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Rheological Evaluation of Pretreated Cladding Removal Waste

**D. McCarthy
M. K. C. Chan
R. O. Lokken**

January 1986

**Prepared for the U.S. Department of Energy
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SUMMARY

Cladding removal waste (CRW) contains concentrations of transuranic (TRU) elements in the 80 to 350 nCi/g range (Nankani 1984). This waste will require pretreatment before it can be disposed of as glass or grout at Hanford. The CRW will be pretreated with a rare earth strike and solids removal by centrifugation to segregate the TRU fraction from the non-TRU fraction of the waste. The centrifuge centrate will be neutralized with sodium hydroxide. This neutralized cladding removal waste (NCRW) is expected to be suitable for grouting. The TRU solids removed by centrifugation will be vitrified.

The goal of the Rheological Evaluation of Pretreated Cladding Removal Waste Program was to evaluate those rheological and transport properties critical to assuring successful handling of the NCRW and TRU solids streams and to demonstrate transfers in a semi-prototypic pumping environment. This goal was achieved by a combination of laboratory and pilot-scale evaluations. The results obtained during these evaluations were correlated with classical rheological models and scaled-up to predict the performance that is likely to occur in the full-scale system.

The Program used simulated NCRW and TRU solid slurries. Rockwell Hanford Operations (Rockwell) provided 150 gallons of simulated CRW and 5 gallons of simulated TRU solid slurry. The simulated CRW was neutralized by Pacific Northwest Laboratory (PNL). The physical and rheological properties of the NCRW and TRU solid slurries were evaluated in the laboratory. The properties displayed by NCRW allowed it to be classified as a pseudoplastic or yield-pseudoplastic non-Newtonian fluid. The TRU solids slurry contained very few solids. This slurry exhibited the properties associated with a pseudoplastic non-Newtonian fluid.

Pilot-scale tests conducted in a 3/4-in. and a 1-in. diameter pipe network confirmed the laboratory finding that NCRW could be treated as a pseudoplastic or yield-pseudoplastic non-Newtonian fluid. As a result of many years of study by the pipeline industry, mathematical relationships have been developed to model this fluid behavior. These models were applied to actual laboratory and

pilot-scale rheological data and used to predict the critical shear rate for NCRW in the 3/4- and 1-in. pipe networks. These predictions are compared to the actual critical shear rate measured during pilot-scale tests in Table 1.

The data obtained during laboratory tests provided a more accurate prediction of actual critical shear rates than data obtained during pilot-scale tests in this instance. This fact is significant since laboratory tests are much less expensive to conduct than pilot-scale tests. Laboratory tests are not expected to be more accurate than pilot-scale tests if the slurry evaluated exhibits time-dependent behavior that can not be modelled by pseudoplastic or yield-pseudoplastic equations.

The full-scale pump-pipe network must transport NCRW and TRU solids slurries at velocities that prevent the deposition of solids in the transfer lines. Laboratory and pilot-scale critical transport velocity estimates were scaled up to predict full-scale performance. These estimates indicate that a critical transport velocity of 0.4 to 0.8 feet per second (fps) will be required to suspend NCRW in the full-scale system. The corresponding velocity for the TRU solids slurry is estimated to be 0.2 fps. These velocities are well below the design velocity in the full scale system (2.1 fps).

The pump used to transport NCRW and TRU solids slurries must be sized to overcome pressure losses that will result as the slurries flow through the full-scale pipe network. Laboratory and pilot-scale data were scaled up to provide estimates of these pressure losses. These estimates are summarized in

TABLE 1. Comparison of Laboratory and Pilot-Scale Predictions of Critical Transport Properties

NCRW Batch	Laboratory Predictions			Pilot-Scale Predictions			Actual Critical Shear Rate, sec ⁻¹
	Pseudoplastic	Yield-Pseudoplastic		Pseudoplastic	Yield-Pseudoplastic		
		Pipe	Shear Rate, sec ⁻¹		Pipe	Shear Rate, sec ⁻¹	
2	102 70	5/4 1	76 53	128 118	3/4 1	126 120	85 53
3	52	1	51	79	1	73	65

Table 2. These estimates assume that each slurry will be pumped at 50°C through a 3-in., schedule 40 carbon steel pipe with an equivalent length of 8400 feet. These assumptions reflect the current design parameters for the full-scale system. The estimates also assume that full-scale transfer piping will exhibit a surface roughness equivalent to that displayed by the carbon steel pipe used during pilot-scale runs. The full-scale pipe has been in place for some time. It may have surface roughness properties that exceed those exhibited by the new carbon steel pipe used during pilot-scale runs. These properties should be determined if a more accurate estimate of full-scale pressure drop is required.

