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Rheological Evaluation of Simulated Neutralized Current Acid Waste — Transuranics

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September 1986

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SUMMARY

At the Hanford Plutonium and Uranium Extraction Plant (PUREX), in Richland, Washington, plutonium and uranium products are recovered from irradiated fuel by a solvent extraction process. A byproduct of this process is an aqueous waste stream that contains fission products. This waste stream, called current acid waste (CAW), is chemically neutralized and stored in double shell tanks (DSTs) on the Hanford Site. This neutralized current acid waste (NCAW) will be transported by pipe to B-Plant, a processing plant located nearby. In B-Plant, the transuranic (TRU) elements in NCAW are separated from the non-TRU elements. The majority of the TRU elements in NCAW are in the solids. Therefore, the primary processing operation is to separate the NCAW solids (NCAW-TRU) from the NCAW liquid. These two waste streams will be pumped to suitable holding tanks before being further processed for permanent disposal.

To ensure that the retrieval and transportation of NCAW and NCAW-TRU are successful, researchers at Pacific Northwest Laboratory (PNL) evaluated the rheological and transport properties of the slurries. This evaluation had two phases. First, researchers conducted laboratory rheological evaluations of simulated NCAW and NCAW-TRU. The results of these evaluations were then correlated with classical rheological models and scaled up to predict the performance that is likely to occur in the full-scale system. This scale-up procedure has already been successfully used to predict the critical transport properties of a slurry (Neutralized Cladding Removal Waste) with rheological properties similar to those displayed by NCAW and NCAW-TRU (McCarthy, Chan and Lokken 1985).

Attempts to characterize the radioactive waste for rheological studies are ongoing. As new samples are retrieved from DSTs, new recipes and preparation methods are generated to more realistically simulate the actual waste. Presently, there are several methods for preparing simulated NCAW. Two of these methods have been used in this rheological study. One was developed at PNL, and the other was developed at Rockwell Hanford Operations (Rockwell). The PNL procedure is based on analyses of radioactive NCAW, and is prepared by

first creating a CAW simulant. The CAW is neutralized and then digested to simulate the aging process in the DSTs. This simulant is called NCAW-PNL. NCAW-RHO was prepared by simulating the waste from the first solvent extraction column at PUREX, then sugar-denitrating and neutralizing it; it was not digested. Simulated NCAW-TRU was prepared by processing the simulated NCAW in a manner similar to the process that the waste would under go in B-Plant. Two NCAW-TRU slurries were prepared: one by processing NCAW-PNL (designated NCAW-TRU-PNL), and one by processing NCAW-RHO (designated NCAW-TRU-RHO).

Comparison of the simulated wastes prepared using the two preparation methods were conducted to determine how sensitive the transport properties of the slurries were to the method of preparation. The sensitivity of the properties of the two simulated wastes relates to the degree of confidence in designing a pump-pipe system capable of handling the actual waste.

The physical and rheological properties of each NCAW and NCAW-TRU slurry at 25°C were evaluated in the laboratory. The properties displayed by the slurries allowed them to be described by any one of the three rheological models: pseudoplastic, yield-pseudoplastic, or Bingham plastic. The Bingham plastic model was chosen to describe the slurries because the data for NCAW-PNL, NCAW-RHO and NCAW-TRU-PNL fit the Bingham plastic model best. The data for NCAW-TRU-RHO fit the pseudoplastic model slightly better than they fit the Bingham plastic model. However, the Bingham plastic model was used to describe NCAW-TRU-RHO in order to compare it with NCAW-TRU-PNL. The classical non-Newtonian model for Bingham plastic fluids was used with laboratory data to predict full-scale pump-pipe network parameters. In addition, a comparison between the pseudoplastic and Bingham plastic models for NCAW-PNL is presented here. The purpose of this comparison was to determine the sensitivity of calculated values of transport properties of the fluid to the model chosen to describe the fluid.

The full-scale pump-pipe network must transport NCAW and NCAW-TRU slurries at velocities that prevent the deposition of solids in the transfer lines. Laboratory estimates of critical velocity were scaled up to predict full-scale performance. These estimates, using the Bingham plastic rheological model, predict that a critical transport velocity of 0.8 and 1.2 feet per second (fps)

will be required to suspend NCAW-PNL and NCAW-RHO, respectively, in the full-scale system. The pseudoplastic model predicts an 18% lower critical transport velocity for NCAW-PNL (0.65 fps). The critical transport velocity for NCAW-TRU-PNL and NCAW-TRU-RHO is 0.7 and 0.4 fps, respectively. These velocities are below the design velocity in the full-scale system (2.1 fps; 50 gpm) and should prevent solids deposition in transfer lines during normal operations.

The pump used to transport NCAW and NCAW-TRU slurries must be sized to overcome pressure losses that will result as the slurries flow through the full-scale pipe network. Laboratory data were scaled up to provide estimates of these pressure losses. The estimates, summarized in Table 1, assume that each slurry is pumped through a 3-in., schedule 40, smooth, carbon steel pipe with an equivalent length of 9,100 feet. These assumptions reflect the current design parameters for the full-scale system. When information about the pipe roughness of the actual full-scale pipe network becomes available, these predictions of pressure drop must be adjusted.

The current Rockwell design for the full-scale pump-pipe system specifies that one pipe volume of water be used for flushing, and that water be delivered at a rate of 75 gpm (3.3 fps). The flushing operation is intended to resuspend the solids that have settled in the pipe during shutdown. The critical flushing velocity must be greater than the critical deposition velocity. The critical deposition velocity will be approximately equal to the velocities associated with the critical Reynolds number. A resuspension velocity of 3.3 fps is approximately 4, 3, 5 and 8 times the full-scale velocities predicted as the laminar-turbulent transition velocities for NCAW-PNL, NCAW-RHO, NCAW-TRU-PNL and NCAW-TRU-RHO, respectively, at 25°C.

TABLE 1. Predictions of Full-Scale Pressure Drop (psi) at 25°C

Flow Rate	NCAW-PNL ^(a) (psi)	NCAW-PNL ^(b) (psi)	NCAW-RHO ^(b) (psi)	NCAW-TRU-PNL ^(b) (psi)	NCAW-TRU-RHO ^(b) (psi)
50 gpm	40	35	35	25	24
75 gpm	77	72	72	53	48

(a) Pseudoplastic rheological model.

(b) Bingham plastic rheological model.

The degree of resuspension achieved during flushing will be a function of the pressure gradient applied to the settled solids, the steady-state fluid velocity achieved in the pipe, and the amount of flush water delivered during the flush. The pressure gradient necessary to resuspend settled NCAW and NCAW-TRU must be established during pilot-scale tests using a pump-pipe test loop. Such tests were beyond the scope of this project.

A series of pilot-scale resuspension tests with Neutralized Cladding Removal Waste (NCRW) was recently completed (McCarthy, Chan, and Lokken 1985). The NCRW slurry exhibited properties that were similar to those exhibited by the NCAW and NCAW-TRU slurries. Some of these properties are summarized in Table 2 for comparison to NCAW and NCAW-TRU slurries.

During the NCRW pilot-scale tests, the pressure gradient applied during resuspension equaled 1.3 times the normal pressure drop associated with a flow velocity of 3.3 fps (75 gpm). If this criterion is applied to the full-scale NCAW and NCAW-TRU system, pressure drops of approximately 95, 95, 69 and 63 psig would result (using the Bingham plastic rheological model to describe the fluid) during flushing of NCAW-PNL, NCAW-RHO, NCAW-TRU-PNL and NCAW-TRU-RHO, respectively. A slightly higher pressure drop of approximately 100 psig would result for NCAW-PNL if the pseudoplastic rheological model were used. These predictions of full-scale line flushing pressure drop requirements are estimates. Actual requirements must be established during pilot-scale tests.

TABLE 2. Comparison of NCAW, NCAW-TRU and NCRW Slurry Properties at 25°C

<u>Property</u>	<u>NCRW</u>	<u>NCAW-PNL</u>	<u>NCAW-RHO</u>	<u>NCAW-TRU-PNL</u>	<u>NCAW-TRU-RHO</u>
Viscosity at 50 s^{-1} , cp	4	7	16	5	2
V_c -full-scale, fps	0.3-0.4	0.6-0.8	1.2	0.7	0.4
ΔP for 9100 ft, psi at 2.1 fps	31-36	35-44	35	25	24

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1.0 INTRODUCTION AND OBJECTIVES

The Hanford Plutonium and Uranium Extraction (PUREX) Plant, located in Richland, Washington, was designed to recover plutonium and uranium products from irradiated fuel. After the Zircaloy cladding is dissolved from the fuel elements, the plutonium and uranium are dissolved in nitric acid. The solution is sent to a solvent extraction system to recover, separate and purify the uranium and plutonium.

The first solvent extraction column separates plutonium and uranium from an aqueous feed stream. The aqueous waste stream containing the fission products from this first column, referred to as current acid waste (CAW), is concentrated and treated with sucrose solution to reduce the nitric acid content. The concentrated, partially denitrated CAW is then neutralized with 19 molar (M) sodium hydroxide (NaOH) to a minimum excess free-hydroxide (OH^-) concentration of 1M.^(a)

The neutralized CAW (NCAW) is stored in double-shell tanks (DSTs) on the Hanford Site. The waste will be pumped from the DSTs to a processing plant, B-Plant, located nearby. The processing plant will separate the low-level radioactive waste from the high-level waste. The wastes will be pumped from B-Plant to suitable holding tanks before being permanently disposed of.

In B-Plant, the transuranic (TRU) elements and cesium in NCAW are separated from the non-transuranic elements. The majority of the transuranic elements in NCAW are assumed to be in the solids. Therefore, the primary processing operation is to separate the NCAW solids from the NCAW liquid (Figure 1.1).

One process being considered by Rockwell Hanford Operations (Rockwell) to separate the solids from the liquid is to allow the solids in the NCAW to settle, then decant off the supernatant. A water wash is performed on the settled solids to remove the non-transuranic elements in the form of sulphates, carbonates and fluorides from the NCAW settled solids. The water wash consists

(a) Kirch, N. W. 1984. "Integrated Aging Waste Tank Processing Flowsheet," PFD-T-200-0005. Rockwell Hanford Operations, Richland, Washington.

FIGURE 1.1. Schematic of Process NCAW Undergoes in B-Plant

of adding water to the solids at a volume ratio of 15 to 1. The resulting slurry is agitated and allowed to settle. The supernate from this step is decanted and combined with the NCAW supernate.

The combined water wash and NCAW supernates would be put through a polishing-filtration step to further separate possible TRU solids in the supernatants. The solids from the polishing step would be added to the existing NCAW solids that contain the TRU elements. Water would be added to the TRU solids until the volume of the combined solids and water reaches the original volume of the NCAW sample. At this time, the slurry would be called NCAW-TRU. Sodium hydroxide and sodium nitrite would be added to the NCAW-TRU as required to conform to Rockwell Tank Farm corrosion specifications.

The transfer of the NCAW-TRU slurry from B-Plant to the holding tank must be conducted in a way that prevents line plugging and particle segregation. Transfer lines and pumps must be specifically designed to handle each slurry. The design of this equipment will be guided by the rheological properties of each slurry.

