PNNL-11146
UC-2030

Defining Waste Acceptance Criteria for the Hanford Replacement Cross-Site Transfer System

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April 1996

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest National Laboratory
Operated for the U.S. Department of Energy
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PNNL-11146

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America

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Available to the public from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161

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Abstract

This document provides a methodology for defining waste acceptance criteria for the Hanford Replacement Cross-Site Transfer System (RCSTS). This methodology includes characterization, transport analysis, and control. A framework is described for each of these functions.

A tool was developed for performing the calculations associated with the transport analysis described in this report. This tool, a worksheet that is available in formats acceptable for a variety of personal computer spreadsheet programs, enables a comparison of the pressure required to transport a given slurry at a rate that particulate suspension is maintained to the pressure drop available from the RCSTS.

Acknowledgments

Much of the initial development of the methodology described in this document was originally performed for Westinghouse Hanford Company under Project W-211, Initial Tank Retrieval Systems. This methodology has been modified and applied to the cross-site transfers as a part of the current work.

The author acknowledges the assistance of Dr. Yasuo Onishi of Pacific Northwest National Laboratory, who was involved in the initial development and selection of the transport calculations. He also acknowledges several useful discussions with Dr. Jon Phillips, also of Pacific Northwest National Laboratory, who was instrumental in developing the strategy for rheological characterization.

Contents

Figures

Tables

1. Introduction

Of the six existing cross-site transfer pipelines between the 200 West and 200 East Areas of the Hanford Site, none is currently considered capable of transporting waste slurries with significant solids loadings. Five of the six lines are considered unusable due to plugging or similar problems. Recently, the sixth line has been successfully used to transfer liquid wastes, but, because of design limitations and age, this line is not considered capable of slurry transport.

A cross-site transfer system is required in the near-term to meet milestones in the Tri-Party Agreement related to interim stabilization of the West Area single-shell tanks while maintaining safe storage of the waste in the limited tank volume available (Ecology 1993). In addition, current disposal plans require the waste from 200 West to be transported to a processing facility in the 200 East area. Because of this, construction of a replacement cross-site transfer system (RCSTS) is under way. This construction is currently in the final design and procurement phase.

With completion of the final design for this transfer system, a methodology for defining waste acceptance to the system is now needed to ensure safe operation and a tolerable risk of equipment loss. This document recommends such a methodology.

2. Overview

The methodology for defining waste acceptance criteria described in this document incorporates three components of the decision making process: characterization, analysis, and control. The roles of each component are briefly defined as follows:

- Characterization: Provides information regarding the slurry to be transported to the analysis component.
- Analysis: Determines the energy required to transfer the slurry safely in the RCSTS; compares the energy required for transport with that available from the designed system to determine the feasibility of transporting the slurry.
- Control: Documents the decision-making process, specifies applicable controls, gives authority for system use, and provides process monitoring and contingency support.

A summary of the waste acceptance strategy is provided in Figure 2.1.

The first activity in this process is to perform a preliminary transport analysis based on the best available chemical constituencies and property information. This analysis, described in Section 4, is performed prior to any requests for characterization. From this analysis, a slurry (e.g., a sludge, diluent, dilution ratio, temperature range, etc.) may be selected that, based on the available information, will be expected to pass the analysis requirements for transport. This phase is intended to reveal actual characterization needs (i.e., what information is outstanding) and to minimize iteration in later characterization and transport steps. The product of this phase is the Slurry Transport Proposal Record (STPR), which defines the components of the slurry proposed for transfer in the RCSTS.

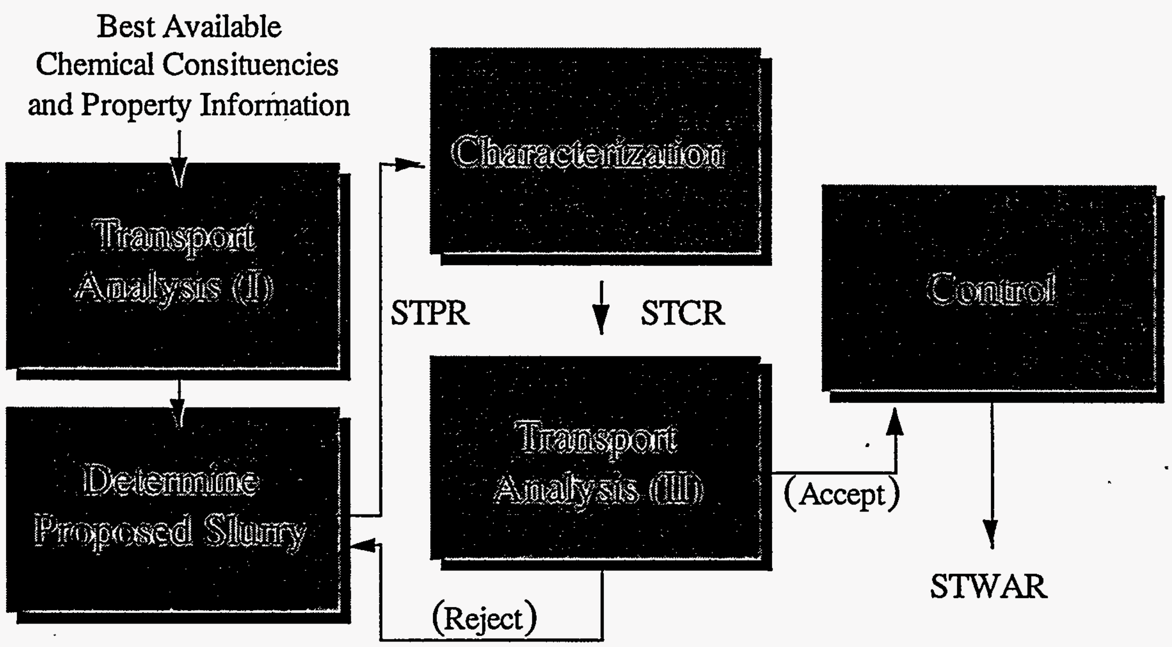

Figure 2.1. A Summary of the Methodology for the Proposed Waste Acceptance Criteria [Slurry Transport Proposal Record (STPR), Slurry Transport Characterization Report (STCR), Slurry Transport Waste Acceptance Report (STWAR)]

The characterization phase follows definition of the proposed slurry. Again, the purpose of this phase is to provide the information required for the transport analysis. The characterization needs are described in some detail in Section 3. The product of the characterization phase is the Slurry Transport Characterization Report (STCR), which documents the waste sampling and characterization efforts.

Once the necessary characterization information is available from the STCR, a transport analysis is performed to estimate the energy requirements for transport of the proposed slurry and to compare these with the capabilities of the RCSTS. When this indicates that the RCSTS is capable of safely transporting the proposed slurry, the results are passed on to the control function. Otherwise, a different slurry (e.g., higher temperature range or diluent ratio) must be proposed, characterized, and analyzed until an acceptable slurry is found. Again, the details of the transport analysis are described in Section 4.

The control function is responsible for documenting and integrating all prior activities. It uses the information resulting from the previous activities to specify controls that apply to the transfer process and authorizes the transfer. This function also monitors the process for any unusual or unplanned system or slurry behavior and provides procedural and systems support for contingencies. A framework for this function is described in Section 5. The product of the control function is the Slurry Transport Waste Acceptance Report (STWAR), which documents the basis for safe transfer, specifies the controls applicable to the transfer, and authorizes system use.

3. Characterization

This section contains details about the information required from the characterization phase. Every effort has been made to give detailed requirements (where needed) to the analytical methods to ensure that the information provided to the transport analysis function is applicable and complete.

3.1. Property Measurement Approach

The goal of the transport analysis is to provide a technical basis for the decision about whether the RCSTS can safely transfer a given slurry. Because the properties of this slurry can vary with temperature and constituent concentrations, the characterization function must provide information on the quantities and their expected variations. For some quantities, characterization at the maximum (or minimum) value is sufficient to give a representative bounding value. For this reason (except where otherwise noted), all measurements are to be performed at the lowest dilution range and the lowest temperature indicated by the STPR. The required characterization includes information about physical, chemical, and rheological properties.

Unlike the requirements of the current Waste Compatibility Data Quality Objectives (WHC 1995), *mixing of the proposed waste slurry constituents is required* to obtain the information necessary for the transport analysis.

3.2. Analyses of Physical Properties

Physical property measurements are required for each of the following: liquid density, mixture density, solids mass fraction, density of centrifuged solids, mass fraction water of the centrifuged solids, and a particle size distribution. While there is some redundancy of information in these requirements, they can be used to determine the overall uncertainty associated with the characterization.

3.2.1. Liquid Density

Measurement of the filtered liquid density from the proposed slurry will be obtained by any suitable analytical method. Filtration and density measurements will be obtained for the endpoints of the temperature range indicated in the STPR.

3.2.2. Mixture (Bulk) Density

Measurement of the mixture, or bulk, density of the proposed slurry will be obtained by any suitable analytical method at the endpoints of the temperature range indicated in the STPR.

3.2.3. Solids Mass Fraction

The solids mass fraction will be determined by thermal gravimetric analysis of the centrifuge filtered solids, or by a similar method, such that the errors associated with residual liquids are minimized. Measurements will be obtained at the endpoints of the temperature range.

3.2.4. Density of Centrifuged Solids

The density of the centrifuged solids will be determined by helium pycnometry or similar method, such that the errors associated with residual water and/or retained gas are minimized. Measurements will be obtained at the endpoints of the temperature range.

3.2.5. Mass Fraction Water of Centrifuged Solids

The mass fraction of water in the centrifuged solids will be determined by thermal gravimetric analysis or similar method, such that the errors associated with residual liquids are minimized. Measurements will be obtained at the endpoints of the temperature range.

3.2.6. Particle Size Distribution

A particle size distribution measurement is required to determine the settling rates and transport requirements. The focus of this measurement is the larger-size components of the slurry. Because of this, any technique capable of detecting particles larger than 1 μm (such as light obscuration or sedimentation-based methods) that provides a size distribution weighted by volume (or mass) would be suitable for this determination. The reported result of this test is a plot of the probability distribution for particle size weighted by volume (or mass). Measurements will be obtained at the endpoints of the temperature range.