The current Rockwell design for the full-scale pump-pipe system specifies that one pipe volume of water will be used for flushing and that this water will be delivered at a rate of 75 gpm (3.3 fps). This criteria was applied to NCRW slurry that was allowed to settle in the 3/4-in. diameter pilot-scale network. The network was effectively cleaned during each flushing test. This flushing schedule is expected to be successful when it is applied to the full-scale system.

The flushing schedule established by Rockwell may be modified in the near future to reduce the velocity of flushing water below 3.3 fps. An attempt was made to estimate the minimum velocity and delivery pressure of flushing water that would be required to resuspend settled NCRW in the full-scale system. The pilot-scale flushing velocity was approximately 4.3 times the velocity V_c , at which the flow pattern in the 3/4-in. pipe changed from a laminar to a turbulent condition. The velocity V_c in the full-scale system is estimated to be 0.4 fps based on the scale-up of laboratory data to 0.7 fps based on the scale-up of pilot-scale data. If the 4.3 criterion is applicable to the full-scale

TABLE 2. Prediction of Full-Scale Pressure Drop

Slurry	From Laboratory Data		From Pilot-Scale Data	
	Full-Scale (50 gpm)	Flow Rate (75 gpm)	Full-Scale 50 gpm	Flow Rate 75 gpm
NCRW	28-31	57-65	32-36	65-74
TRU Solids	21	43	--	--

system, line velocities of 1.7 to 3.0 fps will be required to resuspend settled NCRW. These velocities are likely to produce a pressure drop from 19-25 to 51-68 psig in the full-scale system.

During pilot-scale tests, the pressure gradient required to initiate flow during the flush equaled 1.3 times the normal pressure drop associated with the flow of flush water, once flow began. If this ratio holds for the full-scale system, the flush water pump will have to develop a pressure drop of 25-33 (based on laboratory data) to 66-88 psig (based on pilot-scale data), depending on the actual critical velocity that exists in the system. Laboratory-scale data provided a more accurate estimate of critical shear rates obtained during pilot-scale tests during this test program and may provide more accurate estimates of the performance of the full-scale system. If this is the case, the full-scale flushing pump will have to develop a pressure drop that is closer to 25-33 psig than 66-88 psig.

One of the conclusions arrived at as a result of this study was that the data analysis methods could be applied to other types of slurries. Because many slurries at Hanford [grout, neutralized current acid waste (NCAW)] appear to be pseudoplastic or yield-pseudoplastic fluids, the same data analysis methods described here can be used to scale up rheological data obtained in the laboratory to estimate the critical transport velocity and pressure drop that these slurries will exhibit in full-scale applications. These methods provide a low-cost and rapid means of obtaining information that can be used to formulate efficient and cost effective designs for slurry transportation and processing systems.

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1.0 INTRODUCTION AND OBJECTIVES

The decladding of spent N-Reactor fuel generates cladding removal waste (CRW), which contains concentrations of transuranic (TRU) elements (primarily plutonium and americium) in the 80 to 350 nCi/g range (Nankani 1984). The waste stream will require pretreatment before it can be disposed of as glass or grout at the Hanford site. The CRW will be pretreated with a rare earth strike and solids removal by centrifugation to segregate the TRU fraction from the non-TRU fraction of the waste. A process flow diagram for the CRW pretreatment process is depicted in Figure 1. The centrifuge centrate will be neutralized with sodium hydroxide and is expected to be suitable for grouting. The TRU solids removed by centrifugation will be vitrified.

Although current plans are to treat CRW at the Plutonium and Uranium Extraction (PUREX) Plant, this report was written with the prior assumption that CRW would be treated at B-Plant. Both facilities are operated by Rockwell Hanford Operations (Rockwell) in the 200 Area of the Hanford Site. Under the B-Plant operating scenario, the TRU solids stream will be pumped from B-Plant to the AR vault from which the stream will be pumped to suitable storage tanks to await disposal. The neutralized cladding removal waste, or NCRW (the non-TRU waste) will be pumped directly to storage tanks from B-Plant. Each of the two streams will contain suspended solids and dissolved salts. The transfer and storage of these slurries must be conducted in a fashion to prevent line plugging, particle segregation, cementation and caking. Transfer lines, pumps or jets, and agitation systems must be specifically designed to handle each slurry. The design of this equipment will be guided by the rheological properties of each slurry.

