{if}(\beta_f = 1, K_m, K'_m) \cdot C_s^{\alpha_m} \cdot \left(\frac{f_c(D_{pipe}, v, \rho_L, \mu_L, \varepsilon)}{4}\right)^{\beta_m}}{C_D(D_d, v_\infty(D_d, \rho_s, \rho_L, \mu_L), \rho_L, \mu_L)^{-\gamma_m}} \cdot \left[\frac{v^2}{g \cdot D_{pipe} \cdot \left(\frac{\rho_s}{\rho_L} - 1\right)}\right]^{\delta_m}$$

$$K_t(a,b) := \left(\frac{K_b}{K_a}\right)^{\frac{1}{\delta_a - \delta_b}} \quad \alpha_t(a,b) := \frac{\alpha_b - \alpha_a}{\delta_a - \delta_b} \quad \beta_t(a,b) := \frac{\beta_b - \beta_a}{\delta_a - \delta_b} \quad \gamma_t(a,b) := \frac{\gamma_b - \gamma_a}{\delta_a - \delta_b} \quad K'_t(a,b) := \left(\frac{K'_b}{K'_a}\right)^{\frac{1}{\delta_a - \delta_b}}$$

$K_t(0,1) = 4641.4$	$\alpha_t(0,1) = 1.0818$	$\beta_t(0,1) = 1.0632$	$\gamma_t(0,1) = -0.0616$	$K'_t(0,1) = 31.8$
$K_t(1,2) = 6.8319$	$\alpha_t(1,2) = 0.2261$	$\beta_t(1,2) = -0.2333$	$\gamma_t(1,2) = -0.3841$	$K'_t(1,2) = 2.4113$
$K_t(2,3) = 40.4362$	$\alpha_t(2,3) = 1.0751$	$\beta_t(2,3) = -0.6692$	$\gamma_t(2,3) = -0.9372$	$K'_t(2,3) = 0.2861$
$K_t(1,3) = 12.5143$	$\alpha_t(1,3) = 0.5151$	$\beta_t(1,3) = -0.3817$	$\gamma_t(1,3) = -0.5724$	$K'_t(1,3) = 1.1672$
$K_t(0,2) = 0.1042$	$\alpha_t(0,2) = -0.3227$	$\beta_t(0,2) = -1.0649$	$\gamma_t(0,2) = -0.591$	$K'_t(0,2) = 0.4605$
$K_t(0,3) = 1.6038$	$\alpha_t(0,3) = 0.3183$	$\beta_t(0,3) = -0.8834$	$\gamma_t(0,3) = -0.7498$	$K'_t(0,3) = 0.3702$

Flow regime numbers for selecting appropriate flow regime is given by

(F-53a)

$$R'_{ab}(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, D_d, \rho_s, C_s, a, b, \beta_f) := \frac{C_D(D_d, v_\infty(D_d, \rho_s, \rho_L, \mu_L), \rho_L, \mu_L)^{-\gamma_t(a,b)}}{\mathrm{if}(\beta_f = 1, K_t(a,b), K'_t(a,b)) \cdot C_s^{\alpha_t(a,b)} \cdot \left(\frac{f_c(D_{pipe}, v, \rho_L, \mu_L, \varepsilon)}{4}\right)^{\beta_t(a,b)}}$$

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Location: 200 Area - Hanford Site, Richland, Washington
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$$R_{ab}(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, D_d, \rho_s, C_s, a, b, \beta_f) := R'_{ab}(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, D_d, \rho_s, C_s, a, b, \beta_f) \cdot \frac{v^2}{g \cdot D_{pipe} \cdot \left(\frac{\rho_s}{\rho_L} - 1\right)} \quad \textbf{(F-53b)}$$

The flow regime number retrieval function is given by

$$R_d(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, D_d, \rho_s, C_s, \beta_f) := \left| \begin{array}{l}
r_{01} \leftarrow R_{ab}(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, D_d, \rho_s, C_s, 0, 1, \beta_f) - 1 \\
r_{12} \leftarrow R_{ab}(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, D_d, \rho_s, C_s, 1, 2, \beta_f) - 1 \\
r_{23} \leftarrow R_{ab}(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, D_d, \rho_s, C_s, 2, 3, \beta_f) - 1 \\
r_{02} \leftarrow R_{ab}(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, D_d, \rho_s, C_s, 0, 2, \beta_f) - 1 \\
r_{03} \leftarrow R_{ab}(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, D_d, \rho_s, C_s, 0, 3, \beta_f) - 1 \\
r_{13} \leftarrow R_{ab}(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, D_d, \rho_s, C_s, 1, 3, \beta_f) - 1 \\
0 \text{ if } (r_{01} < 0) \cdot (r_{12} < 0) \cdot (r_{23} < 0) \\
1 \text{ if } (r_{01} > 0) \cdot (r_{12} < 0) \cdot (r_{23} < 0) \\
2 \text{ if } (r_{01} > 0) \cdot (r_{12} > 0) \cdot (r_{23} < 0) \\
3 \text{ if } (r_{01} > 0) \cdot (r_{12} > 0) \cdot (r_{23} > 0) \\
\text{if } (r_{01} < 0) \cdot (r_{12} < 0) \cdot (r_{23} > 0) \\
\quad \left| \begin{array}{l} 0 \text{ if } r_{03} < 0 \\ 3 \text{ otherwise} \end{array} \right. \\
\text{if } (r_{01} < 0) \cdot (r_{12} > 0) \cdot (r_{23} > 0) \\
\quad \left| \begin{array}{l} 0 \text{ if } r_{03} < 0 \\ 3 \text{ otherwise} \end{array} \right. \\
\text{if } (r_{01} < 0) \cdot (r_{12} > 0) \cdot (r_{23} < 0) \\
\quad \left| \begin{array}{l} 0 \text{ if } r_{02} < 0 \\ 2 \text{ otherwise} \end{array} \right. \\
\text{if } (r_{01} > 0) \cdot (r_{12} < 0) \cdot (r_{23} > 0) \\
\quad \left| \begin{array}{l} 1 \text{ if } r_{13} < 0 \\ 3 \text{ otherwise} \end{array} \right. \\
-1 \text{ otherwise}
\end{array} \right. \quad \textbf{(F-54)}$$

The added particle contribution to the friction factor based on flow regime is then given by **(F-55)**

$$f_{dTurian}(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, D_d, \rho_s, C_s, \kappa_f, \beta_f) := \kappa_f \cdot f_{dm}(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, D_d, \rho_s, C_s, R_d(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, D_d, \rho_s, C_s, \beta_f), \beta_f)$$

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Critical velocity based on flow regime transition identification is given by **(F-56a)**

$$v'_{cRabv}(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,\varepsilon,a,b,v,\beta_f) := \left[\frac{\mathrm{if}(\beta_f = 1, K_t(a,b), K'_t(a,b))\cdot C_s^{\alpha_t(a,b)}\cdot\left(\frac{f_c(D_{pipe},v,\rho_L,\mu_L,\varepsilon)}{4}\right)^{\beta_t(a,b)}}{C_D\left(D_d, v_\infty(D_d,\rho_s,\rho_L,\mu_L),\rho_L,\mu_L\right)^{-\gamma_t(a,b)}}\right]^{\frac{1}{2}}$$

$$v_{cRabv}(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,\varepsilon,a,b,v,\beta_f) := v'_{cRabv}(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,\varepsilon,a,b,v,\beta_f)\cdot\sqrt{g\cdot D_{pipe}\cdot\left(\frac{\rho_s}{\rho_L}-1\right)} \quad \textbf{(F-56b)}$$

$$v_{cRab}(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,\varepsilon,a,b,\beta_f) := \mathrm{root}\left(v' - v_{cRabv}(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,\varepsilon,a,b,v',\beta_f), v'\right) \quad \textbf{(F-56c)}$$

$$v_{crR}(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,\varepsilon,\kappa_{cv},\beta_f) := \kappa_{cv}\cdot\frac{m}{sec}\cdot \left|\begin{array}{l}
v_{01} \leftarrow v_{cRab}(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,\varepsilon,0,1,\beta_f)\\
v_{02} \leftarrow v_{cRab}(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,\varepsilon,0,2,\beta_f)\\
v_{03} \leftarrow v_{cRab}(D_{pipe},D_d,\rho_s,C_s,\rho_L,\mu_L,\varepsilon,0,3,\beta_f)\\
R_{02_01} \leftarrow R_{ab}(D_{pipe},v_{01},\rho_L,\mu_L,\varepsilon,D_d,\rho_s,C_s,0,2,\beta_f)\\
R_{03_01} \leftarrow R_{ab}(D_{pipe},v_{01},\rho_L,\mu_L,\varepsilon,D_d,\rho_s,C_s,0,3,\beta_f)\\
R_{01_02} \leftarrow R_{ab}(D_{pipe},v_{02},\rho_L,\mu_L,\varepsilon,D_d,\rho_s,C_s,0,1,\beta_f)\\
R_{03_02} \leftarrow R_{ab}(D_{pipe},v_{02},\rho_L,\mu_L,\varepsilon,D_d,\rho_s,C_s,0,3,\beta_f)\\
R_{01_03} \leftarrow R_{ab}(D_{pipe},v_{03},\rho_L,\mu_L,\varepsilon,D_d,\rho_s,C_s,0,1,\beta_f)\\
R_{02_03} \leftarrow R_{ab}(D_{pipe},v_{03},\rho_L,\mu_L,\varepsilon,D_d,\rho_s,C_s,0,2,\beta_f)\\
v_{01} \text{ if } (R_{02_01} \le 1)\cdot(R_{03_01} \le 1)\\
v_{02} \text{ if } (R_{01_02} \le 1)\cdot(R_{03_02} \le 1)\\
v_{03} \text{ if } (R_{01_03} \le 1)\cdot(R_{02_03} \le 1)\\
-1 \text{ otherwise}
\end{array}\right. \quad \textbf{(F-57)}$$

The following relation is used to plot flow regime (v-D_d) diagrams as shown in Figures 12 through 14.

$$D_{dab}(D_{pipe},v,\rho_L,\mu_L,\varepsilon,\rho_s,C_s,a,b,\beta_f) := -1\cdot\mu m \text{ on error } \mathrm{root}\left(R_{ab}(D_{pipe},v,\rho_L,\mu_L,\varepsilon,D'_d,\rho_s,C_s,a,b,\beta_f) - 1, D'_d\right) \quad \textbf{(F-58)}$$

Turian and Oroskar's (1978) Figure 1 flow regime diagrams for pipe inside diameters 1.58 and 5.25 cm (1/2 and 2 in.) based on Turian, Hsu, and Ma 1987 corrected equations are given in Figures 12 and 13 as a check and also demonstrate the effect of pipe size on the flow regime locations. A smooth pipe with water at 22.5 °C for the carrier liquid is assumed with a 5% solids concentration by volume with a 2.977 gm/cm^3 particle solids density. The flow regime diagrams for the 1.58 and 5.25 cm inside pipe diameters are shown in Figures 12 and 13, respectively. Flow regime diagrams for the 3-inch diameter pipeline of interest are shown in Figure 14 for the conditions indicated.

Figure 15 compares the best-estimate critical velocity predictions from Robinson and Graf (1972), Wasp et al. (1977), Oroskar and Turian (1980) semi-theoretical and empirical equations, and the critical velocity derived from the regime transition boundaries defined in Turian and Yuan (1977) for a smooth pipe with corrected relations given in Turian, Hsu, and Ma (1987).

Note that the critical velocity correlations compared in Figure 15 were obtained for narrow band distributions of median diameter solid particles greater than 100 μm. Hence, the results shown in Figure 15 for solid particles less than 100 μm requires extrapolation and should be used with caution. In addition, it must be recognized that the critical velocity data is based on subjective observations and hence introduce uncertainty in the data upon which the correlations were developed. These correlations were developed for solid particles with narrow distributions. The effect of solid particles with a wide distribution needs to be addressed.

For fine particles (diameter much less than 100 μm) the two-phase approach to determining pressure loss and minimum settling (critical) velocity begins to break down. In this case the liquid-solid flow approaches a homogeneous type behavior in which the fine particle remain suspended but the mixture may exhibit non-Newtonian shear characteristics.

The following additional friction factor correlations ($f - f_c = f_d$) based on large particles are provided for comparison:

Durand (1953) friction factor correlation per equation 11.84a as reported in Grovier and Aziz 1972 **(F-59)**

$$f_{dDurand}(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, D_d, \rho_s, C_s, \kappa_f, K_D) := \kappa_f \cdot K_D \cdot C_s \cdot f_c(D_{pipe}, v, \rho_L, \mu_L, \varepsilon) \cdot \left[\frac{v^2 \cdot \sqrt{C_D(D_d, v_\infty(D_d, \rho_s, \rho_L, \mu_L), \rho_L, \mu_L)}}{g \cdot D_{pipe} \cdot \left(\frac{\rho_s}{\rho_L} - 1 \right)} \right]^{\frac{-3}{2}}$$

Note that Grovier and Aziz (1972) indicate that the abscissa of Figure 10 in the paper by Durand (1953) appears to be mislabeled, and others appear to have erroneously determined from it the value of the constant (K_D) as either 81, 82, or 84.9 rather than 150.

Zandi and Govatos (1967) friction factor correlation per equation 11.85 of Grovier and Aziz 1972

(valid for $N_l = \psi / C_s > 40$)

$$f_{dZandi}(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, D_d, \rho_s, C_s, \kappa_f) := \kappa_f \cdot C_s \cdot f_c(D_{pipe}, v, \rho_L, \mu_L, \varepsilon) \cdot \left| \begin{array}{l} \psi \leftarrow \dfrac{v^2 \cdot \sqrt{C_D(D_d, v_\infty(D_d, \rho_s, \rho_L, \mu_L), \rho_L, \mu_L)}}{g \cdot D_{pipe} \cdot \left(\dfrac{\rho_s}{\rho_L} - 1\right)} \\ 280 \cdot \psi^{-1.93} \text{ if } \psi < 10 \\ 6.30 \cdot \psi^{-0.354} \text{ otherwise} \end{array} \right. \quad \textbf{(F-60)}$$

Heywood (1999) refers to a "recent" reassessment of all available data covering both heterogeneous and moving-bed flow patterns which suggested the following correlation:

$$f_{dHeywood}(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, D_d, \rho_s, C_s, \kappa_f) := \kappa_f \cdot 55.6 \cdot f_c(D_{pipe}, v, \rho_L, \mu_L, \varepsilon) \cdot \left[\frac{v^2 \cdot \sqrt{C_D(D_d, v_\infty(D_d, \rho_s, \rho_L, \mu_L), \rho_L, \mu_L)}}{C_s \cdot g \cdot D_{pipe} \cdot \left(\dfrac{\rho_s}{\rho_L} - 1\right)} \right]^{-1.08} \quad \textbf{(F-61)}$$

The above Durand (1953) and Zandi and Govatos (1967) Darcy friction factor correlations for two-phase liquid-solid particle type pipe flow are compared in Figure 16 to the Turian and Yuan (1977) correlation with the Turian, Hsu, and Ma (1987) correction. The correlations give similar results but the Turian correlation was selected for application because of its purported overall better performance over the full range of flow velocities over each flow regime. However, it is clear that there is a large uncertainty band for any of these correlations.

The combined friction factor for pipe with positive incline to horizontal of θ (deg) per Blevins (1984) is given by

$$f_d(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, D_d, \rho_s, C_s, \beta_f, \kappa_f, \theta) := \left| \begin{array}{l} f_{dTurian}(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, D_d, \rho_s, C_s, \kappa_f, \beta_f) \cdot \cos(\theta) \text{ if } (\beta_f = 1) + (\beta_f = 2) \\ f_{dZandi}(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, D_d, \rho_s, C_s, \kappa_f) \cdot \cos(\theta) \text{ if } \beta_f = 3 \\ f_{dHeywood}(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, D_d, \rho_s, C_s, \kappa_f) \cdot \cos(\theta) \text{ if } \beta_f = 4 \\ f_{dDurand}(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, D_d, \rho_s, C_s, \kappa_f, \beta_f) \cdot \cos(\theta) \text{ otherwise} \end{array} \right. \quad \textbf{(F-62a)}$$

$$f(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, D_d, \rho_s, C_s, \beta_f, \kappa_f, \theta) := \left| \begin{array}{l} f \leftarrow f_c(D_{pipe}, v, \rho_L, \mu_L, \varepsilon) \\ f \text{ if } (\beta_f = 0) + (C_s = 0) \\ f + f_d(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, D_d, \rho_s, C_s, \beta_f, \kappa_f, \theta) \text{ otherwise} \end{array} \right. \quad \textbf{(F-62b)}$$

The friction factor correlation selection key for Equation F-62 is given by

β_f =
- 0 liquid only, no solid particles, $C_s = 0$
- 1 Turian, Hsu, and Ma (1987)
- 2 Turian and Yuan (1977)
- 3 Zandi and Govatos (1967)
- 4 Heywood (1999)
- 82, 150 = K_D Durand (1953)

κ_f is the uncertainty factor on the friction factor due to solid particles, set to 1 to obtain the "best-estimate" prediction. Recommend at least 1.25 for upper bound estimate to account for uncertainties in the correlations.

Figure 17 compares the best-estimate predications of the total friction factor for pipe slurry flow based on Turian, Hsu, and Ma (1987), Durand (1953), Zandi and Govatos (1967), and Heywood (1999) as a function of the flow velocity and pipe roughness estimates of interest. The friction factor (f_c) for the liquid only is also shown for comparison. At velocities below the critical velocity, the friction factor of Turian, Hsu, and Ma (1987) or Heywood (1999) are expected to be more reliable because the data was more systematically evaluated in this regime.

Note that application of the above predicted friction factors for slurry flows with median solid particle diameters less than 100 μm requires extrapolation beyond the database used in the development of the correlations and hence should be used with caution.

6.1.3 Pressure Drop

Head loss for pipe with positive incline to horizontal of θ (deg) per Blevins (1984) is given by

$$\Delta h_L(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, D_d, \rho_s, C_s, L, \beta_f, \kappa_f, \theta) := \frac{L}{D_{pipe}} \cdot \frac{v^2}{2 \cdot g} \cdot f(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, D_d, \rho_s, C_s, \beta_f, \kappa_f, \theta) \ldots + \left[\left(\frac{\rho_s}{\rho_L} - 1\right) \cdot C_s + 1\right] \cdot L \cdot \sin(\theta) \quad \textbf{(F-63)}$$

The corresponding pressure loss is given by

$$\Delta p(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, D_d, \rho_s, C_s, L, \beta_f, \kappa_f, \theta) := \Delta h_L(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, D_d, \rho_s, C_s, L, \beta_f, \kappa_f, \theta) \cdot \rho_L \cdot g \quad \textbf{(F-64)}$$

Hence, the total pressure loss for a combined carbon (CS) and stainless steel (SS) pipeline is given by

$$\Delta p_T(D_{pipe}, v, \rho_L, \mu_L, \varepsilon_{CS}, \varepsilon_{SS}, D_d, \rho_s, C_s, L_{CS}, L_{SS}, \beta_f, \kappa_f, \theta) := \Delta p(D_{pipe}, v, \rho_L, \mu_L, \varepsilon_{CS}, D_d, \rho_s, C_s, L_{CS}, \beta_f, \kappa_f, \theta) \ldots + \Delta p(D_{pipe}, v, \rho_L, \mu_L, \varepsilon_{SS}, D_d, \rho_s, C_s, L_{SS}, \beta_f, \kappa_f, \theta) \quad \textbf{(F-65)}$$

where

L equivalent length of pipe

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The flow area and flow rate are given by

$D_{pipe} := 3.068 \cdot in$

$A(D_{pipe}) := \pi \cdot \frac{D_{pipe}^2}{4}$ flow area of pipe $A(D_{pipe}) = 7.393\,in^2$ **(F-66)**

$Q(v, D_{pipe}) := v \cdot A(D_{pipe})$ pipe flow rate

The following sample pressure drop calculation is provided for comparison of the results from the various pressure drop correlations:

Sample Pressure Drop Calculation - for HLW Transfer AW-105-to-WTP Transfer Route

$D_{pipe} := 3.068 \cdot in$ pipe internal diameter

$\varepsilon_{CS} := \varepsilon_{BOL\_CS}$ roughness of carbon steel pipe segment

$\varepsilon_{SS} := \varepsilon_{BOL\_SS}$ roughness of stainless steel pipe segment

$\rho_L := 1.1 \cdot \frac{kg}{liter}$ carrier liquid density (no solids)

$x_{salt} := 0.9$ salt fraction of dissolved salts

$T := 60\ ^{o}C$ temperature

$\mu_L := \mu_{cL}(\rho_L, T, x_{salt})$ liquid viscosity

$\mu_L = 0.58\,cP$

$\kappa_f := 1$ best-estimate friction factor

$\beta_{cv} := 1.2$ select Oroskar and Turian (1980) empirical critical velocity correlation

$\kappa_{cv} := 1$ best-estimate critical velocity prediction

$L_{CS} := 1566 \cdot ft$ equivalent pipe length of carbon steel pipe segment

$L_{SS} := 4268 \cdot ft$ equivalent pipe length of stainless steel pipe segment

$H := 40.9 \cdot ft$ total elevation change

$\theta := asin\left(\frac{H}{L_{CS} + L_{SS}}\right)$ corresponding pipeline slope

$\rho_s := 2.9 \cdot \frac{kg}{liter}$ solids density

$C_s := 10 \cdot vol\%$ solids concentration

$\boxed{d_{50} := 110 \cdot \mu m}$ median particle size of PSD

$v := 6 \cdot \frac{ft}{sec}$ target flow velocity

Predicted critical velocity

$$v_{cr}(D_{pipe}, d_{50}, \rho_s, C_s, \rho_L, \mu_L, \kappa_{cv}, \beta_{cv}) = 4.523 \frac{ft}{sec}$$

Predicted total pressure drop at target flow velocity

$$\Delta p_T(D_{pipe}, v, \rho_L, \mu_L, \varepsilon_{CS}, \varepsilon_{SS}, d_{50}, \rho_s, C_s, L_{CS}, L_{SS}, \overset{\beta_f}{0}, \kappa_f, \theta) = 193 \frac{lbf}{in^2}$$ liquid only, no solid particles

$$\Delta p_T(D_{pipe}, v, \rho_L, \mu_L, \varepsilon_{CS}, \varepsilon_{SS}, d_{50}, \rho_s, C_s, L_{CS}, L_{SS}, 1, \kappa_f, \theta) = 321 \frac{lbf}{in^2}$$ Turian, Hsu, and Ma (1987)

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Predicted total pressure drop at target flow velocity (continued)

β_f

$$\Delta p_T\left(D_{pipe}, v, \rho_L, \mu_L, \varepsilon_{CS}, \varepsilon_{SS}, d_{50}, \rho_s, C_s, L_{CS}, L_{SS}, 2, \kappa_f, \theta\right) = 198 \frac{lbf}{in^2}$$ Turian and Yuan (1977)

$$\Delta p_T\left(D_{pipe}, v, \rho_L, \mu_L, \varepsilon_{CS}, \varepsilon_{SS}, d_{50}, \rho_s, C_s, L_{CS}, L_{SS}, 3, \kappa_f, \theta\right) = 260 \frac{lbf}{in^2}$$ Zandi and Govatos (1967)

$$\Delta p_T\left(D_{pipe}, v, \rho_L, \mu_L, \varepsilon_{CS}, \varepsilon_{SS}, d_{50}, \rho_s, C_s, L_{CS}, L_{SS}, 4, \kappa_f, \theta\right) = 265 \frac{lbf}{in^2}$$ Heywood (1999)

$$\Delta p_T\left(D_{pipe}, v, \rho_L, \mu_L, \varepsilon_{CS}, \varepsilon_{SS}, d_{50}, \rho_s, C_s, L_{CS}, L_{SS}, 82, \kappa_f, \theta\right) = 244 \frac{lbf}{in^2}$$ K_D = 82, Durand (1953)

$$\Delta p_T\left(D_{pipe}, v, \rho_L, \mu_L, \varepsilon_{CS}, \varepsilon_{SS}, d_{50}, \rho_s, C_s, L_{CS}, L_{SS}, 150, \kappa_f, \theta\right) = 286 \frac{lbf}{in^2}$$ K_D = 150, Durand (1953)

Note that there is a wide variation in results between the various correlations.

For slurry flow in a 3-inch pipe, Figures 18 through 20 show best-estimate pressure drop contour plots per 1,000 ft of pipe, corresponding flow regime contour plots, and critical velocity contour plots for the range of carrier liquid density and particle density of interest for the Hanford waste. The pressure drop results are based on the Turian, Hsu, and Ma (1987) friction factor correlation and the critical velocity results are based on the Oroskar and Turian (1980) empirical correlation. The pressure drop results are shown at a target flow velocity of 6 ft/s for end-of-life (EOF) pipe roughness estimates for carbon and stainless steel as given above. The solid particle size, solid fraction by volume, and temperature of the flow are indicated in the figures. These figures provide an upper bound estimate to the friction pressure loss, particularly for solid particle diameters less than 100 μm. For slurry flows with broad solid particle distributions the method of Wasp et al. (1977) which accounts for the effect of the "fine" and large particles is expected to provide more realistic predictions.

6.2 COMBINED HOMOGENEOUS-HETEROGENEOUS SLURRY FLOW - WASP METHOD

Wasp (1977) developed a method to estimate the pipe pressure loss for a combined homogeneous-heterogeneous flow with multiple particle sizes based on the concept of a "two-phase vehicle." Fine particles join with the carrier liquid to form a homogeneous "vehicle" while the course particles are suspended as a heterogeneous "bed" within this homogeneous vehicle. The fine particles in the vehicle modify the effective liquid density and rheology of the liquid. High concentrations (approaching 30% by volume) of "fine" particles (particle size diameters less than 100 μm) can result in non-Newtonian viscosity characteristics. In the application herein the viscosity of the vehicle is given by Equation F-14 with the concentration of fines determined by the Wasp method.

The Wasp method requires a particle size distribution. In Revision 1 of RPP-5346 (2000) the assumed particle size distribution for the solid particles was based on the "grand-mean" of measured particle size distributions by volume from HLW Tanks AZ-101, AW-103, and C-104 (Jewett and Jensen 2000) using available PSD data at the time. The measured distribution was curve fit to a Rosin-Rammler distribution function (Shook and Roco 1991) and then shifted to obtain a distribution with the target median particle size of interest for analysis. However, the resulting PSDs indicated much larger median particle sizes then had been historically obtained. The application of these PSDs resulted in predicted pressures at the required critical velocity in excess of the pipeline system design pressures for most of the transfer pipeline routes. As discussed in Section 5.0 of Appendix F, this led to a need for a more detailed reassessment of the Hanford waste physical properties at transport conditions. Previous estimated waste physical property data provided in Estey (2000) and Jewett and Jensen (2000) for the in situ Hanford waste were reassessed by Jewett et al. (2002) supported by the results from a new extensive experimental investigation of Hanford HLW PSD data (Bechtold et al. 2002). These new results are presented below and compared to the PSDs used in Revision 1 of RPP-5346 (2000).

6.2.1 Preliminaries

$TOL = 1 \times 10^{-5}$ $\Delta\varepsilon := TOL \cdot 10^{-1}$ $\Delta\varepsilon = 1 \times 10^{-6}$

Return cumulative vector ϕ_{cum} for frequency distribution vector ϕ

$$cum(\phi) := \left| \begin{array}{l} \text{for } j \in 0..length(\phi) - 1 \\ \quad \phi_{cum_j} \leftarrow \sum_{i=0}^{j} \phi_i \\ \phi_{cum} \end{array} \right. \qquad \textbf{(F-67)}$$

Return values of vector ϕ_p in accordance with nonzero values in vector $\phi_z > \Delta\varepsilon$

$$pack(\phi_p, \phi_z) := \left| \begin{array}{l} J \leftarrow length(\phi_z) - 1 \\ k \leftarrow 0 \\ \text{for } j \in 0..J \\ \quad \text{if } \phi_{z_j} > \Delta\varepsilon \\ \quad\quad \left| \begin{array}{l} \phi_k \leftarrow \phi_{p_j} \\ k \leftarrow k + 1 \end{array} \right. \\ \text{if } k = 0 \\ \quad \left| \begin{array}{l} \phi_0 \leftarrow \Delta\varepsilon \\ \phi_1 \leftarrow \Delta\varepsilon \end{array} \right. \\ \phi_1 \leftarrow \Delta\varepsilon \ \text{ if } k = 1 \\ \phi \end{array} \right. \qquad \textbf{(F-68)}$$

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Return class size intervals of density distribution data

$$\Delta(d_p) := \left| \begin{array}{l} J \leftarrow \text{length}(d_p) - 1 \\ \Delta d_0 \leftarrow \dfrac{d_{p_1} - d_{p_0}}{2} \\ \text{for } j \in 1..J-1 \\ \quad \Delta d_j \leftarrow \dfrac{d_{p_{j+1}} - d_{p_{j-1}}}{2} \\ \Delta d_J \leftarrow \dfrac{d_{p_J} - d_{p_{J-1}}}{2} \\ \Delta d \end{array} \right. \qquad \textbf{(F-69)}$$

Return d_β particle diameter that is βth percentile value by volumes

$$D\beta(d_p, \phi_{cum}, \beta) := \left| \begin{array}{l} J \leftarrow \text{length}(\phi_{cum}) - 1 \\ \text{for } k \in 0..J \\ \quad \text{break if } \phi_{cum_k} > \beta \\ \dfrac{d_{p_k} - d_{p_{k-1}}}{\phi_{cum_k} - \phi_{cum_{k-1}}} \cdot \left(\beta - \phi_{cum_{k-1}}\right) + d_{p_{k-1}} \end{array} \right. \qquad \textbf{(F-70)}$$

The Rosin-Rammler cumulative and probability density function from Table 1-1 of Shook and Roco (1991) were applied in curve fits of the particle size distribution data for analysis.

Cumulative distribution function

Probability density function

Rosin-Rammler

$$CDF_{RR}(d, d_{50}, p) := \left[1 - \exp\left[-\ln(2)\cdot\left(\frac{d}{d_{50}}\right)^p\right]\right] \qquad PDF_{RR}(d, d_{50}, p) := \ln(2)\cdot\left(\frac{d}{d_{50}}\right)^p \cdot \frac{p}{d} \cdot \exp\left[-\ln(2)\cdot\left(\frac{d}{d_{50}}\right)^p\right] \qquad \textbf{(F-71)}$$

Partial derivative of Rosin-Rammler CDF with respect to parameter d_{50}

$$CDF_{RR'd50}(d, d_{50}, p) := -\ln(2)\cdot\left(\frac{d}{d_{50}}\right)^p \cdot \frac{p}{d_{50}} \cdot \exp\left[-\ln(2)\cdot\left(\frac{d}{d_{50}}\right)^p\right] \qquad \textbf{(F-72)}$$

Partial derivative of Rosin-Rammler CDF with respect to parameter p

$$CDF_{RR'p}(d, d_{50}, p) := \ln(2)\cdot\left(\frac{d}{d_{50}}\right)^p \cdot \ln\left(\frac{d}{d_{50}}\right) \cdot \exp\left[-\ln(2)\cdot\left(\frac{d}{d_{50}}\right)^p\right] \qquad \textbf{(F-73)}$$

The following functions return an element vector containing the curve fit function and its partial derivatives with respect to its curve fitting parameters needed in Mathcad genfit curve fitting routine (see Section 6.2.5 below).

for single Rosin-Rammler approximation **(F-74)**

$$F_1(x,u) := \begin{pmatrix} CDF_{RR}(x,u_0,u_1) \\ CDF_{RR'd50}(x,u_0,u_1) \\ CDF_{RR'p}(x,u_0,u_1) \end{pmatrix}$$

for double Rosin-Rammler approximation **(F-75)**

$$F_2(x,u) := \frac{1}{2}\cdot\begin{pmatrix} CDF_{RR}(x,u_0,u_1) + CDF_{RR}(x,u_2,u_3) \\ CDF_{RR'd50}(x,u_0,u_1) \\ CDF_{RR'p}(x,u_0,u_1) \\ CDF_{RR'd50}(x,u_2,u_3) \\ CDF_{RR'p}(x,u_2,u_3) \end{pmatrix}$$

$f(x,u_i)$

$\frac{d}{du_i}f$

6.2.2 Wasp's Method for Pressure Drop Estimate

In accordance with Wasp et al. 1977, assume $\beta := 1$ $\kappa := 0.4$ von Karman constant

$$\phi_v(v,\rho_L,\rho_c,\mu_c,d_p,\rho_s,\phi_s,f) := \phi_s\cdot 10^{\frac{-1.8}{\beta\cdot\kappa}\cdot\frac{v_\infty(d_p,\rho_s,\rho_c,\mu_c)}{v\cdot\sqrt{\frac{f\cdot\frac{\rho_L}{\rho_c}}{8}}}} \qquad \textbf{(F-76)}$$

Return total concentration of solid particle attributed to "vehicle" liquid from each particle of particle size distribution using vehicle properties

(F-77)

$$\Phi_c(D,v,\rho_L,\mu_L,d_p,\rho_s,\phi_s,f,\beta_\mu) := \left|\begin{array}{l} J \leftarrow \text{length}(d_p) - 1 \\ \Phi'_v \leftarrow 0.5\cdot\sum_{j=0}^{J}\phi_{s_j} \\ \text{root}\left(\Phi'_v - \sum_{j=0}^{J}\phi_v\left(v,\rho_L,\rho_c(\rho_s,\rho_L,\Phi'_v),\mu_c(\mu_L,\gamma_r(v,D),\Phi'_v,\beta_\mu),d_{p_j},\rho_s,\phi_{s_j},f\right),\Phi'_v\right) \end{array}\right.$$

Darcy friction factor and pressure loss based on Wasp method using Durand friction factor correlation (see Equation **F-59** and 62) with

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$\beta_f = K_D$ $K_D = 82$ (Wasp et al. 1977) or 150 (see Equation (F-59)

$$f_{Wasp\_f}(D,v,\rho_L,\mu_L,\varepsilon,d_p,\rho_s,\phi_s,\beta_f,\theta,\beta_\mu,f) := \left|\begin{array}{l} J \leftarrow \text{length}(d_p) - 1 \\ \Phi_v \leftarrow \Phi_c(D,v,\rho_L,\mu_L,d_p,\rho_s,\phi_s,f,\beta_\mu) \\ \rho_v \leftarrow \rho_c(\rho_s,\rho_L,\Phi_v) \\ \mu_v \leftarrow \mu_c(\mu_L,\gamma_r(v,D),\Phi_v,\beta_\mu) \\ f_W \leftarrow f_c(D,v,\rho_v,\mu_v,\varepsilon)\cdot\dfrac{\rho_v}{\rho_L} \\ \text{for } j \in 0..J \\ \quad \left|\begin{array}{l} \phi_{vj} \leftarrow \phi_v(v,\rho_L,\rho_v,\mu_v,d_{p_j},\rho_s,\phi_{s_j},f) \\ \phi_{aj} \leftarrow \phi_{s_j} - \phi_{vj} \\ \phi_{aj} \leftarrow 0 \text{ if } \phi_{aj} < 0 \\ f_W \leftarrow f_W + f_d(D,v,\rho_L,\mu_L,\varepsilon,d_{p_j},\rho_s,\phi_{aj},\beta_f,1,\theta) \end{array}\right. \\ f_W \end{array}\right.$$

(F-78a)

homogeneous vehicle friction contribution normalized to clear liquid

plus friction (bed) contribution from remaining heterogeneous particles using clear liquid properties

$\kappa_f = 1$

$\Delta\Phi := TOL\cdot 10^{-1}$ $f_f := 0.02$ initial guess

$$f_{Wasp}(D,v,\rho_L,\mu_L,\varepsilon,d_p,\rho_s,\phi_s,\beta_f,\kappa_f,\theta,\beta_\mu) := \left|\begin{array}{l} J \leftarrow \text{length}(d_p) - 1 \\ \Phi_s \leftarrow \displaystyle\sum_{j=0}^{J} \phi_{s_j} \\ f_c(D,v,\rho_L,\mu_L,\varepsilon) \text{ if } \Phi_s < \Delta\Phi \\ \kappa_f\cdot\text{root}(f_f - f_{Wasp\_f}(D,v,\rho_L,\mu_L,\varepsilon,d_p,\rho_s,\phi_s,\beta_f,\theta,\beta_\mu,f_f),f_f) \text{ otherwise} \end{array}\right.$$

(F-78b)

Pressure drop

$$\Delta p_{Wasp}(D,v,\rho_L,\mu_L,\varepsilon,d_p,\rho_s,\phi_s,L,\beta_f,\kappa_f,\theta,\beta_\mu) := \left|\begin{array}{l} J \leftarrow \text{length}(d_p) - 1 \\ \Phi_s \leftarrow \displaystyle\sum_{j=0}^{J} \phi_{s_j} \\ \rho_L\cdot g\cdot\left[\dfrac{L}{D}\cdot\dfrac{v^2}{2\cdot g}\cdot f_{Wasp}(D,v,\rho_L,\mu_L,\varepsilon,d_p,\rho_s,\phi_s,\beta_f,\kappa_f,\theta,\beta_\mu) \ldots \right. \\ \left. + \left[\left(\dfrac{\rho_s}{\rho_L} - 1\right)\cdot\Phi_s + 1\right]\cdot L\cdot\sin(\theta)\right] \end{array}\right.$$

(F-79)

The total pressure drop for a combined carbon (CS) and stainless steel (SS) pipeline is given by **(F-80)**

$$\Delta p_{T\_Wasp}(D, v, \rho_L, \mu_L, \varepsilon_{CS}, \varepsilon_{SS}, d_p, \rho_s, \phi_s, L_{CS}, L_{SS}, \beta_f, \kappa_f, \theta, \beta_\mu) := \Delta p_{Wasp}(D, v, \rho_L, \mu_L, \varepsilon_{CS}, d_p, \rho_s, \phi_s, L_{CS}, \beta_f, \kappa_f, \theta, \beta_\mu) \ldots + \Delta p_{Wasp}(D, v, \rho_L, \mu_L, \varepsilon_{SS}, d_p, \rho_s, \phi_s, L_{SS}, \beta_f, \kappa_f, \theta, \beta_\mu)$$

6.2.3 Critical Velocity Based on Wasp "Vehicle" Concept

This procedure predicts a critical velocity for a given particle size distribution using the Wasp "vehicle" concept to obtain modified liquid (vehicle) properties that are then applied in the selected critical velocity correlation. Although this procedure appears logical, it is provided here for comparison only because it has not been validated by experimental data.

Wasp Modified Critical Deposition Velocity

$$v_{crDvWasp}(D, d_p, \rho_s, \phi_s, \rho_L, \mu_L, \varepsilon, \beta_{cv}, \beta_f, \beta_\mu, v) := \left| \begin{array}{l} J \leftarrow \mathrm{length}(d_p) - 1 \\ f_W \leftarrow f_{Wasp}(D, v, \rho_L, \mu_L, \varepsilon, d_p, \rho_s, \phi_s, \beta_f, 1, \theta, \beta_\mu) \\ \Phi_v \leftarrow \Phi_c(D, v, \rho_L, \mu_L, d_p, \rho_s, \phi_s, f_W, \beta_\mu) \\ \rho_v \leftarrow \rho_c(\rho_s, \rho_L, \Phi_v) \\ \mu_v \leftarrow \mu_c(\mu_L, \gamma_r(v, D), \Phi_v, \beta_\mu) \\ \phi_a \leftarrow 0 \\ \text{for } j \in 0..J \\ \quad \left| \begin{array}{l} \phi_{vj} \leftarrow \phi_v(v, \rho_L, \rho_v, \mu_v, d_{p_j}, \rho_s, \phi_{s_j}, f_W) \\ \phi_{a_j} \leftarrow \phi_{s_j} - \phi_{vj} \\ \phi_{a_j} \leftarrow 0 \text{ if } \phi_{a_j} < 0 \end{array} \right. \\ \phi_{cum} \leftarrow \mathrm{cum}(\phi_a) \\ \Phi_a \leftarrow \displaystyle\sum_{j=0}^{\mathrm{length}(\phi_a)-1} \phi_{a_j} \\ D_{p\beta} \leftarrow D_\beta\left(d_p, \dfrac{\phi_{cum}}{\Phi_a}, 0.5\right) \\ v_{cr}(D, D_{p\beta}, \rho_s, \Phi_a, \rho_v, \mu_v, 1, \beta_{cv}) \end{array} \right.$$ **(F-81a)**

$v' := 2 \cdot ft \cdot sec^{-1}$ initial guess **(F-82b)**

$$v_{crD\_Wasp}(D, d_p, \rho_s, \phi_s, \rho_L, \mu_L, \varepsilon, \kappa_{cv}, \beta_{cv}, \beta_f, \beta_\mu) := \kappa_{cv} \cdot \mathrm{root}(v' - v_{crDvWasp}(D, d_p, \rho_s, \phi_s, \rho_L, \mu_L, \varepsilon, \beta_{cv}, \beta_f, \beta_\mu, v'), v')$$

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Wasp Modified Laminar-to-Turbulent Transition Velocity $\quad Re_T := 2300$

$$v_{crTvWasp}(D, d_p, \rho_s, \phi_s, \rho_L, \mu_L, \varepsilon, \kappa_{cv}, \beta_f, \beta_\mu, v) := \left| \begin{array}{l} J \leftarrow \text{length}(d_p) - 1 \\ f_W \leftarrow f_{Wasp}(D, v, \rho_L, \mu_L, \varepsilon, d_p, \rho_s, \phi_s, \beta_f, 1, \theta, \beta_\mu) \\ \Phi_v \leftarrow \Phi_c(D, v, \rho_L, \mu_L, d_p, \rho_s, \phi_s, f_W, \beta_\mu) \\ \rho_v \leftarrow \rho_c(\rho_s, \rho_L, \Phi_v) \\ \mu_v \leftarrow \mu_c(\mu_L, \gamma_r(v, D), \Phi_v, \beta_\mu) \\ \dfrac{Re_T \cdot \mu_v}{D \cdot \rho_v} \end{array} \right. \qquad \textbf{(F-83a)}$$

$$v_{crT\_Wasp}(D, d_p, \rho_s, \phi_s, \rho_L, \mu_L, \varepsilon, \kappa_{cv}, \beta_f, \beta_\mu) := \kappa_{cv} \cdot \text{root}\left(v' - v_{crTvWasp}(D, d_p, \rho_s, \phi_s, \rho_L, \mu_L, \varepsilon, \kappa_{cv}, \beta_f, \beta_\mu, v'), v'\right) \qquad \textbf{(F-84b)}$$

Wasp Modified Critical Velocity (maximum of deposition critical velocity and transition velocity) **(F-85)**

$$v_{cr\_Wasp}(D, d_p, \rho_s, \phi_s, \rho_L, \mu_L, \varepsilon, \kappa_{cv}, \beta_{cv}, \beta_f, \beta_\mu) := \frac{m}{sec} \cdot \left| \begin{array}{l} J \leftarrow \text{length}(d_p) - 1 \\ \Phi_s \leftarrow \sum_{j=0}^{J} \phi_{s_j} \\ \max\left(\begin{pmatrix} v_{crD\_Wasp}(D, d_p, \rho_s, \phi_s, \rho_L, \mu_L, \varepsilon, \kappa_{cv}, \beta_{cv}, \beta_f, \beta_\mu) \\ v_{crT\_Wasp}(D, d_p, \rho_s, \phi_s, \rho_L, \mu_L, \varepsilon, \kappa_{cv}, \beta_f, \beta_\mu) \end{pmatrix}\right) \text{ if } \Phi_s > \Delta\Phi \\ \dfrac{\kappa_{cv} \cdot Re_T \cdot \mu_L}{D \cdot \rho_L} \text{ otherwise} \end{array} \right.$$

where the critical velocity correlation selection key from Equation F-44 is

1 Oroskar and Turian (1980) maximum of semi-theoretical and empirical equation
1.1 Oroskar and Turian (1980) semi-theoretical equation
1.2 Oroskar and Turian (1980) empirical equation
β_{cv} = 2 Wasp et al. (1977)
3 Zandi and Govatos (1967)
4 Shook (1969)
5 Gogus and Kokpinar (1999)
6 Robinson and Graf (1972)

κ_{cv} is the uncertainty factor on the critical, set to 1 to obtain the "best-estimate" prediction. Recommend at least 1.3 for upper bound estimate to account for uncertainties in the empirical correlation and to include sufficient margin above the critical velocity for minimum operating flow rate.