Attempts to characterize the rheological properties of actual NCAW are ongoing. Difficulties have been encountered because the high gamma radiation

emissions prevent adequate sampling. As new samples are received from the DSTs, new recipes and preparation methods for realistically simulating the actual waste are generated. Presently, there are two methods for preparing simulated NCAW.

PNL prepares NCAW by simulating CAW, neutralizing it, and digesting it to simulate the aging process in the DSTs. The end result is similar to the composition of an actual NCAW sample obtained from one of the DSTs in November 1985. In contrast, Rockwell prepares NCAW by simulating the waste from the first solvent extraction column at PUREX, then sugar-denitrating and neutralizing it; it is not digested. Using these two NCAW slurries, two batches of simulated NCAW-TRU were prepared for these rheology studies by processing the simulated NCAW slurries in a manner that was similar to what they would undergo in B-Plant.

The rheological properties of the simulated slurries are dependent on the way in which they are prepared. Two preparation methods were used to determine how sensitive the transport properties of the slurries were to the method of preparation. The range of properties of the two simulated wastes relates to the degree of confidence in designing a pump-pipe system capable of handling the actual waste. In other words, a large range of measured properties would mean that the rheological properties of the actual waste could be significantly different from the simulations. This difference could affect the ability of the pump-pipe system designed to transport the slurry. Conversely, a similarity in the transport properties of the two slurries would indicate that the method of preparation does not significantly affect the way the slurry behaves in transport, and that the two simulations can be considered realistically representative of the actual waste. This conclusion would increase our confidence that the design of the pump-pipe system is adequate regardless of the characterization of the actual waste.

Rheology is the field of study concerned with the deformation and flow behavior of materials. The goal of the work summarized in this report was to evaluate the rheological and transport properties that are critical to assuring successful handling of the processed NCAW.

The specific objectives of the evaluation were to: 1) evaluate and compare the rheological and transport properties of simulated NCAW prepared by Rockwell (NCAW-RHO) and simulated NCAW prepared by PNL (NCAW-PNL), 2) prepare simulated NCAW-TRU from NCAW-RHO (NCAW-TRU-RHO) and NCAW-PNL (NCAW-TRU-PNL), and 3) evaluate and compare the rheological and transport properties of NCAW-TRU-RHO and NCAW-TRU-PNL.

Chapter 2 of this report describes the theoretical foundation of slurry flow systems by presenting the classical rheological models that are used to describe homogeneous and heterogeneous flow systems. Because the results obtained here are only valid for the slurries utilized, Chapter 3, "Preparation of Simulated NCAW and NCAW-TRU," describes how the NCAW and NCAW-TRU slurries were prepared. The laboratory-scale viscometric results and the physical property results are summarized in Chapter 4, "Laboratory Rheological Evaluations." Chapter 5, "Rheological Models for Flow in Pipes," discusses the analytical models used to determine critical Reynolds numbers and associated pipe flow parameters. Laboratory results are scaled up using the models in Chapter 5 to establish engineering design requirements for a full-scale transfer system, which is described in Chapter 6.

2.0 SLURRY FLOW SYSTEMS

Rheology is the field of study concerned with the deformation and flow behavior of materials. The procedures used to design slurry transport processes are based on classical rheological models for homogeneous and heterogeneous flow systems. These models were used to classify NCAW and NCAW-TRU slurries, and to scale up the laboratory data to predict the behavior of the slurries in a full-scale transport system. The theoretical models used to define the fluid flow behavior of slurries are described in this section.

2.1 CLASSIFICATION OF SLURRIES

A complex mixture can be defined as a single-phase, non-Newtonian fluid, a multiphase mixture of a fluid and a solid, or a mixture of two or more fluids. A classification of complex mixtures based on the effect of phase condition and flow behavior is depicted on Figure 2.1. A multiphase mixture can be classified as a fine dispersion, a coarse dispersion, a macro-mixed flow pattern, or as a stratified flow pattern.

Macro-mixed and stratified heterogeneous flow behavior applies to gas-liquid and liquid-liquid mixtures. Examples of a macro-mixed flow are frothy

Single Phase	Multi-Phase (Gas-Liquid, Liquid-Liquid, Gas-Solid, Liquid-Solid)			
	Fine Dispersion		Coarse Dispersion	Macro-Mixed Stratified
True Homogeneous	Pseudo- Homogeneous		Heterogeneous	
	Laminar Turbulent	Turbulent Only		
<div> <div>Flow Behavior as Single Phase</div> <div></div> </div>			<div> <div>Flow Behavior as Multi-Phase</div> <div></div> </div>	

FIGURE 2.1. Classification of Complex Mixtures

and highly turbulent mixtures of gas and liquid or of immiscible liquids under conditions where neither phase is continuous. Stratified flow exists when each phase of a gas-liquid mixture or a mixture of two immiscible liquids is continuous.

For liquid-solid slurries, a fine dispersion is a mixture of fine particles of solids that are uniformly dispersed in a continuous liquid phase. Solids with a diameter less than about 40 μm usually form fine dispersions and can be considered to be pseudohomogeneous mixtures (Bain and Bonnington 1970). Solid particles with a diameter greater than about 40 μm usually form coarse dispersions, have a tendency to settle, and can be considered to be heterogeneous mixtures. The techniques used to design transport and treatment systems to achieve pseudohomogeneous and heterogeneous mixtures differ markedly. These procedures are described in Section 2.3.

2.2 PSEUDOHOMOGENEOUS MIXTURES

Viscous, single-phase fluids and pseudohomogeneous multiphase fluid mixtures are classified according to their response to shearing stresses. A shear stress is defined as:

$$\tau = \frac{F}{A} \quad (1)$$

where τ = shear stress, N/m^2 (Pascal)

F = force, N

A = area, m^2

For Newtonian fluids in laminar flow:

$$\tau = \mu \frac{dv}{dy} \quad (2)$$

where τ = shear stress, N/m^2 (Pascal)

μ = viscosity, Ns/m^2 (Pascal-sec)

$\frac{dv}{dy}$ = shear rate in y direction, s^{-1}

The viscosity, μ , is a proportionality constant that is independent of shear rate and affected only by pressure and temperature for a fluid system. A plot of shear stress versus rate of shear in the laminar flow region is known as a rheogram (see Figure 2.2a). The slope of the curve is constant for a Newtonian fluid. Non-Newtonian fluids are those that display rheograms that are not linear through the origin at a given temperature and pressure. Non-Newtonian fluids are usually classified as time-independent, time-dependent or viscoelastic fluids.

2.2.1 Time-Independent Non-Newtonian Fluids

Time-independent non-Newtonian fluids are fluids for which rate of shear at a given point is solely dependent upon instantaneous shear stress at the point. Rheograms for classical time-independent non-Newtonian fluids are depicted on Figure 2.2a. The relationship between apparent viscosity and shear rate for these fluids is described on Figure 2.2b.

2.2.1.1 Fluids Without a Yield Stress

Dilatant and pseudoplastic non-Newtonian slurries do not exhibit a shear stress at a shear rate of zero. Pseudoplastic and dilatant materials exhibit a continuous variation of shear stress with shear rate, the slope of the curve decreasing (pseudoplastic) or increasing (dilatant) as shear rate increases (see Figure 2.2a). Equations that relate shear stress and shear rate for these fluids are included in Table 2.1.

Most non-Newtonian slurries exhibit pseudoplastic behavior. Because the exponent, n , is less than unity for pseudoplastic fluids (see Table 2.1), the apparent viscosity, K , decreases with increasing shear rate. Pseudoplastic fluids include rubber solutions, adhesives, polymer solutions, starch suspensions, mayonnaise, soap, detergent slurries, paints, biological sludges, and many other solid-liquid suspensions.

Dilatant fluids are much less common than pseudoplastic fluids. Dilatancy is usually observed only at select solids concentrations in suspensions of irregularly shaped solids. The apparent viscosity of dilatant fluids increases with increasing shear rate because the exponent, n (see Table 2.1), is greater than one. Quicksand, wet beach sand, and some aqueous suspensions of titanium dioxide are examples of dilatant fluids (Skelland 1967).

FIGURE 2.2. Rheograms for Time-Independent Non-Newtonian Fluids

2.2.1.2 Fluids With a Yield Stress

Bingham plastic, yield-pseudoplastic and yield-dilatant pseudohomogeneous slurries exhibit a yield stress at a zero shear rate. This yield stress is caused by the internal structure created by the small particles in the fluid. The structure of particles prevents movement of the fluid for values of the shear stress, τ , less than the yield value, τ_y . When τ exceeds τ_y , the internal particle structure changes, and fluid movement begins. Empirical equations that describe these fluids are included in Table 2.1.

Bingham plastic fluids include thickened hydrocarbon greases, some asphalts and bitumens, and a variety of emulsions. The most common Bingham fluids include water suspensions of clays, fly ash, quartz, metallic oxides, sewage sludge and paint systems. Yield-pseudoplastic materials include clay-water suspensions, solutions of carbonpolymethylene (carbopol), some grout formulations, rubber-benzene solutions, phosphate ore and many coal-water slurries.

TABLE 2.1. Equations for Time-Independent Non-Newtonian Fluids

Type of Fluid	General Equation	Level of Exponent		
		τ_y	n	K
Yield-Dilatant	$\tau - \tau_y = K \left(\frac{dv}{dy} \right)^n$	>0	>1	---
Dilatant	$\tau = K \left(\frac{dv}{dy} \right)^n$	$=0$	>1	---
Yield-Pseudoplastic	$\tau - \tau_y = K \left(\frac{dv}{dy} \right)^n$	>0	<1	---
Pseudoplastic	$\tau = K \left(\frac{dv}{dy} \right)^n$	$=0$	<1	---
Bingham Plastic	$\tau - \tau_y = K \left(\frac{dv}{dy} \right)^n$	>0	$=1$	μ_p
Newtonian	$\tau = K \left(\frac{dv}{dy} \right)^n$	$=0$	$=1$	μ

Yield-dilatant fluids are much less common than Bingham plastic or yield-pseudoplastic fluids. Yield-dilatant fluids will begin to flow when their yield stress is exceeded. Once motion begins, the rate of increase in shear stress with velocity gradient increases as the velocity gradient increases. Some solutions of titania (Metzner and Whitlock 1958), magnetite, and galena (Govier, Shook, and Lilge 1957) can exhibit this behavior.

2.2.2 Time-Dependent Non-Newtonian Fluids

The behavior of time-independent non-Newtonian fluids adjusts instantaneously as shear stresses are applied. The structural configuration and particle orientation of some slurries cannot adjust instantaneously to changes in shear stresses. These time-dependent non-Newtonian fluids are usually classified as thixotropic or rheopectic slurries. Rheograms for these slurries are depicted on Figure 2.3.

Thixotropic slurries exhibit a decrease in shear stress with time at a constant shear rate and temperature. A hysteresis loop (Figure 2.3) will result as the shear rate is steadily increased from zero to a maximum value and then decreased steadily back to zero. The internal particle alignment mechanisms responsible for thixotropic behavior are similar to, but occur at a

FIGURE 2.3. Rheograms for Thixotropic and Rheopectic Non-Newtonian Fluids

slower rate than those causing pseudoplastic behavior. Some oil-well drilling muds, greases, margarines, shortenings, printing inks, and high molecular weight polymers exhibit thixotropic behavior (Jobling and Roberts 1959). Extensive surveys of thixotropic behavior have been prepared (Govier and Aziz 1982).