3.3. Analyses of Chemical Properties and Constituencies

The analyses of chemical properties largely follow the requirements of the Waste Compatibility Data Quality Objectives (WHC 1995). The information from these tests, along with the variations in physical properties associated with the specified temperature range, are used to determine when problematic phase changes might occur.

3.3.1. Ion Analysis

Ion chromatography (IC) will be used to measure the quantity of ionic constituents in the solid and liquid phases. Analyses will be performed at the endpoints of the temperature range.

3.3.2. Elemental Analysis

An elemental analysis will be performed by inductively coupled plasma (ICP) or other suitable method.

3.4. Analyses of Rheological Properties

A great deal of emphasis is placed on the rheological characterization because of the impact these variables have on the transport analysis. The two quantities required from the rheological characterization are the liquid viscosity and a characteristic effective viscosity associated with the mixture rheology.

3.4.1. Liquid viscosity

Filtered liquids will be characterized for viscosity at the endpoints of the temperature range. The rheology of this liquid is expected to be Newtonian. The viscometric configuration must be capable of accurately measuring fluid viscosities from approximately 0.0003 Pa-s (0.3 cP) to 0.05 Pa-s (50 cP). Because the transport analysis can be very sensitive to variations in this quantity, errors in this measurement should be no larger than 10% of the reading. Many capillary rheometers are suitable for these measurements.

3.4.2. Mixture Rheology

The slurry or mixture rheology can have a dramatic impact on the transportability of the proposed slurry. It is likely that many of the slurries that are to be transported in the RCSTS will have essentially Newtonian rheologies; that is, their rheological behavior does not vary significantly with the strain rate experienced or with time. These slurries are readily characterized (from the viewpoint of rheology), and the determination of waste acceptance will be straightforward. For these slurries, the only information needed for the transport assessment is the mixture viscosity, which is given at the minimum temperature of the range indicated on the proposed slurry transport record.

When the slurry rheology varies significantly from Newtonian behavior, waste acceptance and actual waste behavior during transport are more difficult to predict. For these slurries, it is essential to assess the extent of shear rate dependence and thixotropy (i.e., time dependence) in determining waste acceptance. These two behaviors can sometimes have a dramatic and detrimental effect on slurry transport and can lead to plugged transport lines.

This section describes two series of tests intended to assess the rheological behavior of the slurry and outlines a waste acceptance strategy specific to the slurry rheology. More time is devoted to these issues (relative to earlier waste characteristics) because they contribute significantly to the risk of equipment failure. Additionally, the information required in this section differs significantly from that required by the Waste Compatibility Data Quality Objectives (WHC 1995).

3.4.2.1. Thixotropy

Thixotropy is time-dependent rheological behavior that typically results from interactions of particles with one another in the slurry. Often, the more complex the particulate structure, the more thixotropic behavior is observed. Particulate structure may be the result of crystal formation (e.g., high aspect ratio or dendritic crystals) or colloidal interactions. The thixotropic behavior results from the breaking of these structures or from their dynamic rearrangement. Significant thixotropy has been observed in Hanford tank wastes. For example, Tingey reports a significant shear history dependence on the rheology of Tank 241-SY-101 waste.[1]

This section outlines a series of tests that will assess the extent to which thixotropic rheology effects could prove problematic. The complexity of the characterization effort required depends on the extent the behavior varies from Newtonian (i.e., no time-dependent variation). For slurries with essentially Newtonian behavior, relatively few tests are required for characterization. For slurries with significant thixotropic behavior, more tests and a more complex decision matrix are required to determine waste acceptance for the RCSTS.

The tests described below require a rheometer that is capable of controlled strain rate testing. The amount of slurry sample required depends on the geometry of the particular rheometer used. The slurry sample used in these tests must be taken from "undisturbed" waste samples for meaningful results; that is, care should be taken during sample preparation (from extrusion to

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[1] Tingey, J. M. 1992. *Rheological Properties of Waste from Tank 101-SY.* Letter report to Westinghouse Hanford Company. Pacific Northwest Laboratory, Richland, Washington.

sample loading in the rheometer) to ensure that sample handling, particularly operations that shear the sample such as mixing or homogenizing, are minimized. The same sample can be used for all the thixotropic tests provided that the tests are performed in the order in which the directions are provided in the following subsections. The sample used in the this characterization might not be used in the equilibrium stress versus strain rate measurements described below.

Test for Thixotropic Behavior

The test for thixotropic behavior is performed at a single, constant strain rate. The rheometer should be set so that the measured stress is recorded as a function of time. An example stress-versus-time curve for a mixture with significant thixotropic behavior is given in Figure 3.1.

As shown in Figure 3.1, the stress experienced by the mixture will typically rise to a maximum or plateau value after a relatively short time. The time required to reach this value and the length of time the stress remains at this plateau value vary significantly and depend on the characteristics of the mixture. The stress measured at this plateau is the *initial stress*, τ_1, for the mixture at this strain rate. After some time, the recorded stress will approach some asymptotic value. This stress is the *equilibrium stress*, $\tau_{1,\infty}$ for the mixture at this strain rate. The time required to reach the equilibrium stress condition (or within some fraction of the equilibrium stress) is the *equilibrium relaxation time*, t_1. In practice, the asymptotic approach to the equilibrium stress value may be fit with an exponential decay curve. The equilibrium relaxation time would then be given by the time to reach within 10% of the equilibrium stress.

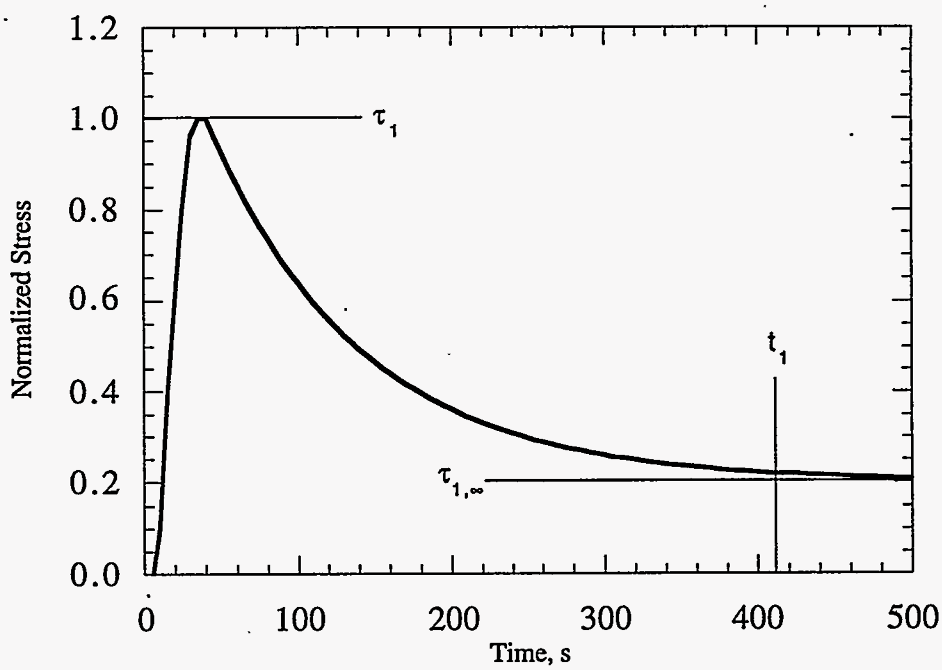

Figure 3.1. Typical Stress Versus Time Curve for a Thixotropic Mixture (relaxation times may vary significantly)

For meaningful results, the signal-to-noise ratio should be well-characterized for the rheometric configuration used. Plots of stress versus time, such as the sample shown in Figure 3.1, should include error bars indicating the expected or measured uncertainty of the measurement.

This test will answer the following three questions:

1. *What is the initial stress?* If the initial stress is below a certain value, the effective viscosity of the slurry will be low enough that any thixotropic effects will be negligible. The effective viscosity of the mixture (at this strain rate) corresponding to the initial stress is given by $\mu_{eff} = \tau_1 / \gamma$, where $\dot{\gamma}$ is the strain rate of the current test.

2. *Is the initial stress approximately equal to the equilibrium stress?* If the answer is yes, no significant thixotropic behavior is indicated at this shear rate. If $\tau_1/\tau_{1,\infty}$ is large (e.g., $\tau_1/\tau_{1,\infty}>2$) the test indicates significant thixotropy, and an additional test is required to characterize the behavior further.

3. *What is the equilibrium relaxation time?* After some time, there will be no significant time dependencies in the rheology at this shear rate. This time will set requirements for the equilibrium stress-versus-strain-rate testing (described below) and may provide insight useful for predicting slurry mobilization requirements.

Second Test of Thixotropic Behavior

When the first test indicates significant thixotropic behavior, a second test is required that is simply a repeat of the first test with a known time between tests. This test answers the following question: Within the time between tests, Δt, does the observed rheology exhibit recovery of the elevated (initial) stress? (That is, are τ_1 and τ_2 approximately equal?)

The transport issue this pertains to is pump failure. The concern here is that, while pumping, the mixture experiences relatively high strain rates. After experiencing these elevated strain rates the effective viscosity of the mixture decreases significantly, easing transport requirements. In the event of pump failure, the mixture may be able to recover the type of structure that gave rise to the higher stresses, those typical of the initial stress. If this initial stress is too high for the transfer system to overcome, plugging will occur.

The second test is an attempt to characterize whether recovery of the thixotropic behavior occurs within the time between tests. From an operations viewpoint, we would like the time between tests to be quite long. If no recovery is observed over a very long time, the urgency for flushing the line is greatly decreased. However, only relatively short times are practical for the analytical lab, because the sample will typically be held in the rheometer between tests. For this reason, we suggest a minimum of two hours between the first and the second tests for thixotropic behavior.