In addition, the viscosity selection parameter from Equation F-14 is

$$\beta_\mu = \begin{cases} 0 & \text{Thomas correlation (Wasp et al. 1977)} \\ 1 & \text{Best-estimate correlation (Jewett et al. 2002)} \\ 2 & \text{Bounding (C104) case (Jewett et al. 2002)} \end{cases}$$

6.2.4 Gillies and Shook (1991) Critical Velocity Correlation

Liddell and Burnett (2000) recommended the Oroskar and Turian (1980) and Gillies and Shook (1991) correlations as the most likely candidates for use in the WFD analysis. As noted by Liddell and Burnett (2000), "the Gillies and Shook correlation was developed for broadly graded slurries consisting of a mixture of particles at least 150 μm in diameter and much smaller particles in a pseudo homogeneous vehicle. As such it is probably capable of better predicting the behavior of tank solids than the equation of Oroskar and Turian, which is the result of multilinear regression of a large amount of literature data, much of it for monosized particles." However, Liddell and Burnett recommended that the correlation be used with caution because of the arbitrary cutoff between course and fine particles of 74 μm. The correlation is given below.

Gillies and Shook Laminar-to-Turbulent Transition Velocity

$d_{pL} := 74 \cdot \mu m$ arbitrary PSD cutoff between coarse and fine particle fractions

$$v_{Tv\_GS}(D, d_p, \rho_s, \phi_s, \rho_L, \mu_L, \beta_\mu, \kappa_{cv}, d_{pL}, v) := \left| \begin{array}{ll} J \leftarrow \text{length}(d_p) - 1 & \\ C_t \leftarrow \sum_{j=0}^{J} \phi_{s_j} & \text{solids volume fraction of total in situ solids} \\ \text{for } j \in 0..J & \\ \quad \left| \begin{array}{l} \phi_{r_j} \leftarrow \phi_{s_j} \text{ if } d_{p_j} \geq d_{pL} \\ \phi_{r_j} \leftarrow 0 \text{ otherwise} \end{array} \right. & \text{PSD of } +d_{pL} \text{ particles} \\ C_r \leftarrow \sum_{j=0}^{\text{length}(\phi_r)-1} \phi_{r_j} & \text{solids volume fraction of } +d_{pL} \text{ particles} \\ C_f \leftarrow C_t - C_r & \text{solids volume fraction of } -d_{pL} \text{ particles} \\ \rho_f \leftarrow \dfrac{\rho_s \cdot C_f + (1 - C_t) \cdot \rho_L}{1 - C_t + C_f} & \text{density of mixture of fluid and } -d_{pL} \text{ particles} \\ \mu_f \leftarrow \mu_c(\mu_L, \gamma_r(v, D), C_f, \beta_\mu) & \text{viscosity of mixture of fluid and } -d_{pL} \text{ particles} \\ \dfrac{Re_T \cdot \mu_f}{D \cdot \rho_f} & \text{laminar-to-tubulent transition velocity} \end{array} \right. \quad \textbf{(F-86a)}$$

$$v_{T\_GS}(D, d_p, \rho_s, \phi_s, \rho_L, \mu_L, \beta_\mu, \kappa_{cv}, d_{pL}) := \kappa_{cv} \cdot \text{root}(v' - v_{Tv\_GS}(D, d_p, \rho_s, \phi_s, \rho_L, \mu_L, \beta_\mu, \kappa_{cv}, d_{pL}, v'), v') \quad \textbf{(F-86b)}$$

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Gillies and Shook Critical Deposition Velocity

$$v_{crDv\_GS}(D, d_p, \rho_s, \phi_s, \rho_L, \mu_L, \beta_\mu, \kappa_{cv}, d_{pL}, v) :=$$

$J \leftarrow \text{length}(d_p) - 1$

$C_t \leftarrow \sum_{j=0}^{J} \phi_{s_j}$ — solids volume fraction of total in situ solids

for $j \in 0..J$

$\phi_{r_j} \leftarrow \phi_{s_j}$ if $d_{p_j} \geq d_{pL}$ — PSD of $+d_{pL}$ particles

$\phi_{r_j} \leftarrow 0$ otherwise

$\phi_{cum} \leftarrow \text{cum}(\phi_r)$ — cummulative distribution of $+d_{pL}$ PSD particles

$C_r \leftarrow \sum_{j=0}^{\text{length}(\phi_r)-1} \phi_{r_j}$ — solids volume fraction of $+d_{pL}$ particles

if $C_r > \Delta\Phi$ **(F-87a)**

$d_{50} \leftarrow D_\beta\left(d_p, \frac{\phi_{cum}}{C_r}, 0.5\right)$ — median particle size of $+d_{pL}$ PSD particles

$C_f \leftarrow C_t - C_r$ — solids volume fraction of $-d_{pL}$ particles

$C_f \leftarrow 0$ if $C_f \leq 0$

$\rho_f \leftarrow \frac{\rho_s \cdot C_f + (1 - C_t)\cdot \rho_L}{1 - C_t + C_f}$ — density of mixture of fluid and $-d_{pL}$ particles

$\mu_f \leftarrow \mu_c(\mu_L, \gamma_r(v, D), C_f, \beta_\mu)$ — viscosity of mixture of fluid and $-d_{pL}$ particles

$v_{sf} \leftarrow v_\infty(d_{50}, \rho_s, \rho_f, \mu_f)$ — settling velocity of median particle size of $+d_{pL}$ PSD particles in mixture of fluid and $-d_{pL}$ particles

$K_1 \leftarrow \left(\frac{\mu_L}{\rho_L}\right)^{\frac{2}{3}} \cdot \left(\frac{1}{g^{\frac{1}{3}} \cdot d_{50}}\right)^{-1}$

$K_2 \leftarrow (K_1 - 0.14)^2$

$C_{Df} \leftarrow C_D(d_{50}, v_{sf}, \rho_f, \mu_f)$ — drag coefficient for particles settling in carrier fluid

$\sqrt{2 \cdot g \cdot D \cdot \left(\frac{\rho_s}{\rho_f} - 1\right)} \cdot \exp(0.165 - 0.073 \cdot C_{Df} - 12.5 \cdot K_2)$ — critical velocity

$0 \cdot v$ otherwise

$$v_{crD\_GS}(D, d_p, \rho_s, \phi_s, \rho_L, \mu_L, \beta_\mu, \kappa_{cv}, d_{pL}) := \kappa_{cv} \cdot \text{root}(v' - v_{crDv\_GS}(D, d_p, \rho_s, \phi_s, \rho_L, \mu_L, \beta_\mu, \kappa_{cv}, d_{pL}, v'), v') \quad \textbf{(F-87b)}$$

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Gillies and Shook Critical Velocity (maximum of deposition critical velocity and transition velocity)

$$v_{cr\_GS}(D, d_p, \rho_s, \phi_s, \rho_L, \mu_L, \beta_\mu, \kappa_{cv}, d_{pL}) := \left| \begin{array}{l} J \leftarrow \text{length}(d_p) - 1 \\ C_t \leftarrow \sum_{j=0}^{J} \phi_{s_j} \\ \text{for } j \in 0..J \\ \quad \left| \begin{array}{l} \phi_{r_j} \leftarrow \phi_{s_j} \text{ if } d_{p_j} \geq d_{pL} \\ \phi_{r_j} \leftarrow 0 \text{ otherwise} \end{array} \right. \\ C_r \leftarrow \sum_{j=0}^{\text{length}(\phi_r)-1} \phi_{r_j} \\ \max\left(\begin{pmatrix} v_{crD\_GS}(D, d_p, \rho_s, \phi_s, \rho_L, \mu_L, \beta_\mu, \kappa_{cv}, d_{pL}) \\ v_{T\_GS}(D, d_p, \rho_s, \phi_s, \rho_L, \mu_L, \beta_\mu, \kappa_{cv}, d_{pL}) \end{pmatrix}\right) \text{ if } C_r > \Delta\Phi \\ v_{T\_GS}(D, d_p, \rho_s, \phi_s, \rho_L, \mu_L, \beta_\mu, \kappa_{cv}, d_{pL}) \text{ otherwise} \end{array} \right. \quad \textbf{(F-88)}$$

However, the Gillies and Shook (1991) correlation was developed using data from water slurries with the following ranges of the independent variables:

pipe diameter = $0.053 \cdot m = 2.087\,in$ to $0.495 \cdot m = 19.488\,in$

mass median diameter of PSD = $0.053 \cdot mm = 53\,\mu m$ to $0.495 \cdot mm = 495\,\mu m$

viscosity of mixture of fluid and -d_{pL} particles, μ_f = 0.5 to 3.4 cP

total in situ solids concentration fraction = 0.14 to 0.44

particle density, ρ_s = 1.374 to 2.650 kg/L

Rosin-Rammler PSD exponent = 0.3 to 3.7

and should *not* be used outside this range of experimental conditions.

Hence, application of this correlation to the recommended PSDs for Hanford HLW would require extrapolation of the correlation beyond its data base with respect to median particle size (see Section 6.2.5 below).

The Oroskar and Turian (1980) and Wasp modified Oroskar and Turian critical velocity correlations are compared in Figures 21 and 22 for the recommended PSDs for Hanford HLW given in Section 6.2.5. However, caution must be excised in the application of either of these critical velocity correlations because they are based on narrow-band PSD test data. Neither of these correlations have been verified for Hanford HLW transfer conditions.

6.2.5 Wasp Stability Criterion

Wasp (personal communication) proposed the following "stability" criterion in place of the deposition critical velocity criterion since no satisfactory deposition critical velocity correlation exist for the broad-band PSD typical of Hanford HLW. Wasp's criterion for a stable pipeline flow (constant discharge pressure and minimized plugging tendency) is that the "bed" pressure drop is equal to or less than 5% of the total pressure drop. The bed pressure drop is defined as the excess pressure drop over that which would occur in a homogeneous fluid of the same bulk properties. The ratio of bed pressure to total pressure drop and required flow velocity at stability tolerance level, S, is calculated from following:

Ratio of "bed" pressure to total pressure drop

(F-89a)

$$\Delta p_r(D,v,\rho_L,\mu_L,\varepsilon_C,\varepsilon_S,d_p,\rho_s,C_s,\phi_s,L_C,L_S,K_D,\kappa_f,\theta,\beta_\mu) := \left|\begin{array}{l} \mu_0 \leftarrow \mu_c(\mu_L,\gamma_r(v,D),0\%,\beta_\mu) \\ p_T \leftarrow \Delta p_{T\_Wasp}(D,v,\rho_L,\mu_0,\varepsilon_C,\varepsilon_S,d_p,\rho_s,C_s\cdot\phi_s,L_C,L_S,K_D,\kappa_f,\theta \\ d_{50} \leftarrow D_\beta(d_p,\mathrm{cum}(\phi_s),50\%) \\ \mu_b \leftarrow \mu_c(\mu_L,\gamma_r(v,D),C_s,\beta_\mu) \\ \rho_b \leftarrow \rho_c(\rho_s,\rho_L,C_s) \\ p_b \leftarrow \Delta p_T(D,v,\rho_b,\mu_b,\varepsilon_C,\varepsilon_S,d_{50},\rho_s,0\%,L_C,L_S,0,\kappa_f,\theta) \\ \dfrac{p_T - p_b}{p_T} \end{array}\right.$$

Stability criterion velocity

$v' := 4\cdot\dfrac{ft}{sec}$ initial guess

(F-89b)

$$v_{stable}(D,\rho_L,\mu_L,\varepsilon_C,\varepsilon_S,d_p,\rho_s,C_s,\phi_s,L_C,L_S,K_D,\kappa_f,\theta,\beta_\mu,S,v') := \mathrm{root}(S - \Delta p_r(D,v',\rho_L,\mu_L,\varepsilon_C,\varepsilon_S,d_p,\rho_s,C_s,\phi_s,L_C,L_S,K_D,\kappa_f,($$

where

$S := 5\%$ recommended stability tolerance value (personal communication with Ed Wasp)

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6.2.6 Particle Size Distribution for Hanford Waste Feed Delivery

In Revision 1 of RPP-5346 (2000) the assumed particle size distribution for the solid particles was based on the "grand-mean" of measured particle size distributions by volume from HLW Tanks AZ-101, AW-103, and C-104 (Jewett and Jensen 2000) using historical PSD data at the time. In these earlier measurements, the samples were held in a 15mL observation cell, where the particulate matter was kept in suspension with a small magnetic stirring bar. Hence, the resulting PSDs may be more representative of in situ conditions than transfer conditions. The resulting grand-mean PSD (Jewett and Jensen 2000) based on mean particle size distributions (by volume) for each of the three tanks is given below (partial listing displayed).

$GM_{fd} :=$

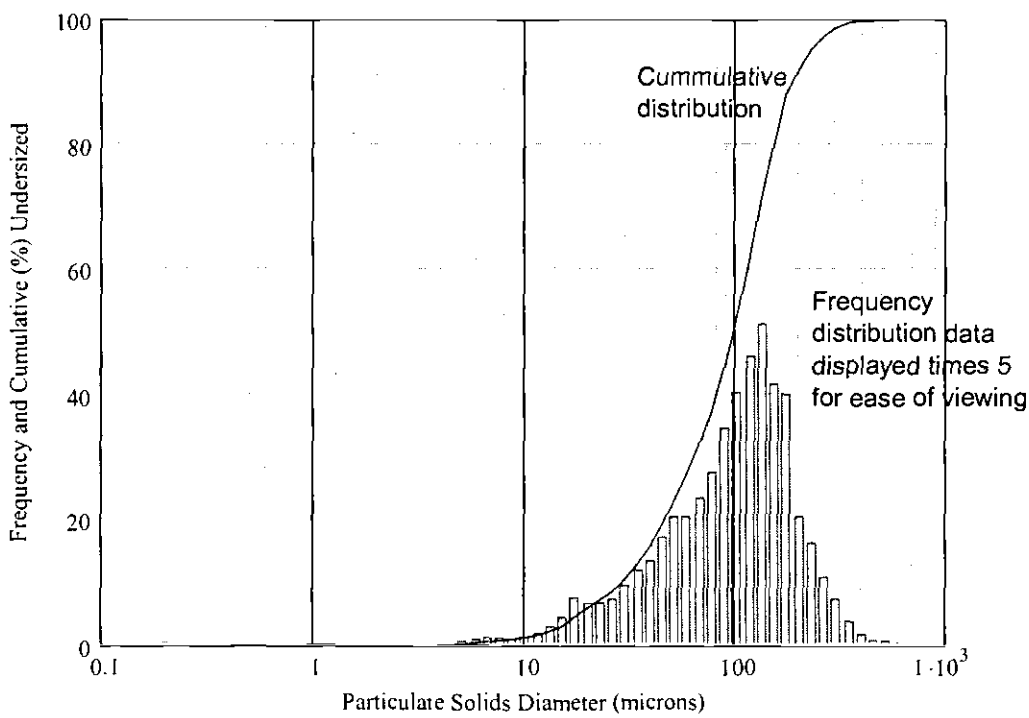
d_p (μm)	volume frequency (%)
13.250	0.536
15.170	0.877
17.380	1.502
19.900	1.334
22.800	1.313
26.110	1.414
29.910	1.915
34.250	2.434
39.230	2.657
44.940	3.431
51.470	4.057
58.950	4.044
67.520	4.629
77.340	5.450
88.580	6.897
101.500	8.033
116.200	9.173
133.100	10.226
152.500	8.291
174.600	8.004
200.000	4.082
229.100	3.249
262.400	2.121
300.500	1.442
344.200	0.754
394.200	0.311

$d_p := GM_{fd}^{\langle 0 \rangle} \cdot \mu m \qquad \phi_{fs} := GM_{fd}^{\langle 1 \rangle} \cdot \% \qquad length(\phi_{fs}) - 1 = 113$

Cumulative undersize volume distribution

$$\Phi_{fs} := \sum_{j=0}^{length(\phi_{fs})-1} \phi_{fs_j} \qquad \Phi_{fs} = 1 \qquad \phi_{cum} := cum(\phi_{fs})$$

Plot of *Grand-Mean* PSD Data (Jewett and Jensen 2000).



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Curve fit to single mode Rosin-Rammler

$d_{50R} := D_\beta(d_p, \phi_{cum}, 50\%)$ $\quad d_{50R} = 98.11\,\mu m$ calculated median particle size from GM_{fd} data

Curve fit to Rosin-Rammler

$$F_{RR}(d,p) := \begin{pmatrix} CDF_{RR}(d, d_{50R}\cdot\mu m^{-1}, p) \\ CDF_{RR'p}(d, d_{50R}\cdot\mu m^{-1}, p) \end{pmatrix}$$

$v_{PRR} := 1.5$ initial guess

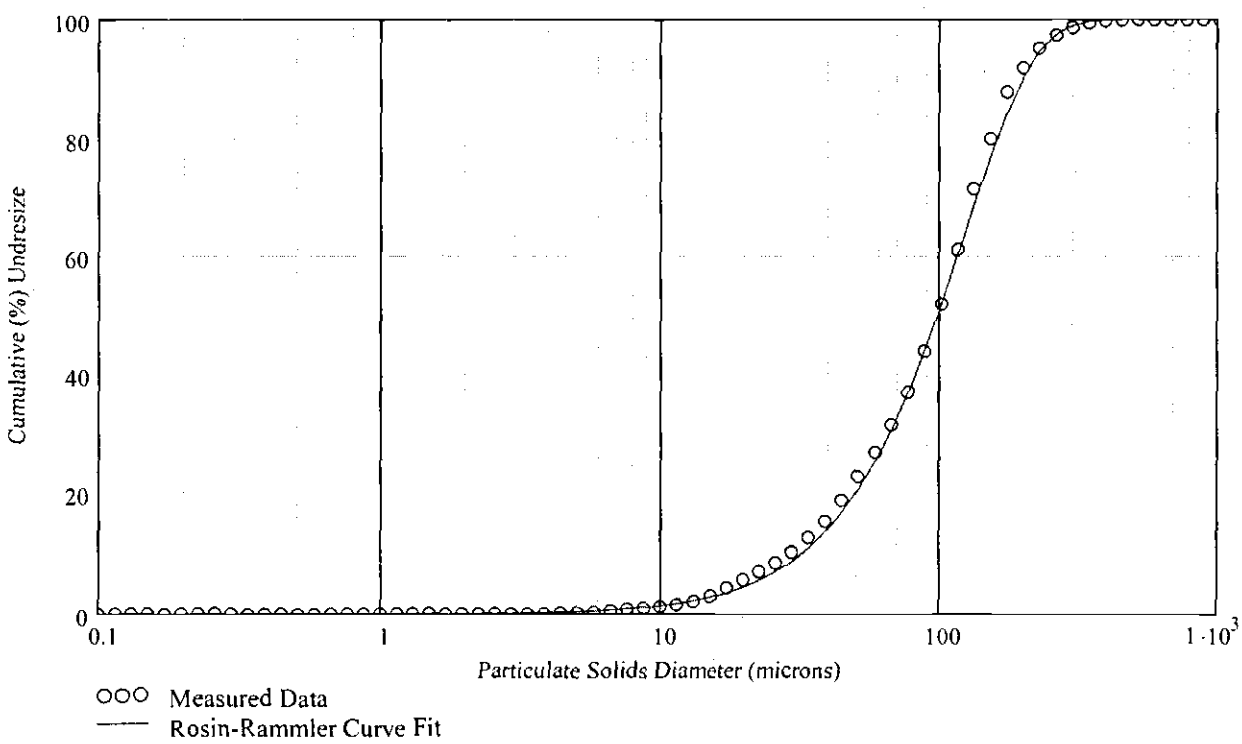
$p_{RR} := genfit(d_p\cdot\mu m^{-1}, \phi_{cum}, v_{PRR}, F_{RR})$

$p_{RR} = 1.693$ $\quad d_{50} := d_{50R}$ curve fit parameters

$J := length(\phi_{fs}) - 1$ $\quad j := 0..J$

Comparison of GM_{fd} cumulative and frequency data to Rosin-Rammler distribution function curve fit shown below.

***Grand-Mean* Particle Size Cumulative Distribution (Jewett and Jensen 2000) Compared to Curve Fit**



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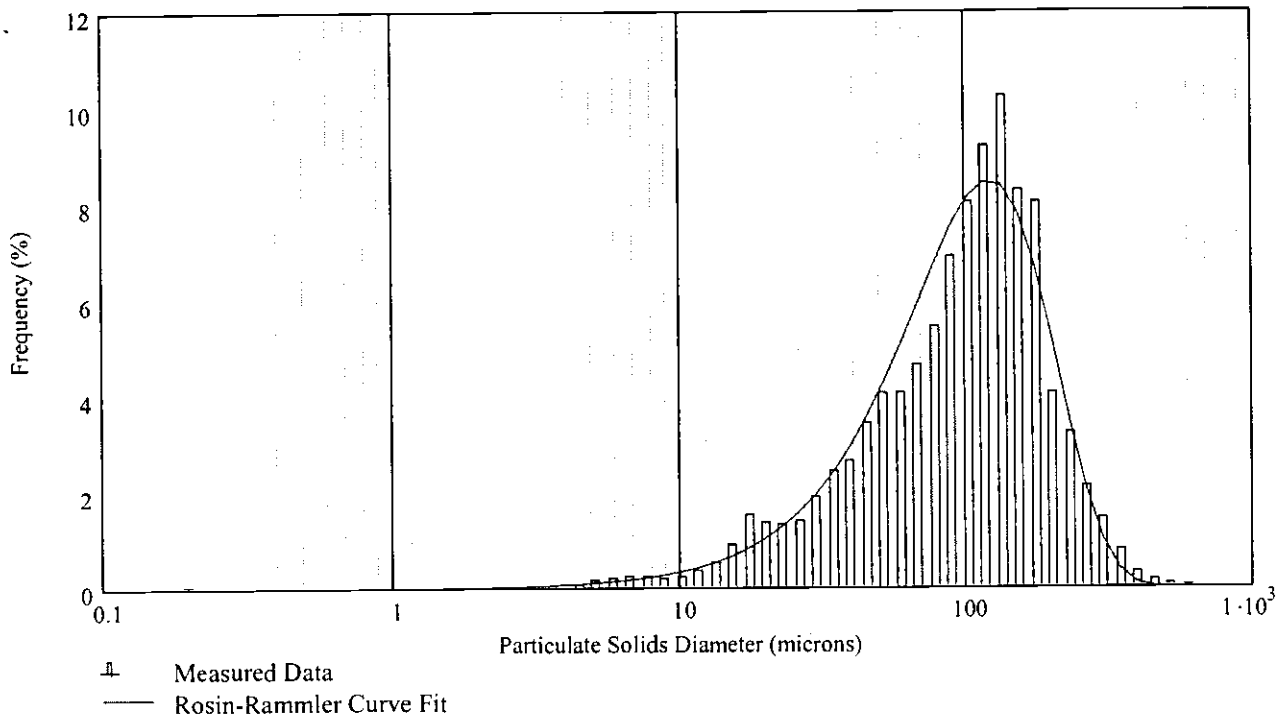
***Grand-Mean* Particle Size Frequency Distribution (Jewett and Jensen 2000) Compared to Curve Fit**



$d_{pR} := d_p \qquad \Delta d_{pR} := \Delta d_p \qquad j_R := 0..\text{length}(d_{pR}) - 1 \qquad \phi_R := \phi_{fs} \qquad \phi_{cumR} := \phi_{cum}$

Pack original solid particle distribution data for analysis to remove zero frequency data for efficiency in calculations

$d_p := \text{pack}(d_p, \phi_{fs}) \qquad \phi_{fs} := \text{pack}(\phi_{fs}, \phi_{fs}) \qquad \phi_{cum} := \text{cum}(\phi_{fs}) \qquad \text{length}(\phi_{fs}) - 1 = 37$

$D_{p_i} := D\beta(d_p, \phi_{cum}, PP_i)$ Percentile points for GM_{fd} data

$PP^T = (5 \;\; 25 \;\; 50 \;\; 75 \;\; 95)\%$

$D_p^T = (18 \;\; 55 \;\; 98 \;\; 141 \;\; 228)\,\mu m$

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$\lambda_{RR} := 1.07162545$ adjustment factor to maintain target d_{50} (approximately) after shifting density function

Return **Rosin-Rammler** probability density function values (d ϕ) shifted to d_{50} from reference distribution and packed for analysis

$$\mathrm{dist}_{RR}(d_p, d_{50}) := \left| \begin{array}{l} J \leftarrow \mathrm{length}(d_p) - 1 \\ \Delta d \leftarrow \Delta(d_p) \\ \text{for } j \in 0..J \\ \quad \phi_j \leftarrow \mathrm{PDF}_{RR}(d_{p_j}, \lambda_{RR} \cdot d_{50}, p_{RR}) \cdot \Delta d_j \\ d \leftarrow \mathrm{pack}(d_p, \phi) \cdot \mu m^{-1} \\ \phi \leftarrow \mathrm{pack}(\phi, \phi) \\ (d \;\; \phi) \end{array} \right. \qquad \textbf{(F-90)}$$

$(d_{pRR} \;\; \phi_{RR}) := \mathrm{dist}_{RR}(d_{pR}, d_{50})$ $\qquad d_{pRR} := d_{pRR} \cdot \mu m$ reset units

$\phi_{RRcum} := \mathrm{cum}(\phi_{RR})$ $\qquad \mathrm{length}(\phi_{RR}) - 1 = 64$

$D_{pRR_i} := D_\beta(d_{pRR}, \phi_{RRcum}, PP_i)$ $\qquad$ Percentile points for **Rosin-Rammler** curve fit to GM_{fd}

$PP^T = (5 \;\; 25 \;\; 50 \;\; 75 \;\; 95)\%$

$D_{pRR}{}^T = (21 \;\; 58 \;\; 98 \;\; 148 \;\; 230)\,\mu m$

$d_{50\_mean} := 110 \cdot \mu m$ $\qquad$ **mean** of tank cummulative median particle size (Jewett and Jensen 2000)

$(d_{pRR} \;\; \phi_{RR}) := \mathrm{dist}_{RR}(d_{pR}, d_{50\_mean})$ $\qquad d_{pRR} := d_{pRR} \cdot \mu m$ reset units

$\phi_{RRcum} := \mathrm{cum}(\phi_{RR})$ $\qquad \mathrm{length}(\phi_{RR}) - 1 = 65$

$D_{pRR_i} := D_\beta(d_{pRR}, \phi_{RRcum}, PP_i)$ $\qquad$ Percentile points for shifted **Rosin-Rammler** curve fit to GM_{fd}

$PP^T = (5 \;\; 25 \;\; 50 \;\; 75 \;\; 95)\%$

$D_{pRR}{}^T = (24 \;\; 65 \;\; 110 \;\; 166 \;\; 259)\,\mu m$

$d_{50\_UL95} := 140 \cdot \mu m$ $\qquad$ upper limit to a one sided 95% **confidence interval** (UL(95%)) on tank cummulative mean median particle size

$(d_{pRR} \;\; \phi_{RR}) := \mathrm{dist}_{RR}(d_{pR}, d_{50\_UL95})$ $\qquad d_{pRR} := d_{pRR} \cdot \mu m$ reset units

$\phi_{RRcum} := \mathrm{cum}(\phi_{RR})$ $\qquad \mathrm{length}(\phi_{RR}) - 1 = 65$

$D_{pRR_i} := D_\beta(d_{pRR}, \phi_{RRcum}, PP_i)$ $\qquad$ Percentile points for shifted **Rosin-Rammler** curve fit to GM_{fd}

$PP^T = (5 \;\; 25 \;\; 50 \;\; 75 \;\; 95)\%$

$D_{pRR}{}^T = (30 \;\; 83 \;\; 140 \;\; 211 \;\; 331)\,\mu m$

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$d_{50\_9595TL} := 275 \cdot \mu m$ **tolerance limit** 95/95TL on tank cummulative mean median particle size

$(d_{pRR}\ \ \phi_{RR}) := dist_{RR}(d_{pR}, d_{50\_9595TL})$ $d_{pRR} := d_{pRR} \cdot \mu m$ reset units

$\phi_{RRcum} := cum(\phi_{RR})$ $length(\phi_{RR}) - 1 = 65$

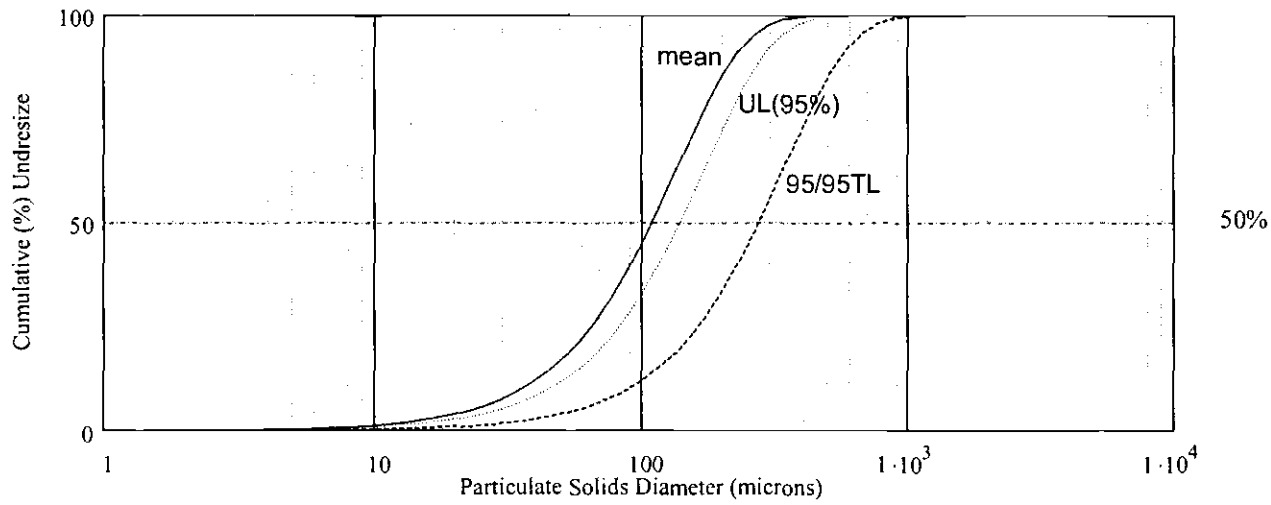
$D_{pRR_i} := D\beta(d_{pRR}, \phi_{RRcum}, PP_i)$ Percentile points for shifted **Rosin-Rammler** curve fit to GM_{fd}

$PP^T = (5\ \ 25\ \ 50\ \ 75\ \ 95)\%$

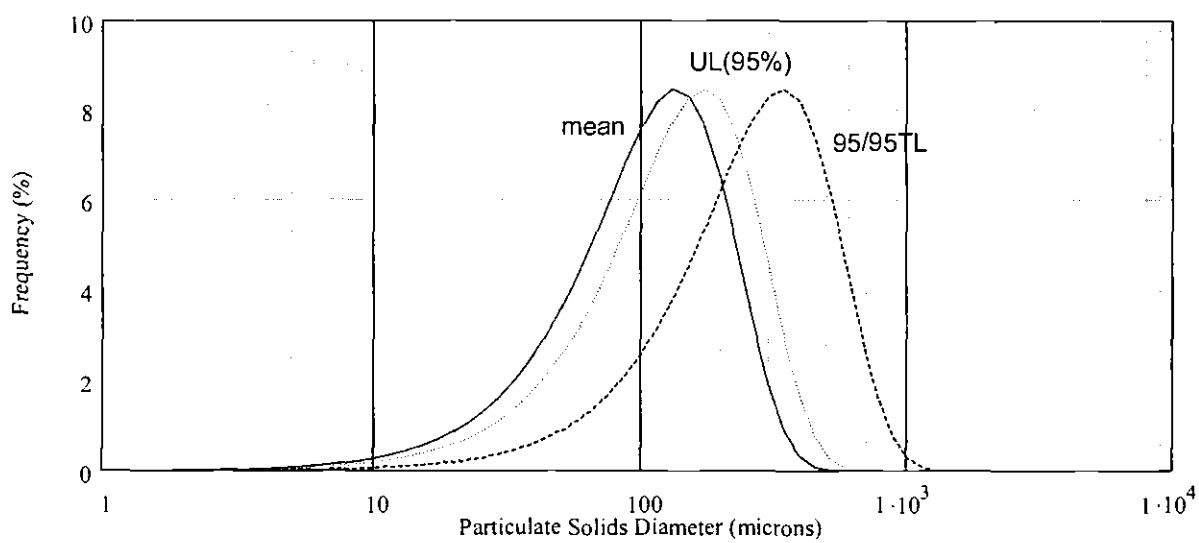
$D_{pRR}{}^T = (59\ \ 164\ \ 275\ \ 414\ \ 650)\ \mu m$

***Grand-Mean, UL(95%), and 95/95 TL* Particle Size Distribution (Jewett and Jensen 2000)**

Particle Size Cumulative Distribution



Particle Size Frequency Distribution



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The above PSDs appeared to have much larger median particle sizes then had been historically obtained. The application of these PSDs resulted in predicted pressures at the required critical velocity in excess of the pipeline system design pressures for most of the transfer pipeline routes (RPP-5346, Revision 1 2000). As discussed in Section 5.0 of Appendix F, this led to a need for a more detailed reassessment of the Hanford waste physical properties at transport conditions. Previous estimated waste physical property data provided in Estey (2000) and Jewett and Jensen (2000) for the in situ Hanford waste were reassessed by Jewett et al. (2002) supported by the results from a new extensive experimental investigation of Hanford HLW PSD data (Bechtold et al. 2002). In the earlier measurements, the sample was held in a 15mL observation cell, where the particulate matter was kept in suspension with a small magnetic stirring bar. In the more recent measurements, the sample particulate were suspended by recirculating roughly 300mL of the sample in a flow loop that passed through the measurement cell.

In light of the agglomerated nature of the particles, the difference between the instrument configurations is critical. By comparing the particle sizes obtained in Jewett and Jensen (2000) and Bechtold et al. (2002), it is clear that even the minimum shear forces required to maintain the waste particles in suspension by turbulence in a flowing stream are greater than the shear applied in the small stirred cell. The PSD data was obtained from seven (AW-103, AY-101, AY-102, AZ-102, C-104, C-107, and SY-102) tanks representing Phase I HLW tank feeds of ten HLW tanks. The PSD data was subdivided into two groups depending on the level of agitation applied to the samples, In the first group the samples were minimally agitated and in the second group the samples were strongly agitated (sonicated) (see Bechtold et al. 2002). The resulting mean, upper limit of one-sided 95% confidence interval on the mean (UL 95), and upper limit to a one-sided 95/95 tolerance limit (95/95 TL) were also statically determined. The resulting cumulative PSDs and results of single and double mode Rossin-Rammler (RR) distribution curve fits are given below.

$d_p := d_{pR}$ $\quad i := 0..6$ $\quad TOL := 1\cdot 10^{-5}$

Minimum Agitated (Least Battered) Mean (Recommended PSD for WFD analysis, Jewett et al. 2002)

Cumulative distribution PSD data

$v\phi_{cum_i} :=$ $\quad vd_{p_i} :=$

1	0.69
5	1.19
25	3.65
50	7.47
75	30.61
95	140.45
99	208.33

$vd_p := vd_p \cdot \mu m$

$v\phi_{cum} := v\phi_{cum} \cdot \%$

$$v\phi_{cum} = \begin{pmatrix} 0.01 \\ 0.05 \\ 0.25 \\ 0.5 \\ 0.75 \\ 0.95 \\ 0.99 \end{pmatrix} \qquad vd_p = \begin{pmatrix} 0.69 \\ 1.19 \\ 3.65 \\ 7.47 \\ 30.61 \\ 140.45 \\ 208.33 \end{pmatrix} \mu m$$

single and double mode Rossin-Rammler distribution curve fits

$$vg_1 := \begin{pmatrix} 20 \\ 2 \end{pmatrix} \qquad vg_2 := \begin{pmatrix} 7 \\ 0.8 \\ 10 \\ 5 \end{pmatrix}$$ initial guesses

$$P_1 := genfit\left(vd_p \cdot \mu m^{-1}, v\phi_{cum}, vg_1, F_1\right) \qquad P_2 := genfit\left(vd_p \cdot \mu m^{-1}, v\phi_{cum}, vg_2, F_2\right)$$

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$P_1 = \begin{pmatrix} 10.724 \\ 0.793 \end{pmatrix}$ median particle size (μm) RR exponent

$P_2 = \begin{pmatrix} 31.652 \\ 0.857 \\ 4.449 \\ 1.78 \end{pmatrix}$ *curve fit parameters*

$CDF_{LB\_M_j} := \frac{1}{2}\cdot\left(CDF_{RR}\left(d_{p_j}, P2_0\cdot\mu m, P2_1\right) + CDF_{RR}\left(d_{p_j}, P2_2\cdot\mu m, P2_3\right)\right)$ ϕ_{cum}

$PDF_{LB\_M_j} := \frac{1}{2}\cdot\left(PDF_{RR}\left(d_{p_j}, P2_0\cdot\mu m, P2_1\right) + PDF_{RR}\left(d_{p_j}, P2_2\cdot\mu m, P2_3\right)\right)\cdot\Delta d_{p_j}$ ϕ

$d_{LB\_M} := pack(d_p, PDF_{LB\_M})$

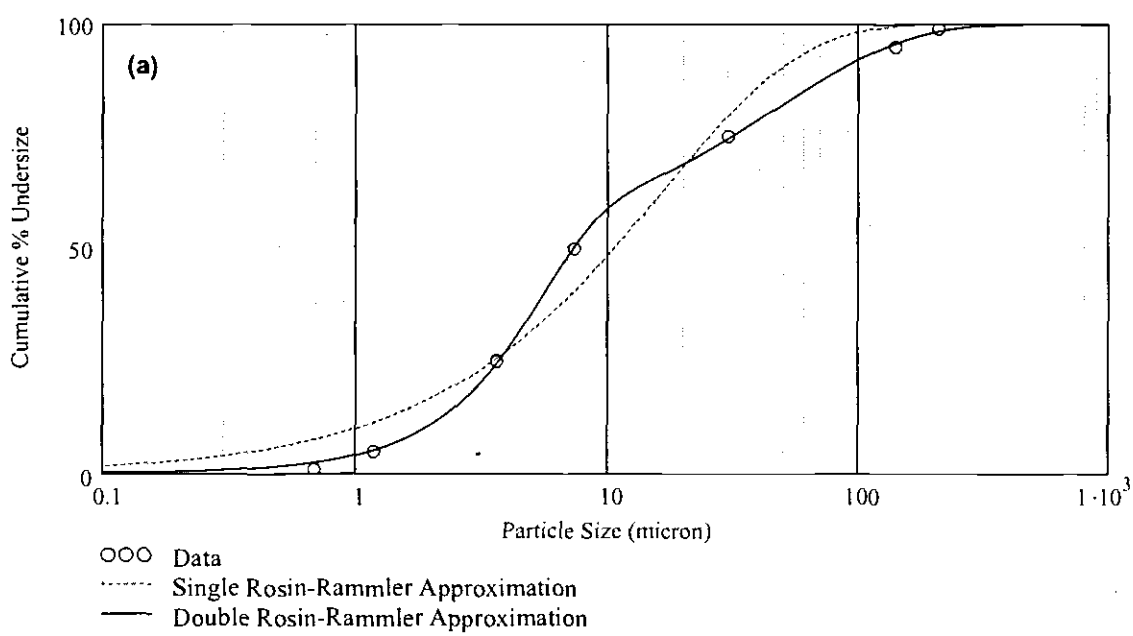
$CDF_{LB\_M} := pack(CDF_{LB\_M}, PDF_{LB\_M})$

$PDF_{LB\_M} := pack(PDF_{LB\_M}, PDF_{LB\_M})$

$j_{LB\_M} := 0 .. length(d_{LB\_M}) - 1$

Cumulative and Frequency Rosin-Rammler Distribution Approximation to *Minimum Agitated* (Least Battered) *Mean* Cumulative Data (Recommended PSD for WFD analysis, Jewett et al. 2002).

Particle Size Cumulative Distribution



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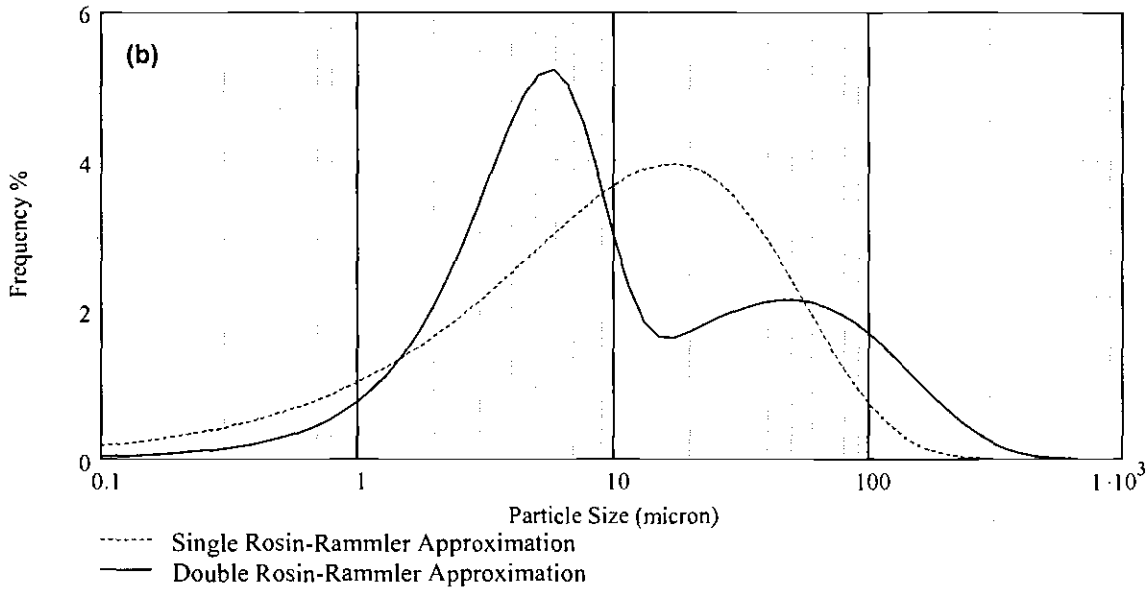
median particle size

$\phi cum_j := CDF_{RR}\left(dp_j, P1_0 \cdot \mu m, P1_1\right)$ — $D\beta\left(vdp, v\phi_{cum}, 50\%\right) = 7.5\,\mu m$ measured date

$D\beta\left(dp, \phi_{cum}, 50\%\right) = 10.7\,\mu m$ single RR curve fit

$\phi cum_j := \frac{1}{2}\cdot\left(CDF_{RR}\left(dp_j, P2_0 \cdot \mu m, P2_1\right) + CDF_{RR}\left(dp_j, P2_2 \cdot \mu m, P2_3\right)\right)$ — $D\beta\left(dp, \phi_{cum}, 50\%\right) = 7.4\,\mu m$ double RR curve fit

Particle Size Frequency Distribution



Minimum Agitated (Least Battered) 95/95TL $vdp := 0$

Cumulative distribution PSD data

$v\phi cum_i =$	$vdp_i :=$
0.01	1.96
0.05	3.12
0.25	9.87
0.5	21.58
0.75	158.96
0.95	461.31
0.99	701.88

$vdp := vdp \cdot \mu m$

$$v\phi_{cum} = \begin{pmatrix} 0.01 \\ 0.05 \\ 0.25 \\ 0.5 \\ 0.75 \\ 0.95 \\ 0.99 \end{pmatrix} \qquad vdp = \begin{pmatrix} 1.96 \\ 3.12 \\ 9.87 \\ 21.58 \\ 158.96 \\ 461.31 \\ 701.88 \end{pmatrix} \mu m$$

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EVALUATION ANALYSIS

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Subject: Critical Velocity and Pressure Drop Study in Support of Waste Tank Feed Transfer System — Date: 02/25/2002 By: L. J. Julyk
Checked: By: S.D. Estey
Location: 200 Area - Hanford Site, Richland, Washington — Revised: By:

single and double mode Rossin-Rammler distribution curve fits

$$vg_1 := \begin{pmatrix} 20 \\ 2 \end{pmatrix} \qquad vg_2 := \begin{pmatrix} 7 \\ 0.8 \\ 10 \\ 5 \end{pmatrix}$$ initial guesses

$$P_1 := genfit\left(vd_p \cdot \mu m^{-1}, v\phi_{cum}, vg_1, F_1\right) \qquad P_2 := genfit\left(vd_p \cdot \mu m^{-1}, v\phi_{cum}, vg_2, F_2\right)$$

$$P_1 = \begin{pmatrix} 40.183 \\ 0.628 \end{pmatrix}$$ median particle size (μm), exponent

$$P_2 = \begin{pmatrix} 158.866 \\ 1.133 \\ 10.307 \\ 1.808 \end{pmatrix}$$ curve fit parameters

$$CDF_{LB\_9595TL_j} := \frac{1}{2} \cdot \left(CDF_{RR}\left(d_{p_j}, P2_0 \cdot \mu m, P2_1\right) + CDF_{RR}\left(d_{p_j}, P2_2 \cdot \mu m, P2_3\right)\right)$$ ϕ_{cum}

$$PDF_{LB\_9595TL_j} := \frac{1}{2} \cdot \left(PDF_{RR}\left(d_{p_j}, P2_0 \cdot \mu m, P2_1\right) + PDF_{RR}\left(d_{p_j}, P2_2 \cdot \mu m, P2_3\right)\right) \cdot \Delta d_{p_j}$$ ϕ

$$d_{LB\_9595TL} := pack\left(d_p, PDF_{LB\_9595TL}\right)$$

$$CDF_{LB\_9595TL} := pack\left(CDF_{LB\_9595TL}, PDF_{LB\_9595TL}\right)$$

$$PDF_{LB\_9595TL} := pack\left(PDF_{LB\_9595TL}, PDF_{LB\_9595TL}\right)$$

$$j_{LB\_9595TL} := 0 .. length\left(d_{LB\_9595TL}\right) - 1$$

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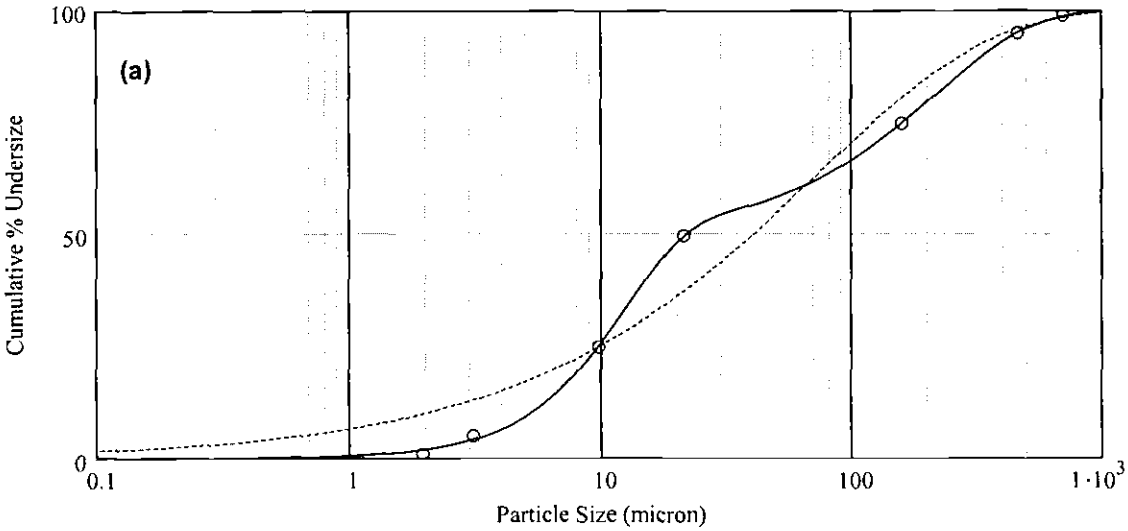
Location: 200 Area - Hanford Site, Richland, Washington

WO/Job No. 500689/BA10
Date: 02/25/2002 By: L. J. Julyk
Checked: By: S.D. Estey
Revised: By:

Cumulative and Frequency Rosin-Rammler Distribution Approximation to *Minimum Agitated* (Least Battered) *95/95TL* Cumulative Data (Jewett et al. 2002).