Rheopectic slurries exhibit an increase in shear stress with time at a constant shear rate and temperature. A hysteresis loop (Figure 2.3) will result as the shear rate is steadily increased from zero to a maximum value and then decreased steadily back to zero. The hysteresis loop produced is a reverse image of the loop created by thixotropic materials. The internal particle alignment mechanisms responsible for rheopectic behavior are similar too, but occur at a slower rate than those causing dilatant behavior. Some bentonite clays, vanadium pentoxide, gypsum and ammonium oleate suspensions exhibit rheopectic behavior (Skelland 1967). Extensive surveys of rheopectic behavior have been prepared (Bauer and Collins 1967).

2.2.3 Viscoelastic Fluids

Viscoelastic fluids exhibit time-dependent non-Newtonian viscous behavior and elastic recovery properties. They flow when subjected to stress but part

of their deformation is gradually recovered when the stress is removed. Viscoelastic fluids include bitumens, flour dough, nylon, and nearly all molten polymers. Solid-liquid slurries rarely display significant degrees of viscoelastic behavior. Constitutive equations that describe viscoelastic behavior have been developed (Skelland 1967; Govier and Aziz 1982).

2.3 HETEROGENEOUS FLOW SYSTEMS

A heterogeneous slurry is a complex mixture of coarse particles in a liquid stream. The solids may not be homogeneously dispersed in the liquid stream. The pseudohomogeneous, non-Newtonian behavior described in Section 2.2 cannot be applied to heterogeneous slurries. These slurries act as two-phase systems. The degree of phase separation is a function of particle size, shape, density, and concentration, and the fluid density and viscosity. The remainder of this section discusses heterogeneous slurry flow patterns in pipes.

A qualitative flow curve (Figure 2.4) is often used to differentiate heterogeneous slurry flow patterns (Govier and Aziz 1982) in pipes. The flow curve is a plot on a logarithmic scale of the pressure drop developed by the slurry as a function of the slurry transport velocity. At sufficiently high velocities, the slurry flows as a pseudohomogeneous suspension. As the velocity decreases, a heterogeneous concentration profile (Figure 2.5) develops. At still lower velocities, a sliding bed forms at the bottom of the pipe (Figure 2.5). The velocity at which the flow pattern changes from a heterogeneous to a sliding regime is known as the "sliding bed velocity" or the "critical deposition velocity" (Hanks and Sloan 1981). The sliding bed velocity V_{cd} , usually corresponds with the minimum of the pressure gradient-velocity curve. As the mixture velocity is decreased still further, the lower portion of the sliding bed becomes stationary, although particles at the top of the bed may continue to move by saltation. The transition from the sliding bed regime to the stationary bed-saltation flow regime is known as the "stationary bed velocity." Slurry transport systems are usually designed to provide line velocities that exceed the critical deposition velocity, V_{cd} .

FIGURE 2.4. Flow Curve for Heterogeneous Slurries

Particle size distribution, density and shape, fluid density and viscosity, the diameter of the transfer pipe, and many other factors will impact the value of the critical deposition velocity. For rigid, spherical particles with a specific gravity of 2.65, it has been suggested (Govier and Aziz 1982) that:

- ultrafine particles, ten microns or smaller, are almost always carried in a fully suspended state
- fine particles, 10 to 100 microns, are usually carried in a fully suspended state, but concentration gradients due to gravitational effects may be encountered

FIGURE 2.5. Heterogeneous Slurry Flow Patterns

- medium-sized particles, 100 to 1000 microns, may be fully suspended at sufficiently high velocities but often will form a moving bed at the bottom of the pipe; in all cases a concentration gradient will exist
- coarse particles, 1000 to 10,000 microns, are seldom fully suspended, and usually form a moving deposit on the bottom of a pipe
- very large particles, larger than 10,000 microns, are not suspended at normal velocities unless they are unusually light and may be transported in a fluid only as a moving bed on the bottom of a pipe.

These guidelines are useful for estimating the type of heterogeneous flow pattern that may exist for differing particle sizes.

Similar guidelines that relate heterogeneous flow patterns to particle size and line velocity have been reported (Newitt et al. 1955). They relate specifically to the transport of graded sand in a 6-in. diameter pipe. These guidelines are shown on Figure 2.6. They are useful for estimating the type of heterogeneous flow pattern that may exist for differing particle diameters and velocities.

Reference: (Newitt et al. 1955)

FIGURE 2.6. Heterogeneous Slurry Flow Patterns; Particle Diameter and Velocity Effects

3.0 PREPARATION OF SIMULATED NCAW AND NCAW-TRU

At PUREX, partially denitrated current acid waste (CAW) is neutralized with 19M sodium hydroxide to a minimum of 1M excess hydroxide ions using a direct-strike method. The neutralized CAW (NCAW), which is stored in DSTs on the Hanford Site, will eventually be transported from the DSTs to B-Plant for processing. In B-Plant the transuranic (TRU) elements in NCAW are separated from the non-TRU elements. The TRU elements are diluted with water to form NCAW-TRU, which will be pumped to an appropriate holding tank before being permanently disposed.

Two simulated NCAW and two simulated NCAW-TRU slurries were used for this rheological evaluation study. NCAW-PNL is the simulated NCAW prepared in the Applied Chemistry laboratory at PNL, and NCAW-RHO is the simulated NCAW prepared by the Pilot Plant group at Rockwell. NCAW-TRU-PNL is the simulated NCAW-TRU that was prepared using NCAW-PNL. Similarly, NCAW-TRU-RHO is the simulated NCAW-TRU that was prepared using NCAW-RHO. Details of the preparation of each slurry are presented here because the rheological properties of the slurry are influenced by the way the slurries are prepared. An objective of this study is to determine how sensitive the predicted transport properties are to the way in which the simulant is prepared.

3.1 NCAW SLURRIES

NCAW-PNL was prepared by neutralizing simulated current acid waste (CAW) with 19M sodium hydroxide (NaOH). The neutralized CAW was digested with refluxing at 90°C for 100 hours. This procedure is intended to simulate the aging process that the waste undergoes in the DSTs. The composition of NCAW-PNL was very close to the composition of a sample of NCAW retrieved by Rockwell, in November 1985, from one of the DSTs. The chemical analysis of this sample of actual NCAW is summarized in Table 3.1.

NCAW-RHO was prepared by making a synthetic waste similar to the waste received from the first solvent extraction column at PUREX. This waste was sugar-denitrated, after which it is called CAW. Caustic (NaOH) was added to

TABLE 3.1. Composition of NCAW from Tank 101AZ

Component	Overall Composition ^(a) (moles/liter NCAW)	Supernate (moles/liter supernate)	Centrifuged Solids (moles/liter centrifuged solids)
SpG (g/mL)	1.20	1.17	1.4
OH	0.97	1.09	
SO ₄	0.15	0.151	0.1224 ^(b)
NO ₃	1.17	1.75	1.404 ^(b)
NO ₂	0.43	0.44	0.348 ^(b)
CO ₃	0.22	0.20	0.40
Na	5.02	4.89	6.1 (65% H ₂ O soluble)
Al	0.50	0.48	0.652 (55% H ₂ O soluble)
K	0.12	0.116	0.13 (71% H ₂ O soluble)
Ca	1.93 x 10 ⁻⁰²	0.0026	0.154 (0.84% H ₂ O soluble)
Cr	1.18 x 10 ⁻⁰²	0.0112	0.017 (55% H ₂ O soluble)
Ps	6.53 x 10 ⁻⁰⁴	0.0004	0.0027 ^(c)
Ms	7.52 x 10 ⁻⁰³	0.00005	0.068 ^(c)
Mo	1.16 x 10 ⁻⁰³	0.0009	0.0033 ^(c)
P	2.30 x 10 ⁻⁰²	0.0173	0.069 ^(c)
F	8.63 x 10 ⁻⁰²	0.089	0.064 ^(b)
Cl		<9.07 x 10 ⁻³	<0.017 ^(b)
Sl	6.64 x 10 ⁻⁰²		0.604 ^(c)
Zr	4.88 x 10 ⁻⁰²		0.444 ^(c)
Ba	9.24 x 10 ⁻⁰⁴		0.0084 ^(c)
B	7.44 x 10 ⁻⁰³		0.0676 ^(c)
Cd	6.64 x 10 ⁻⁰³		0.0604 ^(c)
Ce	1.55 x 10 ⁻⁰³		0.0141 ^(c)
Co	7.70 x 10 ⁻⁰⁵		0.0007 ^(c)
Cu	4.07 x 10 ⁻⁰⁴		0.0037 ^(c)
La	9.24 x 10 ⁻⁰⁴		0.0084 ^(c)
Nd	1.43 x 10 ⁻⁰³		0.013 ^(c)
Ni	9.02 x 10 ⁻⁰³		0.082 ^(c)
Pd	1.21 x 10 ⁻⁰²		0.11 ^(c)
Aa	1.43 x 10 ⁻⁰⁴		0.0013 ^(c)
Sr	4.62 x 10 ⁻⁰⁴		0.0042 ^(c)
Ti	1.32 x 10 ⁻⁰⁴		0.0012 ^(c)
Zn	5.28 x 10 ⁻⁰⁴		0.0048 ^(c)
Fe	7.35 x 10 ⁻⁰²		0.668 ^(c)
Mn	2.09 x 10 ⁻⁰³		0.019 ^(c)

(a) Overall composition is based on 89 volume % supernate and 11% centrifuged solids.

(b) Present in water soluble solids/interstitial liquid.

(c) Present in acid (HNO₃/HF) soluble solids.

the CAW to neutralize it. The NCAW was agitated for three days to allow the aluminum hydroxide ($\text{Al}(\text{OH})_3$) to convert to sodium aluminate (NaAlO_2).

There are two primary differences in the preparation of NCAW-PNL and NCAW-RHO. First, Rockwell simulated the waste from the first solvent extraction column and sugar-denitrated it to form CAW; PNL simulated CAW. Second, PNL digested their NCAW in order to simulate the aging process that the waste undergoes in the DSTs; Rockwell did not. The differences in the compositions of NCAW-PNL and NCAW-RHO can be observed in Table 3.2.

There were very few differences between the appearance of NCAW-PNL and NCAW-RHO. The primary difference was in the color of the supernatants. The NCAW-PNL supernatant was slightly more yellow than the NCAW-RHO supernatant. Both supernatants were clear as opposed to cloudy. In addition, the NCAW-RHO solids settled to approximately half the volume of the NCAW-PNL solids.

3.2 NCAW-TRU SLURRIES

Simulated NCAW-TRU was prepared by processing the two simulated NCAW slurries in a manner similar to the process that the waste would undergo in B-Plant. Two NCAW-TRU slurries were prepared: one by processing NCAW-PNL (NCAW-TRU-PNL) and one by processing NCAW-RHO (NCAW-TRU-RHO).

To prepare simulated NCAW-TRU, a known volume of simulated NCAW was allowed to settle undisturbed until no change in volume of settled solids was observed over a 24-h period. This settling took approximately three days for both NCAW-PNL and NCAW-RHO. The NCAW supernatant was decanted, then a water wash was performed on the settled solids to remove the sulphates, carbonates and fluorides. The water wash consists of adding water to the NCAW solids at a volume ratio of 15 to 1. The resulting slurry is agitated, then allowed to settle.