The degree to which the thixotropic behavior recovers between the first and second tests is defined as the *reversibility*, *R*:

$$R = \frac{\tau_2 - \tau_{2,\infty}}{\tau_1 - \tau_{1,\infty}} \qquad (3.1)$$

This reversibility typically has a value $0 \le R \le 1$. When $R = 0$, the change in structure that occurs during the first test is completely irreversible during the time between tests. In this case, once the mixture experiences this shear rate for a time t_1, no recovery of the initial stress is expected after a period of Δt at zero strain rate. In this case, the characteristic stress for transport $\tau_{1,\infty} = \tau_2 = \tau_{2,\infty}$ is suitable for use in the transport calculations.

When $R > 0$, partial or full recovery of the initial stress is expected after the time between tests. In this case, the stress characteristic of transport is not conservative from the viewpoint of pump failure. Thus $\tau_2 > \tau_{1,\infty}$, and the more conservative value of τ_2 must be used to ensure that plugging will not occur.

Battery of Tests for Thixotropic Behavior

The tests described above should be performed at the following three strain rates: 0.1, 10 and 400 s^{-1}. The lowest strain rate tests will indicate the expected stress recovery behavior during mobilization. The mid-range strain rates tests indicate the expected behavior during transport. Only one test is required at the highest strain rate. The information from this test does not indicate thixotropic behavior but merely indicates the equilibrium relaxation time at this shear rate,[2] which will be used in the equilibrium stress-versus-strain-rate testing described below. Therefore, for this test, the only required recorded information is t_1.

3.4.2.2. Shear Dependent Rheology

The equilibrium stress-versus-strain-rate measurement will determine the degree of strain rate dependence on the mixture rheology. The sample used in this test should also be from "undisturbed" waste material. The sample used in the thixotropic tests *may not* be used in these tests. The rheometer used for this test should be set in a controlled strain rate mode to sweep first from low to high strain rates and then from high to low strain rates. The range of strain rates should typically be between 1 and 400 s^{-1} but may be a subset of this range depending on the mixture characteristics, the capabilities of the rheometer, and the particular rheometer geometry used.

It is critical that a steady, laminar (rheometric) flow be maintained in the rheometer, which may limit the maximum strain rate achievable. In addition, the duration of the measurement at each strain rate must be long enough so that any thixotropic or memory effects become negligible. At low strain rates thixotropic effects can be significant, and the sweep rate of the test must allow a duration longer than the equilibrium relaxation time measured in the tests described above. At high strain rates, inertial effects limit the minimum duration. Here, too, the equilibrium relaxation time measured above will set the upper limit for the sweep rate. For measurements at interim strain rates for which equilibrium relaxation times are unavailable, an equilibrium relaxation time can be estimated by the time required to experience the equivalent total strain of a measured equilibrium relaxation time at a lower strain rate. For example, if the equilibrium relaxation time for a shear rate of 0.1 s^{-1} was determined to be 60 seconds, the estimated equilibrium relaxation time for a shear rate of 1 s^{-1} would be 6 seconds.

The result of this test will be two stress-versus-strain-rate curves (one for the "upward" sweep and one for the "downward" sweep). For the case of negligible thixotropic effects, the curves should essentially overlap. As with the tests for thixotropic behavior, meaningful results require that the signal-to-noise ratio be well-characterized for the rheometric configuration used. Plots of stress versus strain rate should include error bars indicating the expected or measured uncertainty of the measurement.

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[2] At high shear rates, the "equilibrium relaxation time" measured is actually an inertial memory relaxation time, a measure of the time required for the rheometer to "spin up" or come to a steady angular momentum. At high shear rates, this relaxation time is much longer than that associated with thixotropic effects.

The data from the upward sweep should be fit to a curve of the form

$$\mu_M = \beta\dot{\gamma}^{(n-1)} \qquad (3.2)$$

where β is the effective viscosity at a strain rate of 1 s^{-1} (sometimes called a consistency factor) and n is the behavior index. For a Newtonian mixture, $n = 1$ and the effective viscosity is independent of shear rate; if the mixture is *shear-thinning*, $n < 1$.

In transport situations the pipe flows are often turbulent, and the slurry experiences a wide variety of shear rates at a single flow rate. However, for this effort we need a single characteristic viscosity to determine transport requirements. A very gross way of estimating this, yet one that will consistently yield conservative results, is the following: If a slurry is transported in a 3-inch pipe at a bulk velocity of 1 m/s (3 ft/s), the average shear rate experienced will be approximately

$$\frac{U_b}{r} = \frac{36\,\text{in}/\text{s}}{3\,\text{in}/2} = 24\,\text{s}^{-1} \qquad (3.3)$$

or on the order of 10 s^{-1}. Therefore, the mixture viscosity is estimated using Eq. 3.2 and taking $\dot{\gamma}$ as 10 s^{-1}. Using this method, the more shear-thinning behavior the mixture demonstrates, the more conservative are the values given.[3]

3.4.2.3. Summary of Rheometric Characterization for the Slurry Mixture

The logic of the rheometric characterization for the slurry mixture is summarized in Figure 3.2. This strategy includes characterizing the effects of thixotropy (time dependence) and shear dependence on the mixture rheology. The result of this strategy provides a relatively simple analysis for a Newtonian mixture. When the sample demonstrates significant non-Newtonian behavior, the battery of tests provides a conservative effective viscosity for the completion of the transport analysis.

3.5. The Slurry Transport Characterization Record (STCR)

The product of the characterization effort is the Slurry Transport Characterization Report (STCR). This report contains all of the characterization information needed for the transport analysis. If certain tests described above were not performed because the information was already available, the report will also include the references to the prior characterization efforts from which the information was taken. The report should provide sufficient detail so that the control function will be able to verify that the test results are meaningful and applicable to the transport analysis. Where appropriate, appendixes should be provided that present the raw data (and their uncertainties) from which the final data are derived.

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[3] A more accurate, yet still conservative, approach would be to use the expression given in Equation 3.2 and solve the laminar stress solution for the pipe flow of this mixture. The characteristic stress would be given by an area averaging over the pipe cross-section.

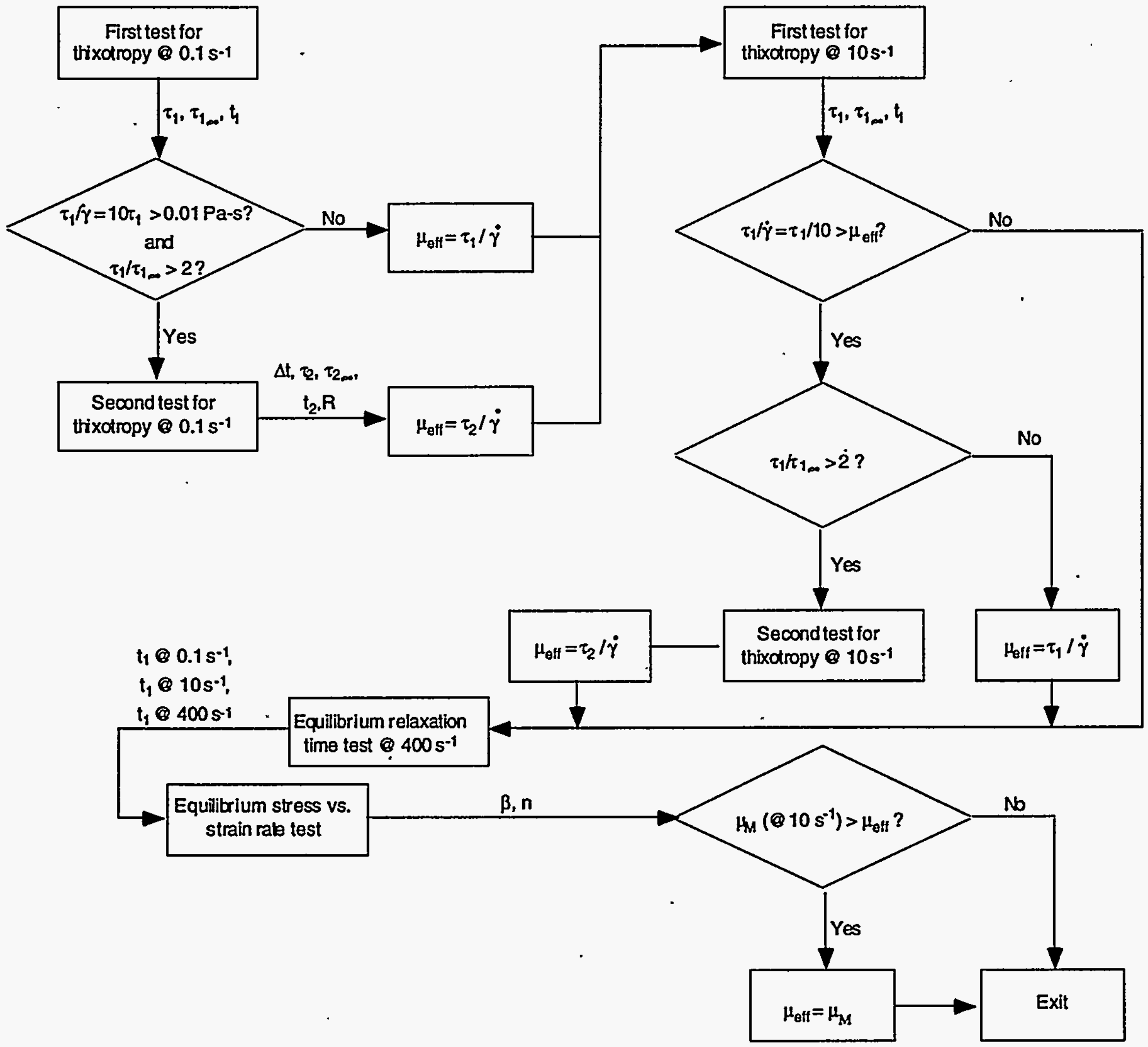

Figure 3.2. Logic for Mixture Rheology Characterization Tests

4. Transport Analysis

The transport analysis uses the available information to determine whether the transfer system (i.e., the RCSTS) is capable of transporting the slurry at a sufficient velocity to ensure that particulate suspension is maintained.