Particle Size Cumulative Distribution



OOO Data
------ Single Rosin-Rammler Approximation
—— Double Rosin-Rammler Approximation

$$\phi_{cum_j} := CDF_{RR}\left(d_{p_j}, P1_0 \cdot \mu m, P1_1\right)$$

$$\phi_{cum_j} := \frac{1}{2} \cdot \left(CDF_{RR}\left(d_{p_j}, P2_0 \cdot \mu m, P2_1\right) + CDF_{RR}\left(d_{p_j}, P2_2 \cdot \mu m, P2_3\right)\right)$$

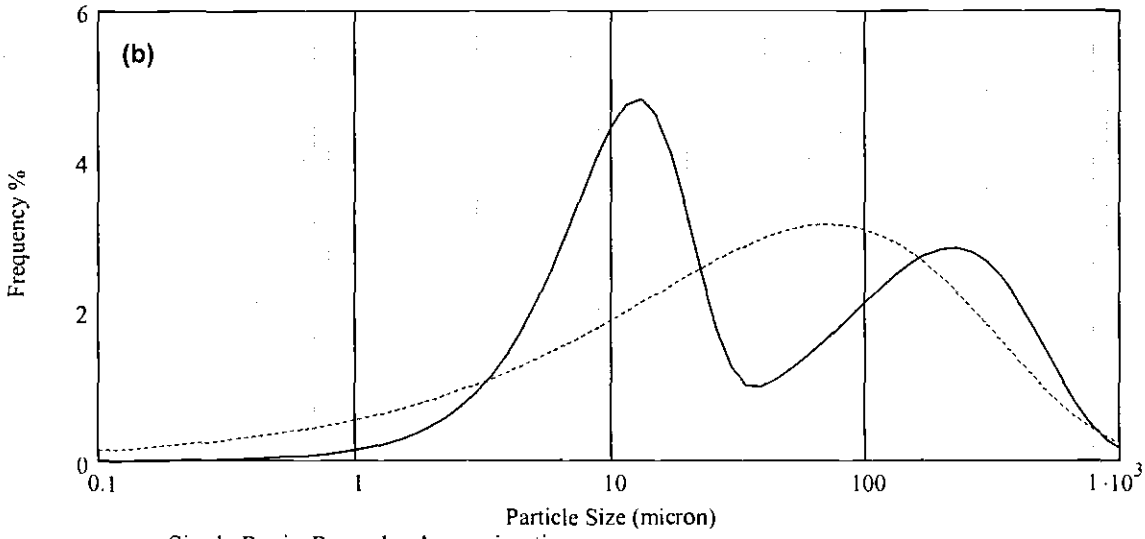
median particle size

$D\beta\left(vd_p, v\phi_{cum}, 50\%\right) = 21.6\,\mu m$ measured date

$D\beta\left(d_p, \phi_{cum}, 50\%\right) = 40.2\,\mu m$ single RR curve fit

$D\beta\left(d_p, \phi_{cum}, 50\%\right) = 21.8\,\mu m$ double RR curve fit

Particle Size Frequency Distribution



------ Single Rosin-Rammler Approximation
—— Double Rosin-Rammler Approximation

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Date: 02/25/2002 By: L. J. Julyk
Checked: By: S.D. Estey
Revised: By:

Minimum Agitated (Least Battered) UL(95%)

$vd_p := 0$

$v\phi_{cum_i}$ =	vd_{p_i} :=
0.01	0.96
0.05	1.61
0.25	4.99
0.5	10.52
0.75	58.34
0.95	209.78
0.99	314.98

$vd_p := vd_p \cdot \mu m$

$$v\phi_{cum} = \begin{pmatrix} 0.01 \\ 0.05 \\ 0.25 \\ 0.5 \\ 0.75 \\ 0.95 \\ 0.99 \end{pmatrix} \qquad vd_p = \begin{pmatrix} 0.96 \\ 1.61 \\ 4.99 \\ 10.52 \\ 58.34 \\ 209.78 \\ 314.98 \end{pmatrix} \mu m$$

single and double mode Rossin-Rammler distribution curve fits

$$vg_1 := \begin{pmatrix} 20 \\ 2 \end{pmatrix} \qquad vg_2 := \begin{pmatrix} 7 \\ 0.8 \\ 10 \\ 5 \end{pmatrix}$$ initial guesses

$$P_1 := genfit\left(vd_p \cdot \mu m^{-1}, v\phi_{cum}, vg_1, F_1\right) \qquad P_2 := genfit\left(vd_p \cdot \mu m^{-1}, v\phi_{cum}, vg_2, F_2\right)$$

$$P_1 = \begin{pmatrix} 17.453 \\ 0.69 \end{pmatrix}$$ median particle size (μm), RR exponent

$$P_2 = \begin{pmatrix} 59.03 \\ 0.977 \\ 5.558 \\ 1.771 \end{pmatrix}$$ curve fit parameters

$$CDF_{LB\_UL95_j} := \frac{1}{2} \cdot \left(CDF_{RR}\left(d_{p_j}, P2_0 \cdot \mu m, P2_1\right) + CDF_{RR}\left(d_{p_j}, P2_2 \cdot \mu m, P2_3\right)\right)$$ ϕ_{cum}

$$PDF_{LB\_UL95_j} := \frac{1}{2} \cdot \left(PDF_{RR}\left(d_{p_j}, P2_0 \cdot \mu m, P2_1\right) + PDF_{RR}\left(d_{p_j}, P2_2 \cdot \mu m, P2_3\right)\right) \cdot \Delta d_{p_j}$$ ϕ

$d_{LB\_UL95} := pack(d_p, PDF_{LB\_UL95})$

$CDF_{LB\_UL95} := pack(CDF_{LB\_UL95}, PDF_{LB\_UL95})$

$PDF_{LB\_UL95} := pack(PDF_{LB\_UL95}, PDF_{LB\_UL95})$

$j_{LB\_UL95} := 0 .. length(d_{LB\_UL95}) - 1$

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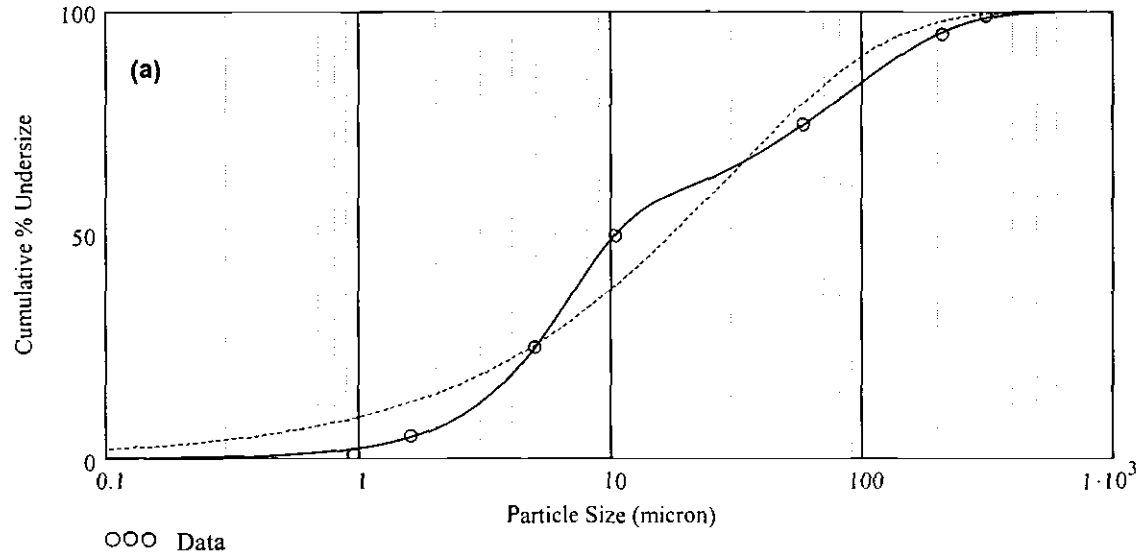
Checked: By: S.D. Estey
Revised: By:

Cumulative and Frequency Rosin-Rammler Distribution Approximation to *Minimum Agitated* (Least Battered) *UL(95%)* Cumulative Data (Jewett et al. 2002).

Particle Size Cumulative Distribution



○○○ Data
------ Single Rosin-Rammler Approximation
—— Double Rosin-Rammler Approximation

$$\phi_{cum_j} := CDF_{RR}\left(d_{p_j}, P1_0 \cdot \mu m, P1_1\right)$$

$$\phi_{cum_j} := \frac{1}{2} \cdot \left(CDF_{RR}\left(d_{p_j}, P2_0 \cdot \mu m, P2_1\right) + CDF_{RR}\left(d_{p_j}, P2_2 \cdot \mu m, P2_3\right)\right)$$

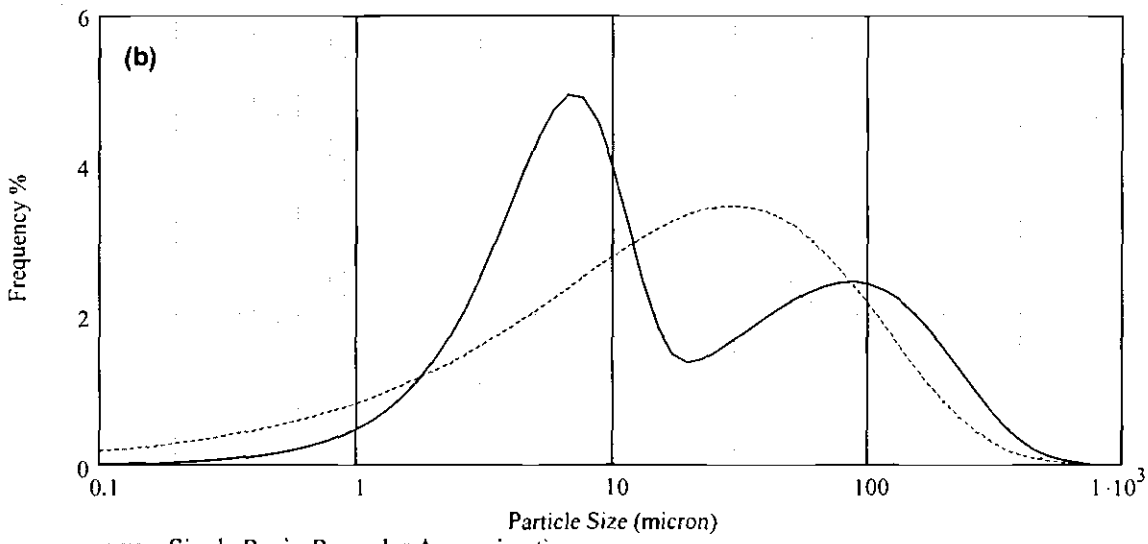
median particle size

$D_\beta(vd_p, v\phi_{cum}, 50\%) = 10.5\,\mu m$ measured date

$D_\beta(d_p, \phi_{cum}, 50\%) = 17.5\,\mu m$ single RR curve fit

$D_\beta(d_p, \phi_{cum}, 50\%) = 10.5\,\mu m$ double RR curve fit

Particle Size Frequency Distribution



------ Single Rosin-Rammler Approximation
—— Double Rosin-Rammler Approximation

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Location: 200 Area - Hanford Site, Richland, Washington
Revised: By:

Strongly Agitated (Most Battered) Mean

$vd_p := 0$

$v\phi_{cum_i}$ =	vd_{p_i} :=
0.01	0.53
0.05	0.81
0.25	2.10
0.5	4.53
0.75	11.31
0.95	31.97
0.99	59.63

$vd_p := vd_p \cdot \mu m$

$$v\phi_{cum} = \begin{pmatrix} 0.01 \\ 0.05 \\ 0.25 \\ 0.5 \\ 0.75 \\ 0.95 \\ 0.99 \end{pmatrix} \qquad vd_p = \begin{pmatrix} 0.53 \\ 0.81 \\ 2.1 \\ 4.53 \\ 11.31 \\ 31.97 \\ 59.63 \end{pmatrix} \mu m$$

single and double mode Rossin-Rammler distribution curve fits

$$vg_1 := \begin{pmatrix} 20 \\ 2 \end{pmatrix} \qquad vg_2 := \begin{pmatrix} 7 \\ 0.8 \\ 10 \\ 5 \end{pmatrix}$$ initial guesses

$$P_1 := genfit\left(vd_p \cdot \mu m^{-1}, v\phi_{cum}, vg_1, F_1\right) \qquad P_2 := genfit\left(vd_p \cdot \mu m^{-1}, v\phi_{cum}, vg_2, F_2\right)$$

$$P_1 = \begin{pmatrix} 5.269 \\ 1.019 \end{pmatrix} \qquad P_2 = \begin{pmatrix} 2.609 \\ 1.658 \\ 11.628 \\ 1.218 \end{pmatrix}$$

median particle size (μm)
RR exponent

curve fit parameters

$$CDF_{MB\_M_j} := \frac{1}{2} \cdot \left(CDF_{RR}\left(d_{p_j}, P2_0 \cdot \mu m, P2_1\right) + CDF_{RR}\left(d_{p_j}, P2_2 \cdot \mu m, P2_3\right)\right)$$ ϕ_{cum}

$$PDF_{MB\_M_j} := \frac{1}{2} \cdot \left(PDF_{RR}\left(d_{p_j}, P2_0 \cdot \mu m, P2_1\right) + PDF_{RR}\left(d_{p_j}, P2_2 \cdot \mu m, P2_3\right)\right) \cdot \Delta d_{p_j}$$ ϕ

$d_{MB\_M} := pack(d_p, PDF_{MB\_M})$

$CDF_{MB\_M} := pack(CDF_{MB\_M}, PDF_{MB\_M})$

$PDF_{MB\_M} := pack(PDF_{MB\_M}, PDF_{MB\_M})$

$j_{MB\_M} := 0 .. length(d_{MB\_M}) - 1$

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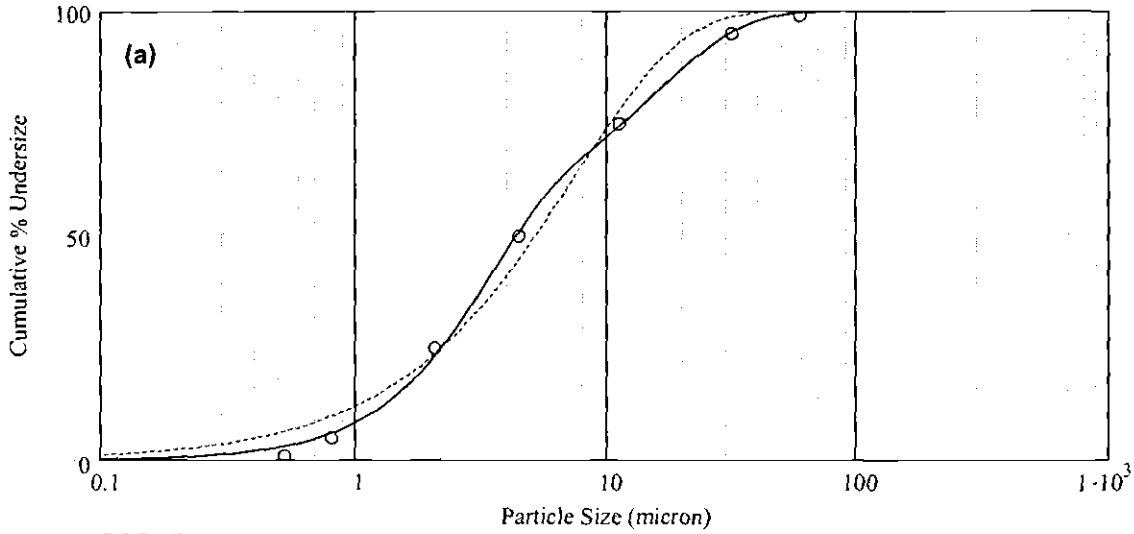
Checked: By: S.D. Estey
Revised: By:

Cumulative and Frequency Rosin-Rammler Distribution Approximation to *Strongly Agitated* (Most Battered) *Mean* Cumulative Data (Bechtold et al. 2002).

Particle Size Cumulative Distribution



ooo Data
------ Single Rosin-Rammler Approximation
—— Double Rosin-Rammler Approximation

$$\phi_{cum_j} := CDF_{RR}\left(d_{p_j}, P1_0 \cdot \mu m, P1_1\right)$$

$$\phi_{cum_j} := \frac{1}{2} \cdot \left(CDF_{RR}\left(d_{p_j}, P2_0 \cdot \mu m, P2_1\right) + CDF_{RR}\left(d_{p_j}, P2_2 \cdot \mu m, P2_3\right)\right)$$

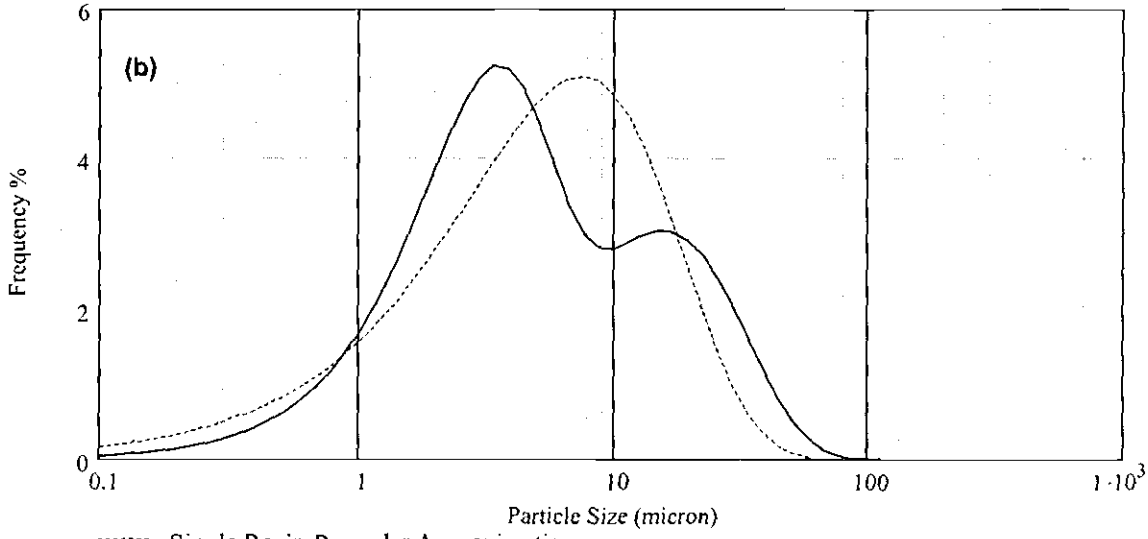
median particle size

$D_\beta\left(vd_p, v\phi_{cum}, 50\%\right) = 4.5\,\mu m$ measured date

$D_\beta\left(d_p, \phi_{cum}, 50\%\right) = 5.3\,\mu m$ single RR curve fit

$D_\beta\left(d_p, \phi_{cum}, 50\%\right) = 4.4\,\mu m$ double RR curve fit

Particle Size Frequency Distribution



------ Single Rosin-Rammler Approximation
—— Double Rosin-Rammler Approximation

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Checked: By: S.D. Estey
Location: 200 Area - Hanford Site, Richland, Washington — Revised: By:

Strongly Agitated (Most Battered) 95/95TL $vd_p := 0$

$v\phi_{cum_i}$ =	vd_{p_i} :=
0.01	1.56
0.05	2.22
0.25	5.53
0.5	10.73
0.75	35.25
0.95	155.95
0.99	277.89

$vd_p := vd_p \cdot \mu m$

$$v\phi_{cum} = \begin{pmatrix} 0.01 \\ 0.05 \\ 0.25 \\ 0.5 \\ 0.75 \\ 0.95 \\ 0.99 \end{pmatrix} \qquad vd_p = \begin{pmatrix} 1.56 \\ 2.22 \\ 5.53 \\ 10.73 \\ 35.25 \\ 155.95 \\ 277.89 \end{pmatrix} \mu m$$

single and double mode Rossin-Rammler distribution curve fits

$$vg_1 := \begin{pmatrix} 20 \\ 2 \end{pmatrix} \qquad vg_2 := \begin{pmatrix} 7 \\ 0.8 \\ 10 \\ 5 \end{pmatrix}$$ *initial guesses*

$$P_1 := genfit\left(vd_p \cdot \mu m^{-1}, v\phi_{cum}, vg_1, F_1\right) \qquad P_2 := genfit\left(vd_p \cdot \mu m^{-1}, v\phi_{cum}, vg_2, F_2\right)$$

$$P_1 = \begin{pmatrix} 14.368 \\ 0.942 \end{pmatrix} \qquad P_2 = \begin{pmatrix} 37.638 \\ 0.906 \\ 6.901 \\ 2.027 \end{pmatrix}$$

median particle size (μm)
RR exponent

curve fit parameters

$$CDF_{MB\_9595TL_j} := \frac{1}{2} \cdot \left(CDF_{RR}\left(d_{p_j}, P2_0 \cdot \mu m, P2_1\right) + CDF_{RR}\left(d_{p_j}, P2_2 \cdot \mu m, P2_3\right)\right) \qquad \phi_{cum}$$

$$PDF_{MB\_9595TL_j} := \frac{1}{2} \cdot \left(PDF_{RR}\left(d_{p_j}, P2_0 \cdot \mu m, P2_1\right) + PDF_{RR}\left(d_{p_j}, P2_2 \cdot \mu m, P2_3\right)\right) \cdot \Delta d_{p_j} \qquad \phi$$

$$d_{MB\_9595TL} := pack\left(d_p, PDF_{MB\_9595TL}\right)$$

$$CDF_{MB\_9595TL} := pack\left(CDF_{MB\_9595TL}, PDF_{MB\_9595TL}\right)$$

$$PDF_{MB\_9595TL} := pack\left(PDF_{MB\_9595TL}, PDF_{MB\_9595TL}\right)$$

$$jMB\_9595TL := 0..\, length\left(d_{MB\_9595TL}\right) - 1$$

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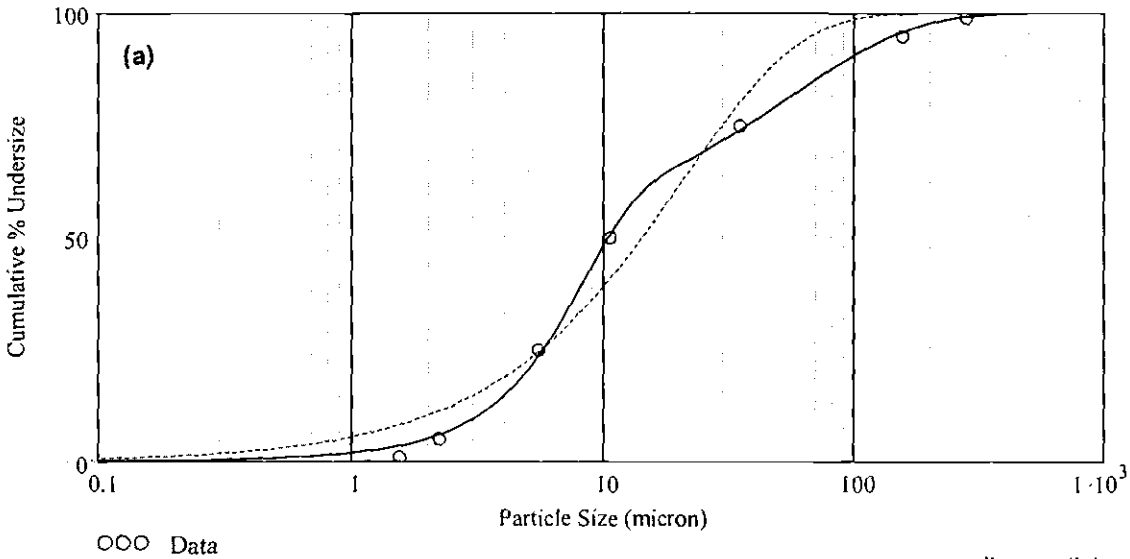
Checked: By: S.D. Estey
Location: 200 Area - Hanford Site, Richland, Washington
Revised: By:

Cumulative and Frequency Rosin-Rammler Distribution Approximation to *Strongly Agitated* (Most Battered) *95/95TL* Cumulative Data (Bechtold et al. 2002).

Particle Size Cumulative Distribution



OOO Data
------ Single Rosin-Rammler Approximation
—— Double Rosin-Rammler Approximation

$$\phi_{cum_j} := CDF_{RR}\left(d_{p_j}, P1_0 \cdot \mu m, P1_1\right)$$

$$\phi_{cum_j} := \frac{1}{2} \cdot \left(CDF_{RR}\left(d_{p_j}, P2_0 \cdot \mu m, P2_1\right) + CDF_{RR}\left(d_{p_j}, P2_2 \cdot \mu m, P2_3\right)\right)$$

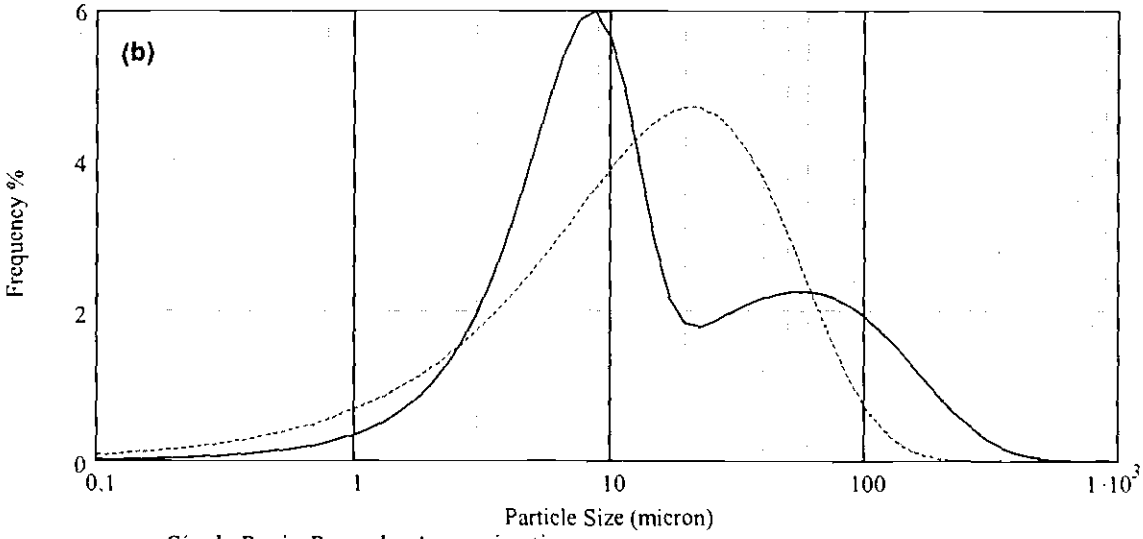
median particle size

$D_\beta\left(vd_p, v\phi_{cum}, 50\%\right) = 10.73\,\mu m$ measured date

$D_\beta\left(d_p, \phi_{cum}, 50\%\right) = 14.39\,\mu m$ single RR curve fit

$D_\beta\left(d_p, \phi_{cum}, 50\%\right) = 10.56\,\mu m$ double RR curve fit

Particle Size Frequency Distribution



------ Single Rosin-Rammler Approximation
—— Double Rosin-Rammler Approximation

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Date: 02/25/2002 By: L. J. Julyk
Checked: By: S.D. Estey
Location: 200 Area - Hanford Site, Richland, Washington
Revised: By:

Strongly Agitated (Most Battered) UL(95%) $vd_p := 0$

$v\phi_{cum_i}$ =	vd_{p_i} :=
0.01	0.75
0.05	1.12
0.25	2.84
0.5	5.87
0.75	16.49
0.95	58.76
0.99	106.79

$vd_p := vd_p \cdot \mu m$

$$v\phi_{cum} = \begin{pmatrix} 0.01 \\ 0.05 \\ 0.25 \\ 0.5 \\ 0.75 \\ 0.95 \\ 0.99 \end{pmatrix} \qquad vd_p = \begin{pmatrix} 0.75 \\ 1.12 \\ 2.84 \\ 5.87 \\ 16.49 \\ 58.76 \\ 106.79 \end{pmatrix} \mu m$$

single and double mode Rossin-Rammler distribution curve fits

$$vg_1 := \begin{pmatrix} 20 \\ 2 \end{pmatrix} \qquad vg_2 := \begin{pmatrix} 7 \\ 0.8 \\ 10 \\ 5 \end{pmatrix}$$ initial guesses

$$P_1 := genfit\left(vd_p \cdot \mu m^{-1}, v\phi_{cum}, vg_1, F_1\right) \qquad P_2 := genfit\left(vd_p \cdot \mu m^{-1}, v\phi_{cum}, vg_2, F_2\right)$$

$$P_1 = \begin{pmatrix} 7.229 \\ 0.987 \end{pmatrix}$$ median particle size (μm), RR exponent

$$P_2 = \begin{pmatrix} 17.256 \\ 1.026 \\ 3.593 \\ 1.802 \end{pmatrix}$$ curve fit parameters

$$CDF_{MB\_UL95_j} := \frac{1}{2} \cdot \left(CDF_{RR}\left(d_{p_j}, P2_0 \cdot \mu m, P2_1\right) + CDF_{RR}\left(d_{p_j}, P2_2 \cdot \mu m, P2_3\right)\right)$$ ϕ_{cum}

$$PDF_{MB\_UL95_j} := \frac{1}{2} \cdot \left(PDF_{RR}\left(d_{p_j}, P2_0 \cdot \mu m, P2_1\right) + PDF_{RR}\left(d_{p_j}, P2_2 \cdot \mu m, P2_3\right)\right) \cdot \Delta d_{p_j}$$ ϕ

$d_{MB\_UL95} := pack(d_p, PDF_{MB\_UL95})$

$CDF_{MB\_UL95} := pack(CDF_{MB\_UL95}, PDF_{MB\_UL95})$

$PDF_{MB\_UL95} := pack(PDF_{MB\_UL95}, PDF_{MB\_UL95})$

$jMB\_UL95 := 0 .. length(d_{MB\_UL95}) - 1$

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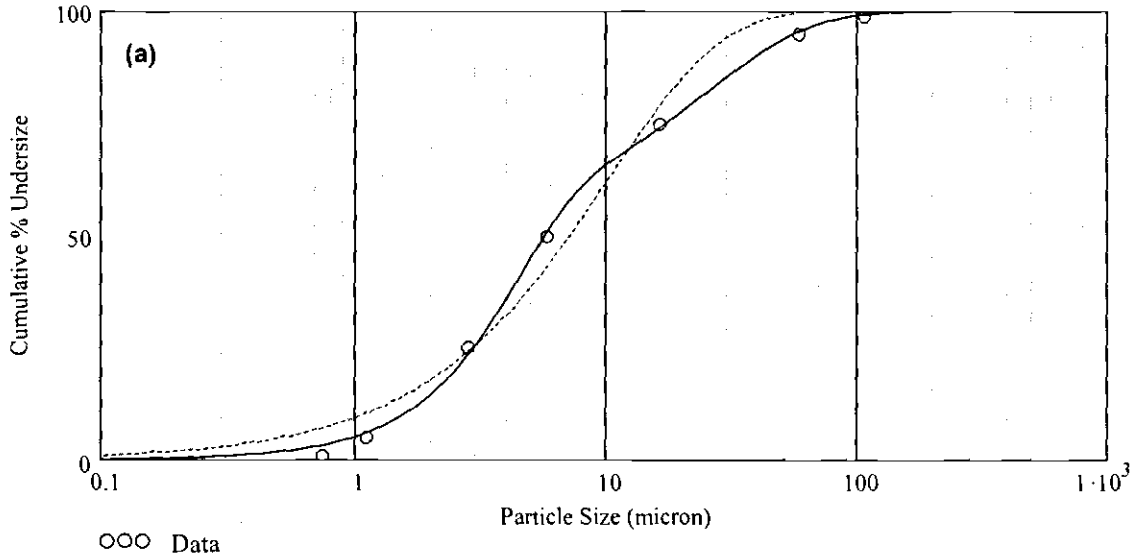
Date: 02/25/2002 By: L. J. Julyk
Checked: By: S.D. Estey
Location: 200 Area - Hanford Site, Richland, Washington
Revised: By:

Cumulative and Frequency Rosin-Rammler Distribution Approximation to *Strongly Agitated* (Most Battered) *UL(95%)* Cumulative Data (Bechtold et al. 2002).

Particle Size Cumulative Distribution



○○○ Data
------ Single Rosin-Rammler Approximation
—— Double Rosin-Rammler Approximation

$$\phi_{cum_j} := CDF_{RR}\left(d_{p_j}, P1_0 \cdot \mu m, P1_1\right)$$

$$\phi_{cum_j} := \frac{1}{2} \cdot \left(CDF_{RR}\left(d_{p_j}, P2_0 \cdot \mu m, P2_1\right) + CDF_{RR}\left(d_{p_j}, P2_2 \cdot \mu m, P2_3\right)\right)$$

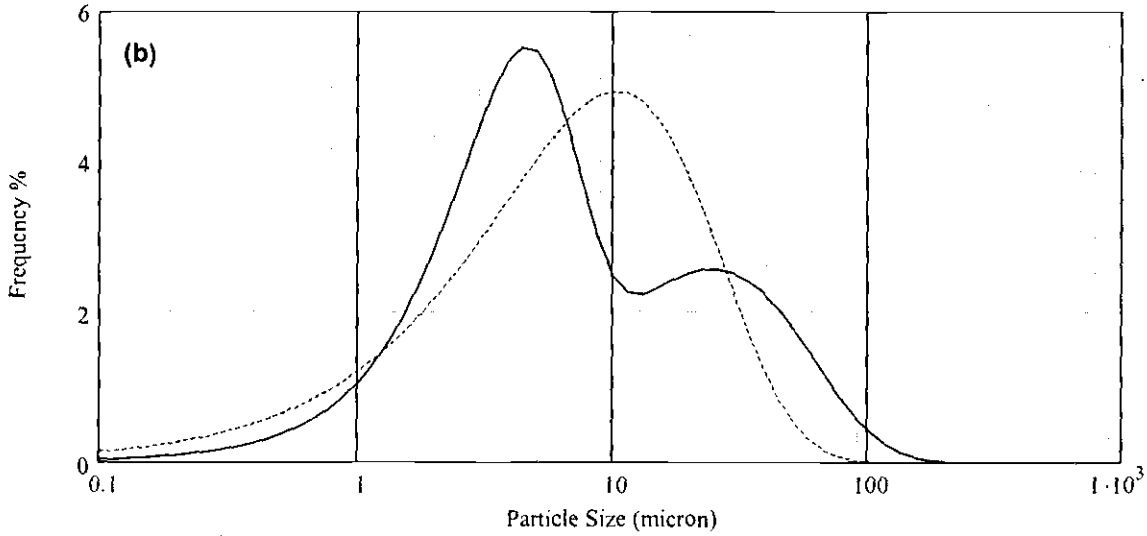
median particle size

$D_\beta\left(vd_p, v\phi_{cum}, 50\%\right) = 5.9\,\mu m$ measured date

$D_\beta\left(d_p, \phi_{cum}, 50\%\right) = 7.2\,\mu m$ single RR curve fit

$D_\beta\left(d_p, \phi_{cum}, 50\%\right) = 5.7\,\mu m$ double RR curve fit

Particle Size Frequency Distribution



------ Single Rosin-Rammler Approximation
—— Double Rosin-Rammler Approximation

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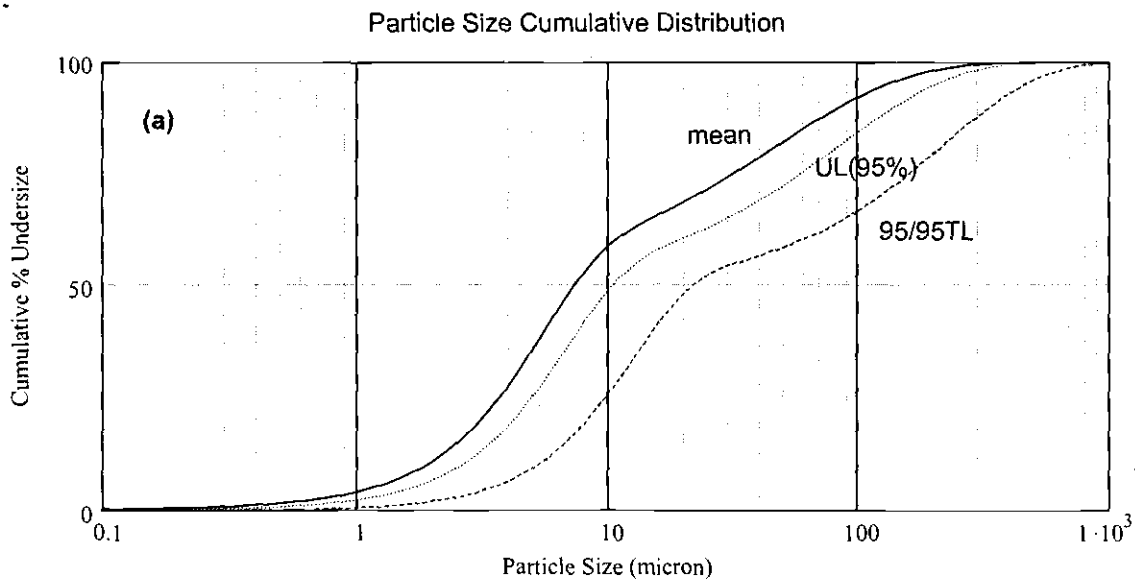
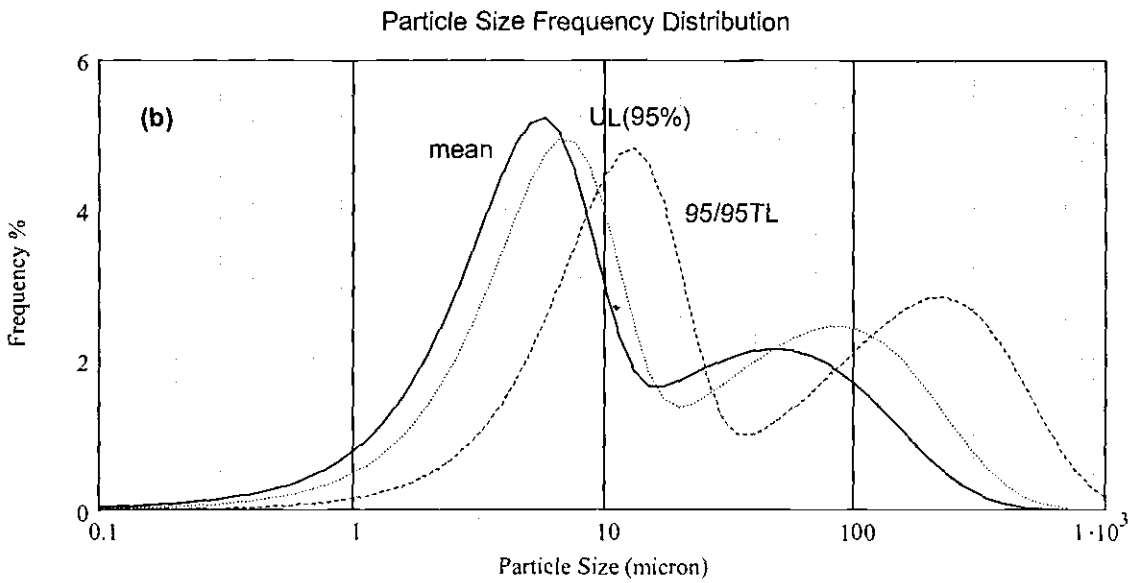
Date: 02/25/2002 By: L. J. Julyk
Checked: By: S.D. Estey
Location: 200 Area - Hanford Site, Richland, Washington
Revised: By:

Cumulative and Frequency Rosin-Rammler Distribution Approximation to *Minimum Agitated* (Least Battered) Cumulative Data (Bechtold et al. 2002 and Jewett et al. 2002).





median particle size (double Rosin-Rammler curve fit)

$D\beta(d_{LB\_M}, CDF_{LB\_M}, 50\%) = 7.4\,\mu m$ mean

$D\beta(d_{LB\_UL95}, CDF_{LB\_UL95}, 50\%) = 10.5\,\mu m$ UL (95%)

$D\beta(d_{LB\_9595TL}, CDF_{LB\_9595TL}, 50\%) = 21.8\,\mu m$ 95/95 TL

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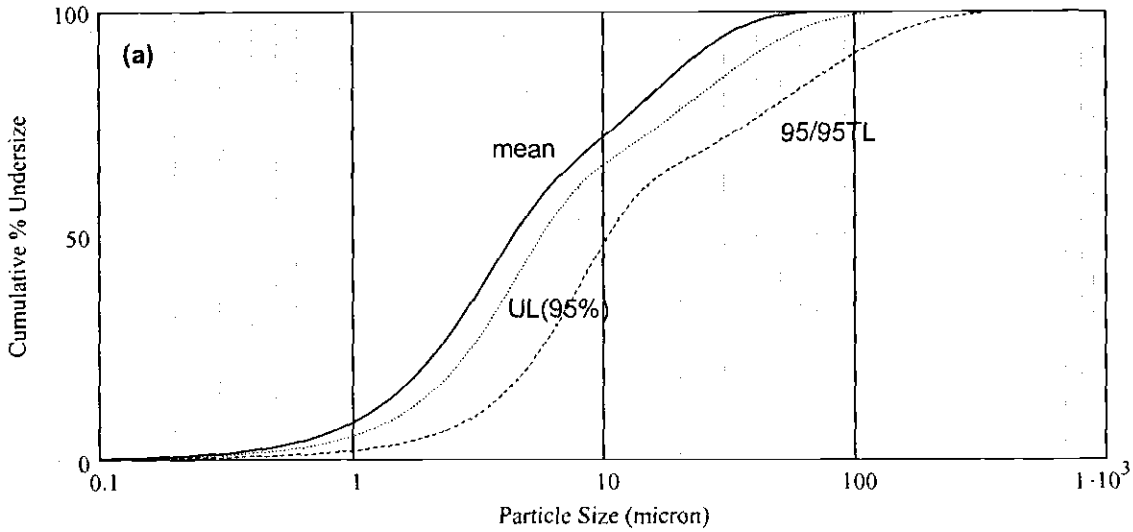
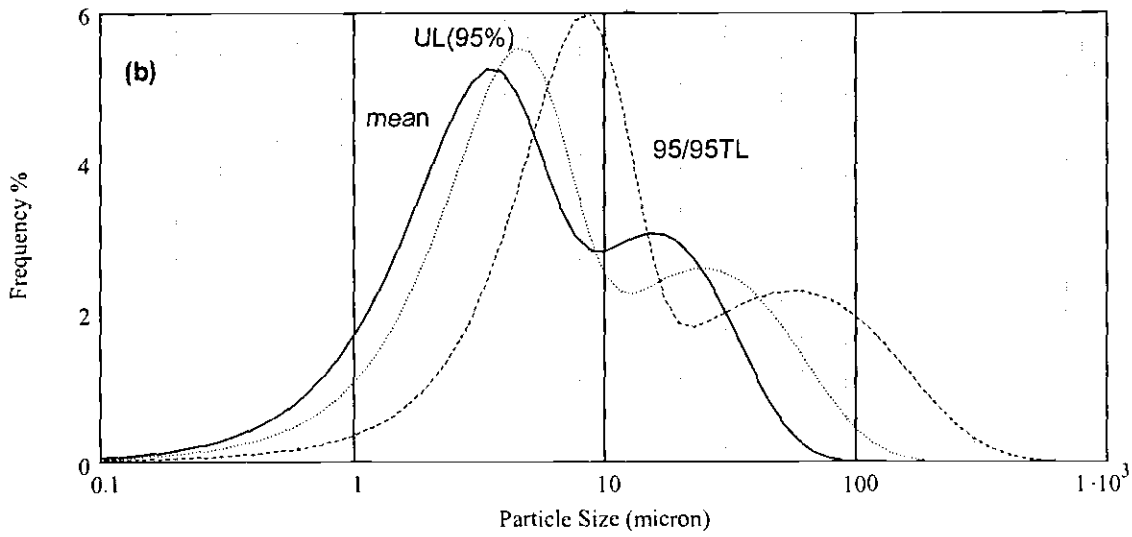
WO/Job No. 500689/BA10
Subject: Critical Velocity and Pressure Drop Study in Support of Waste Tank Feed Transfer System
Date: 02/25/2002 By: L. J. Julyk
Checked: By: S.D. Estey
Location: 200 Area - Hanford Site, Richland, Washington
Revised: By:

Cumulative and Frequency Rosin-Rammler Distribution Approximation to *Strongly Agitated* (Most Battered) Cumulative Data (Bechtold et al. 2002).