This water-solids slurry was allowed to settle undisturbed for 24 hours. After 8 hours, negligible change in volume of settled solids was observed. The water wash was then decanted, and water was added to the remaining solids to bring the volume of washed solids and water back to the original volume of the NCAW sample.

TABLE 3.2. Composition of NCAW-PNL and NCAW-RHO

Component	NCAW-PNL (moles/liter NCAW)	NCAW-RHO (moles/liter NCAW)
Al	0.48	0.30
Ni	0.0084	0.031
Cr	0.0116	0.006
K	0.112	--
Fe	0.071	0.041
Cs	0.0011	0.0018
Sr	4.6E-4	5.4E-4
Rb	ND	ND
Ba	8.9E-4	2E-4
Mn	0.0022	8.4E-4
Na	4.83	9.87
Mo	8.7E-4	0.0017
Ca	0.0224	0.0043
Mg	0.0095	0.0027
Co	ND	ND
Cd	0.0047	--
Cu	3.4E-4	6.3E-4
Zn	4.4E-4	--
Ag	ND	ND
Zr	0.049	0.0053
Pb	6.4E-4	--
B	0.0054	4.9E-4
P	0.023	--
Si	0.115	0.0816
Ti	2.5E-4	1.5E-4
Sm	ND	ND
Cl ⁻	0.019	0.056
NO ₂ ⁻	0.42	0.026
NO ₃ ⁻	2.10	1.08
SO ₄ ⁼	0.133	0.038
F ⁻	0.091	0.087
CO ₃	ND	ND
OH	1.32	4.05

-- = Not Detected.

ND = Not Determined.

The final composition of washed solids and water was adjusted to contain 0.02 M sodium hydroxide (NaOH) (0.8 g) and 0.02 M sodium nitrite (NaNO_2) (1.38 g). This adjustment in composition was made to simulate the adjustment required for conformance to corrosion specifications at the Rockwell Tank Farm. Another part of the simulation was the addition of diatomaceous earth that equaled 10 wt% of the dry solids in the NCAW. Diatomaceous earth is the filter aid used in the polishing-filtration operation in B-Plant.

The same differences between the appearance of NCAW-PNL and NCAW-RHO exist between NCAW-TRU-PNL and NCAW-TRU-RHO. That is, the NCAW-TRU-PNL supernatant is slightly more yellow than the NCAW-TRU-RHO supernatant and the settled solids volume of NCAW-TRU-PNL is nearly twice the volume of the NCAW-TRU-RHO settled solids.

Inductively coupled argon plasma atomic emission spectroscopy (ICP) and ion chromatograph (IC) analyses were performed on the supernatant and solids during various stages in the preparation of NCAW-TRU. These analyses are summarized for NCAW-TRU-PNL and NCAW-TRU-RHO in Tables 3.3 and 3.4, respectively.

Tables 3.3 and 3.4 are useful for showing the amount of each constituent present during each phase of the processing of NCAW-TRU. The tables are set up such that the first number presented in the element column is the number of moles of that element present in the material that was analyzed. The second number in the column represents the percent of the total number of moles originally present in the NCAW. For example, Table 3.4 shows that there was 0.20 moles of aluminum present in 0.7 liters of NCAW-RHO supernatant. This represented 66.9% of all the aluminum in NCAW-RHO. The water wash was able to remove 0.076 moles of aluminum, 25.5% of the total amount. The aluminum remaining in the waste after the processing steps were complete (NCAW-TRU) is the sum of the amount in the first column of the NCAW-TRU Aqueous and the NCAW-TRU Solids rows; 0.0228 moles.

Table 3.3 Analysis of NCAW-PNL During Preparation of NCAW-TRU (1 Liter)

Item	Sample No.	Volume, L	Units	Al	B	Cd	Ca	Ba	Cr	Fe	K	Mg	Mo	Na	Ni	P	Si	Zr	Cs	Pb	Zn	Cu	Mn	Sr	Tl	F ⁻	Cl ⁻	NO ₂ ⁻	NO ₃ ⁻	SO ₄ ⁼
Supernatant	5.2	0.67	Moles % of Total	0.298 62.4	0.0024 44.2	---	---	---	0.0022 19.1	---	0.076 67.8	---	6E-4 67.5	3.2 66.3	---	0.01 43.4	9.4E-4 0.8	---	7.4E-4 67	---	---	---	---	---	---	0.0064 70	0.017 87.5	0.268 63.6	1.47 69.9	0.0864 65.2
H ₂ O Wash	5.1	4.4	Moles % of Total	0.141 29.5	0.0011 20.3	---	---	---	0.001 8.7	---	0.033 29.5	---	2.6E-4 29.7	1.41 29.2	---	0.0038 16.5	3.4E-4 0.3	1.2E-6 Tr	3.3E-4 29.9	---	---	---	---	---	---	0.025 27.5	0.0021 10.8	0.123 29.2	0.576 27.4	0.042 31.9
NCAW-TRU Aqueous	5.3	0.8	Moles % of total	0.0136 2.8	1E-4 1.8	---	---	---	9.6E-5 0.8	---	0.003 2.7	---	2.4E-5 2.7	0.154 3.2	---	2.6E-4 1.1	4.8E-5 0.04	---	3.44E-5 3.1	---	---	---	---	---	---	3E-4 2.5	0.0003 1.6	0.0304 7.2	0.056 2.7	0.0039 2.96
NCAW-TRU Solids	5.4	33g	Moles % of Total	0.025 5.3	0.0018 33.7	0.0047 100	0.0224 100	8.9E-4 100	0.0083 71.4	0.071 100	---	0.0095 100	---	0.064 1.3	0.008 100	0.009 39	0.114 98.8	0.049 100	---	6.4E-4 100	4.4E-4 100	3.4E-4 100	0.0022 100	4.6E-4 100	2.5E-4 100	6.95E-6 Tr	---	7.2E-5 Tr	1.3E-4 Tr	1E-5 Tr
Material Balance, M/L				0.478	0.0054	0.0047	0.0224	8.9E-4	0.0116	0.071	0.112	0.0095	8.7E-4	4.83	0.0084	0.023	0.115	0.049	0.0011	6.4E-4	4.4E-4	3.4E-4	0.0022	4.6E-4	2.5E-4	0.091	0.019	0.422	2.10	0.133

Table 3.4 Analysis of NCAW-RHO During Preparation of NCAW-TRU (1 Liter)

Item	Sample No.	Volume, L	Units	Al	B	Cd	Ca	Ba	Cr	Fe	K	Mg	Mo	Na	Ni	P	Si	Zr	Cs	Pb	Zn	Cu	Mn	Sr	Tl	F ⁻	Cl ⁻	NO ₂ ⁻	NO ₃ ⁻	SO ₄ ⁼
Supernatant	6.1	0.7	Moles % of Total	0.20 66.9	---	---	1.89E-4 4.4	---	2.6E-4 4.6	5.7E-4 1.4	---	---	0.0012 71.5	6.846 69.3	---	---	---	0.0015 29.1	0.0014 76.6	---	---	3.3E-4 52.5	---	---	---	0.0217 25.1	0.0329 58.7	---	0.6265 58	0.0049 12.8
H ₂ O Wash	6.2	4.45	Moles % of Total	0.076 25.5	---	---	---	---	1E-4 1.8	Tr	---	---	4.4E-4 26.7	2.80 28.4	---	---	3.1E-4 0.4	7.12E-5 1.3	4E-4 22.3	---	---	---	---	---	---	0.0623 72.0	0.0223 39.7	---	0.436 40.4	0.0312 81.6
NCAW-TRU Aqueous	6.3	0.92	Moles % of Total	0.0048 1.6	---	---	---	---	2.1E-5 0.4	Tr	---	---	3E-5 1.8	0.200 2.0	---	---	---	Tr 1.1	1.93E-5	---	---	---	---	---	---	0.00258 1.5	8.56E-4 99.9	0.026 1.6	0.0175 5.5	0.00212
NCAW-TRU Solids	6.4	17.5 g	Moles % of Total	0.018 6	4.9E-4 100	---	0.004 95.6	2E-4 100	0.0053 93.3	0.040 98.6	---	0.0027 100	---	0.026 0.3	0.031 100	---	0.0813 99.6	0.0037 69.5	Tr 0	---	---	3E-4 47.5	8.4E-4 100	5.4E-4 100	1.46E-4 100	---	---	1.9E-5 0.1	1.7E-5 Tr	3.6E-6 Tr
Material Balance, M/L				0.30	4.9E-4	---	0.043	2E-4	0.0057	0.041	---	0.0027	1.7E-3	9.875	0.031	---	0.0816	5.3E-3	0.0018	---	---	6.3E-4	8.4E-4	5.4E4	1.5E-4	0.0866	0.056	0.0258	1.08	0.038

4.0 LABORATORY RHEOLOGICAL EVALUATIONS

Laboratory evaluations were conducted to: 1) measure the physical properties of the slurries, 2) classify the rheological behavior of each slurry, and 3) provide background information needed to predict full-scale flow characteristics expected for the NCAW and NCAW-TRU slurries in a pump-pipe system.

Laboratory evaluations were performed on three samples each of NCAW-RHO, NCAW-TRU-RHO, and NCAW-TRU-PNL at 25°C. The samples were prepared according to the recipe and procedures described in Chapter 3. Laboratory evaluations of NCAW-PNL were performed previously (Fow, McCarthy, and Thornton 1986). These results are included in this report so that they can be compared with the rheological properties displayed by NCAW-RHO.

The laboratory procedures and equipment used during this evaluation are presented in Section 4.1. The rheological properties (shear stress, yield stress and viscosity) are presented in the Section 4.2. Section 4.3 summarizes the physical properties of the slurries, such as, pH, density, solids distribution, settling rates and resuspendibility.

4.1 EXPERIMENTAL EQUIPMENT AND PROCEDURES

Laboratory rheological data were obtained with a Haake Rotovisco® viscometer equipped with an M150 measuring/drive head and the NV sensor system. The measurement of viscosity with this instrument (see Figure 4.1) requires that the sample be placed into the gap between two coaxial cylinders. A motor drives the inner cylinder. A viscosity-related torque, caused by the resistance of the sample to shearing, acts on the inner cylinder. This torque deflects a measuring spring placed between the motor and the inner cylinder. The magnitude of the spring deflection correlates linearly with the torque, and the spring deflection is transformed into an electrical signal. The torque and tachometer signals are recorded.

The speed signal required for the determination of the shear rate does in fact not come from the rotor directly but from the tacho-generator (TG) which

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FIGURE 4.1. Schematic of a Haake Rotovisco® Viscometer

sits above the motor and is mechanically linked to it. For slurries that do not exhibit yield stresses, the speeds of the tacho-generator, motor, and the rotor are identical so that the speed signal n_{tg} , also defines the rotor speed n_r . A slurry with a yield stress will "clamp" the rotor to the cup, until the torque, τ , applied is greater than the yield stress, τ_y .