4.1. Overview of the Transport Calculations

The transport calculations are performed by a worksheet that allows entry of data specific to each proposed slurry. The minimum velocity required to transport the slurry is calculated along with the associated head losses and pressure drops. The required pressure drop is compared with that available to the system from the pump. A positive excess pressure indicates that the system is capable of safely transferring the slurry.

An example of the table generated by this worksheet is given in Table 4.1. Details of the calculations presented in this worksheet are given below.

4.2. Details of the Transport Calculations

This section describes the data entry and calculations associated with the transport calculations worksheet entitled, "Waste Acceptance Worksheet for the Replacement Cross-Site Transfer System," available with this report.

4.2.1. User-Entered Data

At the top of the worksheet is a comment field into which the user can enter an identifier for the particular slurry under consideration (only the left-most portion of this field is editable).

A number of fields occur immediately beneath the identifier field to enter information that should be available from the characterization phase. These data include the pure (filtered) liquid density, which includes any dissolved species; a representative particle size; a solids mass fraction; a representative particle density; a pure (filtered) liquid viscosity; and a representative mixture viscosity. All of these fields assume entry in SI units.

The liquid viscosity and particle density (density of the centrifuged solids) are taken to be those measured at the maximum waste temperature, while the mixture viscosity and solids mass fraction are taken at the minimum waste temperature in the range specified in the STPR.

While the correlation below assumes the representative particle size to be the mean of the volume (or mass) weighted distribution, for this analysis we use the 80th percentile value to account for a potentially broad distribution of particle sizes. Additionally, if the distribution is multimodal, the representative particle size should be taken as the mean of the largest mode containing 10% or more of the total volume.

A number of system descriptors are also required for these calculations, including the total equivalent pipe length, which comprises all equivalent lengths for elbows, valves and other fixtures; a maximum elevation increase; a percentage increase of the operational velocity above the critical velocity; and the pipe diameter. The percentage increase above the critical velocity used in

Table 4.1. Example of Waste Acceptance Worksheet

Waste Acceptance Worksheet for the Replacement Cross-Site Transfer System					
Identifier:	RCSTS sample waste description				
Variables:					
Liquid density	ρ_L	1030	kg/m^3	64.2	lbm/ft^3
		1.03	g/mL		
Particle size	d	150	μm	0.00591	in
Solids mass fraction	χ_s	0.05			
Solid density	ρ_s	1800	kg/m^3	112.1	lbm/ft^3
		1.8	g/mL		
Liquid viscosity	μ	0.0010	Pa-s	1	cP
Mixture viscosity	μ_M	0.0300	Pa-s	30	cP
Transport System:					
Total equivalent pipe length	L_{TE}	11,582	m	38,000	ft
Maximum elevation increase	H_c	9.1	m	30	ft
Increase velocity above critical		50%			
by pipe diameter		0.0779	m	3.068	in
Mixture Properties:					
Density:	ρ_M	1053	kg/m^3	65.6	lbm/ft^3
Solids volume fraction	Cv	0.029			
Transport Calculations:					
Critical Velocity	V_c	0.47	m/s	1.5	ft/sec
Req'd Excess		50%			
Operating Velocity	V_O	0.70	m/s	2.3	ft/sec
Eq. Pipe Length	TEL	11,582	m	38,000	ft
Bulk Re	Re_b	1,913			
Mixture Fric. Fact.	f_M	0.0478			
Frictional head loss	H_f	178	m	583	ft
Head loss due to elevation change	H_c	9.1	m	30	ft
Total head required	H_T	187	m	613	ft
Pressure drop required	ΔP	1.9E+6	Pa	279	psi
Flowrate:	Q	0.00334	m^3/s	52.9	gal/min
Head available from pump	H_A	*141*	*m*	*461*	*ft*
Pressure available from pump	ΔP_A	*8.3E+6*	*Pa*	*1200*	*psi*
Excess pressure drop:		*6,344*	*kPa*	*921*	*psi*

industry is typically between 20 and 40%. However, to allow for the inclusion of additional conservatism, the user may select any value above 20%. Because English units are often used in the field for these quantities, these system descriptors are entered in English units in the worksheet.

4.2.2. Calculated Quantities

This section describes the calculation methods used for the remaining elements of the spreadsheet. (Not all of these quantities are shown in the "User" view of the worksheet.)

4.2.2.1. Mixture Density

Mixture density is a function of the solid and the liquid densities as well as of the solids fraction. Another measure of mixture density is the specific gravity, which is the mixture density normalized to that of water at a given temperature (usually taken at 4°C). The mixture density will be available from experimental measurements obtained in the characterization phase. In the worksheet, the mixture density is calculated from a phase mass balance

$$\rho_M = \rho_S C_V + \rho_L (1 - C_V) \tag{4.1}$$

with the solid mass fraction related by

$$\chi_s = C_v \frac{\rho_S}{\rho_M} \tag{4.2}$$

Eq. 4.1 and 4.2 can be rearranged, eliminating C_V, giving

$$\rho_M = \frac{\rho_L}{\left(1 - \chi_S\left(1 - \frac{\rho_L}{\rho_S}\right)\right)} \tag{4.3}$$

The value that appears in the worksheet can then be compared with that reported in the characterization report (STCR) for consistency.

4.2.2.2. Solids Volume Fraction

The solids volume fraction is calculated using the solid mass fraction and the solid and mixture densities. This is calculated by rearranging Eq. 4.2 as

$$\chi_s = C_v \frac{\rho_S}{\rho_M} \tag{4.4}$$

4.2.2.3. Particle Settling Velocity

This is the velocity at which a particle settles in a stagnant fluid (without the influence of other particles). For small particles in liquid (i.e., for Stokes flow), this can be calculated as

$$V_S = \frac{g(\rho_S - \rho_S)d^2}{18\mu_L} \tag{4.5}$$

where g is gravitational acceleration and d is the particle diameter. In slurries with significant solids loadings, Eq. 4.4 will overpredict the actual settling velocity. This is conservative for the critical velocity calculation.

4.2.2.4. Particle Drag Coefficient

The particle drag coefficient is a measure of how well the particle responds to fluid motions. Particles associated with high drag coefficients follow fluid motions well. In most Hanford waste applications nonlinear drag can be ignored; so this can be calculated as

$$C_D = \frac{24\mu_L}{d V_S \rho_S} \tag{4.6}$$

4.2.2.5. Critical Velocity

The critical velocity, sometimes called the deposit or deposition velocity, for slurry transport is that below which particulate suspension is no longer maintained. The lowest energy requirements (i.e., the lowest pressure drops) are associated with transporting the slurry at this bulk velocity. Correlations for the critical velocity are given by a number of authors. For this effort, we use the correlation of Zandi and Govatos (1967) because of the following features:

- a large number of data were included in the study (approximately 1500 data points)
- it includes the effects of changes in the carrier liquid viscosity and solids loadings
- the terms in this correlation are analytical (no additional nomographs are needed)
- it gives values that are conservative relative to (higher than) those of other correlations that have similar features.

The Zandi and Govatos correlation gives the critical velocity as

$$V_c = \sqrt{\frac{40\, C_V D g\left(\frac{\rho_S}{\rho_L} - 1\right)}{\sqrt{C_D}}} \tag{4.7}$$

where D is the pipe diameter. The correlation of Zandi and Govatos (1967) gives similar results to that of Durand (1953) when the viscosity of the carrier fluid is that of water at 25°C.

A more detailed comparison of the available correlations for the critical velocity is given in Appendix A. If a more suitable correlation is obtained, the worksheet can be easily updated.

4.2.2.6. Operating Velocity

The operating velocity is determined by specifying the excess above the critical velocity. The operating velocity is the product of the critical velocity and the specified fractional excess.

4.2.2.7. Bulk Reynolds number

The bulk Reynolds number, Re_b, provides a description of the flow regime that is expected for Newtonian slurries. For Reynolds numbers in excess of 10,000, the flow is fully turbulent; for Reynolds numbers below 2000, the flow is expected to be laminar. For 2,300 $<Re_b<$10,000, the flow can be described as being in transition to turbulence or in "low Reynolds number" turbulence. Fully turbulent flows are not *always* required to maintain particulate suspension.

The Reynolds number is defined as

$$\mathrm{Re}_b = \frac{D U_b \rho_M}{\mu_M} \tag{4.8}$$

where U_b is the bulk (or average) velocity. For these calculations, we use the operating velocity as the bulk velocity for the Reynolds number calculations. Note that the mixture properties are used for the bulk Reynolds number calculation.

4.2.2.8. Required Flowrate

The required flowrate, $\dot{Q}$, is that necessary to achieve the operating velocity. This is calculated as

$$\dot{Q} = 2\pi \frac{D^2}{4} V_o \tag{4.9}$$

4.2.2.9. Darcy (mixture) Friction Factor

The Darcy friction factor is required for the pressure drop estimate. It is calculated assuming a smooth pipe by

$$f_{D,M} = 4(0.0791)\mathrm{Re}_b^{-0.25} \tag{4.10}$$

This friction factor includes the effects of the solids in the mixture because the Reynolds number is calculated using the mixture density and viscosity.

4.2.2.10. Required Pressure Drop

Models and correlations for estimating the pressure drop of a slurry being transported at a given bulk velocity are given by a number of authors. One correlation that has been demonstrated as giving reliable results is that of Durand and Condolios (1953). This correlation has the form

$$\phi = K\psi^m, \tag{4.11}$$

where ϕ is the increase in head loss compared with transport of the fluid with no solids, given by

$$\phi = \frac{i - i_w}{C_V i_w}. \tag{4.12}$$

Here i is the head loss of the slurry and i_w is the head loss (in the same system at the same velocity) of the fluid with no solids. The function ψ is given by

$$\psi = \frac{V^2 \sqrt{C_D}}{g D (s-1)}, \tag{4.13}$$

where V is the bulk velocity. While a number of authors have suggested values for K, Zandi and Govatos (1967) determined that the value of 81 gives the most reliable results over a large range of experimental data. The exponent m in Eq. 4.11 is given by Durand and Condolios as -1.5.