Particle Size Cumulative Distribution



Particle Size Frequency Distribution



median particle size (double Rosin-Rammler curve fit)

$D_\beta(d_{MB\_M}, CDF_{MB\_M}, 50\%) = 4.4\,\mu m$ mean

$D_\beta(d_{MB\_UL95}, CDF_{MB\_UL95}, 50\%) = 5.7\,\mu m$ UL (95%)

$D_\beta(d_{MB\_9595TL}, CDF_{MB\_9595TL}, 50\%) = 10.6\,\mu m$ 95/95 TL

The mean PSD under conditions of *minimal agitation* (7.5 μm median particle size) PSD is considered to be a conservative PSD for WFD analysis because in-tank mixing and pumping of the HLW feed is expected to breakup the larger agglomerated particles. This was observed in lab test under *strong agitation* by sonication of samples as shown above. However, the extent of agglomeration breakup during transfer conditions could not be reliably correlated to the sonicated sample data. Hence, the more conservative non-sonicated sample data was used to establish the recommended PSD for the WFD analysis (Jewett et al. 2002). The corresponding upper limit 95/95 TL of the mean *minimally agitated* PSD is used in sensitivity analyses,

Appendix D provides a tabular listing of the critical velocity, pressure drop at critical velocity, pressure drop at the target flow rate of 140 gal/min, and the maximum operating flow rate and corresponding pressure drop which would not exceed the pipeline system design pressure limit at the pump dead head condition. In some 275 lbf/in^2 limited pipeline transfer routes this required a reduced limit on the pump speed below the maximum pump speed for the Project W-211 transfer pump (3x6A VCM 6 stage SULZER proposed pump curve number 61412 or 61413). No such restrictions were required for the 400 lbf/in^2 limited pipeline transfer routes. In addition, in all cases some 275 lbf/in^2 limited pipeline transfer routes might exceed the pipeline system design pressure at the target flow rate of 140 gal/min.

Appendix E provides the results of a "sensitivity" analysis on selected HLW transfer routes to WTP for the range of waste transfer properties considered appropriate. See main body of this report for a discussion of the detail results. Appendix G provides results of Wasp model verification and Appendix H provides results of independent third parity review.

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7.0 ANALYSIS OF TRANSFER PIPELINES FOR PROPOSED TRANSFERS - Wasp Method

Maximum pipe design pressure

$D_{pipe} := 3.068 \cdot in$ $\quad p_{design\_max} := 400 \cdot \frac{lbf}{in^2}$ $\quad rpm := \frac{1}{min}$ $\quad gpm = 1 \frac{gal}{min}$

$A_P := \frac{\pi}{4} \cdot D_{pipe}^2$ flow area of pipe $\quad A_P = 7.393\, in^2$ $\quad TOL := 10 \cdot 10^{-5}$

$Q_v(v) := A_P \cdot v$ volume flow rate $\quad TOL = 1 \times 10^{-4}$

Project W-211 Transfer Pump (Curve No. 61412 or 61413)
(3x6A VCM 6 Stage Sulzer Pump)

$n_{max} := 3560 \cdot rpm$

$i := 0..6$

$vQ_{W211TP_i} := H_{W211TP_i} :=$

Flow (gpm)	Head (ft)
0	625
80	564
100	550
120	528
140	500
200	400
240	310

$cH_{W211TP} := regress(vQ_{W211TP}, vH_{W211TP}, 3)$

$H_{pump}(Q, n) := interp\left(cH_{W211TP}, vQ_{W211TP}, vH_{W211TP}, \frac{Q}{gpm} \cdot \frac{n_{max}}{n}\right) \cdot ft \cdot \left(\frac{n}{n_{max}}\right)^2$

$p_{pump}(Q, n, \rho) := H_{pump}(Q, n) \cdot \rho \cdot g$ $\quad Q_{runout} := root(H_{pump}(Q, n_{max}), Q)$

$Q_{runout} = 332\, gpm$ run-out flow rate at n_{max}

$\frac{Q_{runout}}{A_P} = 14.408 \frac{ft}{sec}$

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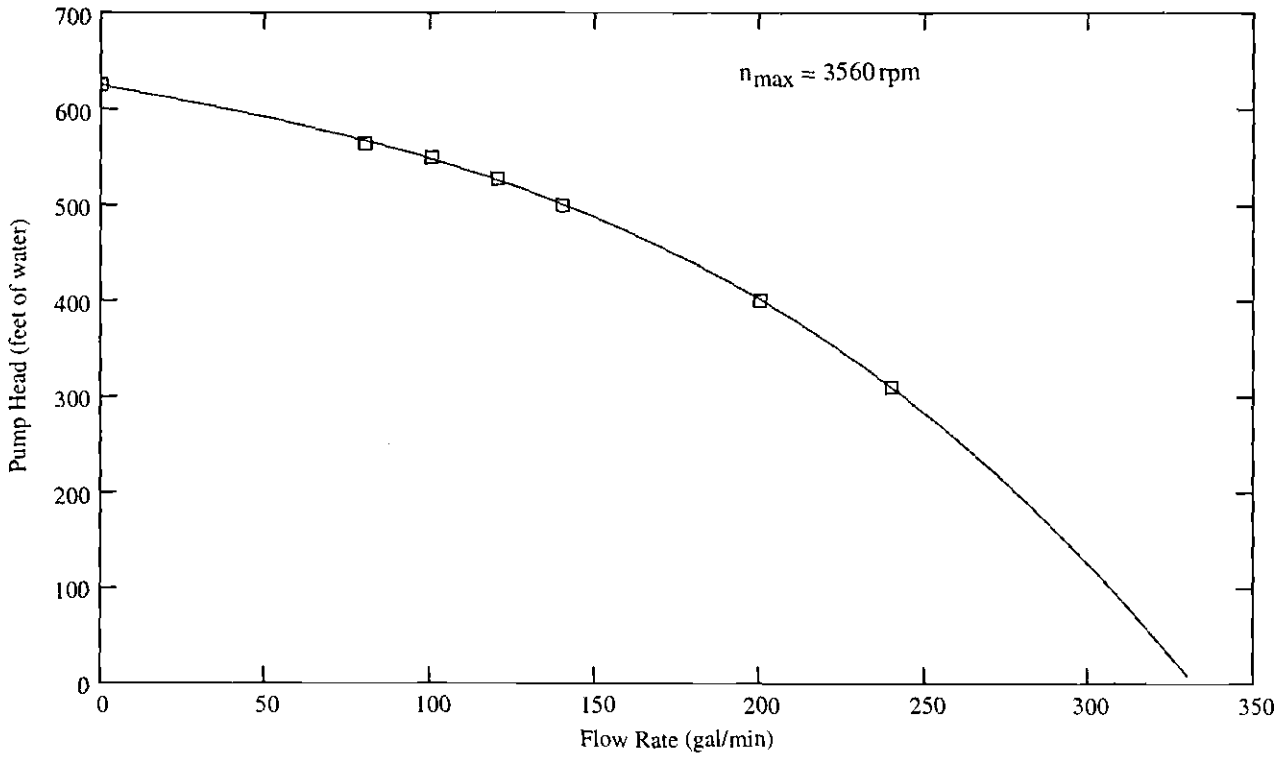
Project W-211 Transfer Pump (Curve No. 61412 or 61413)
(3x6A VCM 6 Stage Sulzer Pump)



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DL :=

[redacted]

Worksheet

read transfer pipeline physical parameters

Output from worksheet

(DL) C18:F89

Interface to WTP $L_{CSW} := 0 \cdot ft$ $L_{SSW} := 857 \cdot ft$ $H_W := 63 \cdot ft$

$$\Theta_W := asin\left(\frac{H_W}{L_{CSW} + L_{SSW}}\right)$$

$p_{design} := DL^{\langle 0 \rangle} \cdot lbf \cdot in^{-2}$

$ii := 0$ $jj := 0..5$

$L_{CS} := DL^{\langle 1 \rangle} \cdot ft$ $L_{SS} := DL^{\langle 2 \rangle} \cdot ft$ $H := DL^{\langle 3 \rangle} \cdot ft$ $N := length(L_{CS})$ $N = 72$ $i := 0..N-1$ $j := 0..11$

$$\Theta := asin\left(\frac{H}{L_{CS} + L_{SS}}\right)$$

$\varepsilon_{BOL\_CS} := 70 \cdot mil$ $\varepsilon_{BOL\_SS} := 2 \cdot mil$

$\varepsilon_{EOL\_CS} := 150 \cdot mil$ $\varepsilon_{EOL\_SS} := 10 \cdot mil$

$\varepsilon_{Aver} := 58 \cdot mil$

BOL for carbon steel lines include 20 years exposure for existing carbon steel lines

The critical velocity and pressure drop correlations are "best-estimate" correlations. In application of these correlations, the uncertainty in the predictive correlation must be considered.

approximate 2σ uncertainty factors on predictive correlations

$\kappa_{cv} := 1.30$ uncertainty factor on predicted critical velocity plus factor to assure operation above the critical velocity

$\kappa_f := 1$ uncertainty factor on predicted friction factor - for best-estimate $\kappa_f = 1$

$\beta_{cv} := 1.2$ Oroskar-Turian critical velocity

$\kappa_{pump} := 1.3$ pump shutoff factor (not used because actual Project W-211 pump curved used)

$K_D := 82$ Wasp

$C_s := 10\%$ solids concentration (vol%)

Viscosity Correlation Parameter

β_μ = 0 Thomas
1 Best-estimate correlation
2 C104 Bounding Viscosity

$\mu_L := 1 \cdot cP$

$\beta_\mu := 1$ $\mu_I := \mu_c\left(\mu_L, \frac{1}{sec}, 0\%, \beta_\mu\right)$ $\mu_I = 1.5 cP$

-95CI, mean, +95CI, and 95/95TL

ρ_s = 2.6, 2.9, 3.2 and 3.9 kg/L solids particle density

$\rho_s := 2.9 \cdot \frac{kg}{liter}$

Particle size distribution (PSD - by volume) measurement data

Least battered (minimum shear or minimually agitated) Mean, UL95, 95/95TL

Most battered (high shear or strongly agitated) Mean, UL95, 95/95TL

$d_{pRR} := 0$ $j_R := 0$ $\phi_{RR} := 0$ $\phi_{RRc} := 0$

$d_{pRR} := d_{LB\_M}$ $j_R := j_{LB\_M}$ $\phi_{RR} := PDF_{LB\_M}$ $\phi_{RRc} := CDF_{LB\_M}$ $d_{50} := D_\beta(d_{pRR}, \phi_{RRc}, 50\%)$

$d_{50} = 7.4 \mu m$

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Data Set R0, R1, R2, and R3 $\boxed{\rho_L := 1.1 \cdot kg \cdot liter^{-1}}$ $R0 := 0$ $R1 := 0$ $R2_{i,j} := 0$ $R3_{ii,jj} := 0$

$\rho_b := C_s \cdot \rho_s + \rho_L \cdot (1 - C_s)$ $\rho_b = 1.28\, kg \cdot liter^{-1}$

Critical velocity: Wasp modified OT

$v_{cr0} := v_{cr\_Wasp}(D_{pipe}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, \rho_L, \mu_1, \varepsilon_{Aver}, \kappa_{cv}, \beta_{cv}, K_D, \beta_\mu)$ $v_{cr0} = 2.597\, ft \cdot sec^{-1}$ $R0 := v_{cr0} \cdot \left(\frac{ft}{sec}\right)^{-1}$

BOL

$\Delta p_{BOLcr_i} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{BOL\_CS}, \varepsilon_{BOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu)$ pressure drop

$\Delta p_{BOLcrI} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{BOL\_CS}, \varepsilon_{BOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CSW}, L_{SSW}, K_D, \kappa_f, \Theta_W, \beta_\mu)$

interface-to-WTP pressure drop

$R2^{\langle 0 \rangle} := \Delta p_{BOLcr} \cdot \left(\frac{lbf}{in^2}\right)^{-1}$ $R3_{0,0} := \Delta p_{BOLcrI} \cdot \left(\frac{lbf}{in^2}\right)^{-1}$

EOL

$\Delta p_{EOLcr_i} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{EOL\_CS}, \varepsilon_{EOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu)$

$\Delta p_{EOLcrI} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{EOL\_CS}, \varepsilon_{EOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CSW}, L_{SSW}, K_D, \kappa_f, \Theta_W, \beta_\mu)$

interface-to-WTP pressure drop

$R2^{\langle 1 \rangle} := \Delta p_{EOLcr} \cdot \left(\frac{lbf}{in^2}\right)^{-1}$ $R3_{0,1} := \Delta p_{EOLcrI} \cdot \left(\frac{lbf}{in^2}\right)^{-1}$

Critical velocity: OT

$v_{cr0} := v_{cr}(D_{pipe}, d_{50}, \rho_s, C_s, \rho_L, \mu_1, \kappa_{cv}, \beta_{cv})$ $v_{cr0} = 3.441\, ft \cdot sec^{-1}$ $R1 := v_{cr0} \cdot \left(\frac{ft}{sec}\right)^{-1}$

BOL

$\Delta p_{BOLcr_i} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{BOL\_CS}, \varepsilon_{BOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu)$ pressure drop

$\Delta p_{BOLcrI} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{BOL\_CS}, \varepsilon_{BOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CSW}, L_{SSW}, K_D, \kappa_f, \Theta_W, \beta_\mu)$

$R2^{\langle 2 \rangle} := \Delta p_{BOLcr} \cdot \left(\frac{lbf}{in^2}\right)^{-1}$ $R3_{0,2} := \Delta p_{BOLcrI} \cdot \left(\frac{lbf}{in^2}\right)^{-1}$

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EOL

$\Delta p_{EOLcr_i} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{EOL\_CS}, \varepsilon_{EOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu)$

$\Delta p_{EOLcrI} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{EOL\_CS}, \varepsilon_{EOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CSW}, L_{SSW}, K_D, \kappa_f, \Theta_W, \beta_\mu)$

$R2^{\langle 3 \rangle} := \Delta p_{EOLcr} \cdot \left(\frac{lbf}{in^2}\right)^{-1}$ $\qquad R3_{0,3} := \Delta p_{EOLcrI} \cdot \left(\frac{lbf}{in^2}\right)^{-1}$

Target Flow Rate $\boxed{Q := 140 \cdot gpm}$

$v_{cr0} := \frac{Q}{A_P}$ $\qquad v_{cr0} = 6.076\, ft \cdot sec^{-1}$

BOL

$\Delta p_{BOLcr_i} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{BOL\_CS}, \varepsilon_{BOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu)$ pressure drop

$\Delta p_{BOLcrI} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{BOL\_CS}, \varepsilon_{BOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CSW}, L_{SSW}, K_D, \kappa_f, \Theta_W, \beta_\mu)$

$R2^{\langle 4 \rangle} := \Delta p_{BOLcr} \cdot \left(\frac{lbf}{in^2}\right)^{-1}$ $\qquad R3_{0,4} := \Delta p_{BOLcrI} \cdot \left(\frac{lbf}{in^2}\right)^{-1}$

EOL

$\Delta p_{EOLcr_i} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{EOL\_CS}, \varepsilon_{EOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu)$

$\Delta p_{EOLcrI} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{EOL\_CS}, \varepsilon_{EOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CSW}, L_{SSW}, K_D, \kappa_f, \Theta_W, \beta_\mu)$

$R2^{\langle 5 \rangle} := \Delta p_{EOLcr} \cdot \left(\frac{lbf}{in^2}\right)^{-1}$ $\qquad R3_{0,5} := \Delta p_{EOLcrI} \cdot \left(\frac{lbf}{in^2}\right)^{-1}$

at specified pipe design pressure

$n' := \frac{n_{max}}{2}$

$p_{D_i} := \min\left(p_{design_i}, p_{pump}\left(Q_v\left(0 \cdot \frac{ft}{sec}\right), n_{max}, \rho_b\right)\right)$ $\qquad$ *min(p_{design}, maximum pump dead head pressure)*

$n_{D_i} := root\left(p_{D_i} - p_{pump}\left(Q_v\left(0 \cdot \frac{ft}{sec}\right), n', \rho_b\right), n'\right)$ $\qquad p_{err} := -1 \cdot \frac{lbf}{in^2}$ $\qquad v_{err} := -1 \cdot \frac{ft}{sec}$ $\qquad v' := 10 \cdot \frac{ft}{sec}$

$v_{BOL_i} := v_{err}$ on error root$\left(\Delta p_{T_Wasp}(D_{pipe}, v', \rho_L, \mu_1, \varepsilon_{BOL_CS}, \varepsilon_{BOL_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu) \ldots, v' + -p_{pump}(Q_v(v'), n_{D_i}, \rho_b)\right)$

$\Delta p_{BOLcr_i} := p_{err}$ on error $\Delta p_{T\_Wasp}(D_{pipe}, v_{BOL_i}, \rho_L, \mu_1, \varepsilon_{BOL\_CS}, \varepsilon_{BOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu)$

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$$v_{EOL_i} := v_{err} \text{ on error root}\left(\begin{array}{l}\Delta p_{T\_Wasp}\left(D_{pipe}, v', \rho_L, \mu_1, \varepsilon_{EOL\_CS}, \varepsilon_{EOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu\right) \ldots, v' \\ + -p_{pump}\left(Q_v(v'), n_{D_i}, \rho_b\right)\end{array}\right)$$

$$\Delta p_{EOLcr_i} := p_{err} \text{ on error } \Delta p_{T\_Wasp}\left(D_{pipe}, v_{EOL_i}, \rho_L, \mu_1, \varepsilon_{EOL\_CS}, \varepsilon_{EOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu\right)$$

$$R2^{\langle 6 \rangle} := p_D \cdot \left(\frac{lbf}{in^2}\right)^{-1} \qquad R2^{\langle 7 \rangle} := n_D \cdot rpm^{-1} \qquad R2^{\langle 8 \rangle} := Q_v(v_{BOL}) \cdot \left(\frac{gal}{min}\right)^{-1} \qquad R2^{\langle 9 \rangle} := Q_v(v_{EOL}) \cdot \left(\frac{gal}{min}\right)^{-1}$$

$$R2^{\langle 10 \rangle} := \Delta p_{BOLcr} \cdot \left(\frac{lbf}{in^2}\right)^{-1} \qquad R2^{\langle 11 \rangle} := \Delta p_{EOLcr} \cdot \left(\frac{lbf}{in^2}\right)^{-1}$$

Data Set R4, R5, R6, and R7 $\boxed{\rho_L := 1.2 \cdot kg \cdot liter^{-1}}$ $R4 := 0$ $R5 := 0$ $R6_{i,j} := 0$ $R7_{ii,jj} := 0$

$$\rho_b := C_s \cdot \rho_s + \rho_L \cdot (1 - C_s) \qquad \rho_b = 1.37\, kg \cdot liter^{-1}$$

Critical velocity: Wasp modified OT

$$v_{cr0} := v_{cr\_Wasp}\left(D_{pipe}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, \rho_L, \mu_1, \varepsilon_{Aver}, \kappa_{cv}, \beta_{cv}, K_D, \beta_\mu\right) \qquad v_{cr0} = 2.44\, ft \cdot sec^{-1} \qquad R4 := v_{cr0} \cdot \left(\frac{ft}{sec}\right)^{-1}$$

BOL

$$\Delta p_{BOLcr_i} := \Delta p_{T\_Wasp}\left(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{BOL\_CS}, \varepsilon_{BOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu\right)$$ pressure drop

$$\Delta p_{BOLcrI} := \Delta p_{T\_Wasp}\left(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{BOL\_CS}, \varepsilon_{BOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CSW}, L_{SSW}, K_D, \kappa_f, \Theta_W, \beta_\mu\right)$$

$$R6^{\langle 0 \rangle} := \Delta p_{BOLcr} \cdot \left(\frac{lbf}{in^2}\right)^{-1}$$

interface-to-WTP pressure drop

$$R7_{0,0} := \Delta p_{BOLcrI} \cdot \left(\frac{lbf}{in^2}\right)^{-1}$$

EOL

$$\Delta p_{EOLcr_i} := \Delta p_{T\_Wasp}\left(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{EOL\_CS}, \varepsilon_{EOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu\right)$$

$$\Delta p_{EOLcrI} := \Delta p_{T\_Wasp}\left(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{EOL\_CS}, \varepsilon_{EOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CSW}, L_{SSW}, K_D, \kappa_f, \Theta_W, \beta_\mu\right)$$

$$R6^{\langle 1 \rangle} := \Delta p_{EOLcr} \cdot \left(\frac{lbf}{in^2}\right)^{-1}$$

interface-to-WTP pressure drop

$$R7_{0,1} := \Delta p_{EOLcrI} \cdot \left(\frac{lbf}{in^2}\right)^{-1}$$

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Critical velocity: OT

$v_{cr0} := v_{cr}(D_{pipe}, d_{50}, \rho_s, C_s, \rho_L, \mu_1, \kappa_{cv}, \beta_{cv})$ $\quad v_{cr0} = 3.206\,ft\cdot sec^{-1}$ $\quad R5 := v_{cr0}\cdot\left(\frac{ft}{sec}\right)^{-1}$

BOL

$\Delta p_{BOLcr_i} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{BOL\_CS}, \varepsilon_{BOL\_SS}, d_{pRR}, \rho_s, C_s\cdot\phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu)$ pressure drop

$\Delta p_{BOLcrl} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{BOL\_CS}, \varepsilon_{BOL\_SS}, d_{pRR}, \rho_s, C_s\cdot\phi_{RR}, L_{CSW}, L_{SSW}, K_D, \kappa_f, \Theta_W, \beta_\mu)$

$R6^{\langle 2\rangle} := \Delta p_{BOLcr}\cdot\left(\frac{lbf}{in^2}\right)^{-1}$ $\quad R7_{0,2} := \Delta p_{BOLcrl}\cdot\left(\frac{lbf}{in^2}\right)^{-1}$

EOL

$\Delta p_{EOLcr_i} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{EOL\_CS}, \varepsilon_{EOL\_SS}, d_{pRR}, \rho_s, C_s\cdot\phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu)$

$\Delta p_{EOLcrl} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{EOL\_CS}, \varepsilon_{EOL\_SS}, d_{pRR}, \rho_s, C_s\cdot\phi_{RR}, L_{CSW}, L_{SSW}, K_D, \kappa_f, \Theta_W, \beta_\mu)$

$R6^{\langle 3\rangle} := \Delta p_{EOLcr}\cdot\left(\frac{lbf}{in^2}\right)^{-1}$ $\quad R7_{0,3} := \Delta p_{EOLcrl}\cdot\left(\frac{lbf}{in^2}\right)^{-1}$

Target Flow Rate $\boxed{Q = 140\,gpm}$

$v_{cr0} := \frac{Q}{A_p}$ $\quad v_{cr0} = 6.076\,ft\cdot sec^{-1}$

BOL

$\Delta p_{BOLcr_i} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{BOL\_CS}, \varepsilon_{BOL\_SS}, d_{pRR}, \rho_s, C_s\cdot\phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu)$ pressure drop

$\Delta p_{BOLcrl} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{BOL\_CS}, \varepsilon_{BOL\_SS}, d_{pRR}, \rho_s, C_s\cdot\phi_{RR}, L_{CSW}, L_{SSW}, K_D, \kappa_f, \Theta_W, \beta_\mu)$

$R6^{\langle 4\rangle} := \Delta p_{BOLcr}\cdot\left(\frac{lbf}{in^2}\right)^{-1}$ $\quad R7_{0,4} := \Delta p_{BOLcrl}\cdot\left(\frac{lbf}{in^2}\right)^{-1}$

EOL

$\Delta p_{EOLcr_i} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{EOL\_CS}, \varepsilon_{EOL\_SS}, d_{pRR}, \rho_s, C_s\cdot\phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu)$

$\Delta p_{EOLcrl} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{EOL\_CS}, \varepsilon_{EOL\_SS}, d_{pRR}, \rho_s, C_s\cdot\phi_{RR}, L_{CSW}, L_{SSW}, K_D, \kappa_f, \Theta_W, \beta_\mu)$

$R6^{\langle 5\rangle} := \Delta p_{EOLcr}\cdot\left(\frac{lbf}{in^2}\right)^{-1}$ $\quad R7_{0,5} := \Delta p_{EOLcrl}\cdot\left(\frac{lbf}{in^2}\right)^{-1}$

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at specified pipe design pressure

$n' := \frac{n_{max}}{2}$

$p_{D_i} := \min\left(p_{design_i}, p_{pump}\left(Q_v\left(0\cdot\frac{ft}{sec}\right), n_{max}, \rho_b\right)\right)$ min(p_{design}, maximum pump dead head pressure)

$n_{D_i} := \text{root}\left(p_{D_i} - p_{pump}\left(Q_v\left(0\cdot\frac{ft}{sec}\right), n', \rho_b\right), n'\right)$ $v_{err} := -1\cdot\frac{ft}{sec}$ $v' := 10\cdot\frac{ft}{sec}$

$v_{BOL_i} := v_{err}$ on error $\text{root}\left(\begin{array}{l}\Delta p_{T\_Wasp}\left(D_{pipe}, v', \rho_L, \mu_1, \varepsilon_{BOL\_CS}, \varepsilon_{BOL\_SS}, d_{pRR}, \rho_s, C_s\cdot\phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu\right) \ldots, v' \\ + -p_{pump}\left(Q_v(v'), n_{D_i}, \rho_b\right)\end{array}\right)$

$\Delta p_{BOLcr_i} := p_{err}$ on error $\Delta p_{T\_Wasp}\left(D_{pipe}, v_{BOL_i}, \rho_L, \mu_1, \varepsilon_{BOL\_CS}, \varepsilon_{BOL\_SS}, d_{pRR}, \rho_s, C_s\cdot\phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu\right)$

$v_{EOL_i} := v_{err}$ on error $\text{root}\left(\begin{array}{l}\Delta p_{T\_Wasp}\left(D_{pipe}, v', \rho_L, \mu_1, \varepsilon_{EOL\_CS}, \varepsilon_{EOL\_SS}, d_{pRR}, \rho_s, C_s\cdot\phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu\right) \ldots, v' \\ + -p_{pump}\left(Q_v(v'), n_{D_i}, \rho_b\right)\end{array}\right)$

$\Delta p_{EOLcr_i} := p_{err}$ on error $\Delta p_{T\_Wasp}\left(D_{pipe}, v_{EOL_i}, \rho_L, \mu_1, \varepsilon_{EOL\_CS}, \varepsilon_{EOL\_SS}, d_{pRR}, \rho_s, C_s\cdot\phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu\right)$

$R6^{\langle 6\rangle} := p_D\cdot\left(\frac{lbf}{in^2}\right)^{-1}$ $R6^{\langle 7\rangle} := n_D\cdot rpm^{-1}$ $R6^{\langle 8\rangle} := Q_v(v_{BOL})\cdot\left(\frac{gal}{min}\right)^{-1}$ $R6^{\langle 9\rangle} := Q_v(v_{EOL})\cdot\left(\frac{gal}{min}\right)^{-1}$

$R6^{\langle 10\rangle} := \Delta p_{BOLcr}\cdot\left(\frac{lbf}{in^2}\right)^{-1}$ $R6^{\langle 11\rangle} := \Delta p_{EOLcr}\cdot\left(\frac{lbf}{in^2}\right)^{-1}$

Data Set R8, R9, R10, and R11 $\boxed{\rho_L := 1.3\cdot kg\cdot liter^{-1}}$ $R8 := 0$ $R9 := 0$ $R10_{i,j} := 0$ $R11_{ii,jj} := 0$

$\rho_b := C_s\cdot\rho_s + \rho_L\cdot(1 - C_s)$ $\rho_b = 1.46\,kg\cdot liter^{-1}$

Critical velocity: Wasp modified OT

$v_{cr0} := v_{cr\_Wasp}\left(D_{pipe}, d_{pRR}, \rho_s, C_s\cdot\phi_{RR}, \rho_L, \mu_1, \varepsilon_{Aver}, \kappa_{cv}, \beta_{cv}, K_D, \beta_\mu\right)$ $v_{cr0} = 2.291\,ft\cdot sec^{-1}$ $R8 := v_{cr0}\cdot\left(\frac{ft}{sec}\right)^{-1}$

BOL

$\Delta p_{BOLcr_i} := \Delta p_{T\_Wasp}\left(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{BOL\_CS}, \varepsilon_{BOL\_SS}, d_{pRR}, \rho_s, C_s\cdot\phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu\right)$ pressure drop

$\Delta p_{BOLcrI} := \Delta p_{T\_Wasp}\left(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{BOL\_CS}, \varepsilon_{BOL\_SS}, d_{pRR}, \rho_s, C_s\cdot\phi_{RR}, L_{CSW}, L_{SSW}, K_D, \kappa_f, \Theta_W, \beta_\mu\right)$

interface-to-WTP pressure drop

$R10^{\langle 0\rangle} := \Delta p_{BOLcr}\cdot\left(\frac{lbf}{in^2}\right)^{-1}$ $R11_{0,0} := \Delta p_{BOLcrI}\cdot\left(\frac{lbf}{in^2}\right)^{-1}$

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EOL

$\Delta p_{EOLcr_i} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{EOL\_CS}, \varepsilon_{EOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu)$

$\Delta p_{EOLcrI} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{EOL\_CS}, \varepsilon_{EOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CSW}, L_{SSW}, K_D, \kappa_f, \Theta_W, \beta_\mu)$

interface-to-WTP pressure drop

$R10^{\langle 1 \rangle} := \Delta p_{EOLcr} \cdot \left(\frac{lbf}{in^2}\right)^{-1}$ $\qquad R11_{0,1} := \Delta p_{EOLcrI} \cdot \left(\frac{lbf}{in^2}\right)^{-1}$

Critical velocity: OT

$v_{cr0} := v_{cr}(D_{pipe}, d_{50}, \rho_s, C_s, \rho_L, \mu_1, \kappa_{cv}, \beta_{cv})$ $\qquad v_{cr0} = 2.991\, ft \cdot sec^{-1}$ $\qquad R9 := v_{cr0} \cdot \left(\frac{ft}{sec}\right)^{-1}$

BOL

$\Delta p_{BOLcr_i} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{BOL\_CS}, \varepsilon_{BOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu)$ pressure drop

$\Delta p_{BOLcrI} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{BOL\_CS}, \varepsilon_{BOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CSW}, L_{SSW}, K_D, \kappa_f, \Theta_W, \beta_\mu)$

$R10^{\langle 2 \rangle} := \Delta p_{BOLcr} \cdot \left(\frac{lbf}{in^2}\right)^{-1}$ $\qquad R11_{0,2} := \Delta p_{BOLcrI} \cdot \left(\frac{lbf}{in^2}\right)^{-1}$

EOL

$\Delta p_{EOLcr_i} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{EOL\_CS}, \varepsilon_{EOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu)$

$\Delta p_{EOLcrI} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{EOL\_CS}, \varepsilon_{EOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CSW}, L_{SSW}, K_D, \kappa_f, \Theta_W, \beta_\mu)$

$R10^{\langle 3 \rangle} := \Delta p_{EOLcr} \cdot \left(\frac{lbf}{in^2}\right)^{-1}$ $\qquad R11_{0,3} := \Delta p_{EOLcrI} \cdot \left(\frac{lbf}{in^2}\right)^{-1}$

Target Flow Rate $\boxed{Q = 140\, gpm}$

$v_{cr0} := \frac{Q}{A_P}$ $\qquad v_{cr0} = 6.076\, ft \cdot sec^{-1}$

BOL

$\Delta p_{BOLcr_i} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{BOL\_CS}, \varepsilon_{BOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu)$ pressure drop

$\Delta p_{BOLcrI} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{BOL\_CS}, \varepsilon_{BOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CSW}, L_{SSW}, K_D, \kappa_f, \Theta_W, \beta_\mu)$

$R10^{\langle 4 \rangle} := \Delta p_{BOLcr} \cdot \left(\frac{lbf}{in^2}\right)^{-1}$ $\qquad R11_{0,4} := \Delta p_{BOLcrI} \cdot \left(\frac{lbf}{in^2}\right)^{-1}$

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EOL

$\Delta p_{EOLcr_i} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{EOL\_CS}, \varepsilon_{EOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu)$

$\Delta p_{EOLcrI} := \Delta p_{T\_Wasp}(D_{pipe}, v_{cr0}, \rho_L, \mu_1, \varepsilon_{EOL\_CS}, \varepsilon_{EOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CSW}, L_{SSW}, K_D, \kappa_f, \Theta_W, \beta_\mu)$

$R10^{\langle 5 \rangle} := \Delta p_{EOLcr} \cdot \left(\frac{lbf}{in^2}\right)^{-1}$ $\qquad R11_{0,5} := \Delta p_{EOLcrI} \cdot \left(\frac{lbf}{in^2}\right)^{-1}$

at specified pipe design pressure

$n' := \frac{n_{max}}{2}$

$p_{D_i} := \min\left(p_{design_i}, p_{pump}\left(Q_v\left(0 \cdot \frac{ft}{sec}\right), n_{max}, \rho_b\right)\right)$ $\qquad$ min(p_{design}, maximum pump dead head pressure)

$n_{D_i} := \text{root}\left(p_{D_i} - p_{pump}\left(Q_v\left(0 \cdot \frac{ft}{sec}\right), n', \rho_b\right), n'\right)$ $\qquad v_{err} := -1 \cdot \frac{ft}{sec}$ $\qquad v' := 10 \cdot \frac{ft}{sec}$

$v_{BOL_i} := v_{err}$ on error $\text{root}\left(\Delta p_{T\_Wasp}(D_{pipe}, v', \rho_L, \mu_1, \varepsilon_{BOL\_CS}, \varepsilon_{BOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu) + -p_{pump}(Q_v(v'), n_{D_i}, \rho_b) \ldots, v'\right)$

$\Delta p_{BOLcr_i} := p_{err}$ on error $\Delta p_{T\_Wasp}(D_{pipe}, v_{BOL_i}, \rho_L, \mu_1, \varepsilon_{BOL\_CS}, \varepsilon_{BOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu)$

$v_{EOL_i} := v_{err}$ on error $\text{root}\left(\Delta p_{T\_Wasp}(D_{pipe}, v', \rho_L, \mu_1, \varepsilon_{EOL\_CS}, \varepsilon_{EOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu) + -p_{pump}(Q_v(v'), n_{D_i}, \rho_b) \ldots, v'\right)$

$\Delta p_{EOLcr_i} := p_{err}$ on error $\Delta p_{T\_Wasp}(D_{pipe}, v_{EOL_i}, \rho_L, \mu_1, \varepsilon_{EOL\_CS}, \varepsilon_{EOL\_SS}, d_{pRR}, \rho_s, C_s \cdot \phi_{RR}, L_{CS_i}, L_{SS_i}, K_D, \kappa_f, \Theta_i, \beta_\mu)$

$R10^{\langle 6 \rangle} := p_D \cdot \left(\frac{lbf}{in^2}\right)^{-1}$ $\qquad R10^{\langle 7 \rangle} := n_D \cdot rpm^{-1}$ $\qquad R10^{\langle 8 \rangle} := Q_v(v_{BOL}) \cdot \left(\frac{gal}{min}\right)^{-1}$ $\qquad R10^{\langle 9 \rangle} := Q_v(v_{EOL}) \cdot \left(\frac{gal}{min}\right)^{-1}$

$R10^{\langle 10 \rangle} := \Delta p_{BOLcr} \cdot \left(\frac{lbf}{in^2}\right)^{-1}$ $\qquad R10^{\langle 11 \rangle} := \Delta p_{EOLcr} \cdot \left(\frac{lbf}{in^2}\right)^{-1}$

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[redacted]

Worksheet

return summary results of analysis to worksheet

(R0 R1 R2 R3 R4 R5 R6 R7 R8 R9 R10 R11)

(R0 R1 R2 R3 R4 R5 R6 R7 R8 R9 R10 R11)

Input to worksheet

R0	G9	Critical velocity: Wasp modified OT
R1	I9	Critical velocity: OT
R2	G18:R89	Pressure drops
R3	G90:L90	Interface-to-WTP pressure drops
R4	S9	
R5	U9	
R6	S18:AD89	
R7	S90:X90	
R8	AE9	
R9	AG9	
R10	AE18:AP89	
R11	AE90:AJ90	

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Figure F-1a. Viscosity of Water vs. Temperature.

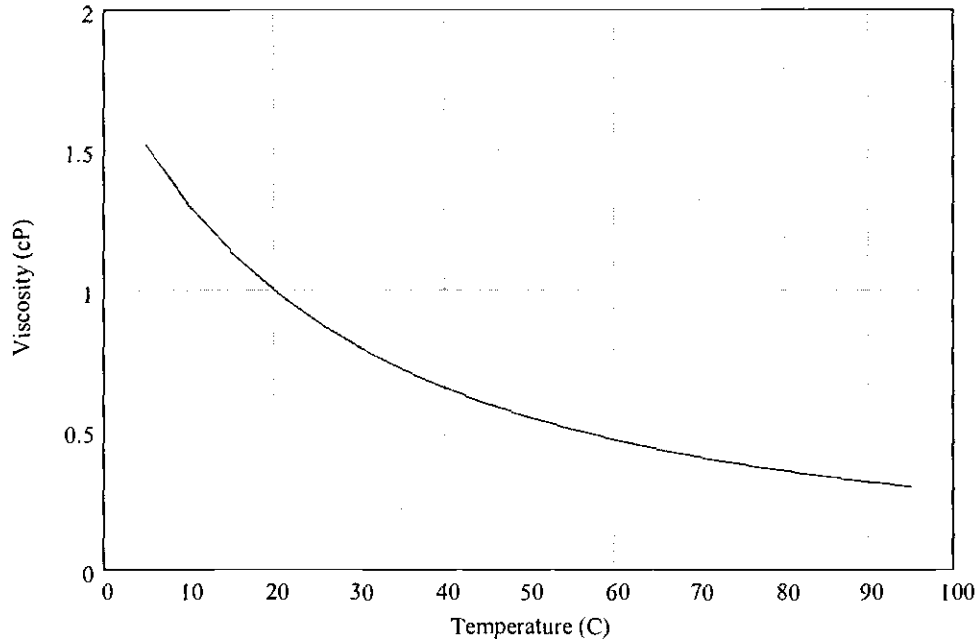

Figure F-1b. Viscosity of Carrier Liquid vs. Density of Carrier Liquid at Selected Temperatures and Salt Fractions (x_{salt}).

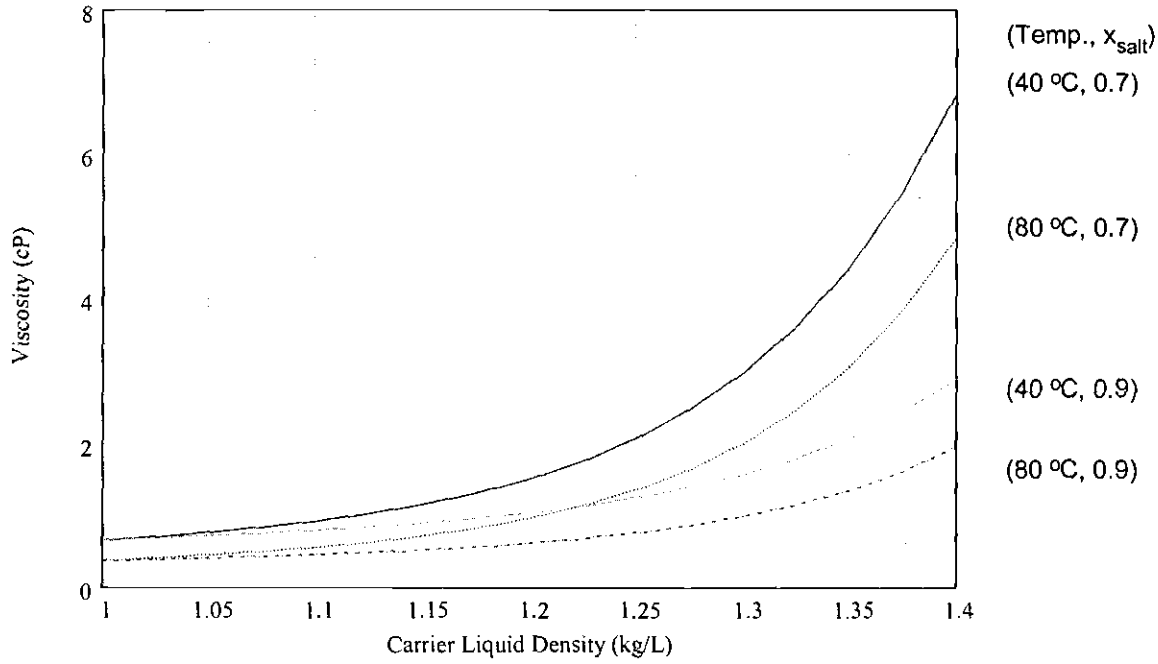

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Figure F-1c. Vehicle-to-Carrier Liquid Density and Viscosity (Thomas) Ratios vs. Vehicle Solids Concentration of Fine Particles from the Solids Particle Size Distribution.