Rheology is the field of study concerned with the deformation and flow of materials. The goal of PNL's Rheological Evaluation of Pretreated Cladding Removal Waste Program was to evaluate those rheological and transport properties critical to assuring successful handling of the processed CRW streams, and to test and demonstrate transfers of the slurries in a semi-prototypic pumping environment. The Department of Energy, Richland Operations Office (DOE-RL)

FIGURE 1. CRW Pretreatment Process Flow Diagram

funded the program. The program was conducted in conjunction with related ongoing activities by Rockwell personnel.

The specific objectives of the Rheological Evaluation of Pretreated CRW Program were 1) to evaluate the rheological behavior of simulated NCRW slurry and TRU solid slurry at one waste stream composition defined by Rockwell; 2) to determine the pipeline transport requirements (critical Reynolds number, fluid velocity) necessary to prevent solids deposition in transfer lines; 3) to verify that the transfer line flush volumes proposed by Rockwell are sufficient to clean lines at the conclusion of each slurry transfer and after an equipment malfunction, 4) to evaluate the resuspendibility of settled NCRW slurry; and 5) to set-up and operate a semi-prototypic (pilot-scale) pump-pipe transfer system to verify laboratory scale results and to simulate the kinematic and dynamic conditions in full-scale pump-pipe transfer systems.

The Program used simulated NCRW and TRU solid slurries. Rockwell provided 150 gallons of simulated CRW and 5 gallons of simulated TRU solid slurry. The simulated CRW was neutralized by PNL. Researchers at PNL evaluated the physical and rheological properties of the NCRW and TRU solid slurries in the laboratory. The NCRW slurry was pumped through a pump-pipe test loop. The pump-pipe test loop data was scaled-up to predict the performance that is likely to occur in the full-scale transfer system.

The format of this report follows the sequence in which the work was conducted. The initial program activity was concerned with gaining an understanding of the theoretical foundation of non-Newtonian flow systems. Section 2 of this report describes the classical rheological models that are used to describe homogeneous and heterogeneous flow systems. Since the results obtained here are only valid for the slurries utilized, Section 3, Preparation of Simulated NCRW and Rare Earth Fluoride-TRU Solid Slurries, describes how the slurries were prepared. The laboratory-scale viscometric and physical property information obtained is summarized in Section 4, Laboratory Rheological Evaluations. Pilot-scale rheological and transport evaluations to determine the pressure drop, critical Reynold's number and line velocity, and flush water requirements for transfer lines are described in Section 5. Laboratory and pilot-scale results are scaled-up to establish engineering design requirements for the full-scale transfer system in Section 6.

2.0 NON-NEWTONIAN FLOW SYSTEMS

The procedures used to design slurry transport and treatment processes are based on classical rheological models for homogeneous and heterogeneous flow systems. These models were used to classify NCRW and TRU solid slurries, and to scale up the laboratory and pilot-scale data collected to predict the behavior of the slurries in the full-scale transport system. The accuracy of these predictions will depend on the degree of similarity that exists between the properties of the full-scale system, the laboratory and pilot-scale system, and the underlying theoretical model. The theoretical models used to define slurry transport and treatment systems 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 or flow behavior is depicted on Figure 2. 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 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

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			
← Flow Behavior as Single Phase →		← Flow Behavior as Multi-Phase →			

FIGURE 2. Classification of Complex Mixtures

systems for pseudohomogeneous slurries and heterogeneous slurries differ markedly. A procedure that can be used to define heterogeneity is discussed in Section 2.3.

2.2 PSEUDOHOMOGENEOUS FLOW SYSTEMS

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, dynes/cm²

F = force, dynes

A = area, cm²

For Newtonian fluids in laminar flow:

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

where τ = shear stress, dynes/cm²

μ = viscosity

$\frac{dv}{dy}$ = shear rate in y direction, sec⁻¹

The viscosity μ , is a proportionality constant which 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 3a). The slope of the curve is constant for a Newtonian fluid. All fluids that display rheograms that are not linear through the origin at a given temperature and pressure are considered to be non-Newtonian. Non-Newtonian fluids are usually classified as time-independent, time-dependent or viscoelastic fluids.

FIGURE 3. Rheograms for Time-Independent Non-Newtonian 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 in Figure 3a. The relationship between apparent viscosity and shear rate for these fluids is described in Figure 3b.

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 3a). Equations that relate shear stress and shear rate for these fluids are included in Table 3.