The pressure drop for the fluid alone is given by

$$\Delta P = f_D \frac{L_{TE}}{gD} \frac{V_O^2}{2}, \tag{4.14}$$

where L_{TE} is the total equivalent length of the transfer line, and f_D is the Darcy friction factor as calculated in Eq. 4.10, except that the Reynolds number calculation uses the liquid density and viscosity rather than the mixture properties. The pressure drop estimate for the liquid alone is calculated in the worksheet for comparison and can be seen in the "full" view at the bottom right of the worksheet.

Note that the estimated pressure drop given by Eq. 4.11 is not a function of mixture viscosity. Because we are concerned with the potential for non-Newtonian rheology effects to impact slurry transport (particularly in the event of pump failure), the pressure drop is also estimated by

$$\Delta P = f_{D,M} \frac{L_{TE}}{gD} \frac{V_O^2}{2}, \tag{4.15}$$

with the effects of the mixture properties included. (This is sometimes referred to as the homogeneous slurry approximation.) The pressure drop estimate that is used is the larger of that calculated by Eq. 4.11 or 4.15, and the calculation method used is indicated on the worksheet.

4.2.2.11. Head Available from the Pump

The head available from the pump is calculated from a fit of the data from the pump performance curve that gives the pump head at various flow rates. The curve for the pump that is to be used in the RCSTS is given in Appendix B. As this pump is equipped with a variable speed drive, the pump head is also a function of the rpm selected. This introduces the pump rpm as a transport system variable. The curve fit, therefore, includes the variation with pump speed as indicated in the pump curve.

4.2.2.12. Pressure Available from the Pump

The pressure available from the pump is simply the product of the head available and the mixture density and gravitational acceleration.

4.2.2.13. Excess Pressure Drop

The excess pressure drop is the difference between the pressure available from the pump and the pressure drop required to transport the slurry at the operating velocity. When this value is positive, the system is capable of performing the transfer at the operating velocity.

4.2.2.14. Error Messages

The spreadsheet includes very limited error checking, which includes the following warning messages:

"*The particle size must be larger than zero.*" Entering a zero particle size causes divide-by-zero errors in several places.

"*The solids mass fraction must be greater than zero.*" Divide-by-zero errors also result from entering a solids mass fraction less than zero.

"*Excess specification is too low.*" Specifying an excess for the operating velocity (above the critical velocity) below 20% does not result in numerical errors but is not advised.

"*Higher pump rpm setting required to achieve V_O.*" This message indicates that more pump energy is required to safely complete the transport. If the pump rpm is set below 3560, increasing the rpm may cause this warning to disappear. Otherwise, the transport system is not capable of transferring this slurry under these criteria.

"*Pump rpm above design maximum.*" This message appears when the pump rpm is set to a value greater than 3560.

4.3. The Transport Waste Acceptance Criterion

The calculations described in this section and performed using the available worksheet are a tool from which a technical basis for safe transport can be developed for each proposed transfer. When the worksheet calculates a positive excess pressure, this indicates that the RCSTS is capable of transferring the slurry at a sufficient velocity to maintain particulate suspension.

The objective in the current effort has been to develop an estimating method for determining whether the RCSTS is capable of transferring a proposed slurry. Rather than building in conservatism to each successive calculation and estimate, the intent has been to allow for the inclusion of conservatism at known operational decision points (e.g., specification of the excess in the operational velocity) and where measurement or behavior uncertainty provides significant risk to system failure. This way, compounding conservatism is minimized to the extent possible.

However, certain assumptions were required to provide a simple yes/no answer that would indicate potentially complex waste behavior. The degree of conservatism included is intended to correspond to the measurement or behavior uncertainty and the contribution to risk of system failure. These assumptions include the following:

- The worst waste transport behavior occurs at the endpoints of the specified temperature range. The solubility of the solid species typically increases while the mixture viscosity typically decreases with increases in the solution temperature. These effects combine to decrease the solids loading and the required pressure drops at higher temperatures. However, the liquid viscosity will also decrease with increasing temperature, allowing particles to settle more quickly, and, for this reason, the transport calculation uses the liquid viscosity at the maximum temperature of the specified range. Similarly, the solids density is typically higher at higher temperatures because a higher fraction of "insoluble" material (which has a higher density) exists there. This can result in specification of too large a temperature range and cause the transport waste acceptance criterion to fail, whereas a subset of the temperature range (either of the higher or lower temperatures) could provide acceptable results.

- Because of potentially broad particle size distributions, an 80th percentile particle size is used as representative, rather than the 50th percentile on which the engineering correlations are based. Along with the multimode provision, this builds some conservatism into the transport calculation; however, this is deemed appropriate to compensate for behavior that is atypical of the data set from which the engineering correlations were developed.
- The rheological characterization provides a characteristic effective viscosity that is increasingly conservative as the waste rheology deviates farther from Newtonian behavior. Because of this, in some cases the methodology for determining this viscosity may fail the criterion when RCSTS transport is viable. However, the conservatism is deemed appropriate here to minimize the risk of system loss in the event of pump failure. When the effects of the non-Newtonian behavior associated with these wastes are better understood in actual transport scenarios, the methodology can be updated to improve its accuracy (and decrease the associated conservatism).

In addition to these assumptions, which explicitly build some conservatism into the transport calculations, there is one implicit, underlying assumption on which the transport criterion rests: the critical velocity correlation of Zandi and Govatos (1967) is applicable to waste slurries. As mentioned earlier, this correlation was developed on the basis of a large set of data from a variety of systems, including coal-water, plastic-water, and glass-water, as well as a number of systems that did not use water as the carrier fluid. However, these systems differ in many ways from the wastes that are proposed to be transferred using the RCSTS. For example, the waste slurries will likely comprise a complex variety of solid species with broad and potentially varied particle size distributions (within the same slurry). Many of the solids will likely be in the form of colloidal aggregates, whose transport behavior is not well understood.

In industrial practice, experiments would be performed on the material to be transported to verify the applicability of the literature correlation. In the present case, there is almost a complete dearth of data relating slurry transport behavior in scaled transport facilities. Thus there is a need to incorporate critical velocity and pressure drop information from tests of this type to confirm that the engineering correlations used in these analyses are appropriate. These data could be taken during experiments designed specifically for obtaining this information using waste simulants. Some information may actually be available or attainable from current or recent evaporator campaigns using actual wastes (although this may currently be limited to particular waste types). Finally, even if no other tests are performed, measurements should be obtained during actual waste transfers to verify or improve these correlations, although it may provide very little information regarding the appropriate lower operating limit.

5. Operational and Procedural Control

This section contains a brief framework for the control function and a description of its role. Many of the details regarding implementation remain undefined.

5.1. Documentation

Because the control function authorizes system use, it is responsible for review and documentation of all previous activities. From the viewpoint of the control function, these activities provide the information necessary to build the technical basis for safe transfer using the RCSTS. The technical basis for the proposed slurry transfer, as well as the bases for resolving an related safety issues, are described in the Slurry Transport Waste Acceptance Report (STWAR) discussed briefly below.

5.2. Control

The control function uses the information from the previous activities to specify all controls which will be applicable for the transfer. The set of controls is documented in the STWAR and is unique to the proposed transfer. Typically, these controls will specify the anticipated waste constituency information that was included in the Slurry Transport Proposal Record (STPR), such as the particular solid or slurry waste, the diluent, the diluent ratio, and the temperature range. Controls related to the transport analysis are also included here; examples include the minimum transport velocity and maximum allowable pressure drop. Controls relating to on-line measurement capabilities, such as mixture viscosity, pressure loss, and solids mass fraction, may also be included to ensure that the slurry being transported remains within tolerable specifications.

5.3. Authority

The control function is also responsible for gaining (and giving) signature authority for use of the RCSTS. This function may also specify controls that differ from those recommended by the transport analysis. Where needed, this can be accomplished by increasing the safety margin to decrease the risk of system loss or safety incident. In some cases, the degree of conservatism may actually be reduced to allow a transfer when the benefits of doing so outweigh the associated risks. In either case, justification for the differing controls will be documented in the STWAR. Because the control function has the authority to specify controls and give signature authority for system use, it must bear the ultimate responsibility for success or failure of the transfer.

5.4. The Slurry Transport Waste Acceptance Report

The STWAR documents the technical bases for safe transfer using the RCSTS, including all applicable controls. Concurrence from signature authorities for this report constitute signature authority for system use within the documented provisions.

5.5. Process Monitoring and Systems Support

Once signature authority is gained, the control function will provide procedural and systems support for the transfer, including monitoring the transfer process, providing procedural and systems support for contingencies such as out of specification occurrences, and integrating the activity with retrieval and receiver tank operations.

6. Conclusions

This document provides a methodology that defines waste acceptance criteria for the RCSTS. The methodology includes characterization, transport analysis, and control.

In many cases, the characterization needs for determining waste acceptance for the RCSTS are similar to those defined by the Waste Compatibility Data Quality Objectives (WHC 1995). Significant differences from these requirements include required mixing of the actual proposed slurry constituents and detailed rheological characterization.

A tool has been developed to estimate the transport velocity required to maintain particulate suspension during transfer. The calculations compare the energy requirements for the transfer with those available from the pump system. However, the tool, a worksheet, depends on the unproved assumption that a generalized engineering correlation exists between the literature and the Hanford waste slurries.

A functional description of the control function is also given in this report. As defined, the control function is the review authority for all other activities and gains signature authority for use of the RCSTS.