$T := 80\ ^{\circ}C \quad \rho_L := 1.2 \cdot \frac{kg}{liter} \quad x_{salt} := 0.9 \quad \mu_L := \mu_{cL}(\rho_L, T, x_{salt}) \quad \mu_L = 0.617\,cP \quad \rho_s := 2.9 \cdot \frac{kg}{liter}$

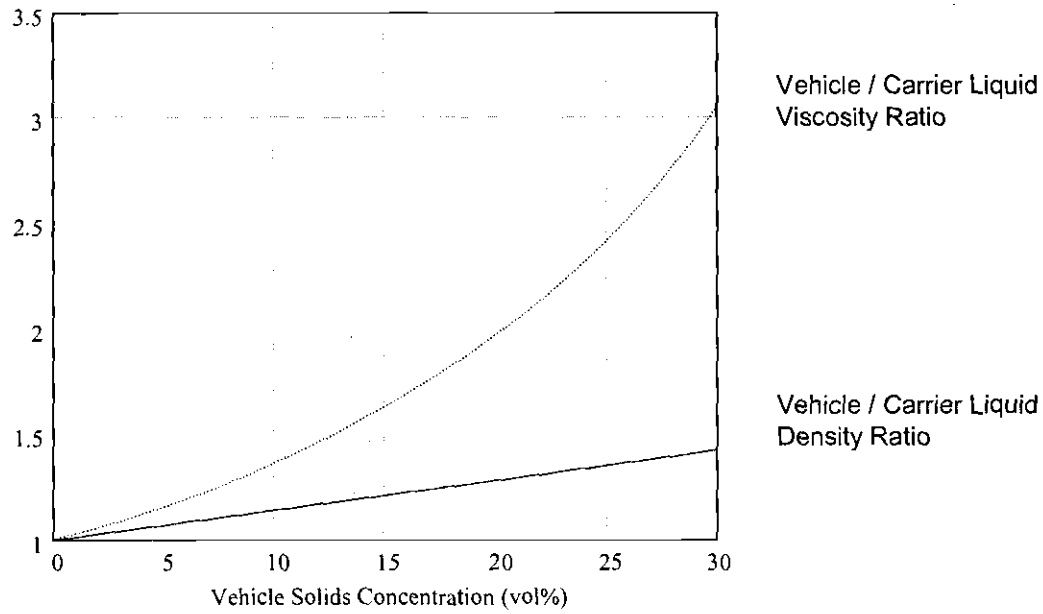

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Figure F-1d. Comparison of "Vehicle" Viscosity Correlations.

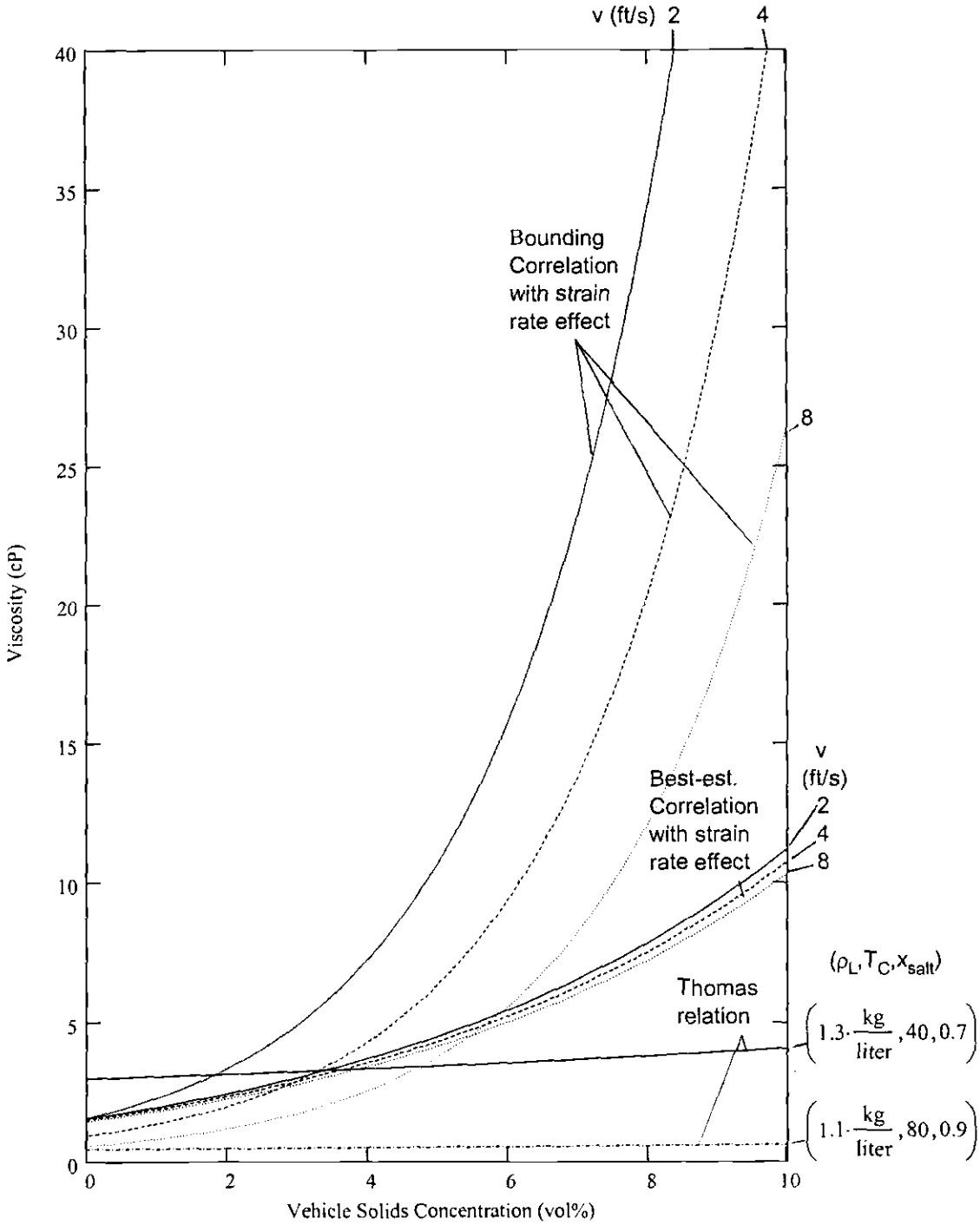

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Figure F-2. Correlations for the Drag Coefficient of a Sphere in Free Fall in a Stagnant Unbound Liquid.

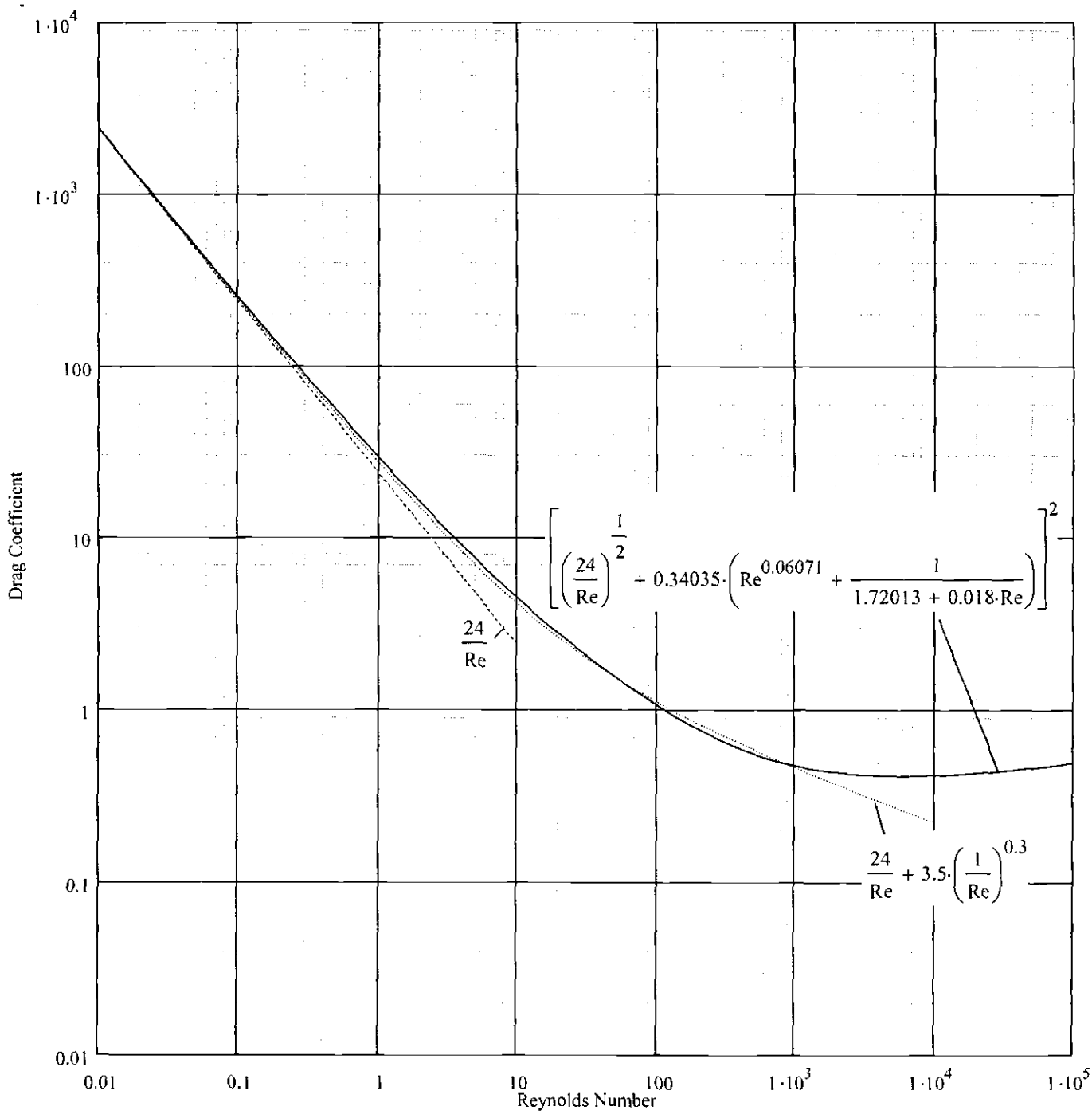

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Figure F-3. Hindering Settling Velocity Exponent as a Function of Particle Reynolds Number.

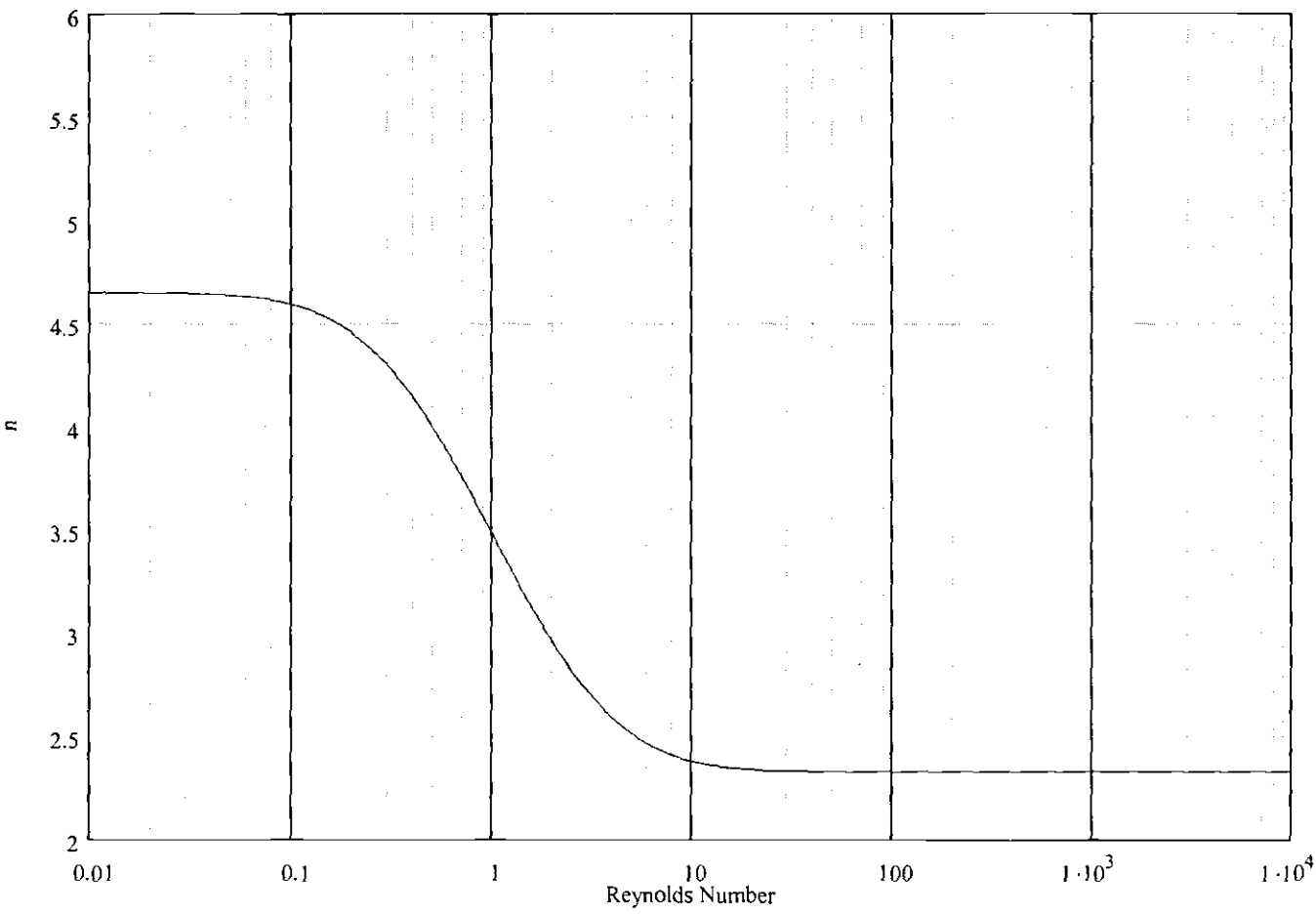

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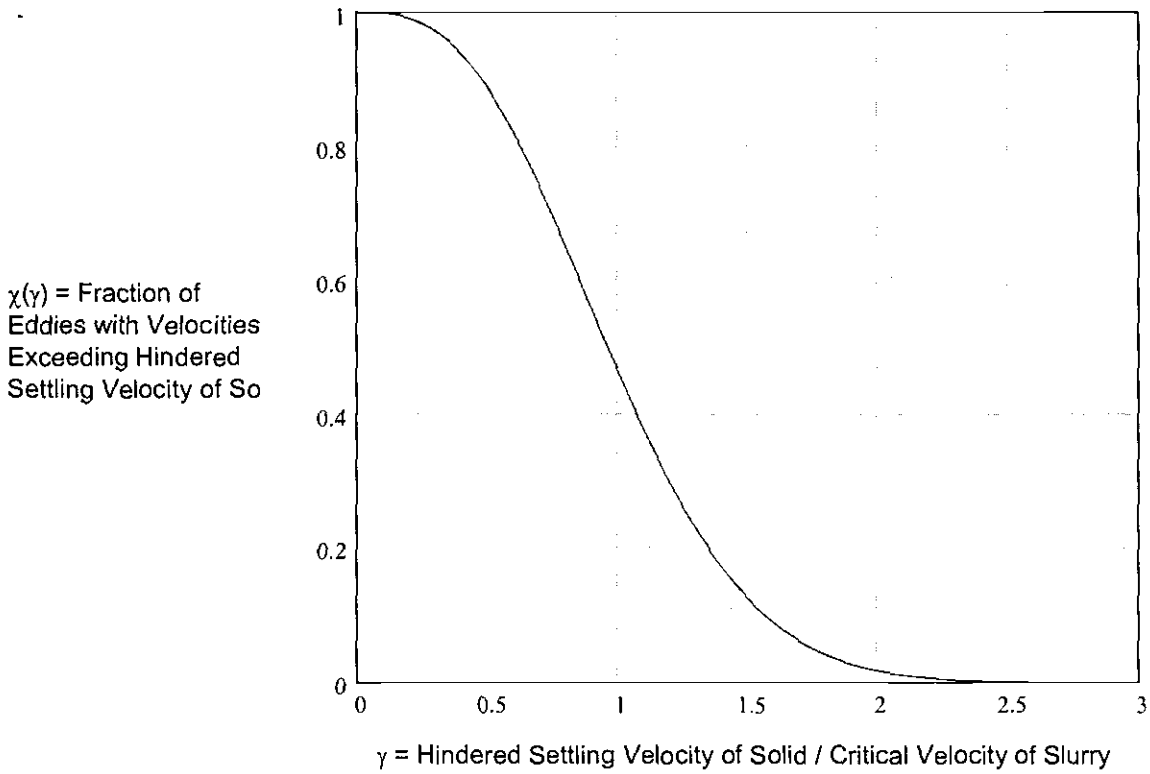
Figure F-4. Plot of χ(γ).



$D_{pipe} := 3.068 \cdot in$ $\quad d_{50} := 110 \cdot \mu m$ $\quad C_s := 10 \cdot vol\%$ $\quad x_{salt} := 0.9$ $\quad \kappa_{cv} := 1$

$N := 50 \quad i := 0..N \quad j := 0..N \quad \rho_{dLL} := 1.401 \cdot \frac{kg}{liter} \quad \rho_{dUL} := 4 \cdot \frac{kg}{liter} \quad \Delta\rho_d := \frac{\rho_{dUL} - \rho_{dLL}}{N} \quad \rho_{d_j} := \rho_{dLL} + \Delta\rho_d \cdot j$

$\rho_{cLL} := 1 \cdot \frac{kg}{liter} \quad \rho_{cUL} := 1.4 \cdot \frac{kg}{liter} \quad \Delta\rho_c := \frac{\rho_{cUL} - \rho_{cLL}}{N} \quad \rho'_{c_i} := \rho_{cLL} + \Delta\rho_c \cdot i$

$T := 80 \quad \mu'_{c_i} := \mu_{cL}(\rho'_{c_i}, T, x_{salt})$

$vt_{cr60_{i,j}} := v_{crOTt}(D_{pipe}, d_{50}, \rho_{d_j}, C_s, \rho'_{c_i}, \mu'_{c_i}, \kappa_{cv}) \quad ve_{cr60_{i,j}} := v_{crOTe}(D_{pipe}, d_{50}, \rho_{d_j}, C_s, \rho'_{c_i}, \mu'_{c_i}, \kappa_{cv})$

$T := 40 \quad \mu'_{c_i} := \mu_{cL}(\rho'_{c_i}, T, x_{salt})$

$vt_{cr10_{i,j}} := v_{crOTt}(D_{pipe}, d_{50}, \rho_{d_j}, C_s, \rho'_{c_i}, \mu'_{c_i}, \kappa_{cv}) \quad ve_{cr10_{i,j}} := v_{crOTe}(D_{pipe}, d_{50}, \rho_{d_j}, C_s, \rho'_{c_i}, \mu'_{c_i}, \kappa_{cv})$

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Figure F-5a. Contour Plot of Oroskar and Turian (1980) *Semi-Theoretical* Equation for the Critical Velocity (ft/s) vs. Particle Solids Density and Carrier Liquid Density - T=80°C (solid line), T=40°C (dash line).

Figure F-5b. Contour Plot of Oroskar and Turian (1980) *Empirical* Equation for the Critical Velocity (ft/s) vs. Particle Solids Density and Carrier Liquid Density - T=80°C (solid line), T=40°C (dash line).

D_{pipe} = 3.068 in d_{50} = 110 μm C_s = 10 vol% x_{salt} = 0.9 κ_{cv} = 1 (Best-estimate)

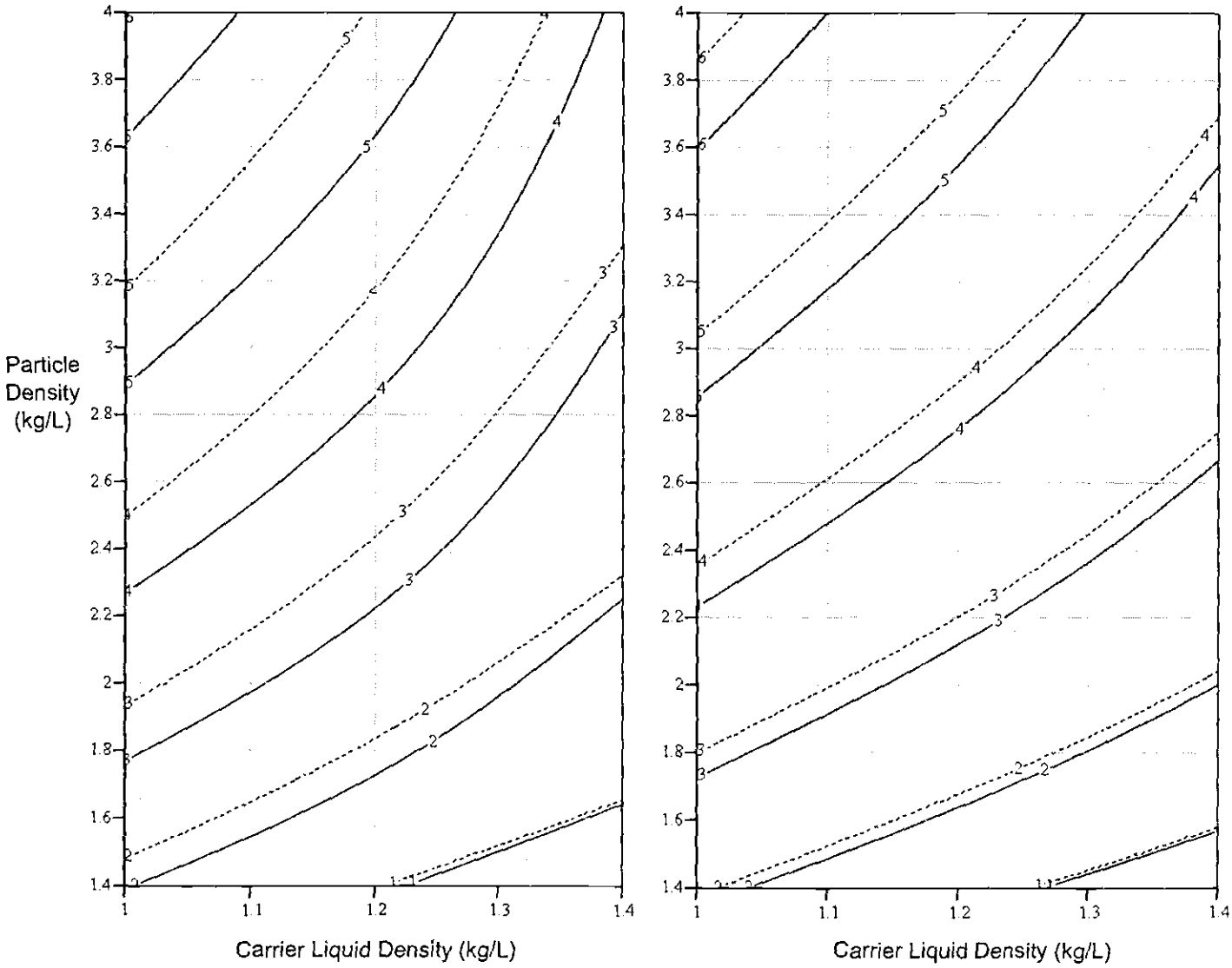

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Figure F-6a. Best-Estimate Critical Velocity Prediction vs. Carrier Liquid Density at Selected Volume Percent Solids - Oroskar and Turian (1980) *Empirical* Equation.

$T := 80$ °C $\beta_{cv} := 1.2$ $\kappa_{cv} := 1$ $D_{pipe} = 3.068\,in$ $x_{salt} = 0.9$ $d_{50} := 110 \cdot \mu m$ $\rho_s := 2.9 \cdot \frac{kg}{liter}$

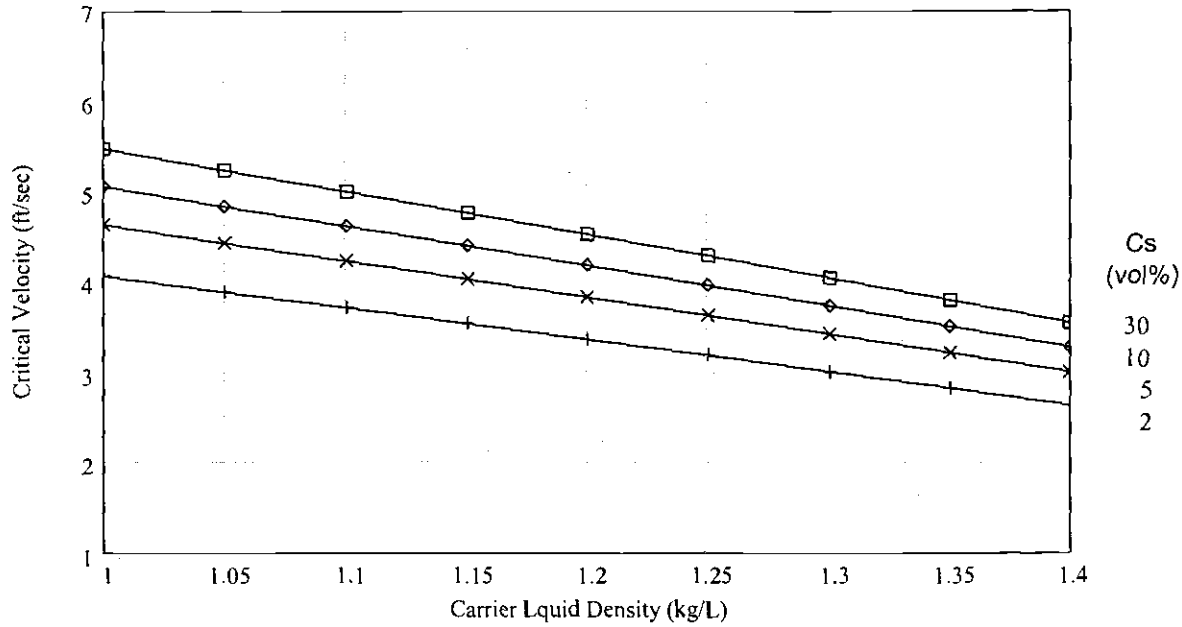

Figure F-6b. Best-Estimate Critical Velocity Prediction vs. Particle Solids Density at Selected Volume Percent Solids - Oroskar and Turian (1980) *Empirical* Equation.

$\rho_L := 1.1 \cdot \frac{kg}{liter}$

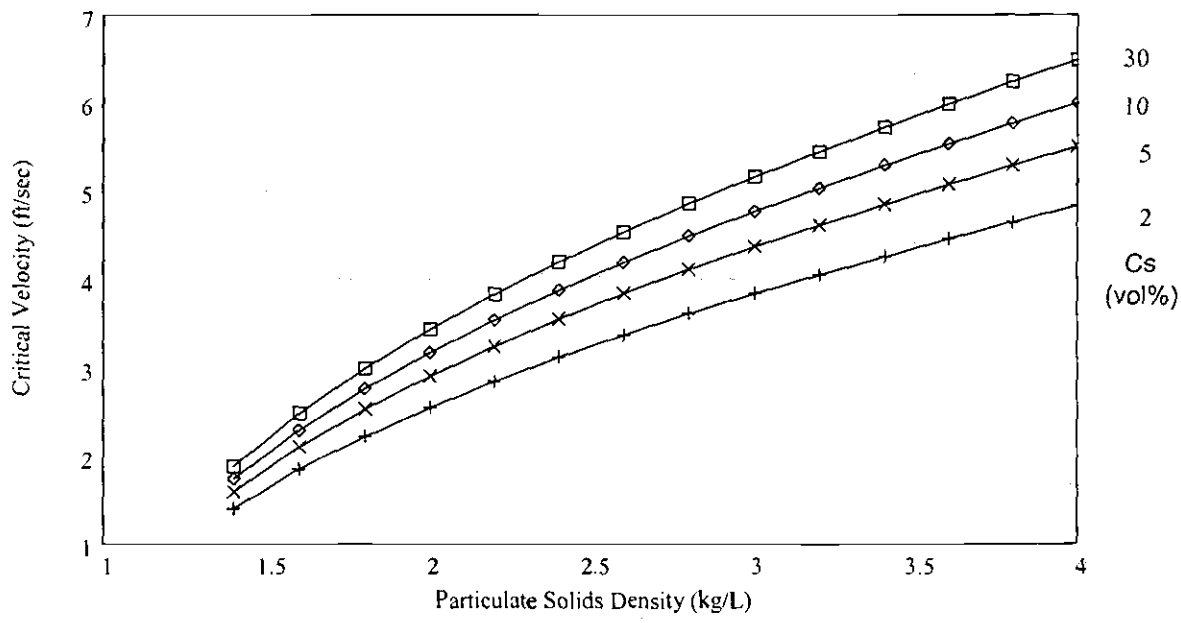

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Figure F-7a. Best-Estimate Critical Velocity Prediction vs. Carrier Liquid Density at Selected Volume Percent Solids - Oroskar and Turian (1980) *Empirical* Equation.

$T = 80\ ^{o}C$ $\beta_{cv} = 1.2$ $\kappa_{cv} = 1$ $D_{pipe} = 3.068\,in$ $x_{salt} = 0.9$ $d_{50} := 50 \cdot \mu m$ $\rho_s := 2.9 \cdot \frac{kg}{liter}$

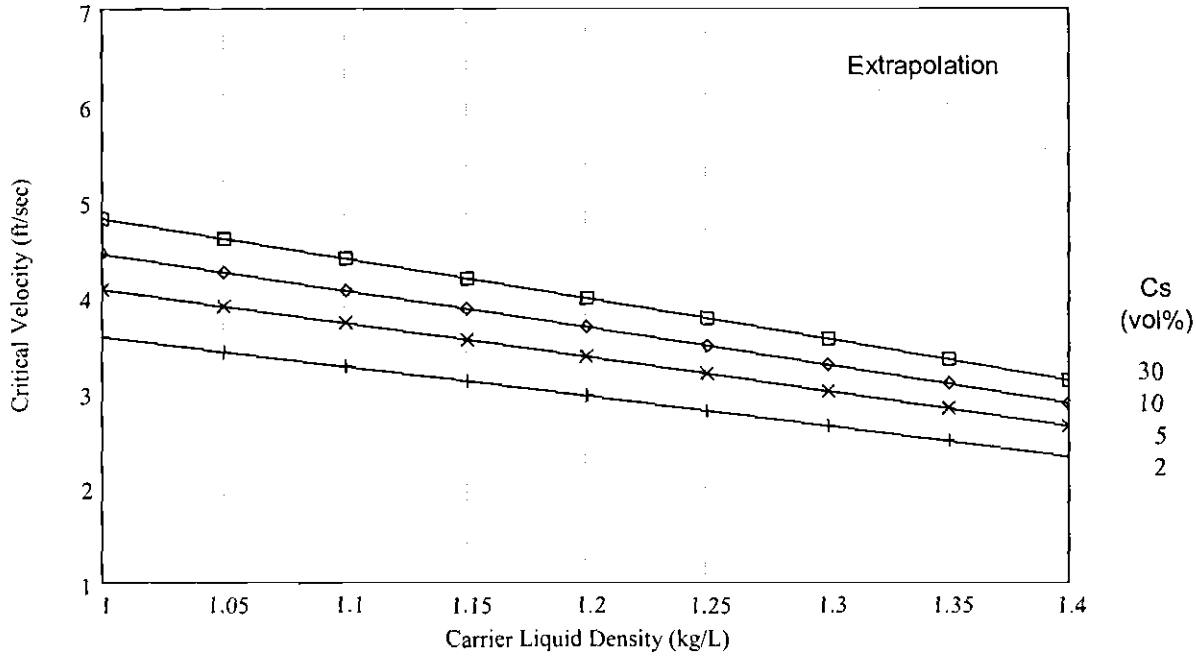

Figure F-7b. Best-Estimate Critical Velocity Prediction vs. Particle Solids Density at Selected Volume Percent Solids - Oroskar and Turian (1980) *Empirical* Equation.

$\rho_L := 1.1 \cdot \frac{kg}{liter}$

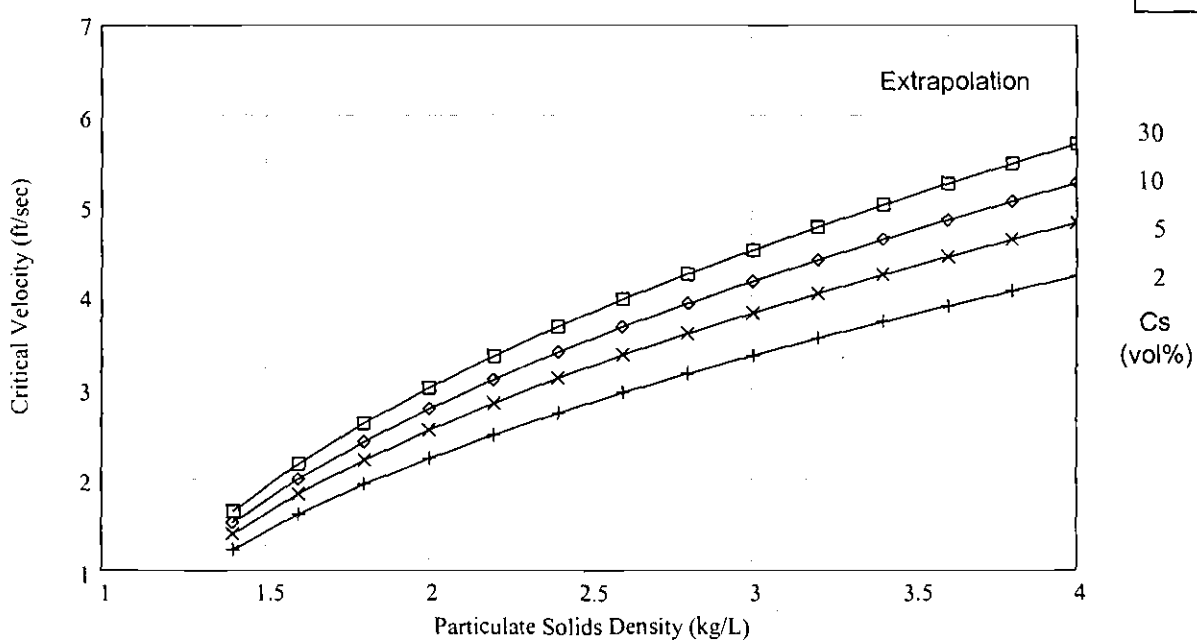

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Figure F-8a. Best-Estimate Critical Velocity Prediction vs. Carrier Liquid Density at Selected Volume Percent Solids - Oroskar and Turian (1980) *Empirical* Equation.

$T = 80\ ^{o}C$ $\beta_{cv} = 1.2$ $\kappa_{cv} = 1$ $D_{pipe} = 3.068\,in$ $x_{salt} = 0.9$ $d_{50} := 25 \cdot \mu m$ $\rho_s := 2.9 \cdot \frac{kg}{liter}$

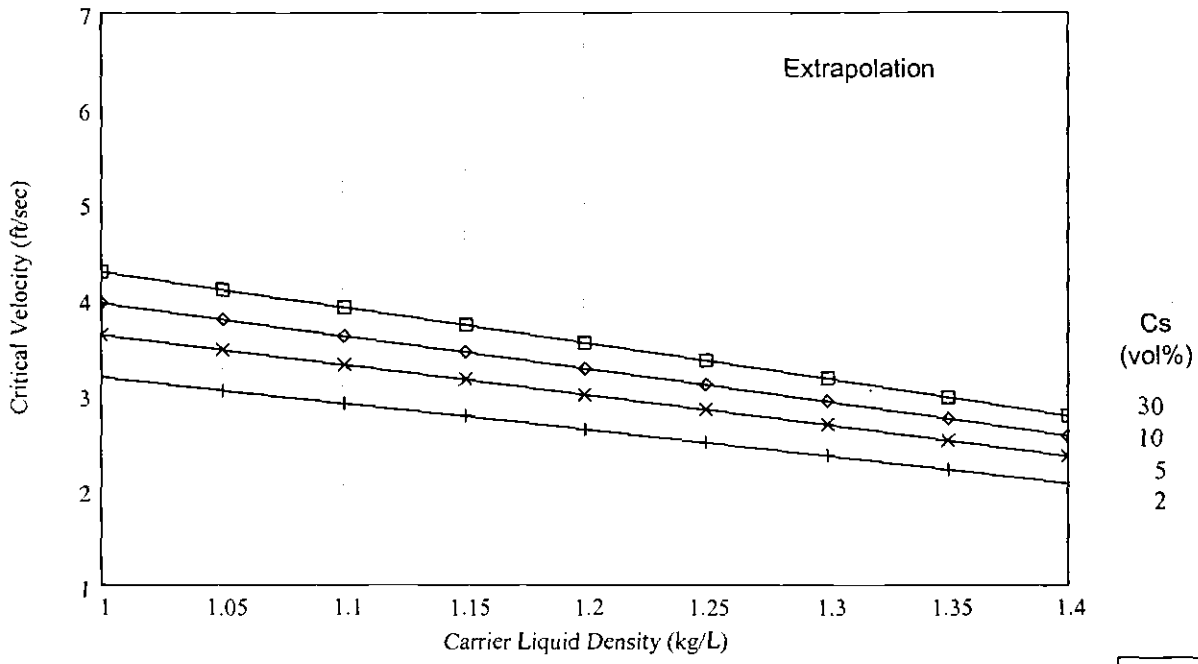

Figure F-8b. Best-Estimate Critical Velocity Prediction vs. Particle Solids Density at Selected Volume Percent Solids - Oroskar and Turian (1980) *Empirical* Equation.

$\rho_L := 1.1 \cdot \frac{kg}{liter}$

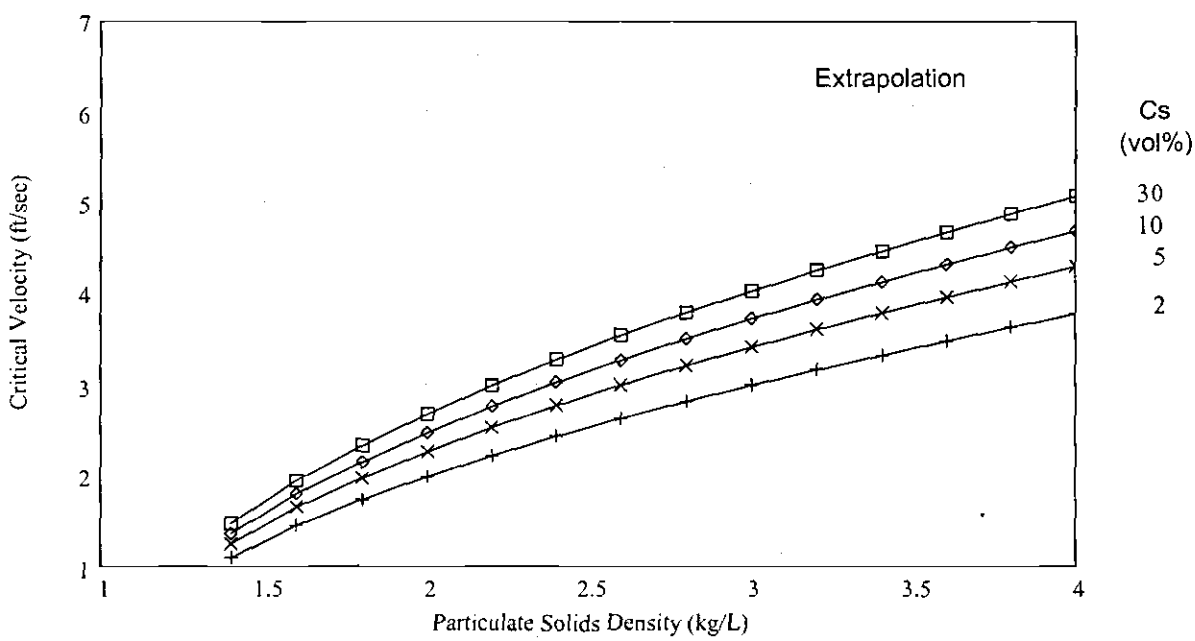

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Figure F=9a. Best-Estimate Critical Velocity Prediction vs. Particle Solids Median Diameter *at Selected Volume Percent Solids - Oroskar and Turian (1980) Empirical* Equation.

$T = 80$ °C $\beta_{cv} = 1.2$ $\kappa_{cv} = 1$ $D_{pipe} = 3.068$ in $x_{salt} = 0.9$ $\rho_L := 1.1 \cdot \frac{kg}{liter}$ $\rho_s := 2.9 \cdot \frac{kg}{liter}$

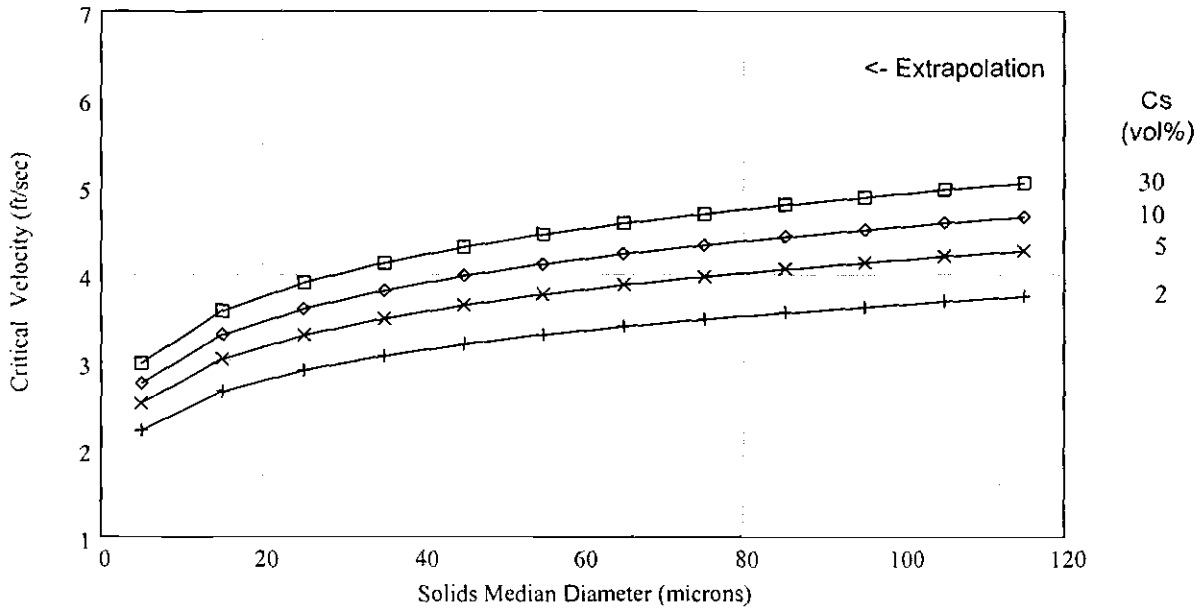

Figure F-9b. Best-Estimate Critical Velocity Prediction for 10-vol% Solids Concentration vs. Particle Solids Median Diameter at Selected Particle Solids Densities - Oroskar and Turian (1980) *Empirical* Equation.

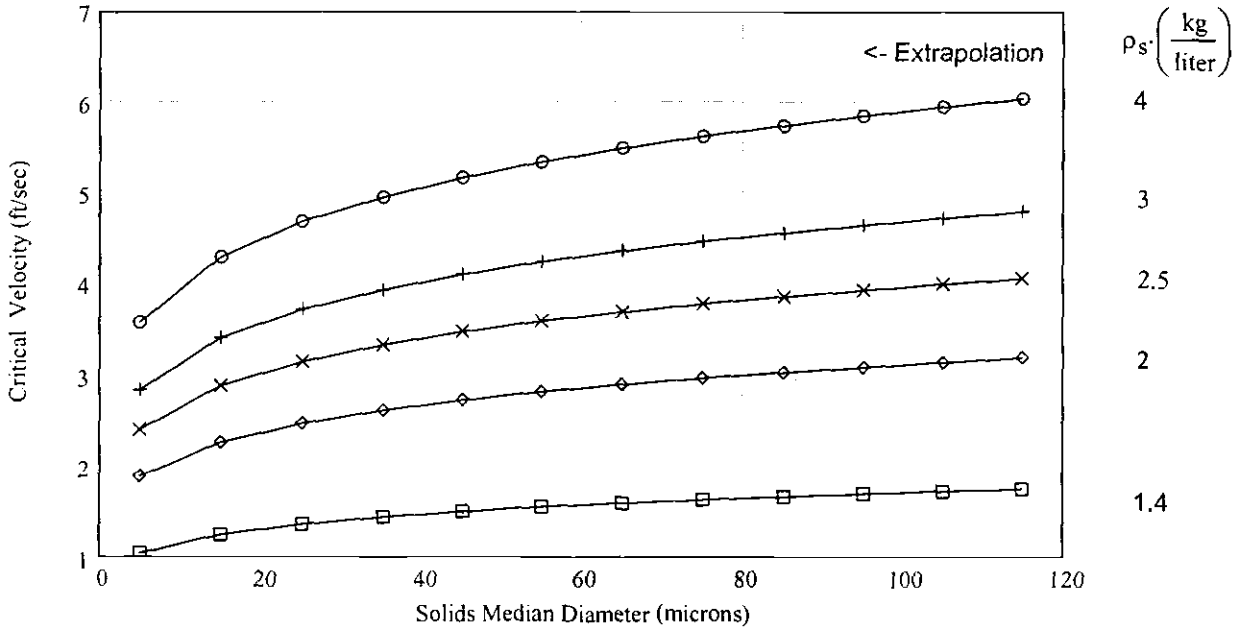

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Figure F-9c. Best-Estimate Critical Velocity Prediction for 5-vol% Solids Concentration vs. Particle Solids Median Diameter at Selected Particle Solids Densities - Oroskar and Turian (1980) *Empirical* Equation.