While the rotor is still clamped and remains at standstill, the motor rotation will cause some spring deflection and consequently a torque signal τ , on the ordinate. For a slurry with a yield stress, a straight line leaning off the vertical with an angle β is recorded initially (see Figure 4.2). When the shear stress surpasses the yield value, τ_y , the rotor breaks loose from its "clamp" and picks up speed, accelerating almost instantaneously to the value n_{tg} . The change in the behavior of the sample becomes apparent in the rapid

FIGURE 4.2. Flow Curve for a Yield-Pseudoplastic Material

turn of the flow curve. The ordinate value of this turning point defines the yield value, τ_y . On the flow curve two regions can be distinguished: the first region is a segment of the "flow curve of a solid," while the second region describes the flow of the material after it has been transformed into a liquid.

Depending on the test conditions selected, one may also get a more or less gradual change of the flow curve from one region to the other. The transition from a solid gel to an easy-flowing liquid may go through a phase of "creep," which makes the turning point less clear. Under these conditions, the yield point is determined by the crossing point of the tangents on both branches.

Standard laboratory techniques were used to measure physical properties such as pH, density, and total solids content of each NCAW and NCAW-TRU slurry sample at 25°C. The standard laboratory technique used to measure total dissolved solids was not used because a suitable filter (0.45 μm) able to withstand a pH greater than 13 could not be found.

To determine the total dissolved solids concentration in each slurry, it was assumed that the supernatant contained only dissolved solids. The accuracy of this assumption was affirmed in a previous study (Fow, McCarthy, and Thornton 1986) by filtering samples of NCAW-PNL through 2.5- μ m filters. The suspended solids concentration determined by filtering were in good agreement ($\pm 10\%$) with the results obtained by assuming the supernatant contained only dissolved solids.

4.2 RHEOLOGICAL PROPERTIES

Laboratory evaluations were conducted to classify the NCAW and NCAW-TRU slurries at 25°C and to determine the effects of shear rate on the apparent viscosity of each slurry. These evaluations provided the background information needed to design and predict the performance of full-scale slurry transport equipment.

4.2.1 Classification of Slurries

An assumption implicit in this evaluation was that the NCAW and NCAW-TRU slurries would be transported at velocities sufficient to prevent particles from settling in the transfer piping. This assumption implies that heterogeneous flow behavior (static bed, moving bed) cannot be tolerated. The objective was to create a pseudohomogeneous or nearly pseudohomogeneous flow regime in the transfer piping. A wide variety of pseudohomogeneous flow regimes are possible (see Section 2.2).

The majority of slurries can be treated as yield-pseudoplastic (Y-P) materials. The behavior of these materials can be defined by the following equations (Hershel and Bulkley 1926):

$$\tau = K \left(\frac{dv}{dy} \right)^n \text{ when } \tau_y = 0 \quad (3)$$

$$\tau = \tau_y + K \left(\frac{dv}{dy} \right)^n \text{ when } \tau_y > 0 \quad (4)$$

where: τ = shear stress, N/m^2 (Pascal)

τ_y = yield stress, N/m^2 (Pascal)

K = consistency index, Ns/m^2 (Pascal-sec)

$\frac{dv}{dy}$ = shear rate in y direction, s^{-1}

n = flow behavior index.

The yield-pseudoplastic model defined by Equation (4) reduces to the Bingham plastic model when $n = 1$, the pseudoplastic model when $\tau_y = 0$, and to the Newtonian model when $\tau_y = 0$ and $n = 1$.

The rheograms for NCAW-PNL and NCAW-RHO at 25°C are depicted in Figure 4.3. These data were "fit" to the yield-pseudoplastic, pseudoplastic and Bingham plastic rheological models. The "goodness of fit" parameters, commonly referred to as regression coefficients, that were obtained for each model exceeded 0.998. This indicates NCAW-PNL and NCAW-RHO can be described by any one of the pseudoplastic, yield-pseudoplastic or Bingham plastic rheological models. This inference arises from the fact that the precision of the Haake viscometer at low shear rates is $\pm 8\text{--}11\%$ (McCarthy, Chan, and Lokken 1985).

The Bingham plastic rheological model will be used to describe the NCAW slurries because the regression coefficient for the Bingham plastic model is slightly higher than the regression coefficient using the pseudoplastic model. In addition, a comparison between the pseudoplastic and Bingham plastic model for NCAW-PNL will be presented throughout this report. The purpose of this comparison is to determine the sensitivity of calculated values of transport properties of the fluid to the model chosen to describe the fluid.

Equations (5) and (6) represent the shear stress for NCAW-PNL at 25°C using the pseudoplastic and Bingham plastic rheological models, respectively. Equation (7) represents the shear stress of NCAW-RHO at 25°C if the Bingham plastic model is utilized.

$$\tau = 0.0149 \left(\frac{dv}{dy} \right)^{0.8} \quad (5)$$

$$\tau = 0.15 + 0.0042 \left(\frac{dv}{dy} \right) \quad (6)$$

FIGURE 4.3. Rheograms for NCAW-PNL and NCAW-RHO at 25°C

$$\tau = 0.15 + 0.013 \left(\frac{dv}{dy} \right) \quad (7)$$

The rheograms for NCAW-TRU-PNL and NCAW-TRU-RHO at 25°C are depicted in Figure 4.4. As with the NCAW slurries, the NCAW-TRU slurries can be described by any one of the pseudoplastic, yield-pseudoplastic or Bingham plastic rheological models. The Bingham plastic model will be used because the regression coefficient for NCAW-TRU-PNL for this model is slightly higher than the regression coefficient for the pseudoplastic model. In order to compare the NCAW-TRU slurries, the Bingham plastic model will be used for both slurries.

FIGURE 4.4. Rheograms for NCAW-TRU-PNL and NCAW-TRU-RHO at 25°C

The resulting shear stress equations for NCAW-TRU-PNL and NCAW-TRU-RHO, respectively, are as follows:

$$\tau = 0.145 + 0.0017 \left(\frac{dV}{dy} \right) \quad (8)$$

$$\tau = 0.047 + 0.0011 \left(\frac{dV}{dy} \right) \quad (9)$$

The data in Figure 4.4 for NCAW-TRU-PNL fit Equation (8) with a regression coefficient of 0.952. The regression coefficient for the pseudoplastic model is 0.940. The data for NCAW-TRU-RHO fit Equation (9) with a regression coefficient of 0.977. The regression coefficient for the pseudoplastic model is 0.983. The confidence in accurately predicting the shear stress for any value of shear rate is slightly higher for NCAW-TRU-RHO than for NCAW-TRU-PNL.

4.2.2 Viscosity of NCAW and NCAW-TRU Slurries

The apparent viscosity of a non-Newtonian fluid is defined as the shear stress divided by the shear rate. The shear stress is evaluated using the yield-pseudoplastic model described in Chapter 2. A reported apparent viscosity for a non-Newtonian fluid only makes sense if it is accompanied by the shear rate. For flow in pipes, the rate at which deformation takes place, the

shear rate, is proportional to the velocity of the fluid and inversely proportional to the pipe diameter. For fluid flowing at 50 and 75 gpm through a 3-in.-diameter pipe, the shear rate is 68 and 102 s^{-1} , respectively.

The rheological information in Figures 4.3 and 4.4 was used to evaluate the apparent viscosity of each sample. Plots of viscosity versus shear rate at 25°C for the NCAW and NCAW-TRU slurries are presented in Figures 4.5, 4.6, and 4.7. As is typical for all yield-pseudoplastic, Bingham plastic, and pseudo-plastic materials, viscosity decreased as the shear rate increased.

The apparent viscosity of NCAW-PNL using the pseudoplastic model is slightly lower at very low shear rates than the apparent viscosity of NCAW-PNL using the Bingham plastic model (Figure 4.5). As the shear rate increases, the apparent viscosity calculated using the pseudoplastic model is slightly higher than the apparent viscosity calculated using the Bingham plastic model. For

FIGURE 4.5. Apparent Viscosity of NCAW-PNL at 25°C using the Bingham Plastic and Pseudoplastic Model

the shear rates of interest in this study, the pseudoplastic model predicts a more conservative (i.e., higher) value for the apparent viscosity.

The apparent viscosity of NCAW-RHO is approximately 2-1/2 times greater than the apparent viscosity of NCAW-PNL. For example, at 50 gpm (68 s^{-1}), the apparent viscosity of NCAW-RHO is 15.3 cP compared to 6.5 cP for NCAW-PNL (Figure 4.6). The apparent viscosity of NCAW-TRU-PNL at 50 gpm is 3.9 cP, twice that of NCAW-TRU-RHO (1.8 cP) at 50 gpm (see Figure 4.7). The fact that NCAW-TRU-PNL has a higher apparent viscosity than NCAW-TRU-RHO whereas NCAW-RHO has a higher apparent viscosity than NCAW-PNL is not necessarily an inconsistency. The NCAW slurries have very different recipes and preparation methods and cannot be expected to perform the same results after being processed.

4.3 PHYSICAL PROPERTIES

Standard laboratory techniques were used to measure physical properties such as pH, slurry density, total solids content, and settling rates of each NCAW and NCAW-TRU sample at 25°C. The standard laboratory technique used to measure total suspended solids was not used because a suitable filter (0.45-micron) able to withstand a pH greater than 13 could not be found.

To determine the total suspended solids, it was assumed that the supernatants contain only dissolved solids. Samples of supernatant of known mass were dried at 105°C in a tared 15-mL plastic beaker until no weight change was noticed over a 24-h period. The weight of the dried supernatant was divided by the initial weight of the sample and multiplied by the percent total liquid in the slurry to obtain the total suspended solids. The total dissolved solids were assumed to be equal to the total solids minus the total suspended solids concentration.

An attempt was made to quantitatively determine the resuspendibility of the NCAW and NCAW-TRU slurries. Three samples of each slurry were placed in graduated cylinders and allowed to settle until no change in solids interface height was detectable over a 24-h period. The cylinders were inverted, then returned to the upright condition without shaking. The inversions were repeated until all the solids were resuspended. The number of inversions required to resuspend the solids is referred to as the "resuspendibility index."

FIGURE 4.6. Apparent Viscosity of NCAW-PNL and NCAW-RHO at 25°C Versus Shear Rate

FIGURE 4.7. Apparent Viscosity of NCAW-TRU-PNL and NCAW-TRU-RHO at 25°C Versus Shear Rate

4.3.1 NCAW-PNL and NCAW-RHO

The pH, density, and solids weight distribution results obtained for each sample of NCAW-PNL and NCAW-RHO at 25°C are summarized in Table 4.1. Reliable pH data are difficult to obtain when the pH level nears pH 14. Several calibrated pH meters were used to assess the pH of NCAW at 25°C. Each of these meters indicated a pH greater than 13.

The total weight percent solids in NCAW-RHO was approximately 37%. In NCAW-PNL, the total wt% solids was 30%. Both slurries have about 2 wt% suspended solids, indicating most of the solids are dissolved in the supernatant.