7. References

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Appendix A

Comparison of Available Correlations for Critical Velocity

Appendix A

A Comparison of Available Correlations for Critical Velocity

Overview

Because of its importance to slurry transport, the determination of critical, or deposit, velocities has been the subject of numerous investigations. Many of these have resulted in published correlations based on experimental data taken with a variety of slurry systems. The correlations have been reviewed, and the discrepancies among them have been documented by Zandi and Govatos (1967), Carleton and Cheng (1974), and Oroskar and Turian (1980). While the comparison given here is by no means intended to be exhaustive, models typical of those appearing in the literature are compared in this appendix.

Early models, such as those given by Durand (1953) and Sinclair (1962), were largely empirical or based on limiting phenomena. Durand's correlation is

$$V_c = F_L\sqrt{2gD(s-1)} \tag{A.1}$$

where F_L is a constant that includes variations in particle size and solids volume loading (given in a nomograph), D is the pipe diameter, and s is the particle-to-fluid density ratio. Sinclair found that when the particle size is small compared with the pipe (i.e., when d/D < 0.001 - d <80 μm for the RCSTS), the critical velocity is independent of pipe size. His correlation is

$$V_c = \sqrt{650g\frac{4}{3}d(s-1)^{0.8}} \tag{A.2}$$

Because the data on which these correlations were based used water, at ambient conditions, as the carrier fluid, the effects of liquid viscosity are not incorporated into their correlations. Models such as those described by Zandi and Govatos (1967), Babcock (1968), and Shook (1969) include these effects. In addition, the correlation of Zandi and Govatos included a large variety of data (1452 points) from a variety of slurry systems. The Zandi and Govatos correlation was given as Equation 4.7:

$$V_c = \sqrt{\frac{40\,C_V D g(s-1)}{\sqrt{C_D}}}$$

where C_V is the solids volume fraction and C_D is the particle drag coefficient given in Equation 4.6. Babcock's correlation is essentially identical, differing only by a factor of two:

$$V_c = \sqrt{\frac{10\,C_V D g(s-1)}{\sqrt{C_D}}} \tag{A.3}$$

Shook et al. suggested a somewhat different relationship:

$$V_c = 2.43\,C_V^{1/3}\sqrt{\frac{2Dg(s-1)}{\sqrt{C_D}}} \tag{A.4}$$

which normally gives values between that of Zandi and Govatos and that of Babcock. The expected accuracy of these correlations is typically ± 20%.

More recently, transport models have been developed that potentially give more accurate results than the empirical or semi-empirical models. These include the model suggested by Oroskar and Turian (1980). The application of this model is probably restricted to relatively small particles (<0.5 mm) and includes the effect of hindered settling. With this constraint the model has been shown to give impressive results. However, the formulation of the model is implicit so that iteration is required for determination of V_c. This feature makes the incorporation of the Oroskar and Turian model inconvenient for inclusion in the worksheet tool.

Gillies' model, as suggested by Shook and Roco (1991), may also provide more accurate results than many of the earlier models. They suggest binning the particle sizes such that the effects of the particle fraction below 74 µm in size is included with the liquid. The solids measurements include only the solids fraction above 74-µm size. An attractive feature of this model is that it includes the effects of variation in liquid viscosity, particle size, pipe size, etc. However, binning the solids as suggested by this approach may be impractical during the characterization phase outlined in Chapter 3 of the main report.

Comparison of the Correlation Predictions

In this section we compare the predictions of several models for what will likely be typical values of variables for the slurries to be transferred in the RCSTS. In this effort, the models of Zandi and Govatos (1967), Babcock (1968), Shook (1969), Durand (1953), and Sinclair (1962) are compared. The cases for each of the comparisons are summarized in Table A.1.

Figures A.1 - A.6 demonstrate the parametric variation of the predicted critical velocity from each of the correlations. In each of these figures, the critical velocity predicted by each of the correlations is plotted as a function of the liquid viscosity. Because the correlations of Durand and Sinclair do not vary with the liquid viscosity, they appear as straight lines. The correlation of Sinclair does not apply to the larger particle sizes (particularly for Case 6) but is presented for reference.

The correlation of Durand is a good approximation of that of Zandi and Govatos for large particle sizes (Case 6) when the liquid viscosity is around 0.001 Pa-s (1 cP), probably because the data on which Durand's correlation was based were taken from large-particle-size slurries of coal and sand particles in water at ambient temperatures. Further (as mentioned in Section 4), note that the correlation of Zandi and Govatos predicts the highest (most conservative) critical velocities of the correlations, including the effect of liquid viscosity.

Table A.1. Summary of Comparison Cases

Case	1	2	3	4	5	6
s	1.2	3.0	2.0	2.0	2.0	2.0
χ_s	0.10	0.10	0.05	0.20	0.10	0.10
d (µm)	100	100	100	100	50	500

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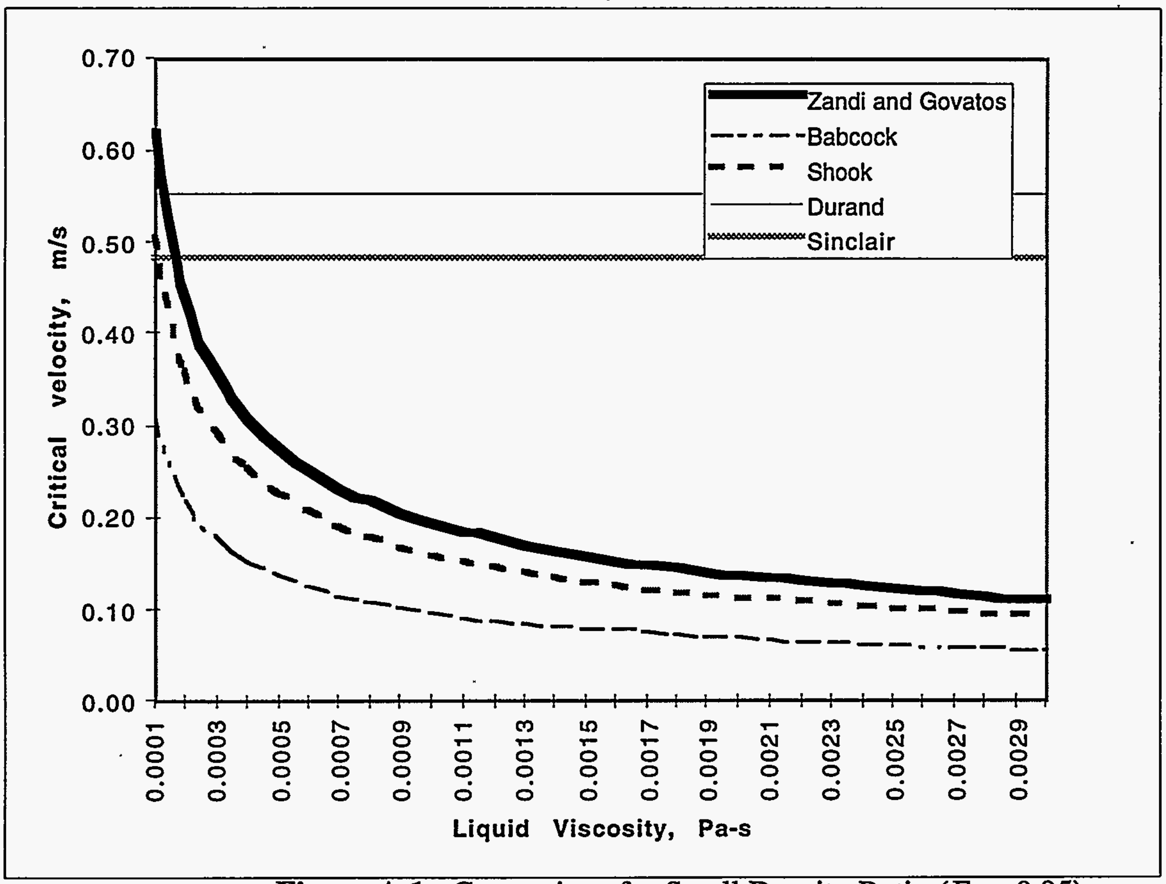


Figure A.1. Comparison for Small Density Ratio ($F_L = 0.95$)

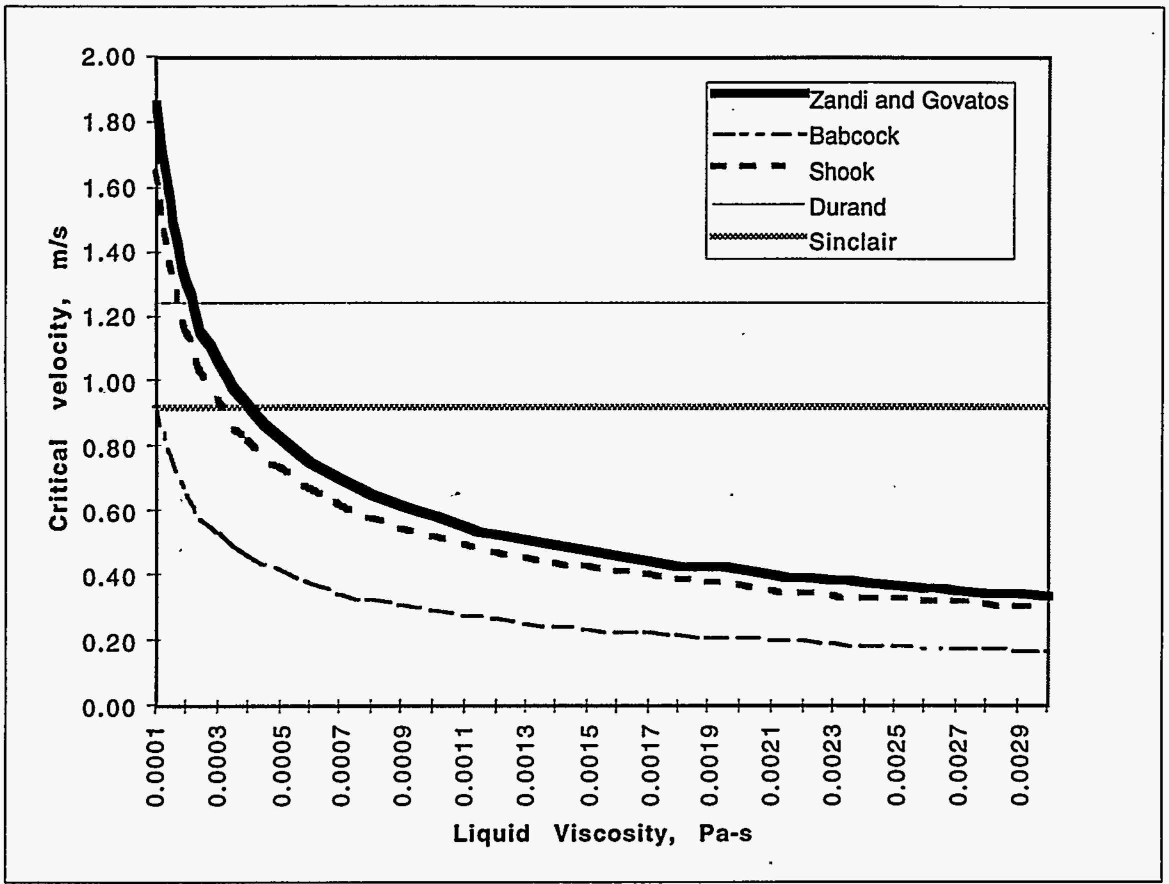


Figure A.2. Comparison for Large Density Ratio ($F_L = 0.95$)