$T = 80$ °C $\beta_{cv} = 1.2$ $\kappa_{cv} = 1$ $D_{pipe} = 3.068\,in$ $x_{salt} = 0.9$ $\rho_L := 1.1 \cdot \frac{kg}{liter}$

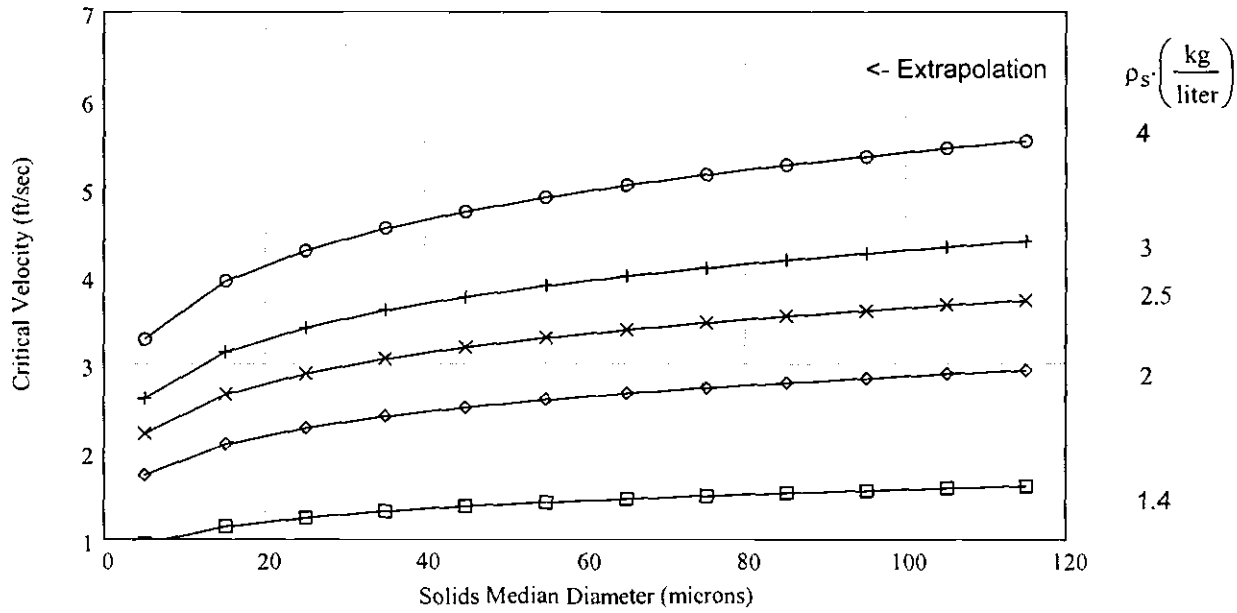

Figure F-9d. Best-Estimate Critical Velocity Prediction for 2-vol% Solids Concentration vs. Particle Solids Median Diameter at Selected Particle Solids Densities - Oroskar and Turian (1980) *Empirical* Equation.

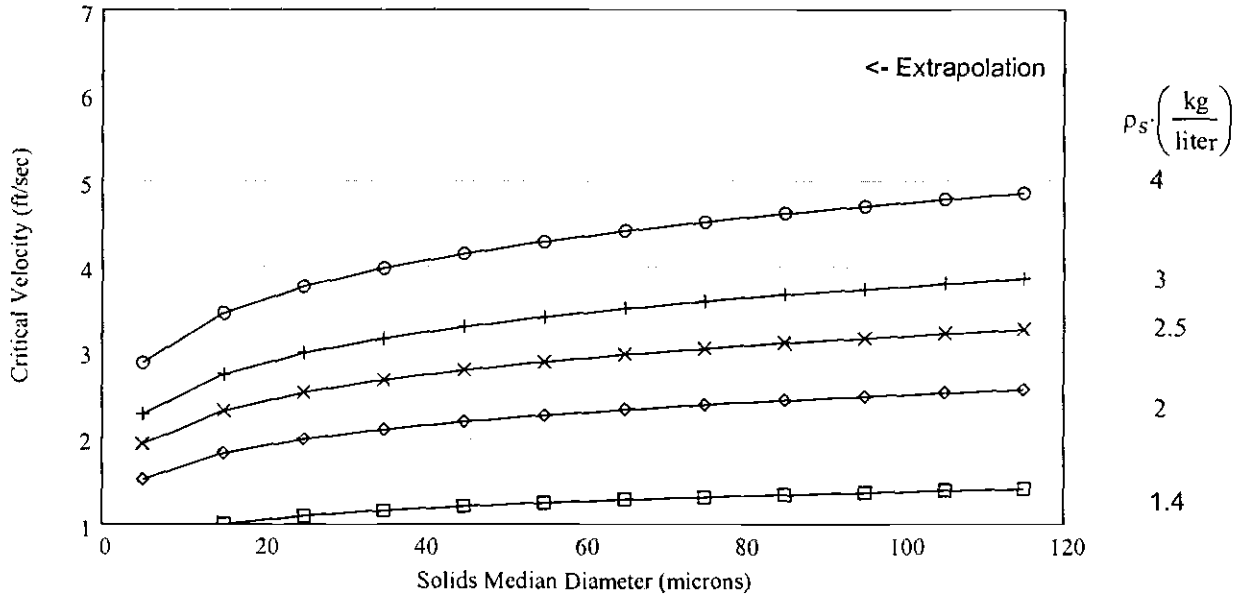

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Figure F-10a. Best-Estimate Critical Velocity Prediction vs. Carrier Liquid Density at Selected Volume Percent Solids - Oroskar and Turian (1980) *Empirical* Equation.

$T := 40$ °C $\beta_{cv} = 1.2$ $\kappa_{cv} = 1$ $D_{pipe} = 3.068$ in $x_{salt} = 0.9$ $\rho_s := 2.9 \cdot \frac{kg}{liter}$ $d_{50} := 110 \cdot \mu m$

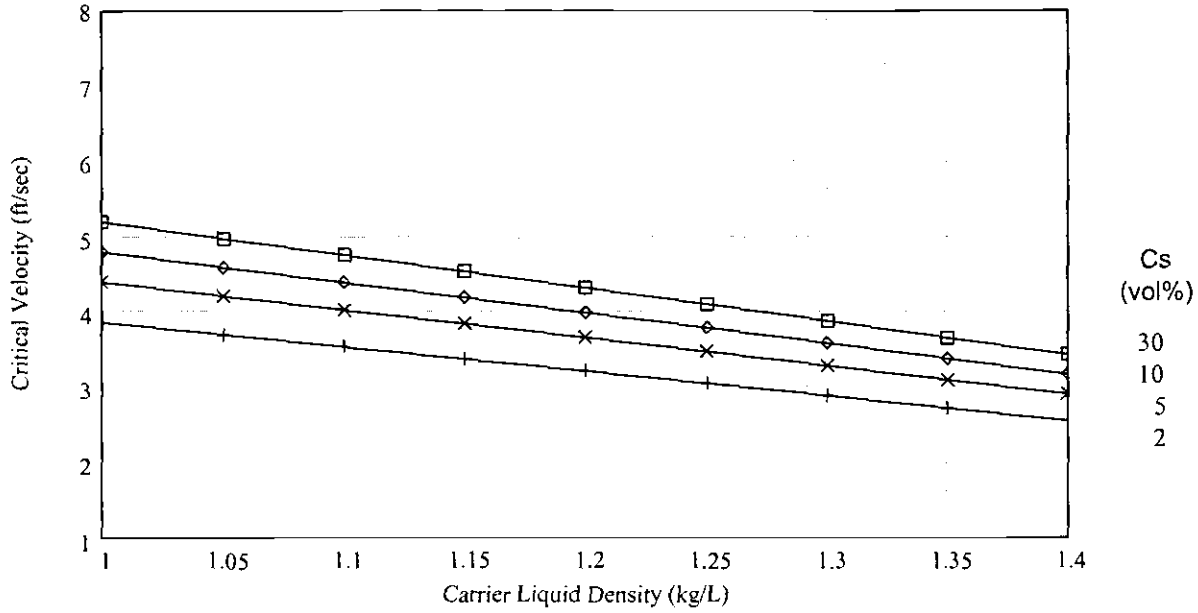

Figure 10b. Best-Estimate Critical Velocity Prediction vs. Carrier Liquid Density at Selected Volume Percent Solids - Oroskar and Turian (1980) *Empirical* Equation.

$d_{50} := 50 \cdot \mu m$

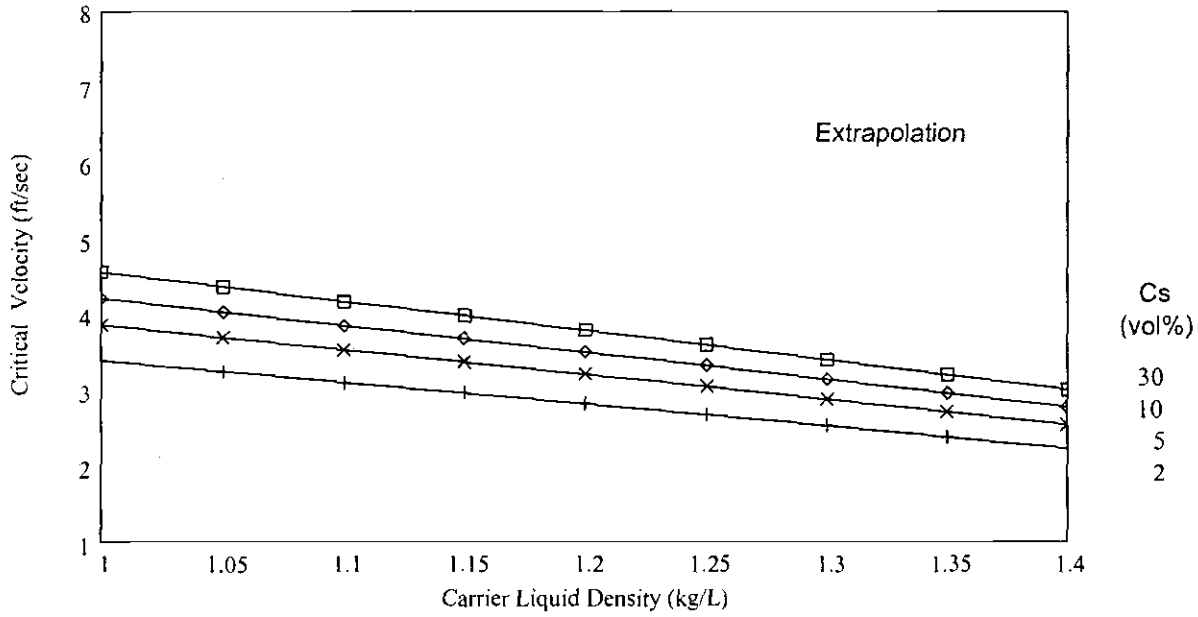

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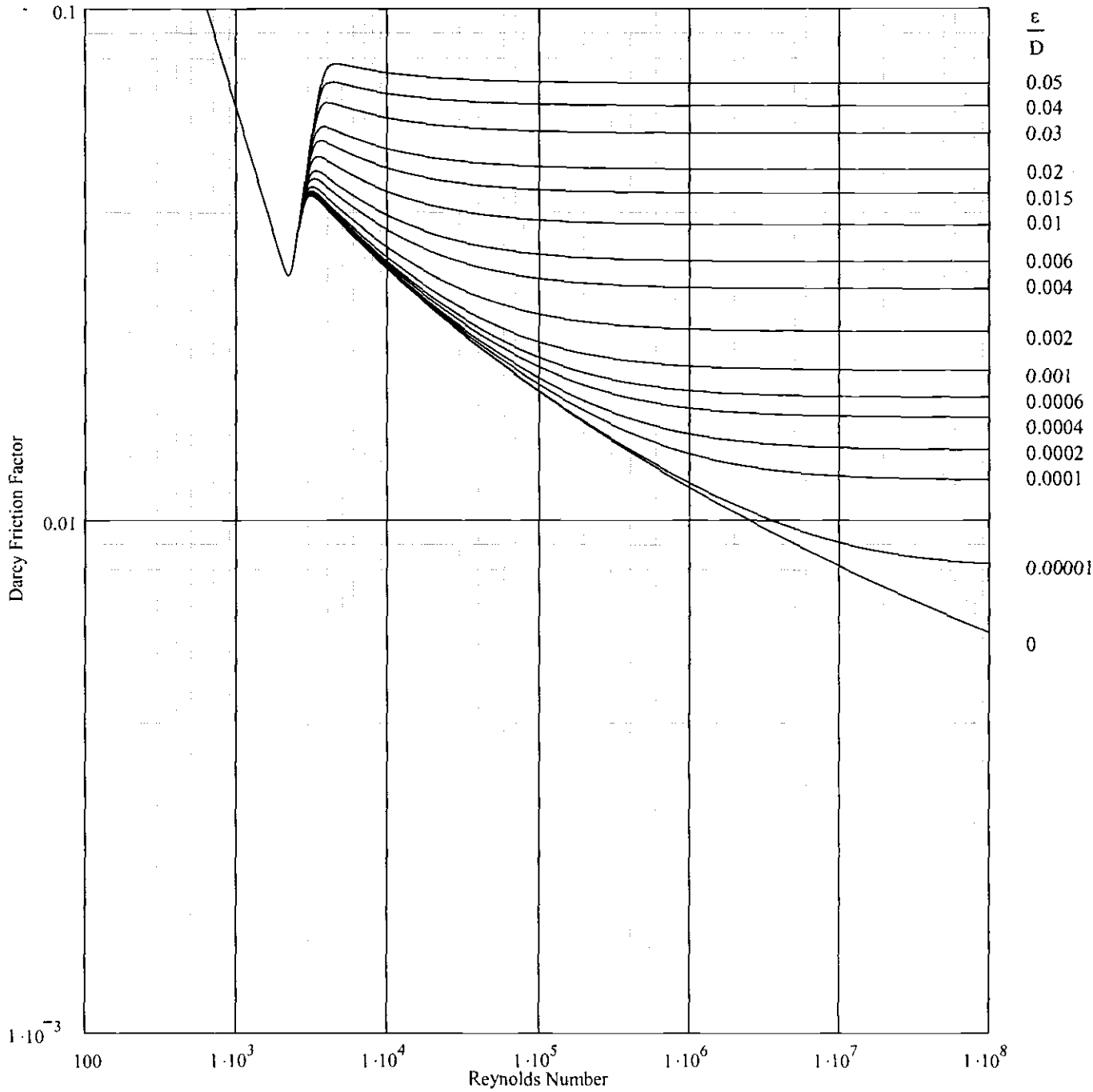
Figure F-11. Darcy Friction Factor vs. Reynolds Number and Relative Roughness.



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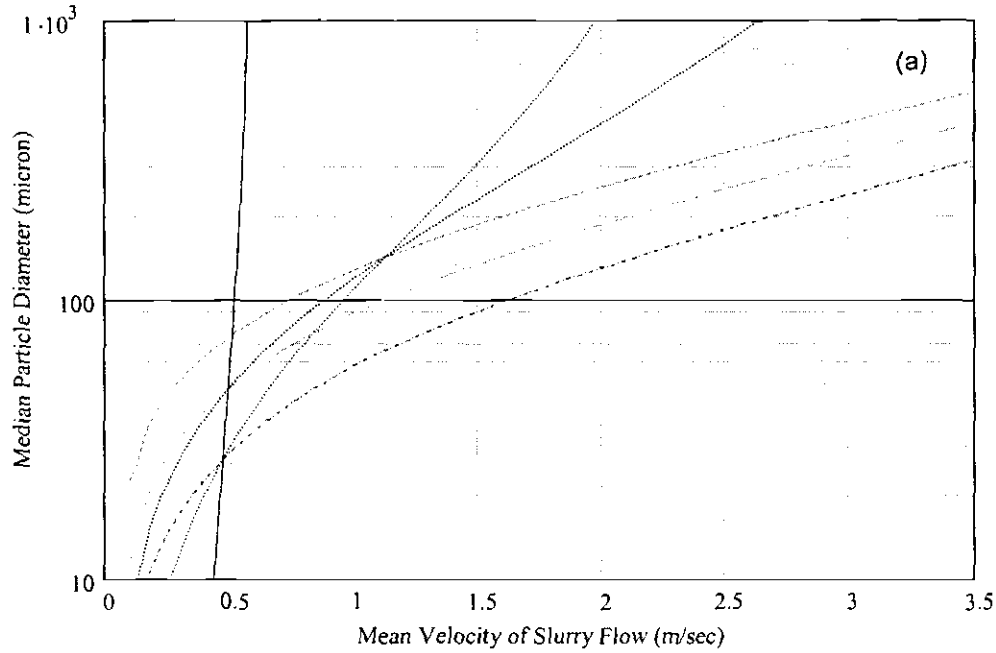
$T := 22.5\ ^{o}C$ $\rho_L := \rho_{water}(T)$ $\rho_L = 0.998\,kg \cdot liter^{-1}$ $\rho_s := 2.977 \cdot gm \cdot cm^{-3}$ $\theta := 0 \cdot deg$ $\beta_f := 1$

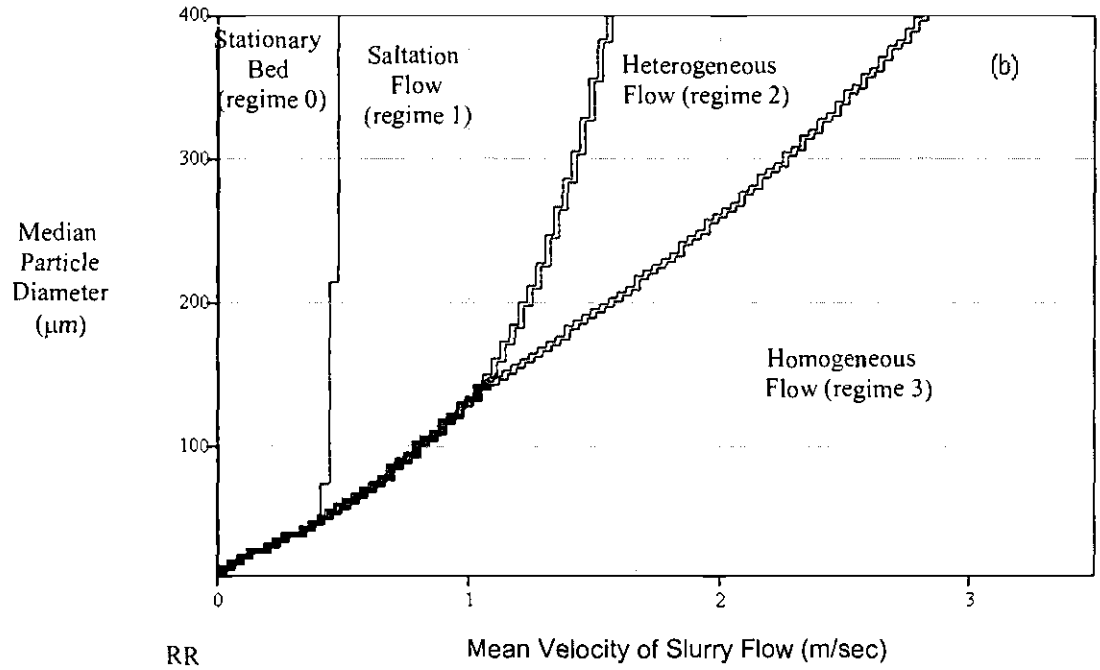
$\mu_L := \mu_{water}(T)$ $\mu_L = 0.944\,cP$ $C_s := 5 \cdot vol\%$ $\varepsilon := 0 \cdot \mu m$ $\kappa_f := 1$

Figure F-12. Flow Regime Diagram for 1/2-in. Pipe - Check Case.

$D_{pipe} := 1.58 \cdot cm$

$R_{01}=1$ $R_{12}=1$ $R_{13}=1$





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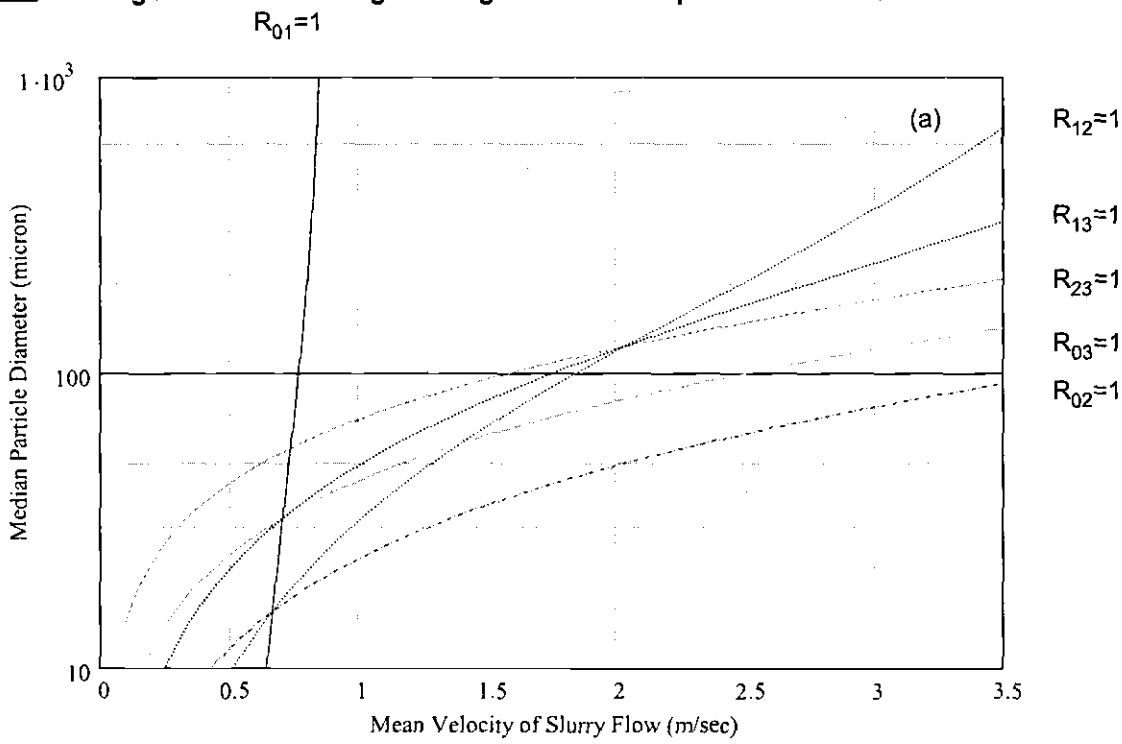
$D_{pipe} := 5.25 \cdot cm$

Figure F-13. Flow Regime Diagram for 2-in. Pipe - Check Case.



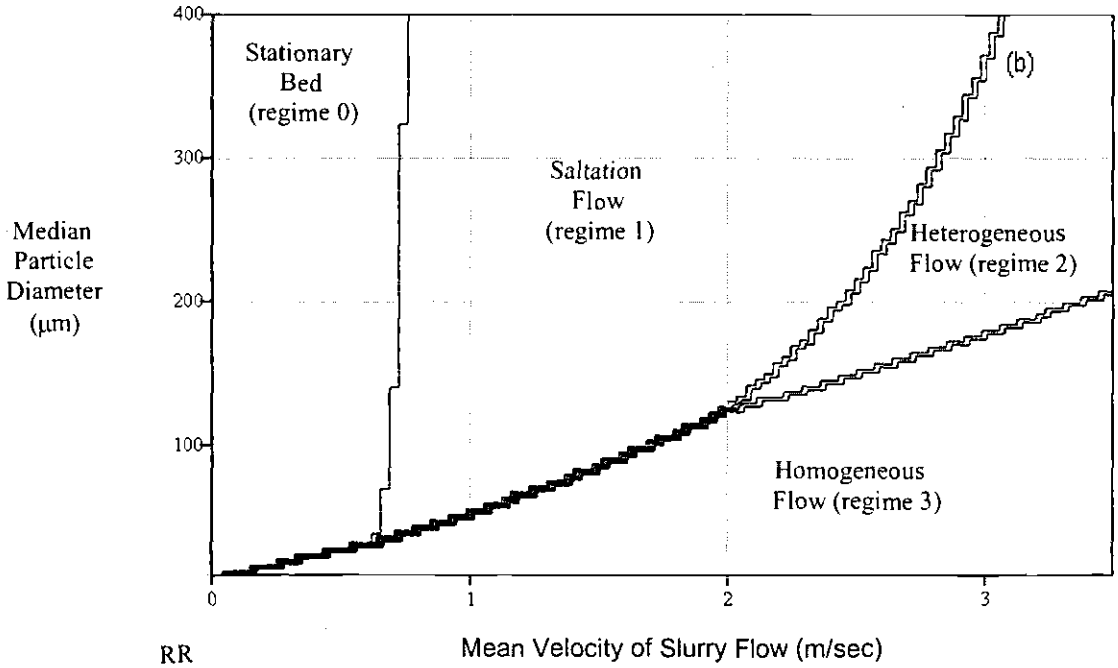


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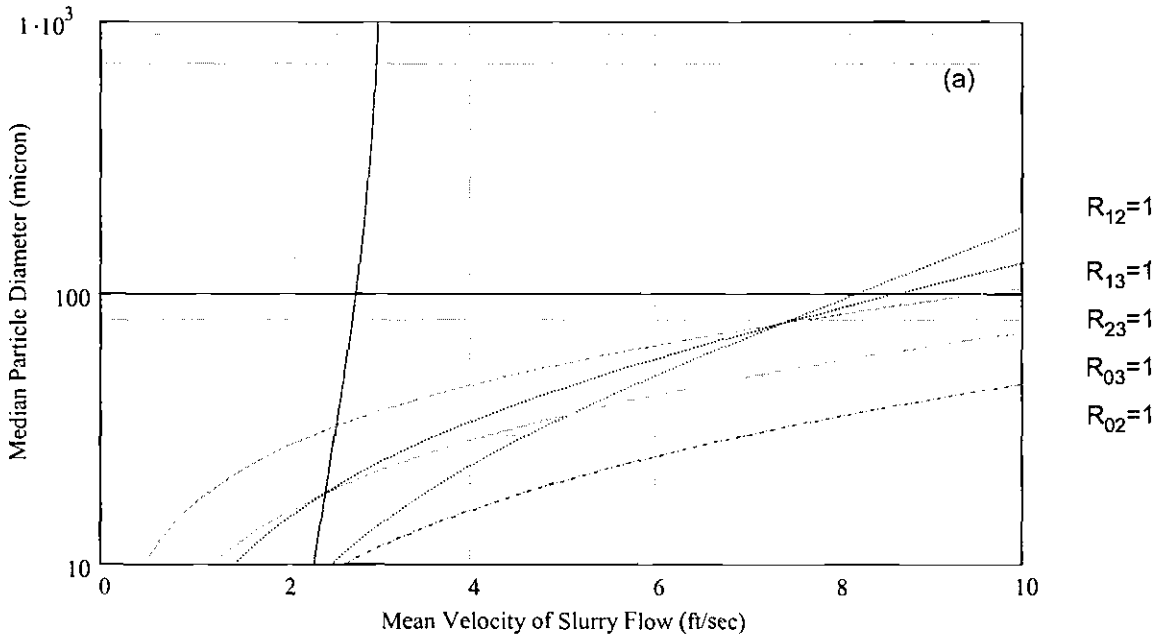
Figure F-14a. Flow Regime Diagram for 3-in. Pipe with 5-vol% Solids Concentration.

$T := 80\ ^{o}C$ $\rho_L := 1.1 \cdot \frac{kg}{liter}$ $x_{salt} = 0.9$ $\mu_L := \mu_{cL}(\rho_L, T, x_{salt})$ $\rho_s := 2.9 \cdot \frac{kg}{liter}$ $C_s := 5 \cdot vol\%$ $\varepsilon = 2\ mil$ $\beta_f := 1$

$D_{pipe} := 3.068 \cdot in$ $\mu_L = 0.455\ cP$ $\kappa_f := 1$



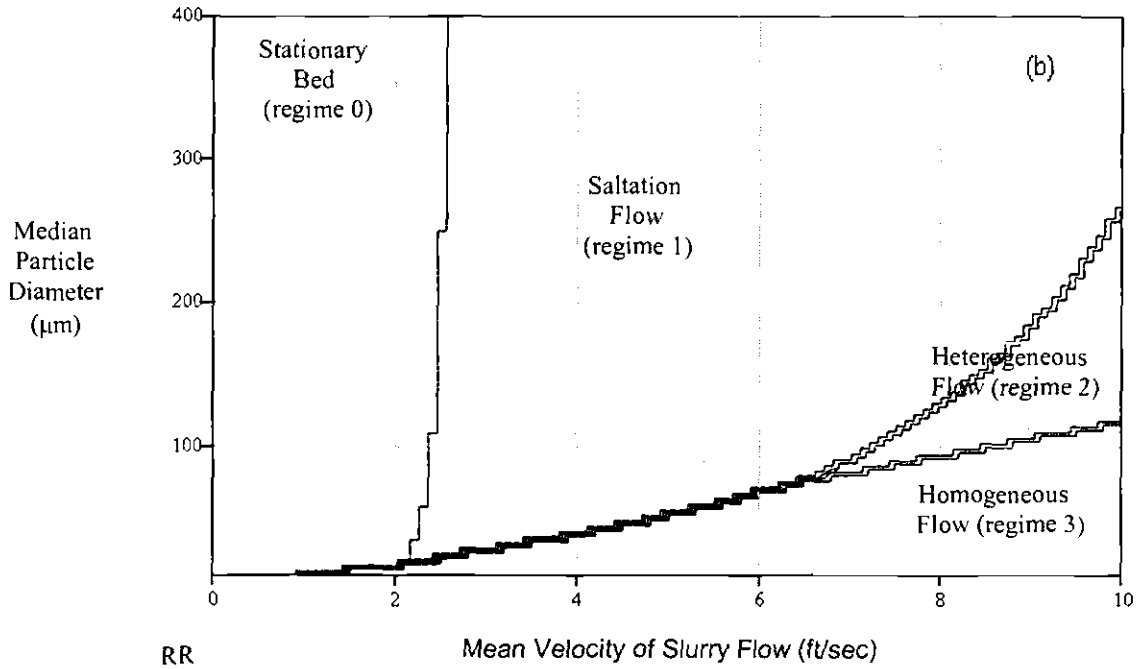


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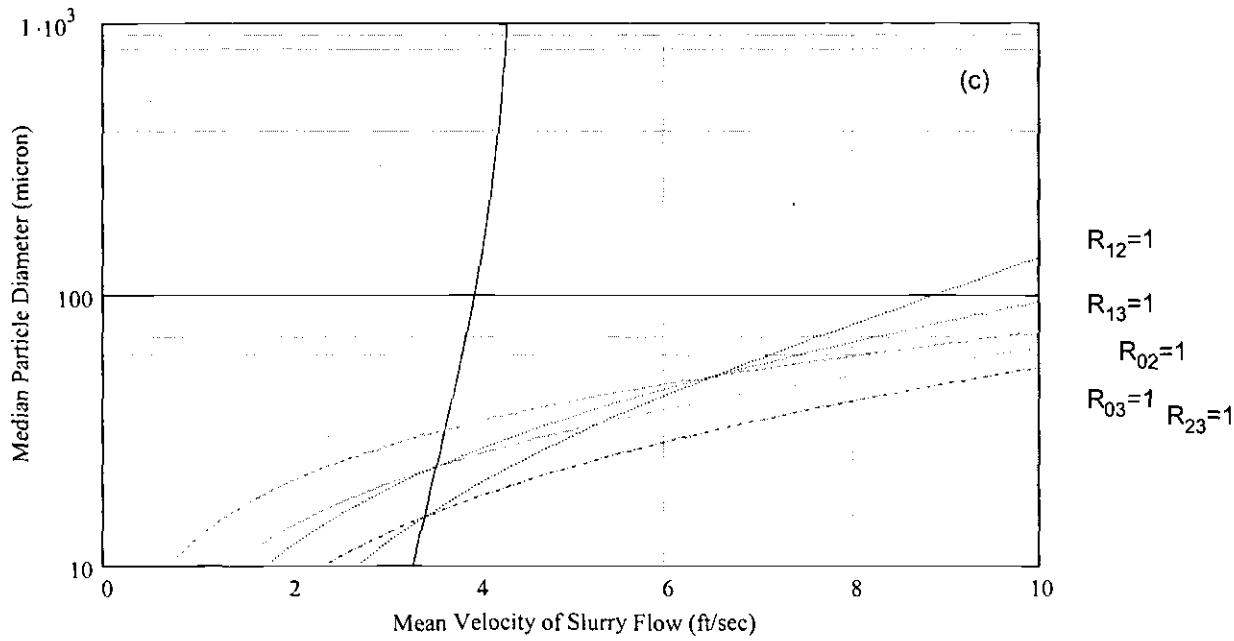
Figure F-14b. Flow Regime Diagram for 3-in. Pipe with 10-vol% Solids Concentration.

$T = 80\ ^{o}C$ $\rho_L = 1.1 \frac{kg}{liter}$ $\mu_L = 0.455\,cP$ $\rho_s = 2.9 \frac{kg}{liter}$ $C_s := 10\cdot vol\%$ $\varepsilon = 2\,mil$ $\beta_f = 1$

$D_{pipe} = 3.068\,in$ $\kappa_f = 1$



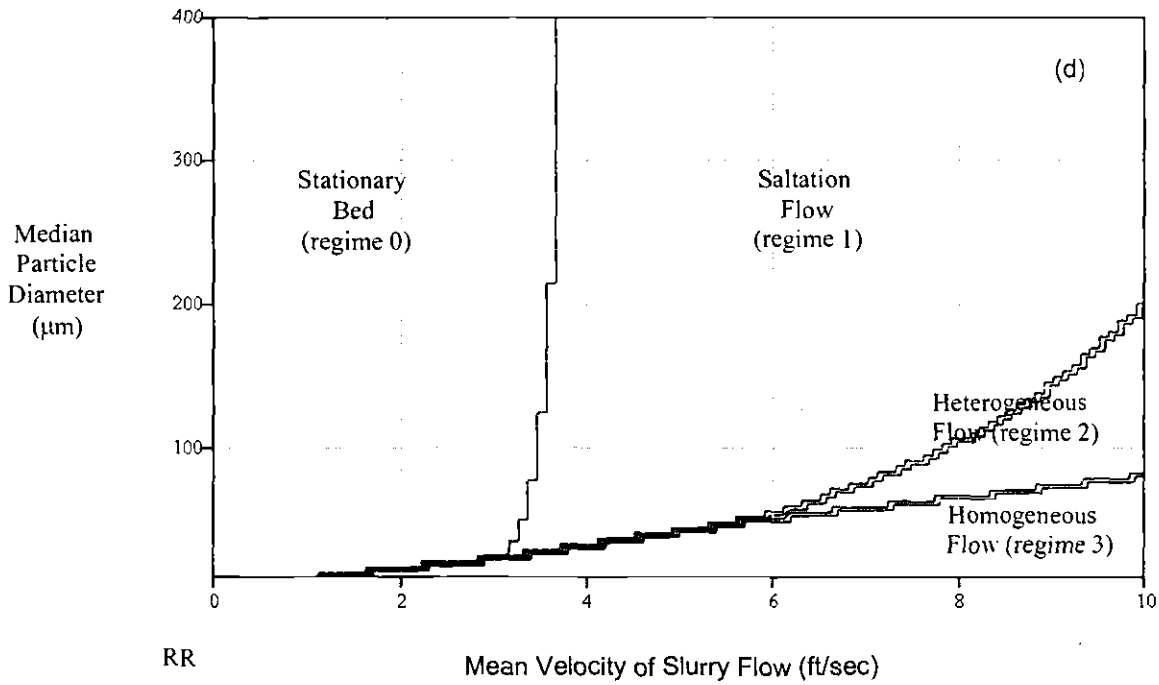


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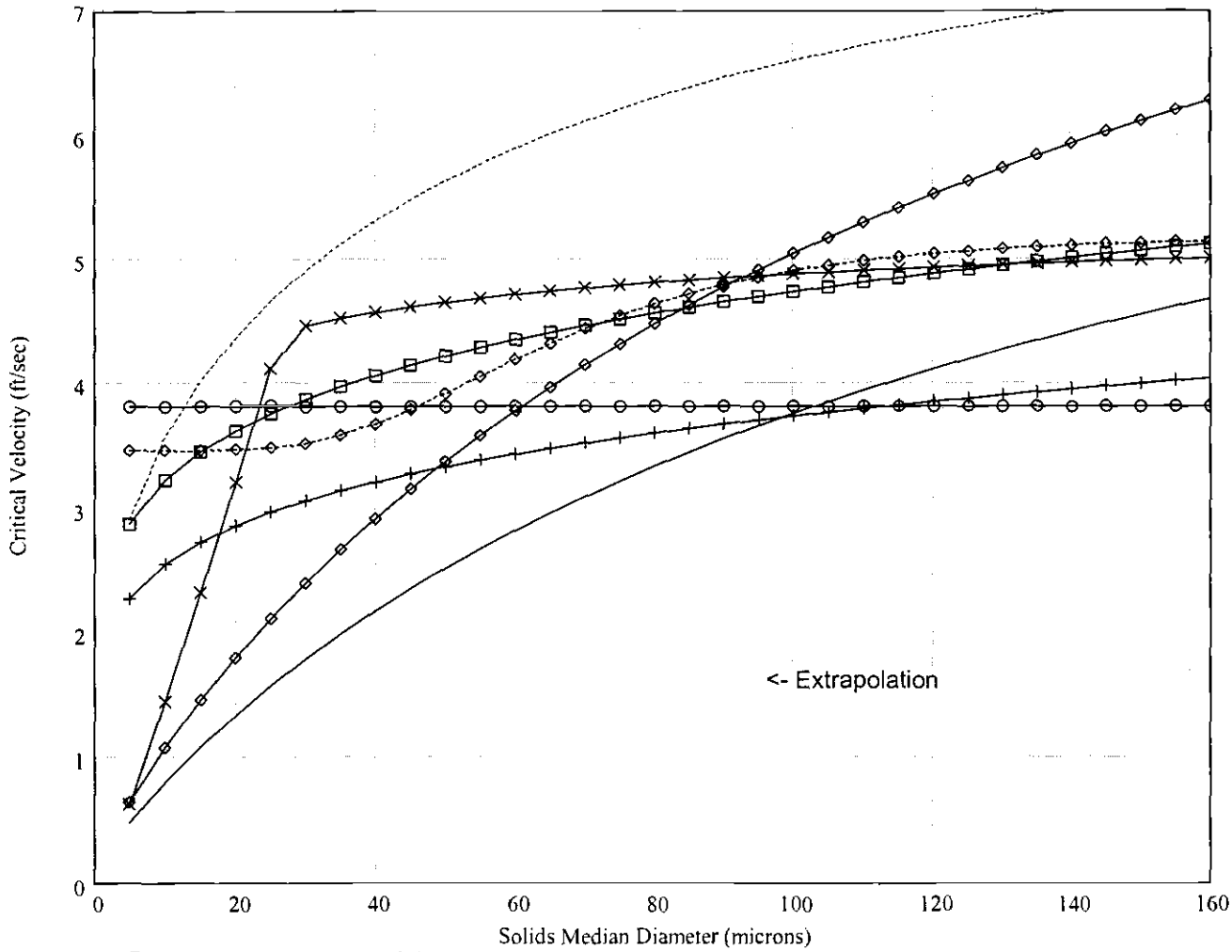
Figure F-15a. Comparison of Best-Estimate Critical Velocity Predictions with 15-vol% Solids Concentration vs. Particle Solids Median Diameter.

$T := 80\ ^{o}C \quad \kappa_{cv} = 1 \quad x_{salt} = 0.9$

$D_{pipe} := 3.068 \cdot in \quad \rho_L := 1.1 \cdot \frac{kg}{liter} \quad \mu_L := \mu_{cL}(\rho_L, T, x_{salt}) \quad \mu_L = 0.455\,cP \quad \rho_S := 2.9 \cdot \frac{kg}{liter} \quad \boxed{C_S := 15vol\%}$



Oroskar and Turian (1980) empirical
Oroskar and Turian (1980) semi-theoretical
Turian, Hsu, and Ma (1987) (based on regime transition)
Wasp et al. (1977)
Robinson and Graf (1972)
Zandi and Govatos (1967)
Shook (1969)
Gogus and Kokpinar (1999)

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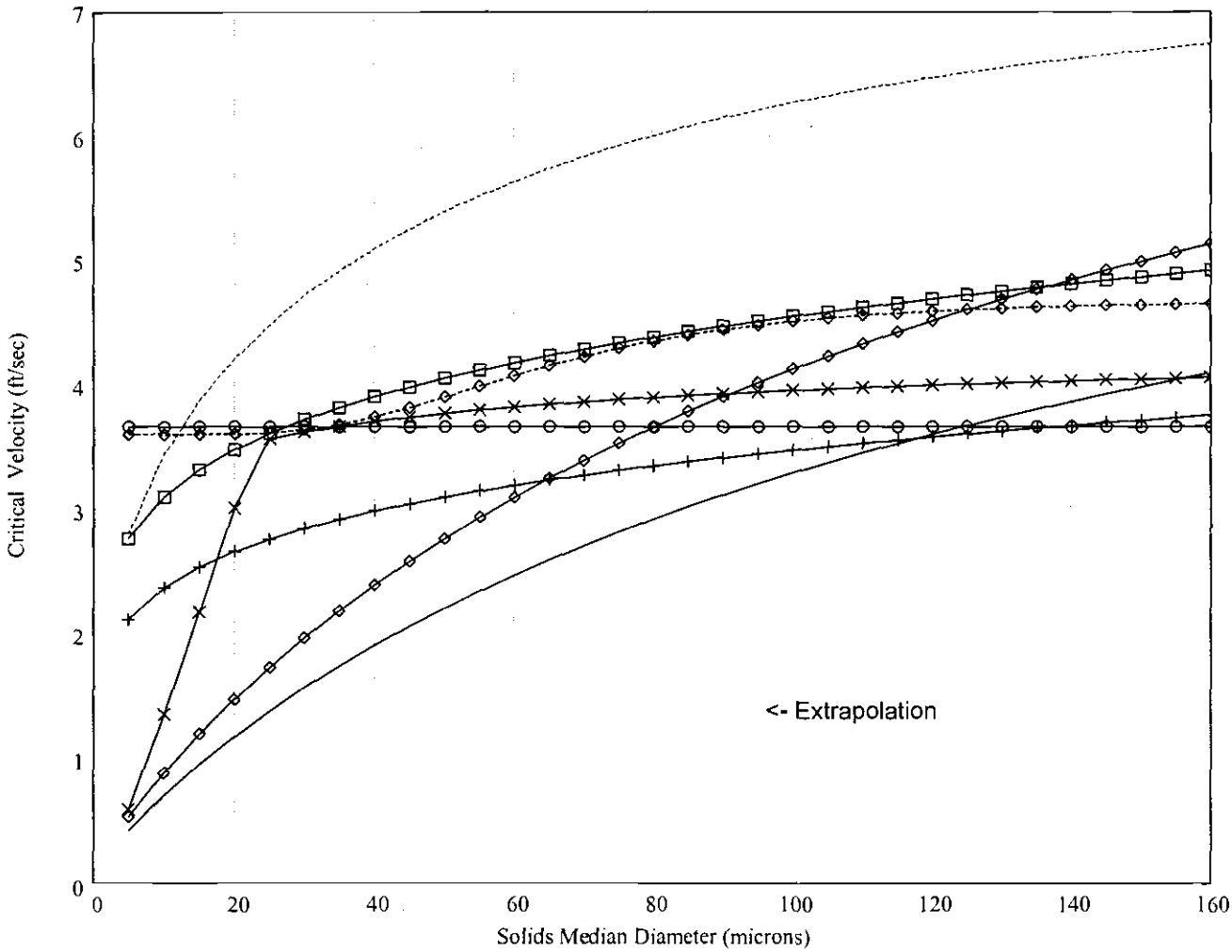
Figure F-15b. Comparison of Best-Estimate Critical Velocity Predictions with 10-vol% Solids Concentration vs. Particle Solids Median Diameter.