To determine the suspended solids settling rate, samples of simulated NCAW were placed in 100-mL graduated cylinders, shaken, then allowed to settle. The

TABLE 4.1. Physical Properties of NCAW-RHO and NCAW-PNL at 25°C

Item	NCAW-RHO					NCAW-PNL				
	Sample Number									
	#1	#2	#3	$\bar{X}^{(b)}$	$S^{(c)}$	#1	#3	#5	$\bar{X}^{(b)}$	$S^{(c)}$
pH	>13	>13	>13			>13	>13	>13		
Density (g/cc)	1.35	1.36	1.36	1.36	0.01	1.26	1.27	1.27	1.27	0.01
Total Solids (wt%)	37.2	37.1	37.1	37.1	0.06	30.5	30.4	30.2	30.4	0.15
Total Dissolved Solids (wt%)	30.8	30.1	29.9	30.3	0.47	28.4	28.2	28.8	28.5	0.31
Total Suspended Solids (wt%)	1.8	1.9	1.6	1.8	0.15	2.1	2.2	1.4	1.90	0.44

(a) Values from previous study (Fow, McCarthy, and Thornton 1986).

(b) $\bar{X}$ = Mean value.

(c) S = Standard deviation.

level of the solids-liquid interface was recorded as it descended in the cylinder. Plots of interface height versus time were prepared for each sample. Figure 4.8 depicts the average settling rate of three samples of NCAW-PNL and three samples of NCAW-RHO.

FIGURE 4.8. NCAW-PNL and NCAW-RHO Suspended Solids Settling Curve at 25°C. These curves represent the average settling rate of three laboratory samples of each slurry.

The average interface settling rates taken from the linear portion of the NCAW-PNL and NCAW-RHO settling curves are 0.55 and 0.42 cm/h, respectively. The slow settling rates are not a primary design concern for the piping network but could be a concern in B-Plant where the solids/liquid separation operations are performed. The settling rate data for each sample, along with the ultimate settled solids height, are presented in Table 4.2. The solids in NCAW-PNL settled to approximately 40% of the total volume. The solids in NCAW-RHO settled to approximately 18% of the total volume. Both slurries have about the same wt% suspended solids (2 wt%). The digesting operation performed on NCAW-PNL during preparation may account for this difference in settled solids volume.

Resuspendibility data for NCAW-TRU-PNL and NCAW-TRU-RHO are summarized in Table 4.2. After 12 days of settling, NCAW-PNL required four inversions to resuspend the solids. NCAW-RHO solids were resuspended after 16 days of settling with 4 inversions. Both slurries were considered relatively "easy" to

TABLE 4.2. Settling Rates and Resuspendibility Index for NCAW-RHO and NCAW-PNL at 25°C

Item	NCAW-RHO					NCAW-PNL ^(a)				
	Sample Number									
	#1	#2	#3	$\bar{X}^{(b)}$	$S^{(c)}$	#1	#3	#5	$\bar{X}^{(b)}$	$S^{(c)}$
Settling Rate (cm/hr)	0.42	0.42	0.41	0.42	0.01	0.58	0.46	0.62	0.55	0.08
Ultimate Settled Solids Height (% Column Height)	17.5	18.0	18.0	17.8	0.29	41.0	40.0	38.0	40.5	0.71
Resuspendability Index	4	4	4	---	---	2	2	4	---	---
Number of Settling Days Before Resuspension	16	16	16	---	---	7	7	12	---	---

(a) Values from previous study (Fow, McCarthy, and Thornton 1986).

(b) $\bar{X}$ = Mean value.

(c) S = Standard deviation.

resuspend. Actual NCAW slurry in DSTs may remain settled for longer periods of time, which may make them more difficult to resuspend. Actual NCAW solids would not be allowed to remain in transfer piping for very long. Resuspension of the solids in the transfer piping is discussed in Chapter 6.

4.3.2 NCAW-TRU-PNL and NCAW-TRU-RHO

The pH, density and solids weight distribution results obtained for each sample of NCAW-TRU slurry at 25°C are summarized in Table 4.3. The pH of the NCAW-TRU slurries was slightly lower than the pH of NCAW slurries.

The total solids concentration of the NCAW-TRU slurries decreased nearly ten-fold below the solids concentration of the corresponding NCAW slurries. This result was expected because NCAW-TRU was prepared by decanting the NCAW supernatant and washing the NCAW solids. For NCAW-TRU-RHO, the total solids concentration was 2.3 wt% compared to 37.1 wt% for NCAW-RHO. For NCAW-TRU-PNL, the total solids concentration was 4.1 wt% compared to 30.4 wt% for NCAW-PNL. The suspended solids concentration for NCAW-TRU-RHO and NCAW-TRU-PNL was 1.2 and 2.8 wt%, respectively. This corresponds to a 33% decrease in suspended solids for NCAW-TRU-RHO compared to NCAW-RHO and a 34% increase in suspended

TABLE 4.3. Physical Properties of NCAW-TRU-RHO and NCAW-TRU-PNL at 25°C

Property	NCAW-TRU-RHO					NCAW-TRU-PNL				
	Sample Number									
	#4	#5	#6	$\bar{X}^{(a)}$	$S^{(b)}$	#7	#8	#9	$\bar{X}^{(a)}$	$S^{(b)}$
pH	12.96	12.97	12.98	12.97	0.01	12.35	12.42	12.39	12.39	0.04
Density (g/cc)	1.02	1.02	1.02	1.02	0.0	1.01	1.02	1.02	1.02	0.01
Total Solids (wt%)	2.3	2.3	2.4	2.3	0.06	4.1	4.1	4.1	4.1	0.0
Total Dissolved Solids (wt%)	1.1	1.1	1.1	1.1	0.0	1.3	1.3	1.4	1.3	0.06
Total Suspended Solids (wt%)	1.2	1.2	1.3	1.2	0.06	2.8	2.8	2.7	2.8	0.06

(a) $\bar{X}$ = Mean value.

(b) S = Standard deviation.

solids for NCAW-TRU-PNL compared to NCAW-PNL. The NCAW-TRU slurry ultimate settled solids height was slightly higher than the corresponding NCAW slurry height. The addition of diatomaceous earth during the preparation of NCAW-TRU (see Chapter 3) may account for this increase in settled solids volume.

The settling rates of slurries are a function of the yield strength and viscosity of the fluids, and a variety of other physical/chemical properties. The NCAW-TRU slurries have lower yield strengths and lower viscosities than the NCAW slurries and would be expected to have higher settling rates. The settling rates for each sample of NCAW-TRU slurry are summarized in Table 4.4. These settling rates are from four to ten times faster than the corresponding settling rates for the NCAW slurries. The average settling rate for each NCAW-TRU slurry is depicted in Figure 4.9.

TABLE 4.4. Settling Rates and Resuspendibility Index for NCAW-TRU-RHO and NCAW-TRU-PNL at 25°C

Item	NCAW-TRU-RHO					NCAW-TRU-PNL				
	Sample Number									
	#4	#5	#6	$\bar{X}^{(a)}$	$S^{(b)}$	#7	#8	#9	$\bar{X}^{(a)}$	$S^{(b)}$
Settling Rate (cm/hr)	4.8	4.9	4.8	4.8	0.06	2.3	2.3	2.3	2.3	0.0
Ultimate Settled Solids Height (% Column Height)	22.5	22.5	23.0	22.7	0.29	41.5	41.5	42.0	41.7	0.29
Resuspendability Index	3	3	3	---	---	4	4	4	---	---
Number of Settling Days Before Resuspension	16	16	16	---	---	16	16	16	---	---

^(a) $\bar{X}$ = Mean value.

^(b) S = Standard deviation.

FIGURE 4.9. NCAW-TRU-PNL and NCAW-TRU-RHO Suspended Solids Settling Curve at 25°C. These curves represent the average settling rate of three laboratory samples of each slurry.

Resuspendibility data for NCAW-TRU-PNL and NCAW-TRU-RHO are summarized in Table 4.4. After 16 days of settling, NCAW-TRU-PNL required four inversions to resuspend the settled solids; NCAW-TRU-RHO required three. Qualitatively, both NCAW-TRU slurries are relatively "easy" to resuspend.

5.0 RHEOLOGICAL MODELS FOR FLOW IN PIPES

A wide variety of empirical equations have been developed to model the flow behavior of non-Newtonian pseudohomogeneous suspensions (Govier and Aziz 1982; Skelland 1967; Lazarus 1980). A few theoretically consistent models have been developed for the flow of pseudoplastic, and yield-pseudoplastic materials in circular pipes. These models permit the calculation of Reynolds numbers, critical velocities, and line pressure drops for these non-Newtonian fluids. This section will describe the pseudoplastic and yield-pseudoplastic theoretical models used to scale up laboratory rheological data to predict the performance of full-scale pump-pipe networks.

5.1 PSEUDOPLASTIC FLUIDS

The relationship between shear stress and rate of shear for pseudoplastic materials (see Figure 2.2) was defined as:

$$\tau = K \left(\frac{dV}{dy} \right)^n \quad (10)$$

For the incompressible flow of time-independent pseudoplastic materials in circular pipes (Metzner and Reed 1955), Equation (10) reduces to:

$$\tau_w = \frac{D \Delta P}{4L} = K' \left(\frac{8V}{D} \right)^n \quad (11)$$

where: τ_w = shear stress at wall, lb_f/ft^2
 n = flow behavior index
 K' = consistency index $\text{lb}_f\text{sec}/\text{ft}^2$
 D = diameter, ft
 V = velocity, ft/sec
 ΔP = pressure drop lb_f/ft^2
 L = equivalent length, ft

The graphical procedures described in Section 4.2.1 are used to determine values of K and n . The consistency index K' is applicable to the flow of fluids in circular pipe. It is related to the generic consistency index K by:

$$K' = K \left[\frac{3n+1}{4n} \right] \quad (12)$$

The generic consistency index, K , is independent of the type of apparatus in which the measurements were made. The rotational viscometer used during the laboratory evaluations described in Section 4 yields values of the generic consistency index K .

The Fanning friction factor is defined as:

$$f = \frac{D \Delta P}{4L} / \frac{\rho V_c^2}{2g_c} \quad (13)$$

Metzner and Reed substituted the right side of Equation (11) into Equation (13) and obtained:

$$f = \frac{16\gamma}{D^n V_c^{2-n} \rho} \quad (14)$$

$$\text{where } \gamma = g_c K' 8^{n-1} \quad (15)$$

They then let $f = 16/Re$, for the laminar flow of non-Newtonian fluids, and rearranged Equation (14) to yield a Reynolds number,

$$(Re)_{M-R} = \frac{D^n V_c^{2-n} \rho}{\gamma}, \quad (16)$$

that applies to the pseudohomogeneous flow of time-independent pseudoplastic materials in circular tubes. For Newtonian fluids ($n = 1$, $K' = \mu/g_c$; $\gamma = \mu$) Equation (16) reduces to the traditional Newtonian Reynolds number.

Metzner and Reed believed that all pseudoplastic materials would follow the usual f versus Re relationship in the laminar region when Equation (16) was used to calculate Re , as long as no "slip" at the wall of the pipe occurred. The "no-slip" assumption is implicit in the development of Equation (13). Metzner and Reed used Equation (16) to calculate Reynolds numbers in the turbulent region as well. They defined the onset of turbulence as the point at which f just declines below about 0.008 or when $(Re)_{M-R}$ reaches a value of 2000-2500.