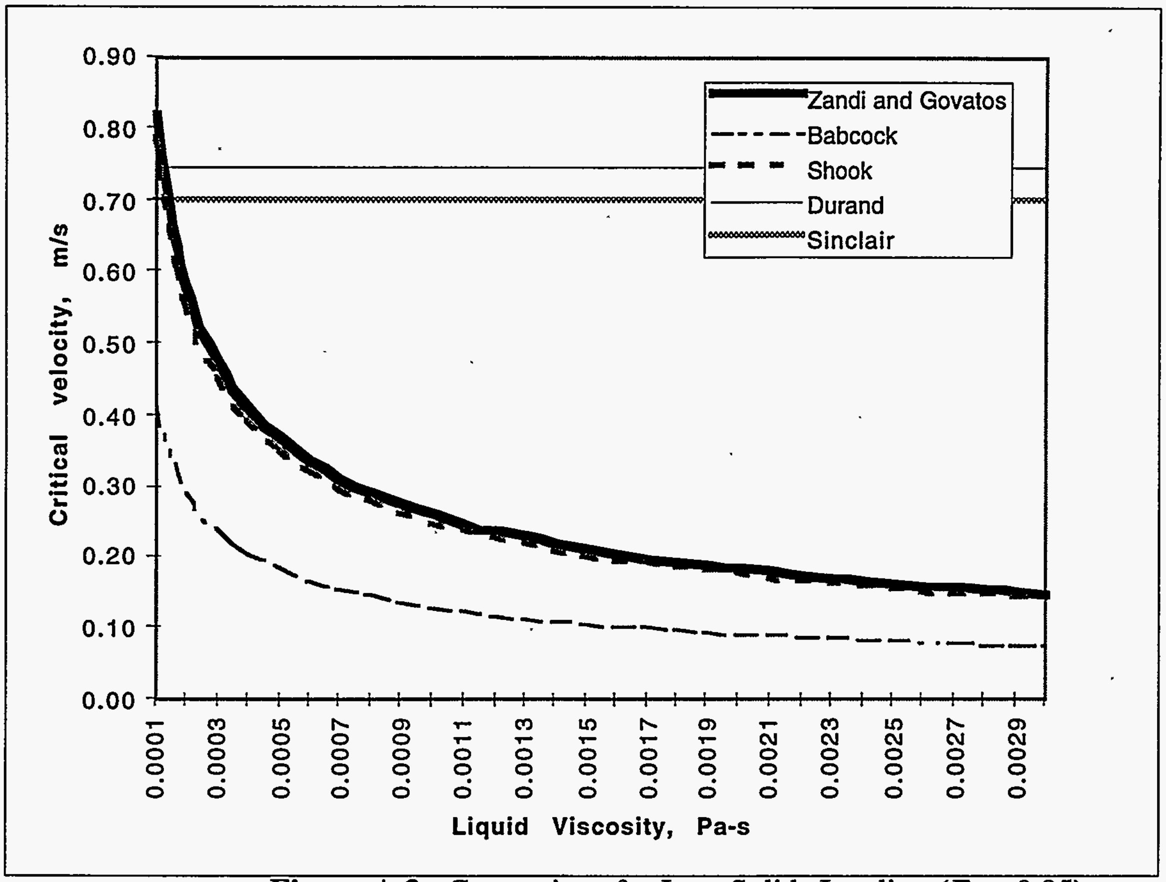


Figure A.3. Comparison for Low Solids Loading ($F_L = 0.85$)

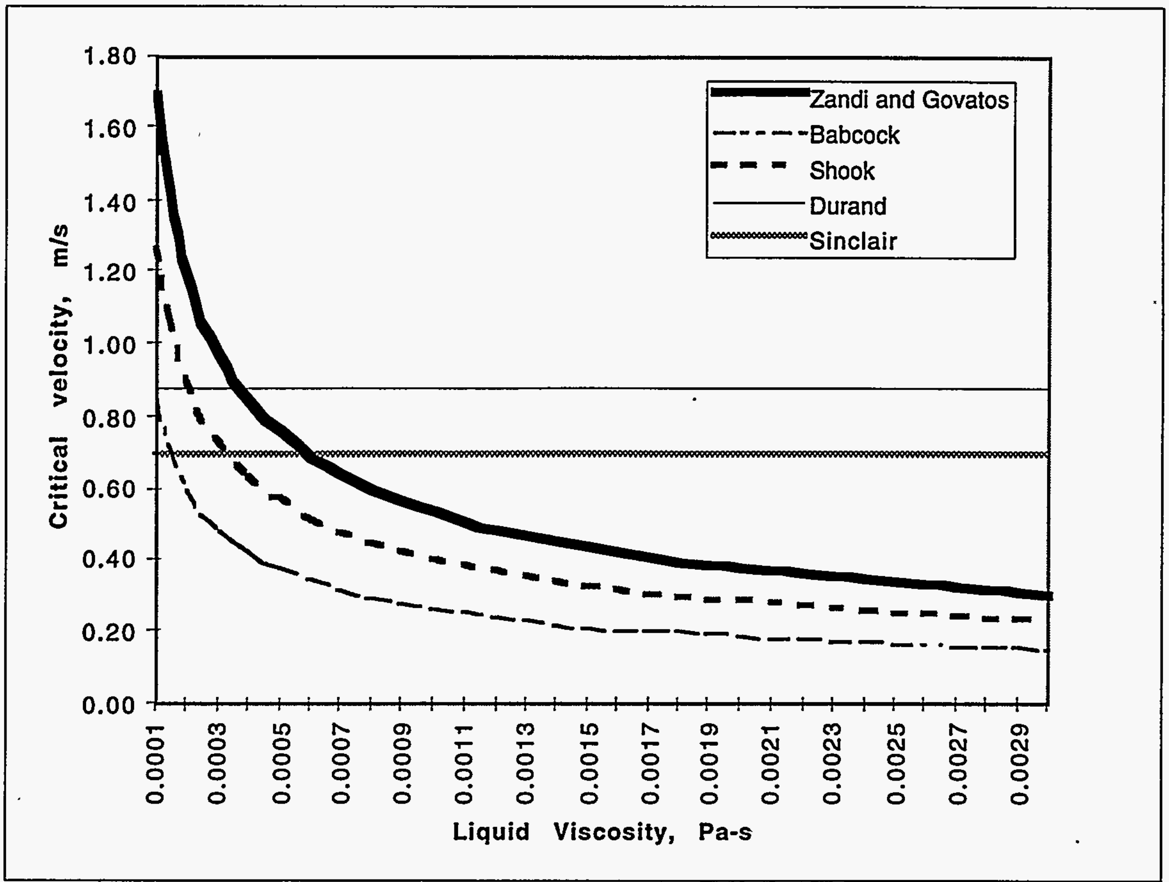


Figure A.4. Comparison for High Solids Loading ($F_L = 1.0$)