$T = 80\ ^{o}C$ $\kappa_{cv} = 1$ $x_{salt} = 0.9$

$D_{pipe} = 3.068\,in$ $\rho_L = 1.1\,\frac{kg}{liter}$ $\mu_L = 0.455\,cP$ $\rho_s = 2.9\,\frac{kg}{liter}$ $C_s := 10 \cdot vol\%$



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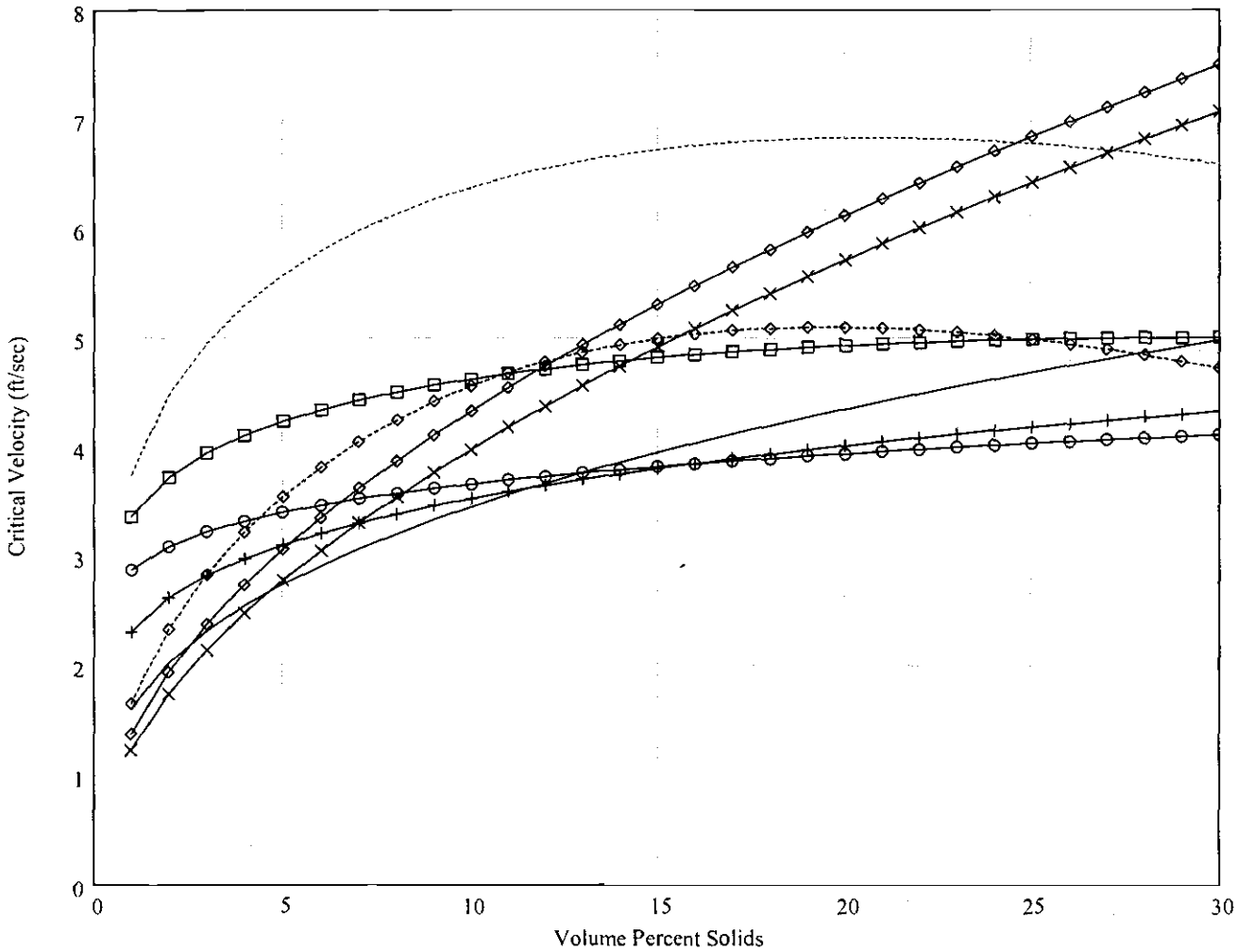
Subject: Critical Velocity and Pressure Drop Study in Support of Waste Tank Feed Transfer System
Date: 02/25/2002 By: L. J. Julyk
Checked: By: S.D. Estey
Location: 200 Area - Hanford Site, Richland, Washington
Revised: By:

Figure F-15c. Comparison of Best-Estimate Critical Velocity Predictions vs. Volume Percent Solids.

$T = 80\ ^{o}C$ $\kappa_{cv} = 1$ $D_{pipe} = 3.068\,in$ $\rho_L = 1.1\,\frac{kg}{liter}$ $\mu_L = 0.455\,cP$ $\rho_s = 2.9\,\frac{kg}{liter}$ $d_{50} := 110 \cdot \mu m$



Oroskar and Turian (1980) empirical
Oroskar and Turian (1980) semi-theoretical
Turian, Hsu, and Ma (1987) (based on regime transition)
Wasp et al. (1977)
Robinson and Graf (1972)
Zandi and Govatos (1967)
Shook (1969)
Gogus and Kokpinar (1999)

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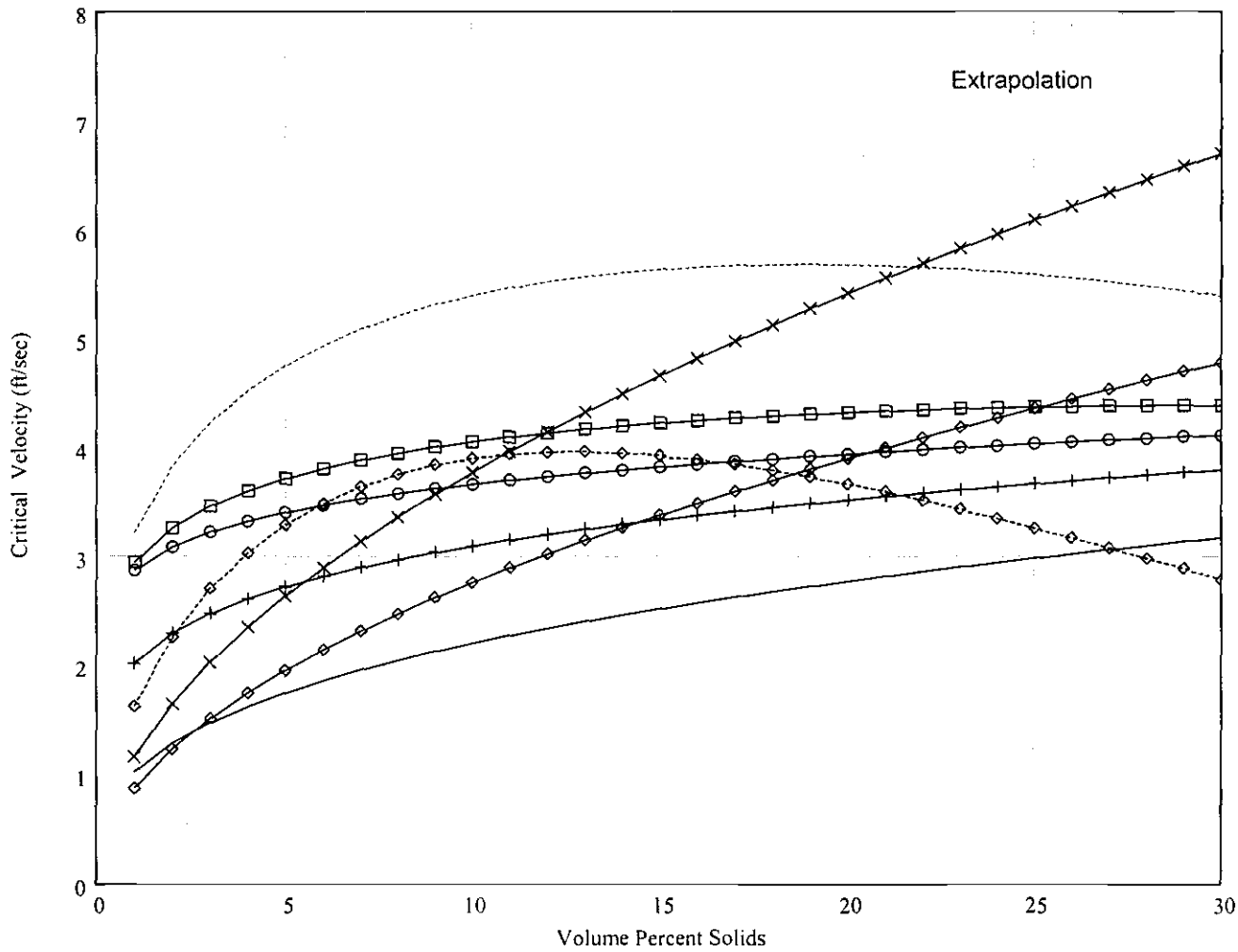
Checked: By: S.D. Estey
Revised: By:

Figure F-15d. Comparison of Best-Estimate Critical Velocity Predictions vs. Solid Particle Volume Fraction.

$T = 80\ ^{o}C$ $\kappa_{cv} = 1$ $D_{pipe} = 3.068\,in$ $\rho_L = 1.1\,\frac{kg}{liter}$ $\mu_L = 0.455\,cP$ $\rho_s = 2.9\,\frac{kg}{liter}$ $d_{50} := 50 \cdot \mu m$

$x_{salt} = 0.9$



- Oroskar and Turian (1980) empirical
- Oroskar and Turian (1980) semi-theoretical
- Turian, Hsu, and Ma (1987) (based on regime transition)
- Wasp et al. (1977)
- Robinson and Graf (1972)
- Zandi and Govatos (1967)
- Shook (1969)
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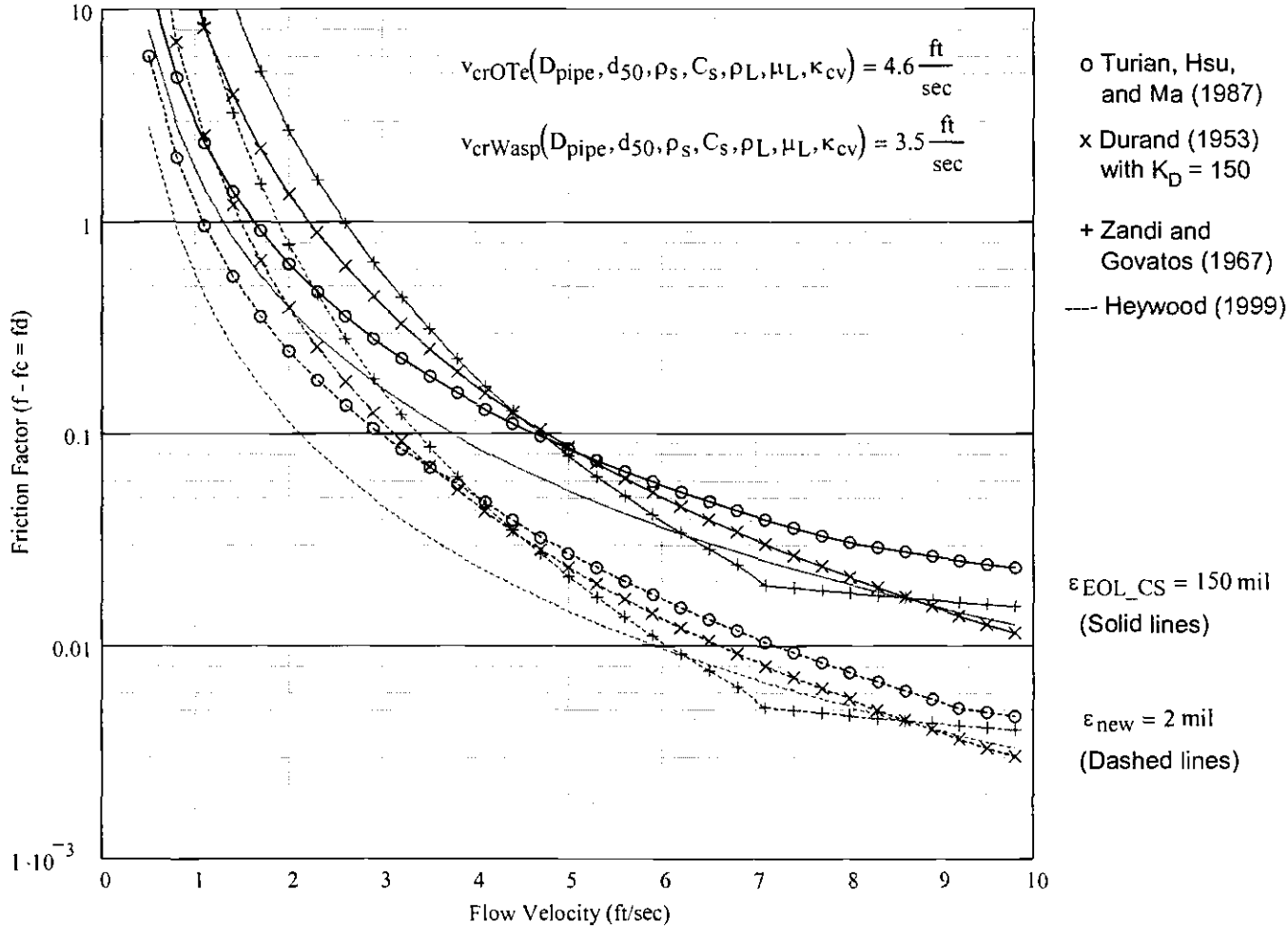
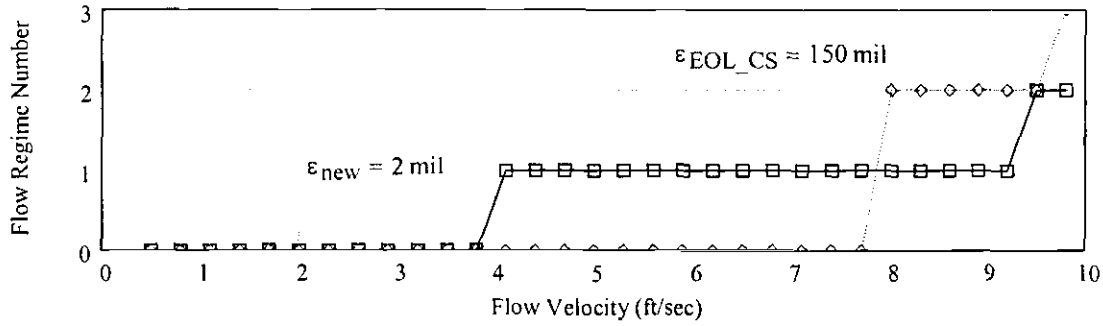
Figure F-16. Δ Friction Factor ($f_d = f - f_c$) Comparison.

$T = 80\ ^{\circ}C$ $D_{pipe} = 3.068\,in$ $\rho_L := 1.1 \cdot \frac{kg}{liter}$ $d_{50} := 110 \cdot \mu m$ $\rho_s := 2.9 \cdot \frac{kg}{liter}$ $\theta := 0 \cdot deg$ $\kappa_f := 1$

$\mu_L := \mu_{cL}(\rho_L, T, x_{salt})$ $\mu_L = 0.455\,cP$ $C_s := 10 \cdot \%$ $x_{salt} = 0.9$ $\kappa_{cv} := 1$





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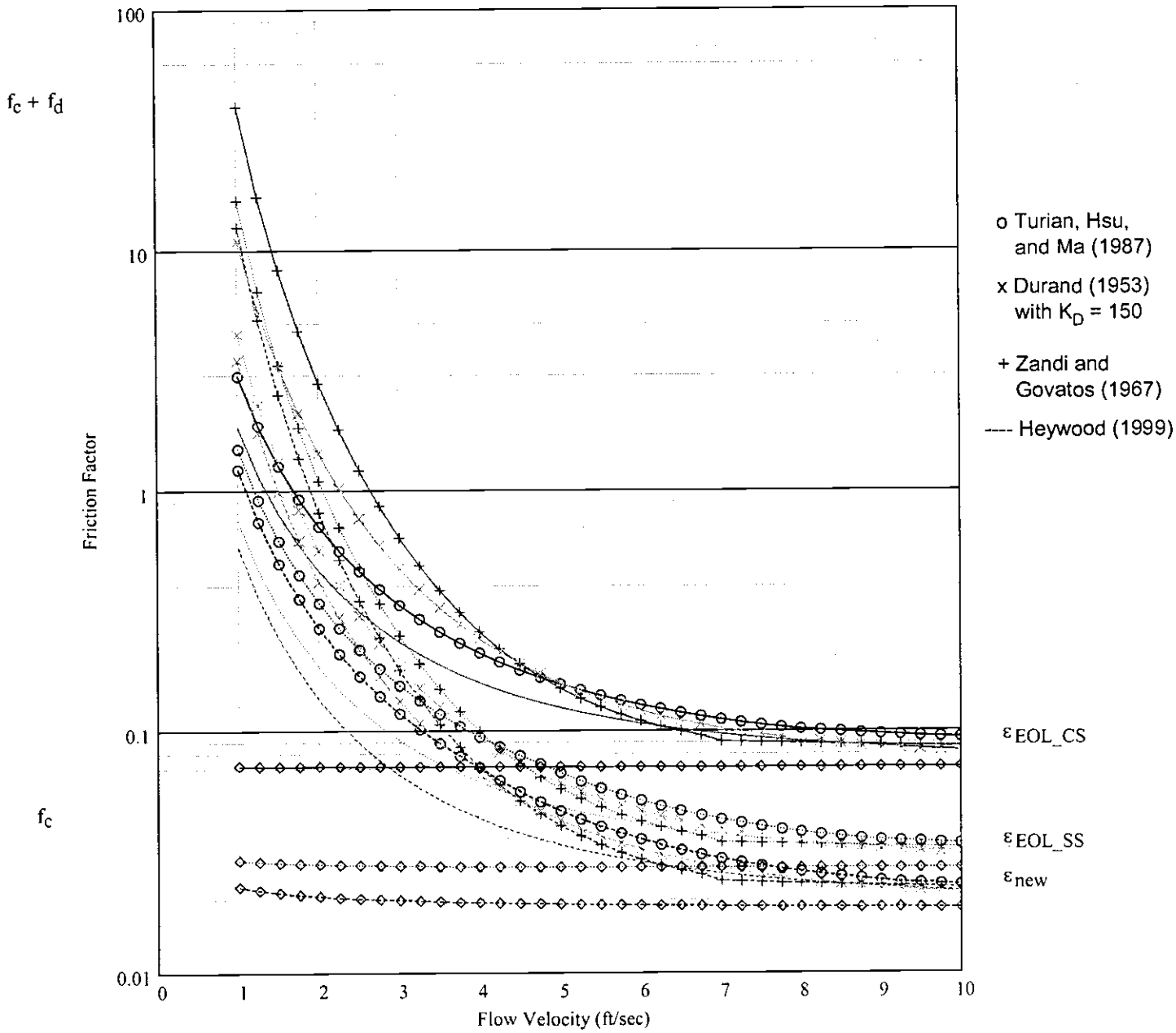
Revised: By:

Figure 17. Friction Factor vs. Carrier Liquid Flow Velocity Comparison.

$T = 80\ ^{\circ}C$ $D_{pipe} = 3.068\,in$ $\rho_L = 1.1\,\frac{kg}{liter}$ $d_{50} = 110\,\mu m$ $x_{salt} = 0.9$ $\kappa_{cv} := 1$

$\mu_L = 0.455\,cP$ $C_s = 10\,vol\%$ $\rho_s := 2.9\cdot\frac{kg}{liter}$ $\theta = 0\,deg$ $\kappa_f := 1$



f_c, non-slurry liquid without particles, $\alpha_d = 0$

$f_c + f_d$, slurry with particles

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Checked: By: S.D. Estey
Revised: By:

$\kappa_f := 1 \quad \beta_f := 1 \quad T = 80\ ^{\circ}C \quad \boxed{d_{50} := 110 \cdot \mu m} \quad \boxed{C_s := 10 \cdot \%} \quad D_{pipe} := 3.068 \cdot in \quad L := 1000 \cdot ft \quad \theta := 0 \cdot deg \quad \boxed{v := 6 \cdot \frac{ft}{sec}}$

$x_{salt} = 0.9$

$\Delta pCS_{i,j} := \Delta p\left(D_{pipe}, v, \rho'_{c_i}, \mu'_{c_i}, \varepsilon_{EOL\_CS}, d_{50}, \rho_{d_j}, C_s, L, \beta_f, \kappa_f, \theta\right)$

$\Delta pSS_{i,j} := \Delta p\left(D_{pipe}, v, \rho'_{c_i}, \mu'_{c_i}, \varepsilon_{EOL\_SS}, d_{50}, \rho_{d_j}, C_s, L, \beta_f, \kappa_f, \theta\right)$

$RCS_{i,j} := R_d\left(D_{pipe}, v, \rho'_{c_i}, \mu'_{c_i}, \varepsilon_{EOL\_CS}, d_{50}, \rho_{d_j}, C_s, 1\right)$

$RSS_{i,j} := R_d\left(D_{pipe}, v, \rho'_{c_i}, \mu'_{c_i}, \varepsilon_{EOL\_SS}, d_{50}, \rho_{d_j}, C_s, 1\right)$

Figure 18a. Contour Plot of Best-Estimate Pressure Drop (psi) per 1000 ft of Pipe at Specified Flow Velocity (6 ft/s) (CS solid line, SS dashed line) vs.Particle Solids Density and Carrier Liquid Density - (Turian, Hsu, and Ma 1987)

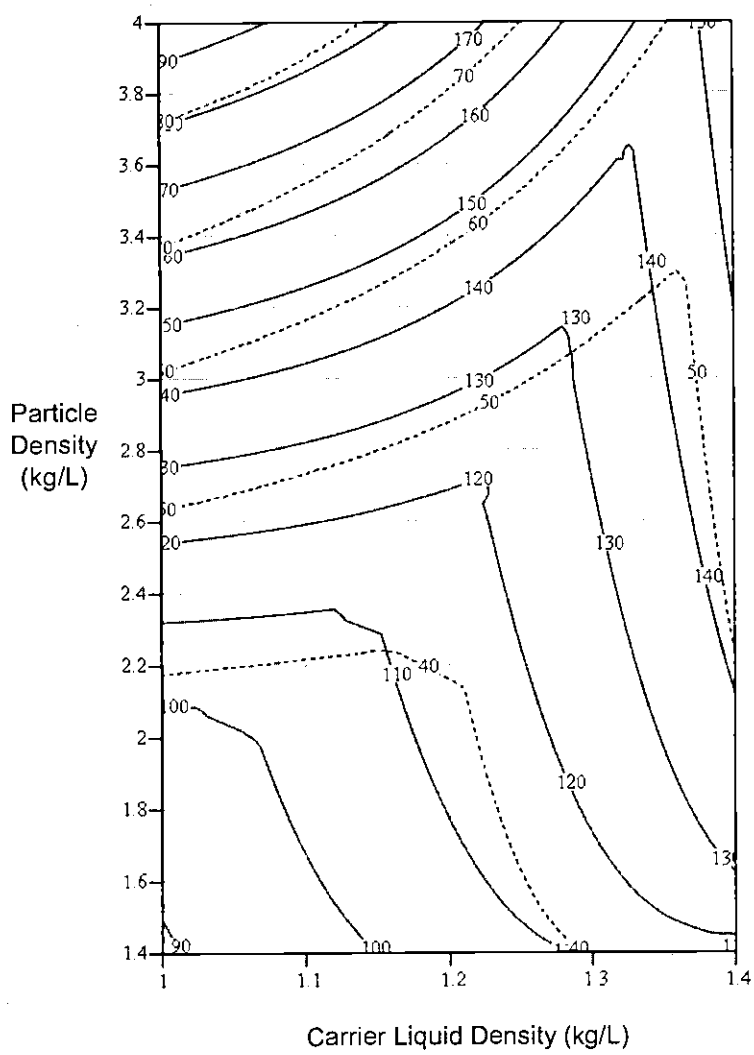
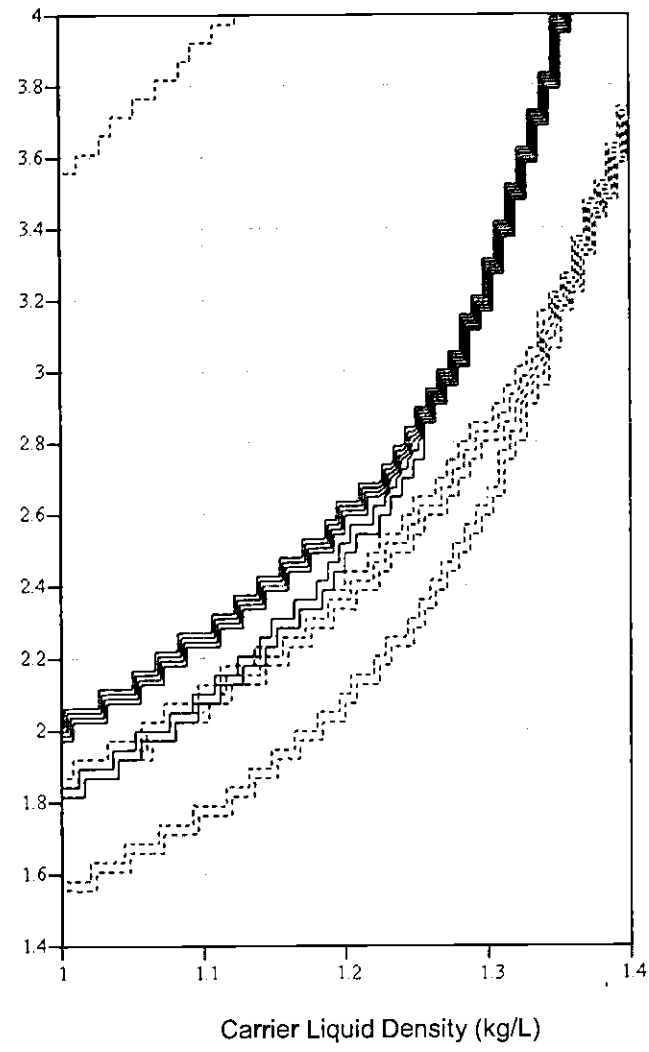


Figure 18b. Corresponding Flow Regime Contour Plot.

$RCS_{0,N} = 0 \quad RSS_{0,N} = 0 \quad RCS_{N,N} = 3 \quad RSS_{N,N} = 1$

$RCS_{0,0} = 3 \quad RSS_{0,0} = 3 \quad RCS_{N,0} = 3 \quad RSS_{N,0} = 3$



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WO/Job No. 500689/BA10
Date: 02/25/2002 By: L. J. Julyk
Checked: By: S.D. Estey
Revised: By:

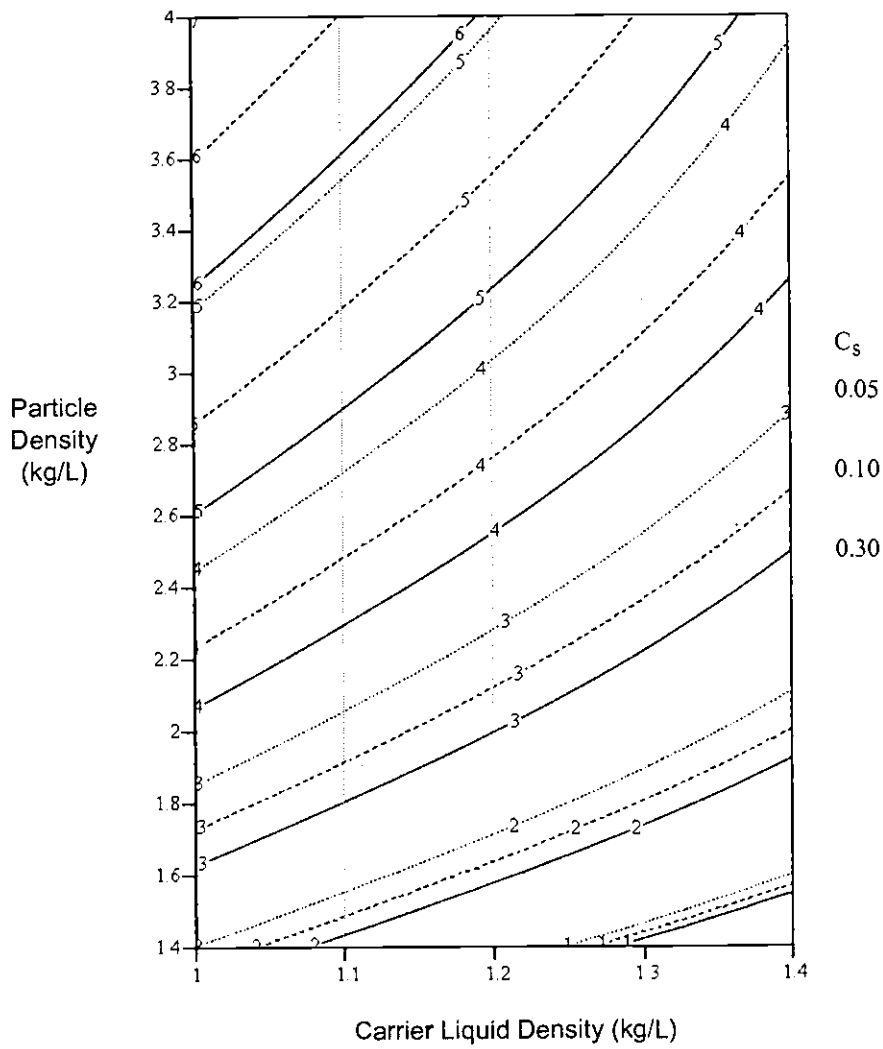
$\kappa_{cv} := 1$ $\beta_{cv} := 1.2$ $T = 80$ °C $\boxed{d_{50} = 110\,\mu m}$ $D_{pipe} = 3.068\,in$

$x_{salt} = 0.9$

$v1_{crit_{i,j}} := v_{cr}(D_{pipe}, d_{50}, \rho_{d_j}, 0.30, \rho'_{c_i}, \mu'_{c_i}, \kappa_{cv}, \beta_{cv})$

$v2_{crit_{i,j}} := v_{cr}(D_{pipe}, d_{50}, \rho_{d_j}, 0.10, \rho'_{c_i}, \mu'_{c_i}, \kappa_{cv}, \beta_{cv})$ $v3_{crit_{i,j}} := v_{cr}(D_{pipe}, d_{50}, \rho_{d_j}, 0.05, \rho'_{c_i}, \mu'_{c_i}, \kappa_{cv}, \beta_{cv})$

Figure 18c. Contour Plot of Best-Estimate Critical Velocity (ft/s) (Oroskar and Turian 1980) vs. Carrier Liquid Density and Particle Density for Selected Particle Volume Fractions.



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Checked: By: S.D. Estey
Revised: By:

$\kappa_f = 1$ $T = 80$ °C $d_{50} := 50 \cdot \mu m$ $C_s := 10 \cdot \%$ $D_{pipe} = 3.068$ in $L = 1000$ ft $\theta = 0$ deg $v := 6 \cdot \frac{ft}{sec}$

$x_{salt} = 0.9$

$\Delta p_{CS_{i,j}} := \Delta p\left(D_{pipe}, v, \rho'_{c_i}, \mu'_{c_i}, \varepsilon_{EOL\_CS}, d_{50}, \rho_{d_j}, C_s, L, \beta_f, \kappa_f, \theta\right)$

$\Delta p_{SS_{i,j}} := \Delta p\left(D_{pipe}, v, \rho'_{c_i}, \mu'_{c_i}, \varepsilon_{EOL\_SS}, d_{50}, \rho_{d_j}, C_s, L, \beta_f, \kappa_f, \theta\right)$

$R_{CS_{i,j}} := R_d\left(D_{pipe}, v, \rho'_{c_i}, \mu'_{c_i}, \varepsilon_{EOL\_CS}, d_{50}, \rho_{d_j}, C_s, 1\right)$

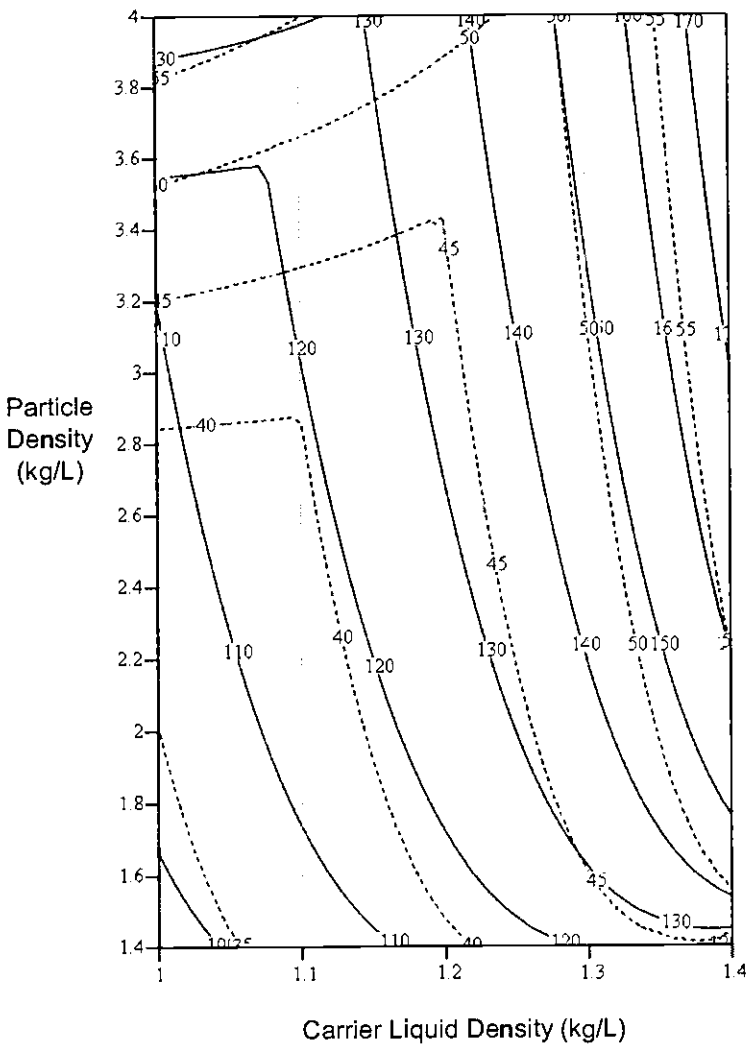
$R_{SS_{i,j}} := R_d\left(D_{pipe}, v, \rho'_{c_i}, \mu'_{c_i}, \varepsilon_{EOL\_SS}, d_{50}, \rho_{d_j}, C_s, 1\right)$

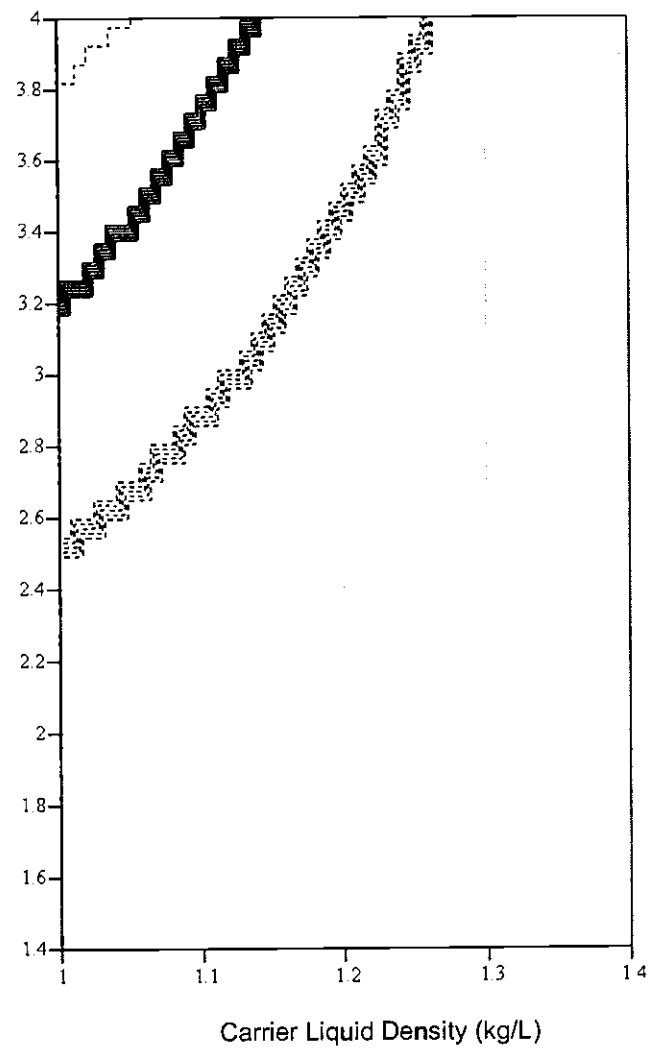
Figure 19a. Contour Plot of Best-Estimate Pressure Drop (psi) per 1000 ft of Pipe at Specified Flow Velocity (5 ft/s) (CS solid line, SS dashed line) vs.Particle Solids Density and Carrier Liquid Density - (Turian, Hsu, and Ma 1987).

Figure 19b. Corresponding Flow Regime Contour Plot.

$R_{CS_{0,N}} = 0$ $R_{SS_{0,N}} = 0$ $R_{CS_{N,N}} = 3$ $R_{SS_{N,N}} = 3$

$R_{CS_{0,0}} = 3$ $R_{SS_{0,0}} = 3$ $R_{CS_{N,0}} = 3$ $R_{SS_{N,0}} = 3$





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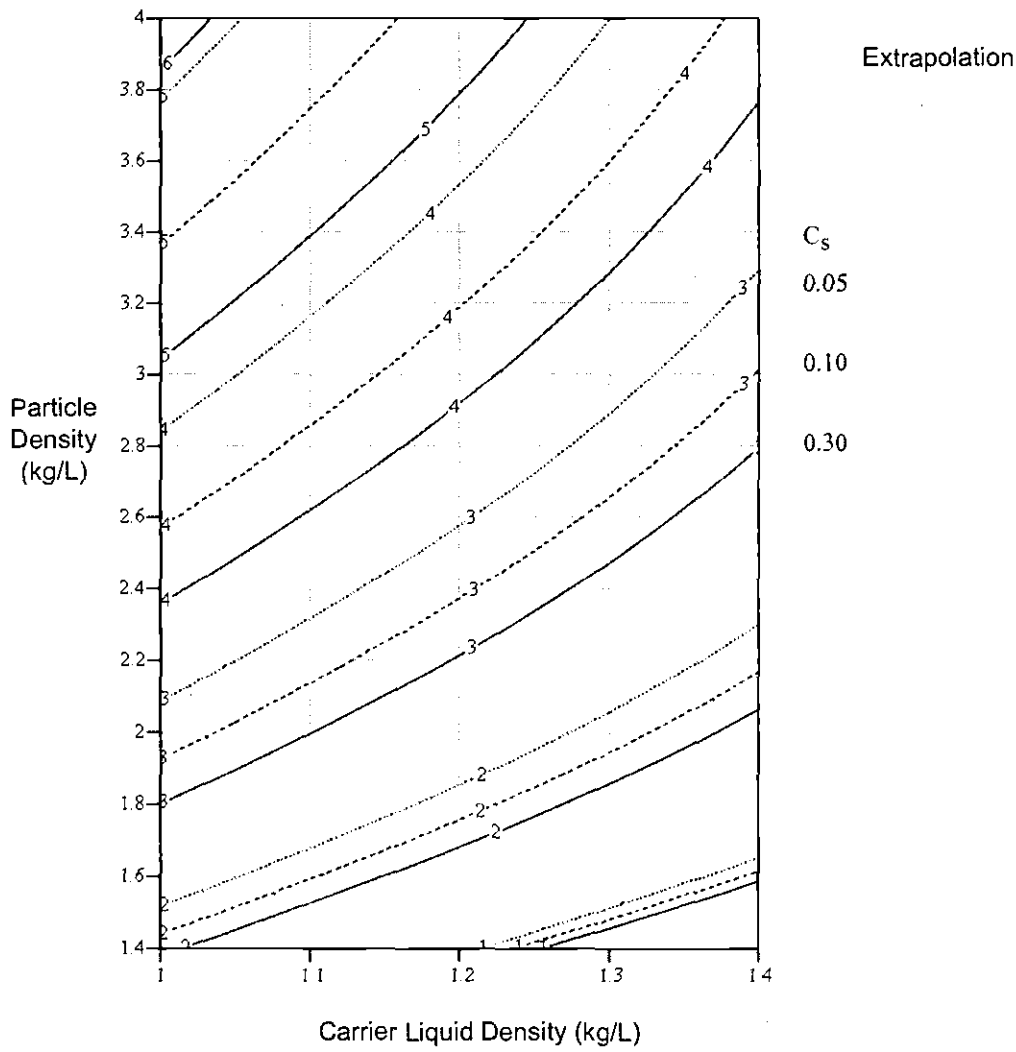
Date: 02/25/2002 By: L. J. Julyk
Checked: By: S.D. Estey
Revised: By:

$\kappa_{cv} = 1 \quad \beta_{cv} = 1.2 \quad T = 80\ ^{o}C \qquad \boxed{d_{50} = 50\,\mu m} \qquad D_{pipe} = 3.068\,in$

$$v1_{crit_{i,j}} := v_{cr}\left(D_{pipe}, d_{50}, \rho_{d_j}, 0.30, \rho'_{c_i}, \mu'_{c_i}, \kappa_{cv}, \beta_{cv}\right)$$

$$v2_{crit_{i,j}} := v_{cr}\left(D_{pipe}, d_{50}, \rho_{d_j}, 0.10, \rho'_{c_i}, \mu'_{c_i}, \kappa_{cv}, \beta_{cv}\right) \quad v3_{crit_{i,j}} := v_{cr}\left(D_{pipe}, d_{50}, \rho_{d_j}, 0.05, \rho'_{c_i}, \mu'_{c_i}, \kappa_{cv}, \beta_{cv}\right)$$

Figure 19c. Contour Plot of Best-Estimate Critical Velocity (ft/s) (Oroskar and Turian 1980) vs. Carrier Liquid Density and Particle Density for Selected Particle Volume Fractions.



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Date: 02/25/2002 By: L. J. Julyk
Checked: By: S.D. Estey
Revised: By:

$\kappa_f = 1$ $T = 80\ ^{\circ}C$ $d_{50} := 25 \cdot \mu m$ $C_s := 10 \cdot \%$ $D_{pipe} = 3.068\,in$ $L = 1000\,ft$ $\theta = 0\,deg$ $v := 6 \cdot \frac{ft}{sec}$

$x_{salt} = 0.9$

$\Delta pCS_{i,j} := \Delta p\left(D_{pipe}, v, \rho'c_i, \mu'c_i, \varepsilon_{EOL\_CS}, d_{50}, \rho d_j, C_s, L, \beta_f, \kappa_f, \theta\right)$

$\Delta pSS_{i,j} := \Delta p\left(D_{pipe}, v, \rho'c_i, \mu'c_i, \varepsilon_{EOL\_SS}, d_{50}, \rho d_j, C_s, L, \beta_f, \kappa_f, \theta\right)$

$RCS_{i,j} := R_d\left(D_{pipe}, v, \rho'c_i, \mu'c_i, \varepsilon_{EOL\_CS}, d_{50}, \rho d_j, C_s, 1\right)$

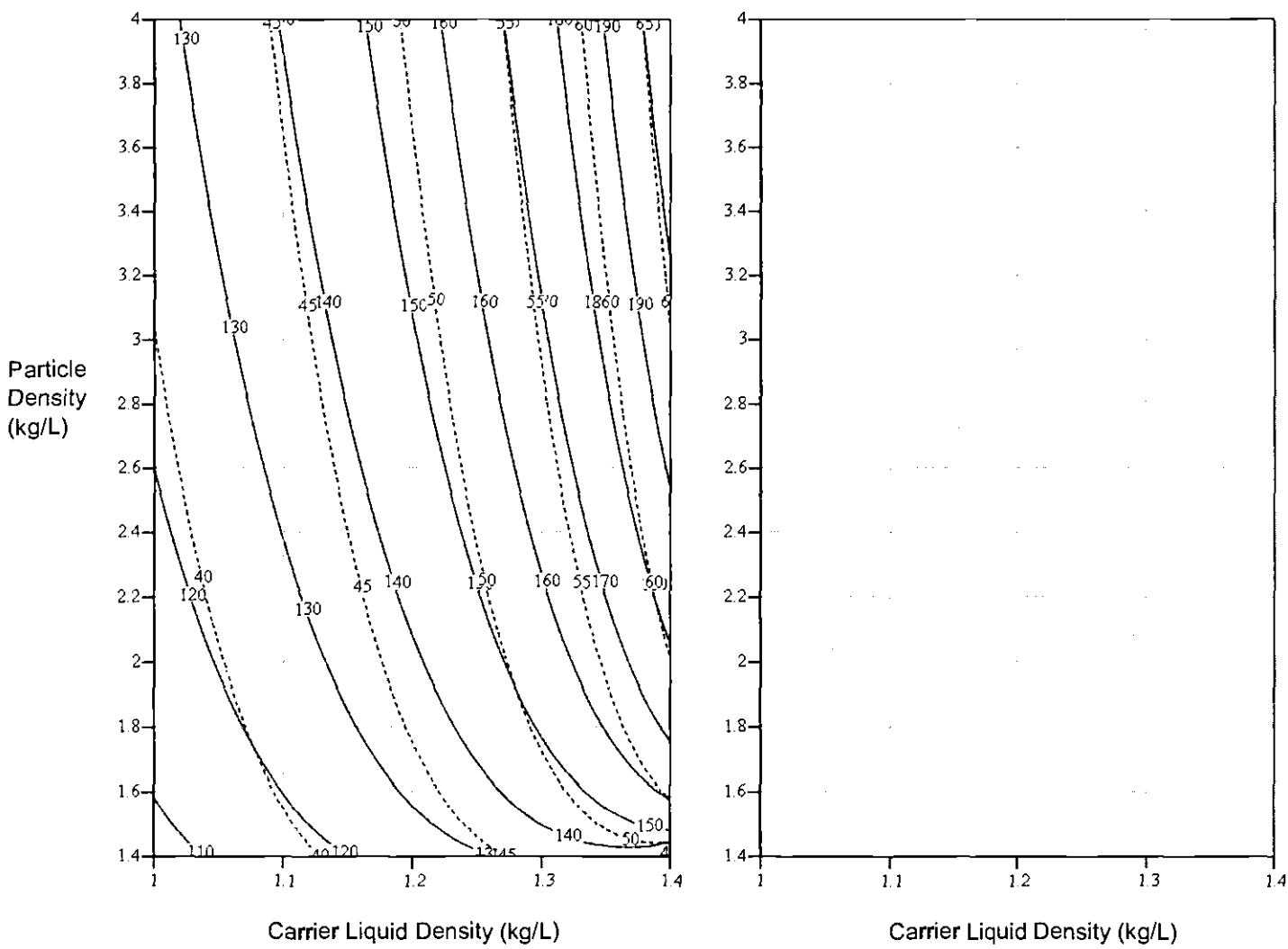
$RSS_{i,j} := R_d\left(D_{pipe}, v, \rho'c_i, \mu'c_i, \varepsilon_{EOL\_SS}, d_{50}, \rho d_j, C_s, 1\right)$

Figure 20a. Contour Plot of Best-Estimate Pressure Drop (psi) per 1000 ft of Pipe at Specified Flow Velocity (5 ft/s) (CS solid line, SS dashed line) vs.Particle Solids Density and Carrier Liquid Density - (Turian, Hsu, and Ma 1987).