Metzner and Dodge (1959) extended Metzner's earlier work to correlate friction factors and Reynolds numbers in the turbulent flow regime. They determined that f versus $(Re)_{M-R}$ data for a wide variety of time-dependent, inelastic pseudoplastic slurries fit an empirical model:

$$\frac{1}{\sqrt{f}} = \frac{4.0}{n^{0.75}} \log (Re)_{M-R} f^{(1-n/2)} - \frac{0.40}{n^{1.2}} \quad (17)$$

This model is depicted in graphical form on Figure 5.1. This figure implies that the onset of turbulence occurs at values of $(Re)_{M-R}$ greater than 2100, and tends to occur at increasing values as the value of n declines. Metzner and Dodge postulate that fluid "slip" at the wall of the pipe might be one reason for the reduced values of f that they experienced.

The use of Equation (16) to calculate Reynolds numbers in the turbulent flow range has been challenged recently (Hanks 1979). Hanks point out that Equation (16) is only valid for laminar flow of true pseudoplastic materials (no yield stress, $n \leq 1$) in circular pipes with linear shear stress distributions. The Metzner and Reed approach was pursued here since NCAW-PNL is a pseudoplastic material (Chapter 4).

5.2 YIELD-PSEUDOPLASTIC FLUIDS

The relationship between shear stress and rate of shear for a yield-pseudoplastic material was defined as:

$$\tau = K \left(\frac{dV}{dy} \right)^n \text{ when } \tau_y = 0 \quad (3)$$

FIGURE 5.1. Metzner and Reed Friction Factor - Re Relationships

$$\tau = \tau_y + \left(\frac{dV}{dy}\right)^n \text{ when } \tau_y > 0 \quad (4)$$

The yield pseudoplastic model reduces to the Bingham plastic model when $n = 1$, the pseudoplastic model when $\tau_y = 0$, and the Newtonian model when $\tau_y = 0$ and $n = 1$.

Theoretical design equations based on mixing length theory and Equations (18) and (19) have been developed to permit the design of pipelines for the pseudohomogeneous flow of yield-pseudoplastic fluids (Hanks 1978). The equations merge with similar equations developed for pseudoplastic fluids (Hanks and Ricks 1975; Hanks and Dadia 1971). The derivation of the equations is a complex exercise that will not be repeated here; rather, some of the concepts developed will be described.

The existence of a yield stress, τ_y , distinguishes yield-pseudoplastic fluids. The yield stress must be exceeded before flow can begin. The particle structure that creates the yield stress will affect the velocity distribution patterns developed during laminar flow. A higher shear rate is required to achieve a given velocity distribution pattern for a yield-pseudoplastic fluid than is required for a fluid without a yield stress. This additional shear rate requirement produces a higher value of the Fanning friction factor at a given laminar Reynolds number for fluids with yield stresses, and increases the value of the critical Reynolds number, Re_c , the Reynolds number that occurs at the transition from laminar to turbulent flow.

Hedstrom was the first investigator to account for the effects of τ_y on Re_c (Hedstrom 1952). He identified a parameter, later known as the Hedstrom number, He , that accounts for these τ_y effects. The Hedstrom number is defined as:

$$He = \frac{D^2 \rho}{K'} \left(\frac{\tau_y}{K'} \right)^{\frac{2-n}{n}} \quad (18)$$

where: D = pipe diameter, m
 ρ = fluid density, kg/m^3
 τ_y = yield stress, Pa
 K' = flow consistency index, Pa-s
 n = flow behavior index.

The effects of He on f and Re_c have been examined in detail by Hanks (Hanks 1978), and are depicted on Figures 5.2, 5.3 and 5.4. As the value of He increases, 1) the friction factor increases substantially at a given Reynolds number and 2) the critical Reynolds number occurs at values much higher than 2100.

The calculation procedure suggested by Hanks (1978) accounts for the effects of τ_y on laminar and turbulent velocity profiles and the resulting effects on calculated values of Re and f . An outline of these procedures is summarized on Figure 5.5. The equations referred to in Figure 5.5 are listed in Table 5.1. Nomenclature for Table 5.1 is summarized in Table 5.2.

FIGURE 5.2. Bingham Plastic Design Curve - f Versus Re ($n = 1.0$)

FIGURE 5.3. Yield-Pseudoplastic Design Curve - f Versus Re ($n = 0.7$)

FIGURE 5.4. Yield-Pseudoplastic Design Curve - f Versus Re ($n = 0.5$)

E = Explicit Function
I = Implicit Function

FIGURE 5.5. Hanks' Calculation Procedure for the Flow of Yield-Pseudoplastic Fluids in Pipes (Hanks 1978)

TABLE 5.1. Hanks' Equations for the Flow of Yield-Pseudoplastic Fluids in Pipes (Hanks 1978)

$$\langle v_z \rangle = a \left(\frac{\tau_0}{\eta} \right)^{1/m} \frac{m(1-\xi_0)^{(1+m)/m}}{\xi_0^{1/m}} \left[\frac{(1-\xi_0)^2}{1+3m} + \frac{2\xi_0(1-\xi_0)}{1+2m} + \frac{\xi_0^2}{1+m} \right]^m \quad (19)$$

$$f = 16/\psi Re \quad (20)$$

$$Re = 8 \left(\frac{m}{1+3m} \right)^m \frac{a^m \langle v_z \rangle^{2-m}}{\eta} \quad (21)$$

$$\psi = (1+3m)^m (1-\xi_0)^{1+m} \left[\frac{(1-\xi_0)^2}{1+3m} + \frac{2\xi_0(1-\xi_0)}{1+2m} + \frac{\xi_0^2}{1+m} \right]^m \quad (22)$$

$$He = \frac{D^2 \rho}{\eta} \left(\frac{\tau_0}{\eta} \right)^{(2-m)} = \frac{D^2 \rho}{\tau_0} \left(\frac{\tau_0}{\eta} \right)^{2/m} \quad (23)$$

$$Re_c = \frac{6464m}{(1+3m)^m} (2+m)^{\frac{2+m}{1+m}} \left[\frac{\frac{(1-\xi_{oc})^2}{1+3m} + \frac{2\xi_{oc}(1-\xi_{oc})}{1+2m} + \frac{\xi_{oc}^2}{1+m}}{(1-\xi_{oc})^m} \right]^{2-m} \quad (24)$$

$$He = \frac{3232}{m} (2+m)^{\frac{2+m}{1+m}} \frac{\xi_{oc}}{(1-\xi_{oc})^{1+m}} \frac{2-m}{m} \left(\frac{1}{1-\xi_{oc}} \right)^m \quad (25)$$

$$R = \left(\frac{1+3m}{m} \right) \left[Re \left(\frac{f}{16} \right)^{\frac{2-m}{2}} \right]^{1/m} \quad (26)$$

$$Re = (1-\xi_0)^{\frac{2-m}{m}} \left(\frac{m}{1+3m} \right) R^2 \left[\int_{\xi_0}^1 \xi^2 \zeta(\xi, \xi_0, R) d\xi \right]^{2-m} \quad (27)$$

$$R^2 = 2He/\xi_0^{(2-m)/m} \quad (28)$$

TABLE 5.2. Nomenclature for Table 5.1

Symbol	Definition	Units
a	Pipe radius	m
D	Pipe diameter	m
f	Fanning friction factor	--
He	Generalized Hedstrom number	--
m	Flow behavior index	--
R	Turbulence parameter	--
R_c	Value of R at laminar-turbulent transition	--
Re	Reynolds number	--
Re_c	Laminar-turbulent transition value of Re	--
v_z	Axial velocity component	m/s
$\langle v_z \rangle$	Area mean value of v_z	m/s
$\langle v_z \rangle_c$	Laminar-turbulent transition value of $\langle v_z \rangle$	m/s
z	Axial coordinate	--
η	Yield-power law consistency index	Pa $\cdot$ s
ζ	Dimensionless shear rate	--
ξ	Dimensionless radial coordinate, r/a	--
ξ_0	Dimensionless unsheared plug radius, τ_0/τ_w	
ξ_{oc}	Laminar-turbulent transition value of ξ_0	--
ρ	Slurry density	kg/m ³
τ_0	Yield stress	Pa
τ_w	Value of τ_{rz} at $r = a$	Pa
ϕ	Laminar flow function	--

6.0 DESIGN REQUIREMENTS FOR THE FULL-SCALE SYSTEM

One goal of this rheological evaluation of NCAW-TRU was to evaluate those rheological and transport properties critical to assuring the successful handling of the slurry in a full-scale pump-pipe network. The purpose of this section is to scale up laboratory results to establish the process design needs of the full-scale pump-pipe network that will transport NCAW-TRU slurries from B-Plant to the storage tanks.

The full-scale pump-pipe network must transport NCAW-TRU slurries at velocities that prevent the deposition of solids in the transfer lines. Laboratory critical transport property estimates will be scaled up to predict full-scale performance in Section 6.1. The centrifugal pump used to transport NCAW-TRU must be sized to deliver the NCAW-TRU slurries through approximately 9100 feet of 3-in., Schedule 40, smooth, carbon steel pipe. The pressure drop that can be expected to occur in this pipe will be estimated in Section 6.2. Full-scale line-flushing requirements will be discussed in Section 6.3.

6.1 SCALE-UP OF LABORATORY RHEOLOGICAL DATA

The pseudoplastic (Metzner and Reed 1955) and yield-pseudoplastic (Hanks 1978) rheological models were used to scale up laboratory data. The critical Reynolds number predicted by the pseudoplastic model is only a function of the flow behavior index, n (see Figure 5.1). For instance, for an n of 0.8, the pseudoplastic model will predict a Re_c of about 2150 for any pipe diameter.

The yield-pseudoplastic model accounts for the effects of τ_y and pipe diameter on Re_c and provides a way to predict Re_c for various combinations of τ_y , n , K' , and pipe diameter. The pseudoplastic, and yield-pseudoplastic approaches to the scale-up of pump-pipe test loop data are discussed in this section. Each model has been used successfully to scale up laboratory rheological data to predict critical transport properties in pump-pipe networks (McCarthy, Chan, and Lokken 1985).

6.1.1 Pseudoplastic Model

The pseudoplastic n and K' parameters, the predicted $(Re_c)_{M-R}$ values and critical pipeline velocities for NCAW-PNL at 25°C in the full-scale system are summarized in Table 6.1. The critical velocity value is based on the assumption that the full-scale pipe system is "smooth." The actual roughness of this pipe system must be determined before more accurate predictions of performance can be made.

6.1.2 Yield-Pseudoplastic Model

The yield-pseudoplastic model relies on the approach summarized in Figure 5.5. The available estimates of τ_y , n , K' , fluid density and pipe diameter are used to calculate the value of the Hedstrom number, He . This value of He is used to define the laminar-turbulent transition value of τ_y/τ_w . The Re_c for the system can be estimated once the laminar-turbulent transition value of τ_y/τ_w has been established. An iterative calculation procedure is required to determine this value of τ_y/τ_w (see Figure 5.5).

The yield-pseudoplastic rheological parameters obtained during laboratory tests were used to predict values of Re_c for the NCAW and NCAW-TRU slurries in a 3-in. diameter, schedule 40, smooth, carbon steel pipe. These predictions

TABLE 6.1. Predictions of Full-Scale Critical Flow Properties:
Pseudoplastic Model^(a)

Item	NCAW-PNL
n	0.8
K' (Pa-sec)	0.0149
$(Re_c)_{M-R}$	2150
V_c (fps)	0.62
Q_c (gpm)	13.8

(a) Values are based on the average values of K' and n obtained with three laboratory samples of NCAW-PNL.

are summarized in Table 6.2. All of the predicted values of V_c are below the design velocity of 2.1 fps (50 gpm) for the full-scale system. These predictions of V_c are based on the assumption that the full-scale pipe system is "smooth." The actual roughness of this pipe system must be determined before more accurate predictions of performance can be made.