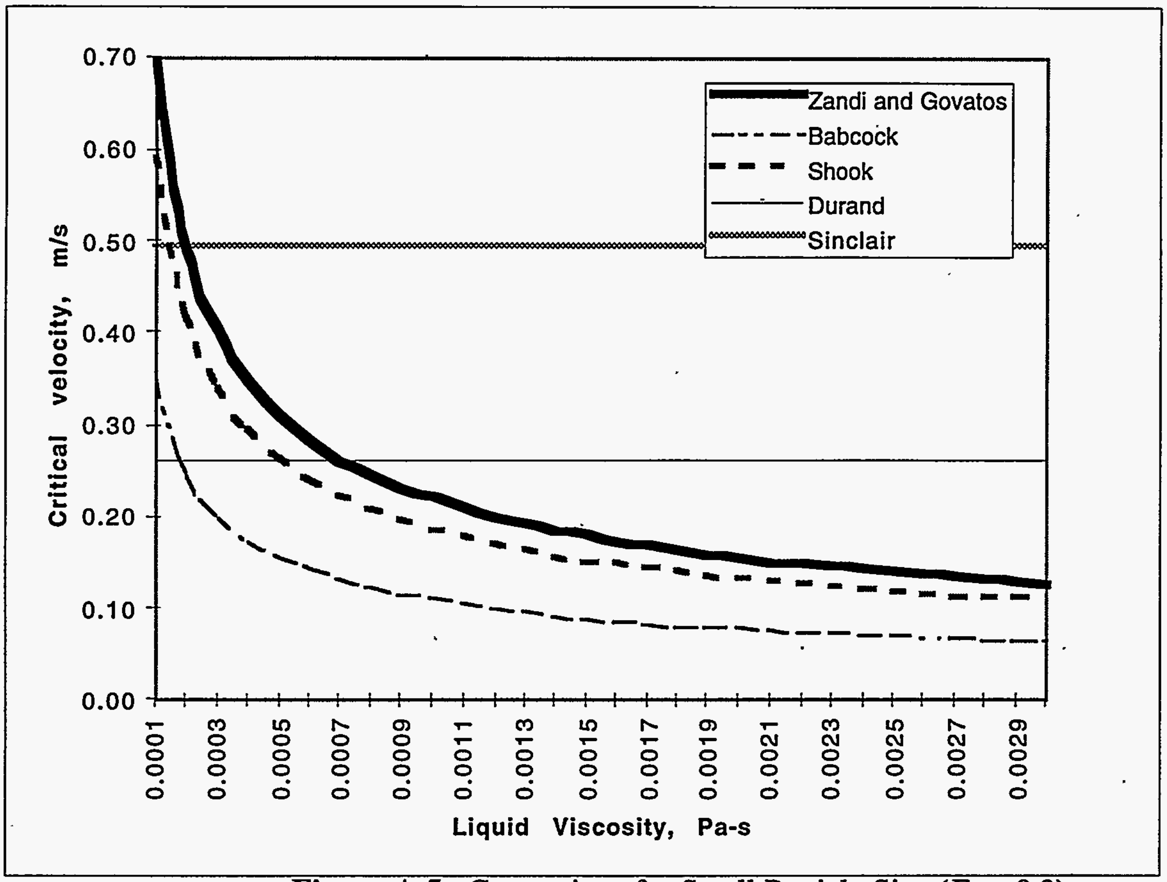


Figure A.5. Comparison for Small Particle Size ($F_L = 0.3$)

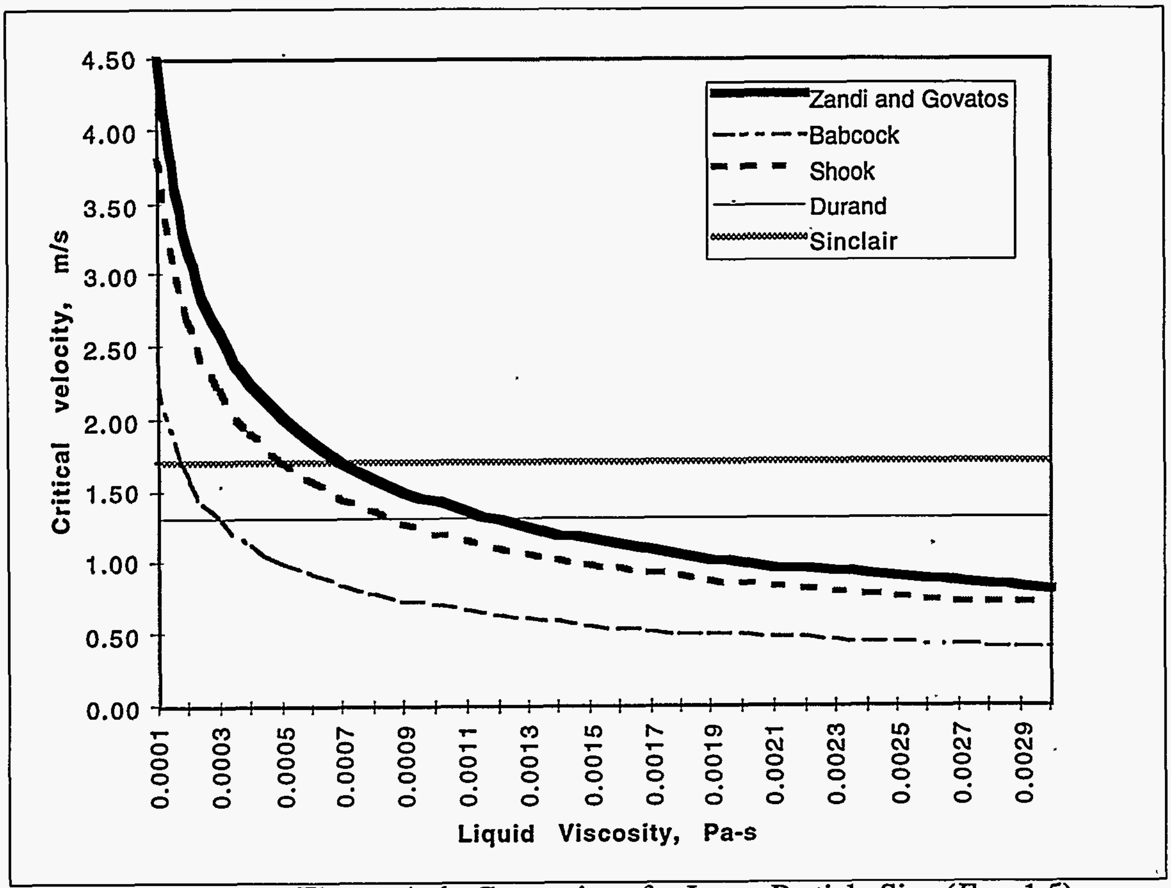
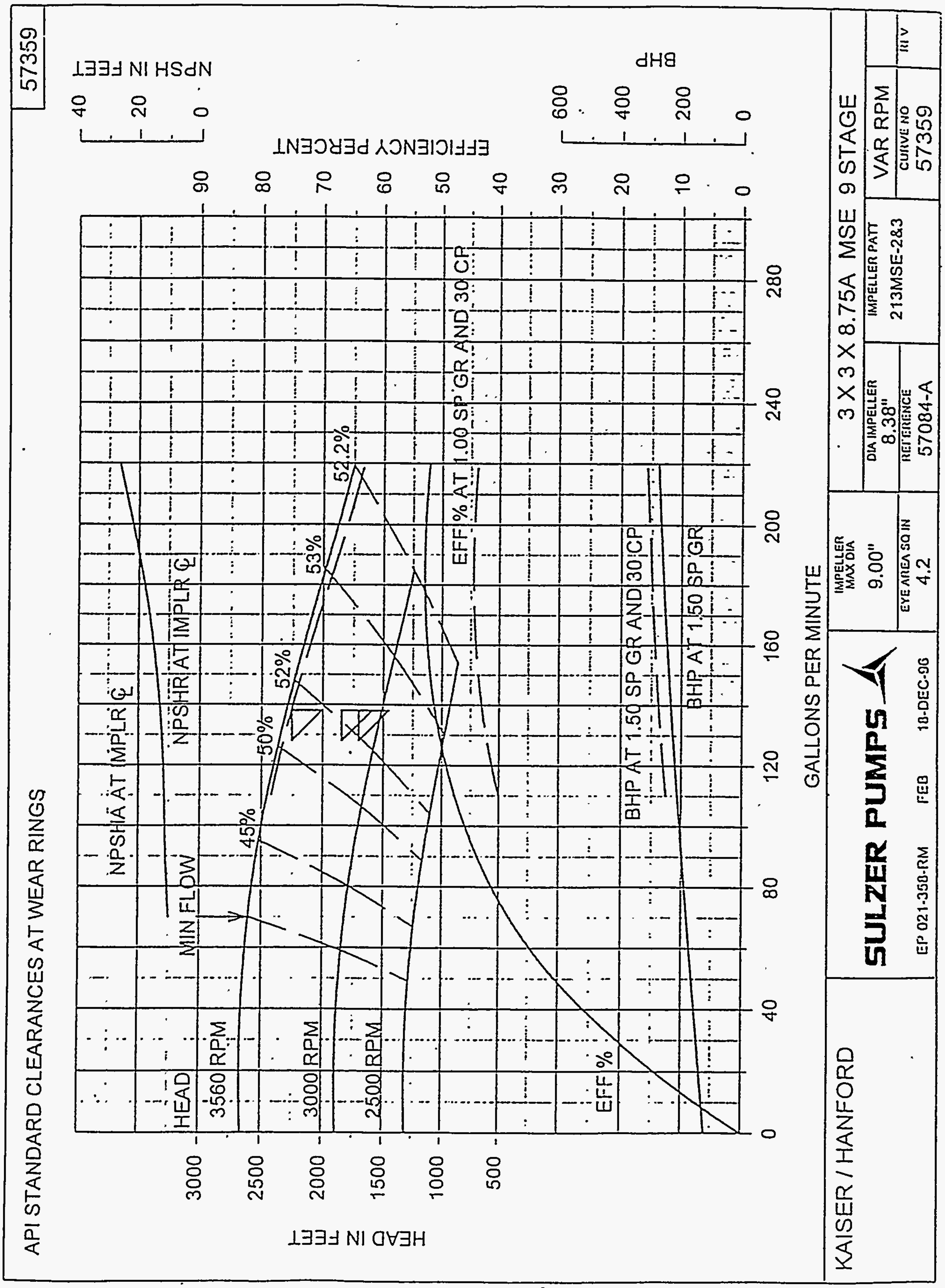


Figure A.6. Comparison for Large Particle Size ($F_L = 1.5$)

Appendix B

Pump Performance Curve for the Hanford Replacement Cross-Site Transfer System


57359
API STANDARD CLEARANCES AT WEAR RINGS
NPSH IN FEET
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20
0
EFFICIENCY PERCENT
90
80
70
60
50
40
30
20
10
0
BHP
600
400
200
0
HEAD IN FEET
3000
2500
2000
1500
1000
500
0
40
80
120
160
200
240
280
GALLONS PER MINUTE
HEAD
3560 RPM
3000 RPM
2500 RPM
EFF %
NPSHA AT IMPLR ℄
NPSHR AT IMPLR ℄
MIN FLOW
45%
50%
52%
53%
52.2%
EFF % AT 1.00 SP GR AND 30 CP
BHP AT 1.50 SP GR AND 30 CP
BHP AT 1.50 SP GR
KAISER / HANFORD
SULZER PUMPS
EP 021-350-RM
FEB
18-DEC-96
IMPELLER MAX DIA
9.00"
EYE AREA SQ IN
4.2
DIA IMPELLER
8.38"
REFERENCE
57084-A
3 X 3 X 8.75A MSE 9 STAGE
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