Figure 20b. Corresponding Flow Regime Contour Plot.

$RCS_{0,N} = 3$ $RSS_{0,N} = 3$ $RCS_{N,N} = 3$ $RSS_{N,N} = 3$

$RCS_{0,0} = 3$ $RSS_{0,0} = 3$ $RCS_{N,0} = 3$ $RSS_{N,0} = 3$



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Date: 02/25/2002 By: L. J. Julyk
Checked: By: S.D. Estey
Location: 200 Area - Hanford Site, Richland, Washington
Revised: By:

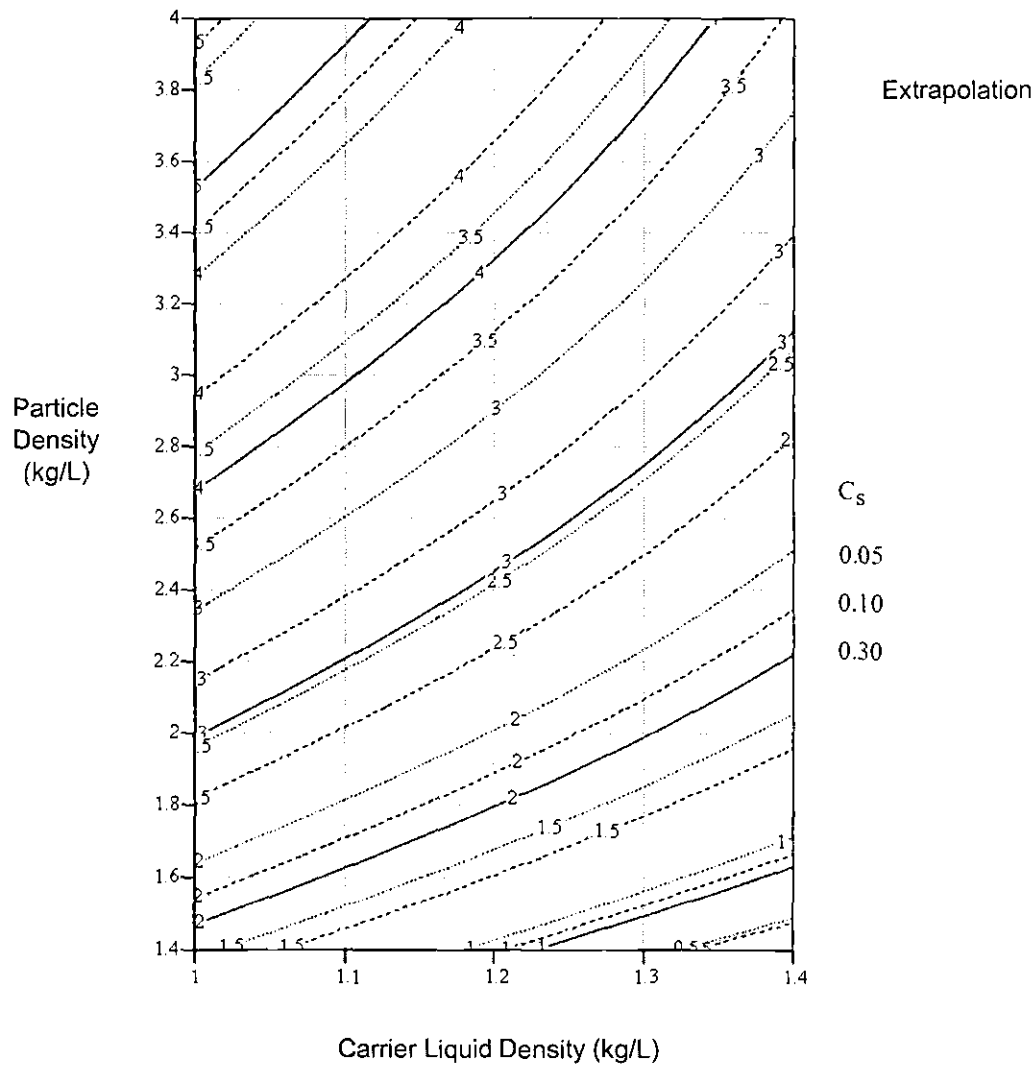
$\kappa_{cv} = 1$ $\beta_{cv} = 1.2$ $T = 80$ °C $\boxed{d_{50} = 25\,\mu m}$ $D_{pipe} = 3.068\,in$

$x_{salt} = 0.9$

$v1crit_{i,j} := v_{cr}(D_{pipe}, d_{50}, \rho d_j, 0.30, \rho'c_i, \mu'c_i, \kappa_{cv}, \beta_{cv})$

$v2crit_{i,j} := v_{cr}(D_{pipe}, d_{50}, \rho d_j, 0.10, \rho'c_i, \mu'c_i, \kappa_{cv}, \beta_{cv})$ $v3crit_{i,j} := v_{cr}(D_{pipe}, d_{50}, \rho d_j, 0.05, \rho'c_i, \mu'c_i, \kappa_{cv}, \beta_{cv})$

Figure 20c. Contour Plot of Best-Estimate Critical Velocity (ft/s) (Oroskar and Turian 1980) vs. Carrier Liquid Density and Particle Density for Selected Particle Volume Fractions.



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Date: 02/25/2002 By: L. J. Julyk
Checked: By: S.D. Estey
Location: 200 Area - Hanford Site, Richland, Washington
Revised: By:

Figure F-21. Critical Velocity (Best-estimate) Comparison - Minimum Agitated Mean Particle Size Distribution, ρ_L=1.1 kg/L, ρ_s=2.9 kg/L, Best-estimate and Upper-bound Viscosity.

$d_{pRR} := d_{LB\_M}$ $\quad j_R := j_{LB\_M}$ $\quad \phi_{RR} := PDF_{LB\_M}$ $\quad \phi_{RRc} := CDF_{LB\_M}$ $\quad d_{50} := D_\beta(d_{pRR}, \phi_{RRc}, 50\%)$

$d_{50} = 7.4\,\mu m$ median particle size

$D_{pipe} = 3.068\,in$

$\rho_L := 1.1 \cdot kg \cdot liter^{-1}$ liquid density

$\rho_s := 2.9 \cdot kg \cdot liter^{-1}$ solids density

$\beta_{cv} := 1.2$

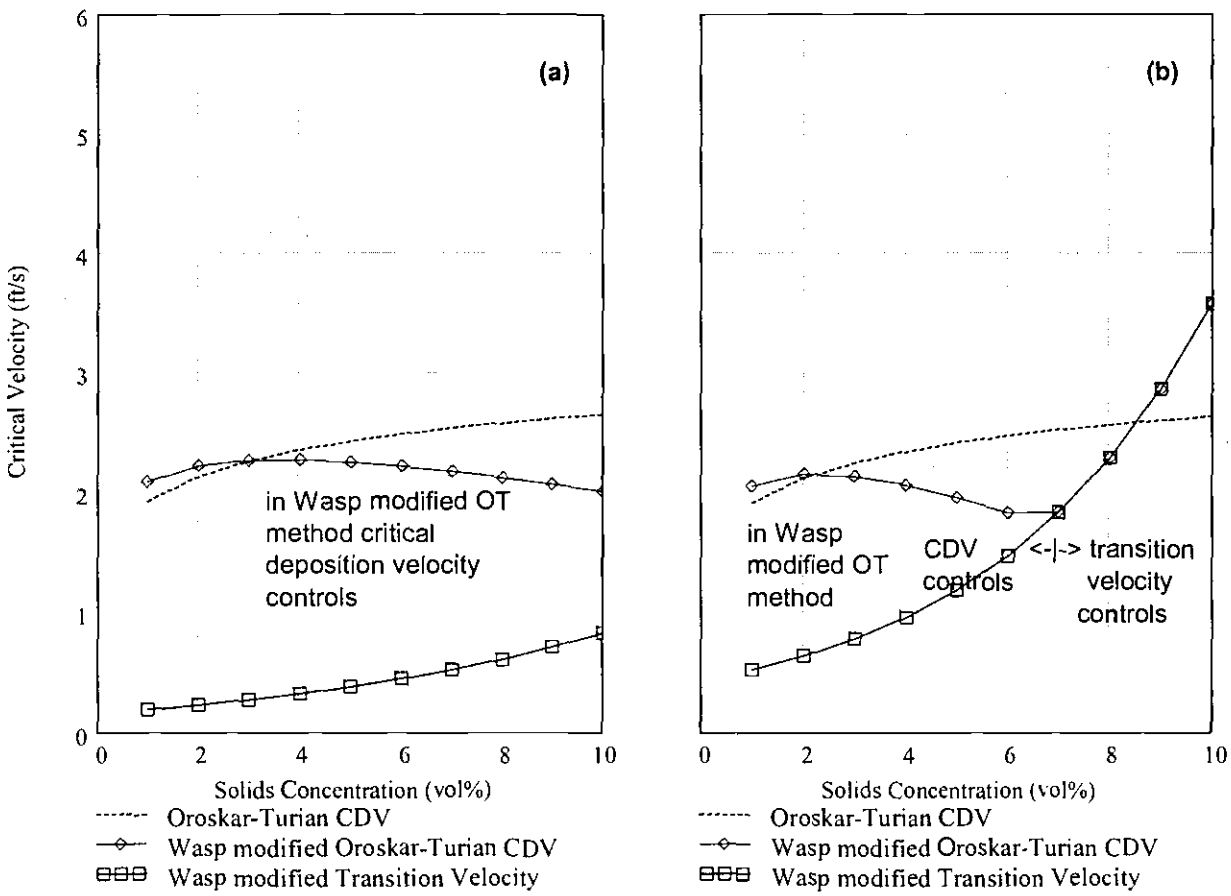
$\kappa_{cv} := 1$

$K_D := 82$

Oroskar and Turian (1980) critical velocity -empirical equation (best-estimate)

Oroskar and Turian (1980) and Wasp Modified Oroskar and Turian Deposition Velocity (CDV)

Best-estimate Viscosity **Upper-bound Viscosity**



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Subject: Critical Velocity and Pressure Drop Study in Support of Waste Tank Feed Transfer System
Location: 200 Area - Hanford Site, Richland, Washington

WO/Job No. 500689/BA10
Date: 02/25/2002 By: L. J. Julyk
Checked: By: S.D. Estey
Revised: By:

Figure F-22. Critical Velocity (Best-estimate) Comparison - Minimum Agitated 95/95TL Particle Size Distribution, ρ_L=1.1 kg/L, ρ_s=2.9 kg/L, Best-estimate and Upper-bound Viscosity.

$d_{pRR} := d_{LB\_9595TL}$ $j_R := j_{LB\_9595TL}$ $\phi_{RR} := PDF_{LB\_9595TL}$ $\phi_{RRc} := CDF_{LB\_9595TL}$ $d_{50} := D_\beta(d_{pRR}, \phi_{RRc}, 50\%)$

$d_{50} = 21.8\,\mu m$ median particle size

$D_{pipe} = 3.068\,in$

$\rho_L := 1.1 \cdot kg \cdot liter^{-1}$ liquid density

$\rho_s := 2.9 \cdot kg \cdot liter^{-1}$ solids density

$\beta_{cv} := 1.2$

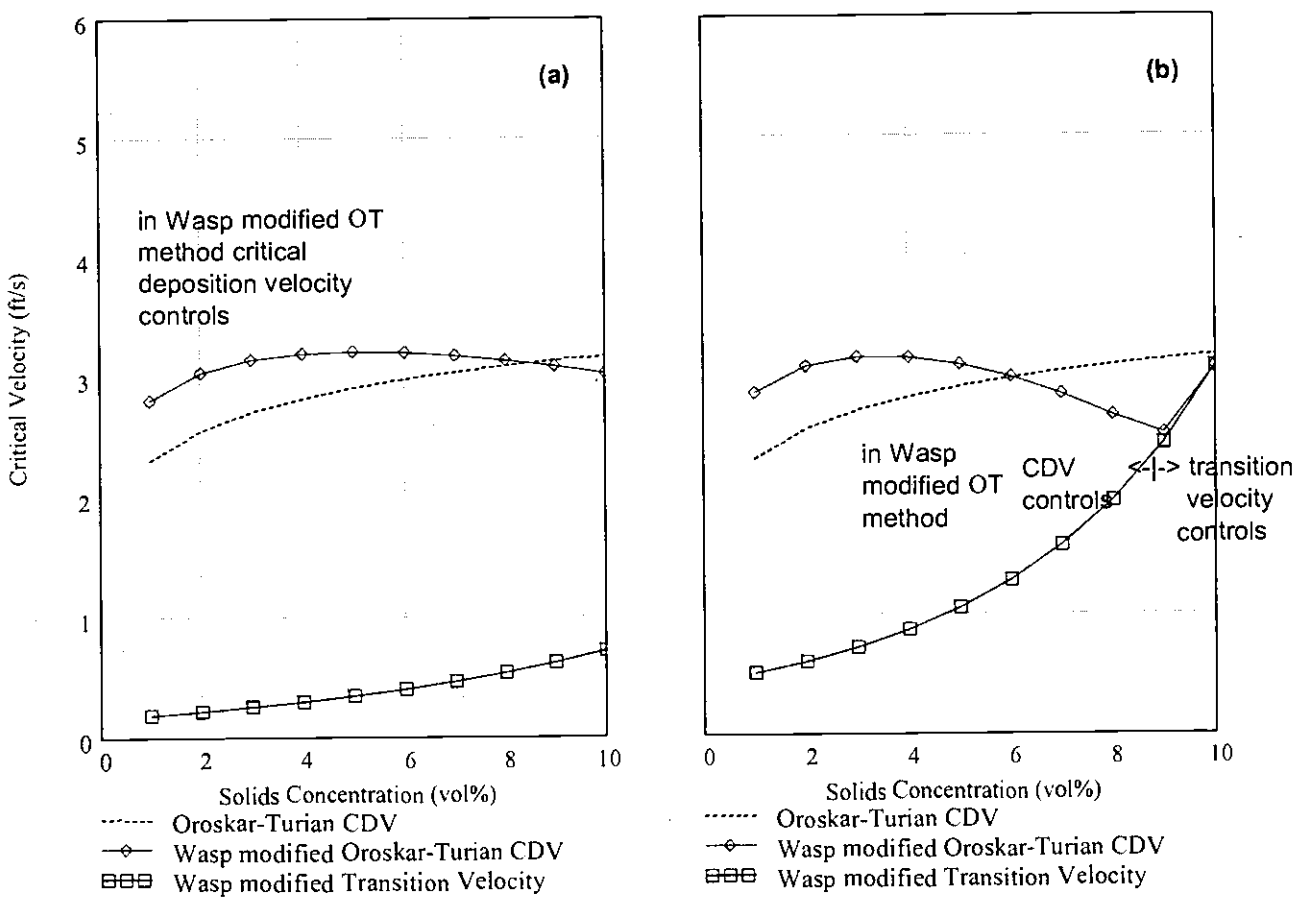
$\kappa_{cv} := 1$

$K_D = 82$

Oroskar and Turian (1980) critical velocity -empirical equation (best-estimate)

Oroskar and Turian (1980) and Wasp Modified Oroskar and Turian Deposition Velocity (CDV)

Best-estimate Viscosity **Upper-bound Viscosity**



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APPENDIX G

WASP MODEL VERIFICATION

Calculations contained herein were produced in Mathcad 2000 Professional (Mathcad is a registered trademark of MathSoft, Inc. of Cambridge, Massachusetts).

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CONVERSIONS

ft	feet = 0.3048 meter (m)
in.	inch = 2.54 centimeters (cm)
lbf/in^2	pounds per square inch = 0.006895 megapascals (MPa)
mils	0.001 in. = 0.0254 millimeter (mm)
gpm	0.0631 liter/second (L/s)
cP	centipose = 0.001 kilogram/meter-second (kg/m-s)

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Revision: 0
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Client: Numatec Hanford Corporation
Subject: Critical Velocity and Pressure Drop Study in Support of Waste Tank Feed Transfer System (Wasp Test Case)
Location: 200 Area - Hanford Site, Richland, Washington

WO/Job No. 110299 & 110300/BA10
Date: 09/06/2000 By: L. J. Julyk
Checked: 10/11/00 By: TC OTEN
Revised: By:

PROBLEM

Verification check of Wasp method against published example.

APPROACH

Compare results of Wasp et al. 1977, illustrative example, page 95, with results obtained through application of equations given in Appendix F. All necessary equations are copied from Appendix F with following modifications unique to the check problem:

1. The viscosity relation from Wasp et al. 1977, illustrative example, page 95 is used.
2. Stokes flow for the settling particles is assumed in accordance with the illustrative example.

CONCLUSION

Less than 0.2% error is shown between results obtained through application of equations given in Appendix F and results of Wasp et al. 1977, illustrative example, page 95. This validates the implementation of the Wasp method in Appendix F.

REFERENCES

Wasp, E. J., J. P. Kenny, and R. L. Gandhi, 1977, *Solid-Liquid Flow -- Slurry Pipeline Transportation*, Trans. Tech. Publ., Rockport, MA.

PRELIMINARIES

$TOL = 1 \times 10^{-7}$

$\mu m \equiv 10^{-6} \cdot m$

$cP \equiv 10^{-2} \cdot poise$

$\Delta\varepsilon := TOL \cdot 10^{-1} \quad \Delta\varepsilon = 1 \times 10^{-8}$

Return values of vector ϕ_p in accordance with nonzero values in vector $\phi_z > \Delta\varepsilon$

```
pack(φp, φz) := | J ← length(φz) − 1
                | k ← 0
                | for j ∈ 0..J
                |   if φz_j > Δε
                |     | φk ← φp_j
                |     | k ← k + 1
                | if k = 0
                |   | φ0 ← Δε
                |   | φ1 ← Δε
                | φ
```

Return d_β particle diameter that is βth percentile value by volumes

```
Dβ(dp, φcum, β) := | J ← length(φcum) − 1
                   | for k ∈ 0..J
                   |   break if φcum_k > β
                   | (dp_k − dp_(k−1)) / (φcum_k − φcum_(k−1)) · (β − φcum_(k−1)) + dp_(k−1)
```

CH2MHILL Hanford Group, Inc.
EVALUATION ANALYSIS

Calc. No. RPP-LJJ-002
Revision: 0
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Client: Numatec Hanford Corporation
Subject: Critical Velocity and Pressure Drop Study in Support of Waste Tank Feed Transfer System (Wasp Test Case)
Location: 200 Area - Hanford Site, Richland, Washington

WO/Job No. 110299 & 110300/BA10
Date: 09/06/2000 By: L. J. Julyk
Checked: 10/11/00 By:
Revised: By:

The Reynolds Number for Newtonian flow is defined as

$$Re(D, v, \rho, \mu) := D \cdot v \cdot \frac{\rho}{\mu}$$

where D is a characteristic length, v is the flow velocity, ρ is the fluid density, and μ is the fluid viscosity.

The terminal settling velocity (v_∞) of spherical particle settling in a stagnant unbound liquid is given by the following:

For Stokes flow ($Re < 0.1$) the drag coefficient of a spherical particle is given by

$$C_D(D_d, v, \rho_c, \mu_c) := \frac{24}{Re(D_d, v, \rho_c, \mu_c)}$$

which leads the following explicit relation for v_∞

$$v_\infty(D_d, \rho_d, \rho_c, \mu_c) := g \cdot (\rho_d - \rho_c) \cdot (D_d)^2 \cdot (18 \cdot \mu_c)^{-1}$$

Note that the check problem assumes Stokes flow.

The approximation developed by Churchill in 1977 that includes the laminar and turbulent regimes as well as the transition regime between laminar and turbulent flow is used for the friction factor, i.e.;

$$f_c(Re, \eta) := \left| \begin{array}{l} A \leftarrow \left[2.457 \cdot \ln\left[\dfrac{1}{\left(\dfrac{7}{Re}\right)^{0.9} + (0.27 \cdot \eta)} \right] \right]^{16} \\ B \leftarrow \left(\dfrac{37530}{Re} \right)^{16} \\ 8 \cdot \left[\left(\dfrac{8}{Re}\right)^{12} + \left(\dfrac{1}{A + B}\right)^{\frac{3}{2}} \right]^{\frac{1}{12}} \end{array} \right.$$

or $f_c(D_{pipe}, v_c, \rho_c, \mu_c, \varepsilon) := f_c\left(Re(D_{pipe}, v_c, \rho_c, \mu_c), \dfrac{\varepsilon}{D_{pipe}} \right)$

where v_c flow velocity of carrier liquid

Density of water as a function of temperature (°C)

$$\rho_{water}(T) := \left[999.7 - 0.10512 \cdot (T - 10) - 0.005121 \cdot (T - 10)^2 + 0.00001329 \cdot (T - 10)^3 \right] \cdot \frac{kg}{m^3}$$

mass density of water (5 °C < T <100 °C)

Viscosity of water as a function of temperature (°C)

$$\mu_{water}(T) := \left| \begin{array}{ll} 100 \cdot \exp\left[\ln(10) \cdot \left[\dfrac{1301}{998.333 + 8.1855 \cdot (T - 20) + 0.00585 \cdot (T - 20)^2} - 3.30233 \right] \right] \cdot cP & \text{if } T \le 20 \\ (1.002) \cdot \exp\left[\ln(10) \cdot \left[\dfrac{\left[1.3272 \cdot (20 - T) - 0.001053 \cdot (T - 20)^2 \right]}{T + 105} \right] \right] \cdot cP & \text{otherwise} \end{array} \right.$$

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WO/Job No. 110299 & 110300/BA10
Date: 09/06/2000 By: L. J. Julyk
Checked: 10/11/00 By:
Revised: By:

$T_F(t_C) := \frac{9}{5} \cdot t_C + 32$ $\quad T_C(t_F) := \frac{5}{9}(t_F - 32)$ $\quad T_C(68) = 20$ $\quad \rho_L := \rho_{water}(T_C(68))$ $\quad \mu_L := \mu_{water}(T_C(68))$

$\rho_L = 0.998 \frac{kg}{liter}$ $\quad \mu_L = 1.002\,cP$

Liquid Density as a Function of Solids Concentration

$\rho_c(\rho_s, \rho_L, \Phi_v) := \rho_s \cdot \Phi_v + \rho_L \cdot (1 - \Phi_v)$

Viscosity as a function of solids concentration per

Wasp 1977, illustrative example, page 95

$i1 := 0..5$ $\quad v\phi_{1_{i1}} := \quad v\mu_{c1_{i1}} :=$

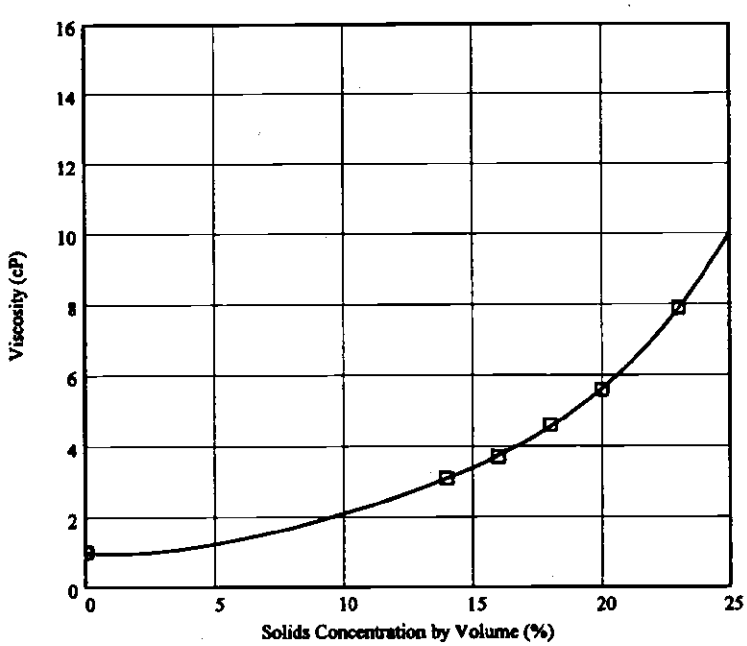
0	1.002
14	3.1
16	3.7
18	4.6
20	5.6
23	7.9

$v\phi_1 := v\phi_1 \cdot \%$

$v\mu_{c1} := v\mu_{c1} \cdot cP$

$vs_1 := regress\left(v\phi_1, \frac{v\mu_{c1}}{cP}, 4\right)$ $\quad \mu_c(\mu_L, \Phi_v) := interp\left(vs_1, v\phi_1, \frac{v\mu_{c1}}{cP}, \Phi_v\right) \cdot cP$

Comparison of Viscosity Relations vs. "Vehicle" Solids Concentration.



Wasp et al. 1977, illustrative example, page 95

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Date: 09/06/2000 By: L. J. Julyk
Checked: 10/11/00 By: TCD
Revised: By:

Wasp's Method for Pressure Drop Estimate (Wasp et al. 1977)

assume $\beta := 1$ $\kappa := 0.4$

$$\frac{-1.8}{\beta\cdot\kappa}\cdot\frac{v_\infty(d_p,\rho_s,\rho_c,\mu_c)}{v\cdot\sqrt{\frac{f\cdot\frac{\rho_L}{\rho_c}}{8}}}$$

$$\phi_v(v,\rho_L,\rho_c,\mu_c,d_p,\rho_s,\phi_s,f) := \phi_s\cdot 10$$

$$\Phi_c(v,\rho_L,\mu_L,d_p,\rho_s,\phi_s,f) := \left|\begin{array}{l} J \leftarrow \text{length}(d_p) - 1 \\ \Phi'_v \leftarrow 0.5\cdot\sum_{j=0}^{J}\phi_{s_j} \\ \text{root}\left(\Phi'_v - \sum_{j=0}^{J}\phi_v\left(v,\rho_L,\rho_c(\rho_s,\rho_L,\Phi'_v),\mu_c(\mu_L,\Phi'_v),d_{p_j},\rho_s,\phi_{s_j},f\right),\Phi'_v\right)\end{array}\right.$$

Durand friction factor correlation ($f_d = f - f_c$) using clear liquid density and viscosity properties of carrier liquid.

$$f_{dDurand}(D_{pipe},v,\rho_L,\mu_L,\varepsilon,D_d,\rho_d,\alpha_d,K_D) := K_D\cdot\alpha_d\cdot f_c(D_{pipe},v,\rho_L,\mu_L,\varepsilon)\cdot\left[\frac{v^2\cdot\sqrt{C_D(D_d,v_\infty(D_d,\rho_d,\rho_L,\mu_L),\rho_L,\mu_L)}}{g\cdot D_{pipe}\cdot\left(\frac{\rho_d}{\rho_L}-1\right)}\right]^{\frac{-3}{2}}$$

$$\Delta p_{Durand}(D_{pipe},v,\rho_L,\mu_L,\varepsilon,D_d,\rho_s,\alpha_d,L,\theta,K_D) := \rho_L\cdot g\cdot\left[\frac{L}{D_{pipe}}\cdot\frac{v^2}{2\cdot g}\cdot\left(\begin{array}{l} f_c(D_{pipe},v,\rho_L,\mu_L,\varepsilon)\ldots \\ +f_{dDurand}(D_{pipe},v,\rho_L,\mu_L,\varepsilon,D_d,\rho_s,\alpha_d,K_D)\cdot\cos(\theta)\end{array}\right)\ldots \\ +\left[\left(\frac{\rho_s}{\rho_L}-1\right)\cdot\alpha_d+1\right]\cdot L\cdot\sin(\theta)\right]$$

Wasp friction factor and pressure loss

$$f_{Wasp\_f}(D_{pipe},v,\rho_L,\mu_L,\varepsilon,d_p,\rho_s,\phi_s,\theta,f) := \left|\begin{array}{l} J \leftarrow \text{length}(d_p) - 1 \\ \Phi_v \leftarrow \Phi_c(v,\rho_L,\mu_L,d_p,\rho_s,\phi_s,f) \\ \rho_v \leftarrow \rho_c(\rho_s,\rho_L,\Phi_v) \\ \mu_v \leftarrow \mu_c(\mu_L,\Phi_v) \\ f_W \leftarrow f_c(D_{pipe},v,\rho_v,\mu_v,\varepsilon)\cdot\frac{\rho_v}{\rho_L} \\ \text{for } j \in 0..J \\ \quad \left|\begin{array}{l} \phi_{vj} \leftarrow \phi_v(v,\rho_L,\rho_v,\mu_v,d_{p_j},\rho_s,\phi_{s_j},f) \\ \phi_{aj} \leftarrow \phi_{s_j} - \phi_{vj} \\ f_W \leftarrow f_W + f_{dDurand}(D_{pipe},v,\rho_L,\mu_L,\varepsilon,d_{p_j},\rho_s,\phi_{aj},82)\cdot\cos(\theta)\end{array}\right. \\ f_W\end{array}\right.$$

vehicle friction contribution normalized to liquid

plus friction contribution from remaining heterogeneous particles using clear liquid properties

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$f_f := 0.025$ initial guess

$$f_{Wasp}(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, d_p, \rho_s, \phi_s, \theta) := \mathrm{root}(f_f - f_{Wasp\_f}(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, d_p, \rho_s, \phi_s, \theta, f_f), f_f)$$

$$\Delta p_{Wasp}(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, d_p, \rho_s, \phi_s, L, \theta) := \left| \begin{array}{l} J \leftarrow \mathrm{length}(d_p) - 1 \\ \Phi_s \leftarrow \sum_{j=0}^{J} \phi_{s_j} \\ \rho_L \cdot g \cdot \left[\frac{L}{D_{pipe}} \cdot \frac{v^2}{2 \cdot g} \cdot f_{Wasp}(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, d_p, \rho_s, \phi_s, \theta) \ldots \right. \\ \left. + \left[\left(\frac{\rho_s}{\rho_L} - 1 \right) \cdot \Phi_s + 1 \right] \cdot L \cdot \sin(\theta) \right] \end{array} \right.$$

$$\Delta p_L(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, L, \theta) := \rho_L \cdot g \cdot \left(\frac{L}{D_{pipe}} \cdot \frac{v^2}{2 \cdot g} \cdot f_c(D_{pipe}, v, \rho_L, \mu_L, \varepsilon) + L \cdot \sin(\theta) \right)$$ pressure drop for liquid only

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Wasp et al. 1977, Illustrative example, page 95 $d_p := 0$ $\phi_s := 0$ $\phi_{cum} := 0$ $\theta := 0 \cdot deg$

Given solid particle size distribution

data :=

d_p (cm)	volume frequency (%)
0.0021	19.55
0.0059	2.3
0.0111	1.15

$d_p := data^{\langle 0 \rangle} \cdot cm$

$\phi_s := data^{\langle 1 \rangle} \cdot \%$

$$d_p = \begin{pmatrix} 21 \\ 59 \\ 111 \end{pmatrix} \mu m$$

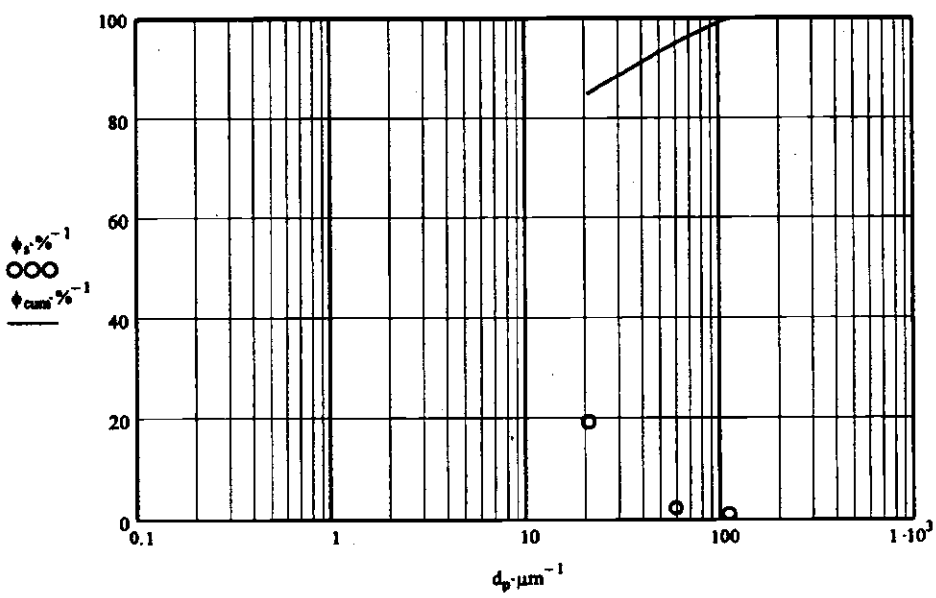
Given parameters

$\mu_L := \mu_{water}(T_C(68))$	Carrier liquid viscosity	$\mu_L = 1.002\,cP$
$\rho_L := \rho_{water}(T_C(68))$	Carrier liquid density	$\rho_L = 0.998 \frac{kg}{liter}$
$\rho_s := 5 \cdot \frac{kg}{liter}$	Average solids density	
$D_{pipe} := 12 \cdot in$	ID of pipe	
$\varepsilon := 0.002 \cdot in$	pipe roughness	
$v := 4.5 \cdot \frac{ft}{sec}$	flow velocity	
$L := 1 \cdot ft$	pipe unit length	

$J := length(\phi_s) - 1$ $J = 2$

$\Phi_s := \sum_{j=0}^{length(\phi_s)-1} \phi_{s_j}$ $\Phi_s = 0.23$ $j := 0..J$ $\phi_{cum_j} := \frac{1}{\Phi_s} \cdot \sum_{i=0}^{j} \phi_{s_i}$

Cumulative undersize volume distribution



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$TOL = 1 \times 10^{-7}$

$f_W := f_{Wasp}(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, d_p, \rho_s, \phi_s, \theta)$ $\quad f_W = 0.05282$

$\dfrac{\Delta p_{Wasp}(D_{pipe}, v, \rho_L, \mu_L, \varepsilon, d_p, \rho_s, \phi_s, L, \theta)}{\rho_L \cdot g} = 0.01662\,ft$ (ft of water/ft of pipe) 0.01659 ft water / ft of pipe reported in Wasp et al. 1977 as approximate answer

$\dfrac{0.01662 - 0.01659}{0.01659} = 0.18\%$ error **Check OK**

$\Phi_v := \Phi_c(v, \rho_L, \mu_L, d_p, \rho_s, \phi_s, f_W)$ $\quad \Phi_v = 22.152\%$

$\rho_v := \rho_c(\rho_s, \rho_L, \Phi_v)$ $\quad \mu_v := \mu_c(\mu_L, \Phi_v)$

$\rho_v = 1.885 \dfrac{kg}{liter}$ $\quad \mu_v = 7.154\,cP$

$v_{t_j} := v_\infty(d_{p_j}, \rho_s, \rho_v, \mu_v)$

$\phi_{vv_j} := \phi_v(v, \rho_L, \rho_v, \mu_v, d_{p_j}, \rho_s, \phi_{s_j}, f_W)$

$\phi_{va_j} := \phi_{s_j} - \phi_{vv_j}$

$j =$	$\frac{d_{p_j}}{\mu m} =$	$\frac{v_{t_j}}{\frac{ft}{sec}} =$	$Re(d_{p_j}, v_{t_j}, \rho_v, \mu_v) =$	$C_D(d_{p_j}, v_{t_j}, \rho_v, \mu_v) =$	$\phi_{vv_j} =$		$\phi_{va_j} =$		$j =$
0	21	0.00034	0.001	41469.3	19.29	%	0.26	%	0
1	59	0.00271	0.013	1869.9	2.07		0.23		1
2	111	0.00959	0.085	280.8	0.79		0.36		2

$\sum_{j=0}^{J} \phi_{vv_j} = 22.15\%$ $\quad \sum_{j=0}^{J} \phi_{va_j} = 0.85\%$

$v_{t_j} := v_\infty(d_{p_j}, \rho_s, \rho_L, \mu_L)$

$j =$	$\frac{d_{p_j}}{\mu m} =$	$\frac{v_{t_j}}{\frac{ft}{sec}} =$	$Re(d_{p_j}, v_{t_j}, \rho_L, \mu_L) =$	$C_D(d_{p_j}, v_{t_j}, \rho_L, \mu_L) =$
0	21	0.00315	0.020	1195.5
1	59	0.02485	0.445	53.9
2	111	0.08796	2.965	8.1

$\dfrac{\varepsilon}{D_{pipe}} = 0.00017$ $\quad Re(D_{pipe}, v, \rho_v, \mu_v) = 1.101 \times 10^5$ $\quad Re(D_{pipe}, v, \rho_L, \mu_L) = 4.165 \times 10^5$

Fanning friction factor $\quad \dfrac{f_c(D_{pipe}, v, \rho_v, \mu_v, \varepsilon)}{4} = 0.00463$ $\quad \dfrac{f_c(D_{pipe}, v, \rho_L, \mu_L, \varepsilon)}{4} = 0.00387$

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APPENDIX H

INDEPENDENT EXPERT PEER REVIEW

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APPENDIX H

PEER REVIEW

STI INTERNATIONAL ASSOCIATES

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March 19, 2002

Dr. Yauso Onishi
Pacific Northwest National Laboratory
902 Battelle Blvd.
P.O. Box 999
Richland, WA 99352

Mr. Tom Conrads
332 Scott Street
Richland, WA 99352

Subject: STI Review of Dr. Larry J. Julyk's Sensitivity Analysis – AN-107 to WTP Transfer Route (Contract No. 411278-AU6 Additional Work)

Dear Dr. Onishi and Mr. Conrads:

STI has completed a review of the subject study using a median size of 7.5 microns and Dr. Julyk's best estimate of the viscosity.

Our review concentrated on the following aspects of Dr. Julyk's work:

1. Comments on Julyk's best estimate viscosity of waste slurry as a function of concentration.

2. Pressure drop for the 3.068 inch inside diameter pipe system of 557 feet of carbon steel and 6814 feet of stainless steel pipe in series for beginning of life (B.O.L.) and End of Life (E. O. L.) cases.

3. STI comments of the critical deposition and transition velocities.

Table 1 is a summary of the other basic parameters used in our review.

Following is a summary of our major findings:

- The "best estimate" of Dr. Julyk's viscosity represents the viscosity we would associate with very fine slurries of a 7.5 micron median size.

- STI pressure losses agree with Julyk's within a few percent of each other. (Table 2).

- A 4 ft./sec. velocity is recommended for the median size 7.5 micron slurry. This velocity will result in a steady state of operation with a 10% volume concentration. The risk of plugging will be minimized with a 4 ft./sec. velocity.

Sincerely,

Edward J. Wasp
President

Cc: Larry F. Julyk

STI INTERNATIONAL ASSOCIATES (STI)
REVIEW OF
SENSITIVITY ANALYSIS – AN-197 TO WTP TRANSFER ROUTE
BY DR. LARRY J. JULYK

VISCOSITY

The radioactive nature of the slurry makes it difficult to measure the rheology of the slurry. The best estimate viscosity of Julyk is the result of considerable experimental effort and was used in this report.

STI has found over many years that most fine slurries (such as the subject slurry) can best be correlated by:

$$\eta / \mu = 10^{Vr K}$$

η = effective viscosity
μ = viscosity of carrier fluid taken as 1.5 C_p
Vr = volume ratio of solids to carrier liquid
K = is a constant determined by lab rheology analaysis

STI would recommend that K = 7.5 in order to correlate the best estimate viscosity with the STI format. The following is a comparison of STI's correlation with Julyk's best correlation with strain effect.

Vol %	Vol. Ratio	η (STI) *cp*	η Best Est. (Julyk) *cp*
0	0	1.5	1.5
4	0.0417	3.1	3.0
8	0.087	6.7	7.0
10	0.111	10.1	10.0
Note: η (STI) = 1.5 $\mu = 10^{Vr K}$			

The exponent used in the STI correlation is for a very fine slurry such as the 7.5 micron median slurry of this report. The correlation is excellent.

PUMP DISCHARGE PRESSURE

Table 3 depicts the pump discharge pressure required to move the 10% volume slurry at 4 ft./sec. for B.O.L. and E.O.L. conditions. The agreement between STI and Julyk is excellent (maximum difference 5%). Most important, the maximum discharge pressure is under 200 psi.

CRITICAL VELOCITY AND HETERGENEOUS FLOW

The term critical velocity as defined in this report means the velocity at which in a steady state the system's discharge pressure will remain constant. Much below this velocity the discharge pressure will fluctuate and the slurry concentration will vary at the discharge of the pipeline.

Time did not permit a review of the Oroskar-Turian correlation as modified by Larry Julyk. However, the use of the median size for this very fine size consist (median 7.5 microns) is satisfactory. (We have independently checked the critical velocity results using our own proprietary correlation). We calculate a deposition velocity of 2.5 ft./sec. (10% volume) which compares favorably with Julyk's 2.6 ft./sec.

However, we would recommend a minimum velocity of 4 ft./sec. We have no continuous commercial experience below 4 ft./sec. At velocity below 4 ft./sec. the line will be very sensitive to tramp material accumulating in the line.

With respect to laminar turbulent transition viscosity at 10% volume we would expect these transition velocities to be lower than the critical deposition velocity. The 10% volume slurry is very dilute and we would not expect a yield to exist. We would suggest a water flush connection at the base of the receiving tank to flush the vertical leg after completion of a transfer.

TABLE 1
SUMMARY OF PARAMETERS

Pipe I.D.	3.068
C.S. Ft.	557
SS Ft.	6814
Elevation Change	+61.1 feet
Sp. Gr. Solid	2.9
Viscosity Carrier Fluid	1.5 C_p
Viscosity of Slurry	Julyk's Best Estimate
Range of Concentration	0.5 – 10 Vol. %
Median Size Consist	7.5 Microns
Beginning of Life (B.O.L.) Roughness	ε/D
C.S. 70 mils	0.0230
S.S. 2 mils	0.0007
End of Life (E.O.L.) Roughness	
C.S. 150 mils	00.049
S.S. 10 mils	0.0037

TABLE 2
PRESSURE LOSS COMPARISON
(PSI)

	STI	**JULYK**
Carrier Fluid 4 ft./sec	110	110
B.O.L. 4 ft./sec, 10% Vol	164	160
E.O.L. 4 ft./sec., 10% Vol	176	185

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