6.2 PRESSURE DROP EXPECTED IN THE FULL-SCALE SYSTEM

The pressure drop in the full-scale system can be estimated by the following equation:

$$\Delta P = \frac{4 L f}{D} \frac{\rho V^2}{2 g_c} \quad (29)$$

The pressure drop in the full-scale system will be a function of the equivalent length, L , of the system, the diameter of the transfer pipe, D , the velocity in the pipe, V , and the friction factor, f , developed as the fluid passes through the pipe. The friction factor is in turn a function of the physical and rheological properties of the fluid, the Reynolds number, and the roughness of the internal surface of the pipe.

TABLE 6.2. Predictions of Full-Scale Critical Flow Properties:
Yield-Pseudoplastic Model^(a)

<u>Item</u>	<u>NCAW-PNL</u>	<u>NCAW-RHO</u>	<u>NCAW-TRU-PNL</u>	<u>NCAW-TRU-RHO</u>
n	1.0	1.0	1.0	1.0
τ_y (Pa)	0.15	0.15	0.145	0.047
K' (Pa-s)	0.0042	0.013	0.0017	0.0011
$(RE_c)_H$	5900	3086	10,117	9,243
V_c (ft/s)	0.8	1.2	0.7	0.4
Q_c (gpm)	18.6	28.1	16.0	9.5

(a) Values are based on the average values of τ_y , K' and n obtained with three laboratory samples of each slurry.

The pressure drop estimates discussed in this section are all based on assumptions listed in Table 6.3. These assumptions reflect the current design parameters for the full-scale system.

The relationship between f and Re depends on the rheological model used to calculate Re . The Bingham plastic model (yield-pseudoplastic model with $n=1$) was used to evaluate NCAW-RHO and both NCAW-TRU slurries at 25°C. The Bingham plastic and the pseudoplastic model were used to evaluate NCAW-PNL.

6.2.1. Pseudoplastic Model

The Reynolds number for pseudoplastic fluids is given by Equation (30):

$$(Re)_{M-R} = \frac{D^n V^{2-n} \rho}{g_c K' 8^{n-1}} \quad (30)$$

The parameters n and K' obtained during laboratory tests with NCAW-PNL were used to calculate $(Re)_{M-R}$ for the normal and maximum fluid velocities indicated in Table 6.4. This value of $(Re)_{M-R}$ was used to establish the friction factor, f (Figure 5.1). The predicted values of pressure drop for the full-scale system are summarized in Table 6.4.

For the normal flow case, the predicted value of pressure drop for 9100 feet of 3-in. diameter schedule-40 pipe for NCAW-PNL at 25°C is 41 psig and, 79 psig for the maximum flow case. These predictions of pressure drop must be adjusted when information about the pipe roughness of the actual full-scale pipe network becomes available.

TABLE 6.3. Assumptions in Full-Scale Pressure Drop Calculations

Item	Symbol	Value
Equivalent length	L	9100 feet
Pipe roughness	ϵ	smooth pipe
Temperature	-	25°C
Pipe diameter	D	3.068 inches
Line velocities	V	2.17 fps normal (50 gpm) 3.31 fps maximum (75 gpm)

TABLE 6.4. Prediction of Full-Scale Pressure Drop: Pseudoplastic Model^(a)

Item	NCAW-PNL
n	0.8
$g_c K' (lb_m/ft\text{-}sec)$	0.0101
$\rho (lb_m/ft^3)$	79.2
$(Re)_{M-R\text{-}normal}$	9,650
$(Re)_{M-R\text{-}maximum}$	15,700
f-normal	0.007
f-maximum	0.006
ΔP normal (psi/1000 ft)	4.4
ΔP maximum (psi/1000 ft)	8.5

(a) ΔP values are based on average values obtained with three laboratory samples of NCAW-PNL.

6.2.2. Yield-Pseudoplastic Model

The Reynolds number for yield-pseudoplastic fluids is calculated by the iterative procedure summarized on Figure 5.5. The parameters n , K' and τ_y obtained during laboratory tests were used to calculate $(Re)_H$ for the normal and maximum fluid velocities indicated in Table 6.5. The predicted values of pressure drop for the full-scale system are summarized in Table 6.5.

For the normal flow case, using the Bingham plastic rheological model, the predicted value of pressure drop for 9100 feet of 3-in. diameter, schedule 40 pipe for NCAW-PNL and NCAW-RHO at 25°C is 35 psig. This value is approximately 15% lower than the pressure drop predicted for NCAW-PNL using the pseudoplastic model. For the maximum flow case, the predicted value of pressure drop for NCAW-PNL and NCAW-RHO is 72 psig. This value is approximately 9% lower than the pressure drop predicted for NCAW-PNL using the pseudoplastic model. For NCAW-TRU-PNL, the predicted normal and maximum flow pressure drops are 25 and 53 psig, respectively. The predicted pressure drops are 24 and 48 psig for

TABLE 6.5. Prediction of Full-Scale Pressure Drop: Yield-Pseudoplastic Model^(a)

Item	NCAW-PNL	NCAW-RHO	NCAW-TRU-PNL	NCAW-TRU-RHO
n	1.0	1.0	1.0	1.0
K' (Pa-s)	0.0042	0.013	0.0017	0.0011
τ_y (Pa)	0.15	0.15	0.145	0.047
ρ (g/cm ³)	1.27	1.36	1.02	1.02
(Re) _H -normal	15,240	5,272	30,925	46,735
(Re) _H -maximum	22,714	7,921	45,430	70,209
f-normal	0.0059	0.0055	0.0055	0.0050
f-maximum	0.0055	0.0050	0.0050	0.0046
ΔP -normal (psi/1000 ft)	3.8	3.8	2.8	2.6
ΔP -maximum (psi/1000 ft)	7.9	7.9	5.8	5.3

(a) ΔP s are based on average values obtained with three laboratory samples of each slurry.

NCAW-TRU-RHO for the normal and maximum flows. These predictions must be adjusted as information about the full-scale pipe roughness becomes available.

6.3 FULL-SCALE LINE-FLUSHING REQUIREMENTS

The full-scale pump-pipe network will be subject to process upsets, which could cause NCAW and/or NCAW-TRU slurry to remain in the transfer piping for extended periods of time. The solids will settle from the suspension during this time period. The full-scale pump must be able to resuspend settled NCAW and NCAW-TRU solids and clean the pipe network after a process upset.

The "resuspendibility" of a slurry will depend on the complex chemical and physical interactions that occur between the solid and liquid phases of the slurry. Several empirical relationships have been developed to account for these interactions and identify resuspension velocities. These relationships are described in Section 6.3.1.

6.3.1 Empirical Estimates

Resuspension has been defined as the condition in which settled particles are influenced by an accelerating fluid to become suspended by the increasing fluid turbulence until the system reaches its final steady-state condition (no further acceleration). The phenomenon in which there is impending motion of a number of particles from a stationary bed of granular materials into a liquid medium is termed "incipient motion." Incipient motion is reached when the forces acting on the settled particles equal the forces resisting movement of the particles. Further increases in flow rate will increase particle movement until a steady state flow condition (stationary bed, moving bed, heterogeneous, pseudohomogeneous) is achieved (Kao et al. 1978).

The degree of resuspension achieved will be a function of the pressure gradient applied to the settled solids and the steady-state fluid velocity achieved in the pipe. This relationship is described on Figure 6.1. Incipient motion is achieved at point A on Figure 6.1. An additional force is required to break through particle cohesive forces and resuspend the settled solids (point B). Once this condition is reached, an increase in fluid velocity and decrease in pressure drop will occur (point C). The pressure gradient will then increase slowly with velocity until a steady-state heterogeneous or pseudohomogeneous flow condition is reached.

The critical flushing velocity must be greater than the critical deposition velocity, V_{cd} , indicated by point C on Figure 6.1. Many empirical methods have been developed to estimate V_{cd} (Wiedenoth, Ing, and Kirchner 1972; Govier and Aziz 1982). These methods were developed for specific solids-liquid systems and are not generally applicable to other systems. They require a detailed knowledge of particle size distribution, particle shape and particle density that are not available for NCAW and NCAW-TRU slurries. The critical deposition velocity, V_{cd} , will be approximately equal to the velocities associated with the critical Reynolds number discussed in Section 6.2. These velocities are smaller than the line-flushing velocities that will be utilized by Rockwell.

The current Rockwell design for the full-scale pump-pipe system specified that one pipe-volume of water be used for flushing, and that this water be

FIGURE 6.1. Effects of Pressure Applied and Fluid Velocity on the Resuspension of Settled Solids

delivered at a rate of 75 gpm (3.3 fps). A resuspension velocity of 3.3 fps is approximately 4, 3, 5, and 8 times the full-scale velocities predicted as the laminar-turbulent transition velocities for NCAW-PNL, NCAW-RHO, NCAW-TRU-PNL and NCAW-TRU-RHO, respectively, at 25°C.

The degree of resuspension achieved during flushing will be a function of the pressure gradient applied to the settled solids, the steady-state fluid velocity achieved in the pipe, and the amount of flush water delivered during the flush. The pressure gradient necessary to resuspend settled NCAW must be established during pilot-scale tests using a pump-pipe test loop. These tests were beyond the scope of this project.

A series of pilot-scale resuspension tests with Neutralized Cladding Removal Waste (NCRW) was completed recently (McCarthy, Chan, and Lokken

1985). The NCRW slurry exhibited properties that were similar to those exhibited by the NCAW slurries. Some of these properties are summarized in Table 6.6.

TABLE 6.6. Comparison of NCAW and NCRW Slurry Properties at 25°C

Property	NCRW	NCAW-PNL	NCAW-RHO	NCAW-TRU-PNL	NCAW-TRU-RHO
Viscosity at 50 s ⁻¹ , cP	4	7	16	5	2
V _c -full-scale, fps	0.3-0.4	0.6-0.8	1.2	0.7	0.4
ΔP for 9100 ft, psi at 2.1 fps	31-36	35-44	35	25	24

During the NCRW pilot-scale tests, the pressure gradient applied during resuspension equaled about 1.3 times the normal pressure drop associated with a flow velocity of 3.3 fps. If this criterion is applied to the full-scale NCAW system, pressure drops of approximately 95 psig would result during flushing of NCAW-PNL and NCAW-RHO. For the full-scale NCAW-TRU system, pressure drops of approximately 69 and 63 psi would result during flushing of NCAW-TRU-PNL and NCAW-TRU-RHO, respectively. These predictions of pressure drop requirements during full-scale line-flushing are estimates. Actual requirements must be established during pilot-scale tests.

The pressure gradient applied, flush water velocity and amount of flush water used act singularly and in combination to resuspend slurry and to clean transfer lines. The laboratory experiments conducted were not designed to examine the way in which these factors interact during the flushing procedure. Additional pilot-scale tests will be required to define these interactions and to identify the optimal flushing design for NCAW and NCAW-TRU slurries.

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