The majority of non-Newtonian slurries exhibit pseudoplastic behavior. Since the exponent n is less than unity for pseudoplastic fluids (see Table 3), the apparent viscosity K , decreases with increasing shear rate. The particles in most slurries will be asymmetric. They will be characterized by extensive entanglement of the particles when the fluid is at rest. Progressive disentanglement should occur under the influence of shearing forces, the particles tending to orient themselves in the direction of shear. This orienting influence is proportional to shear rate and is opposed by the randomly disorienting effects of Brownian movement, the extent of which is determined only by temperature for a given fluid. Complete orientation at high shear rates and complete disorientation at very low shear rates would account for the observed Newtonian behavior in these regions (Skelland 1967).

Pseudoplastic behavior may also be caused by the existence of highly solvated molecules or particles in the dispersion. Progressive reduction of solvated layers with increasing shear rate would result in decreasing interaction

TABLE 3. 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

between the particles (because of their smaller effective size) and consequent reduction in apparent viscosity. Linearity of the flow curve at very high shear rates might correspond to complete removal of the solvated layers, with the interaction between particles therefore becoming constant. Destruction of these layers might be very slight at small values of dv/dy , so that particle interactions would again be constant. This would in turn cause linearity of the flow curve in this region (Skelland 1967).

Pseudoplastic fluids include rubber solutions, adhesives, polymer solutions, starch suspensions, mayonnaise, soaps, detergent slurries, Napalm, paints, biological sludges, and many other solid-liquid suspensions. Rigorous pipeline and processing equipment design techniques for pseudoplastic fluids were first proposed in 1954 (Metzner 1954). Since then these methods have been refined by many other investigators (Metzner and Reed 1955; Dodge and Metzner 1959; Hanks and Christiansen 1962; Bogue and Metzner 1963; Tia and Bhattacharya 1973; Kao 1974; Hanks and Ricks 1975; Mohammad et al. 1975; Ooi 1980).

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 since the exponent n (see Table 3) is greater than one. One explanation for this behavior (Skelland 1967) suggests that particles in a concentrated suspension will be oriented at rest so that the void space is a minimum. The suspending liquid is just sufficient to fill the voids in this state. The increase in voidage caused by shearing a dilatant material means that the space between particles becomes incompletely filled with liquid. Under these conditions of inadequate "lubrication," the surfaces of adjacent particles come into direct contact, causing an increase in apparent viscosity with increasing shear rate. Because such substances do not exhibit rheological dilatancy at the lowest shear rates, it is possible that the closely packed particle structure is not fully disrupted, with accompanying significant increase in voidage, until somewhat higher shear rates are reached. Several more complex explanations have been proposed by other investigators (Govier et al. 1957; Metzner and Whitlock 1958; Jobling and Roberts 1959).

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 the 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 3.

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. The behavior of Bingham plastic fluids has been examined by many investigators (Thomas 1960, 1961a, 1961b; Hanks and Christiansen 1962; Hanks 1963, 1978a, 1979a, 1980; Hanks and Pratt 1967; Hanks and Dadia 1971).

Yield-pseudoplastic materials include clay-water suspensions, solutions of carbonylpolymethylene (carbopol), some grout formulations, rubber-benzene solutions, phosphate ore, and many coal-water slurries. The behavior of yield-pseudoplastic materials has been investigated since 1926 (Herschel and Bulkley 1926; Hanks and Ricks 1974; Robertson and Stiff 1976; Hanks 1978b, 1979b; Lazarus 1980).

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 et al. 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 in Figure 4.

Thixotropic slurries exhibit a decrease in shear stress with time at a constant shear rate and temperature. A hysteresis loop (Figure 4) 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 slower rate than those causing pseudoplastic behavior (Section 2.2.1.1). 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 4) 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

FIGURE 4. Rheograms for Thixotropic and Rheopectic Non-Newtonian Fluids

occur at a slower rate than those causing dilatant behavior (Section 2.2.1.1). 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, Napalm, 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 heterogenous slurry is a complex mixture of coarse particles in a liquid stream (see Figure 2). The solids may not be homogeneously dispersed in the liquid stream. The pseudo-homogeneous, non-Newtonian behavior described in Section 2.2 can not be applied to heterogenous slurries. These slurries act as two-phase systems. The degree of phase separation is a function of 1) particle size, shape, density, and concentration, and 2) the fluid density and viscosity.

2.3.1 Heterogeneous Slurry Flow Patterns

A qualitative flow curve (Figure 5) 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 6) develops. At still lower velocities, a sliding bed forms at the bottom of the pipe (Figure 6). The velocity at which the flow pattern changes from a heterogeneous to a

FIGURE 5. Flow Curve for Heterogeneous Slurries

sliding regime is known as the "sliding bed velocity" or the "critical deposition velocity" (Hanks and Sloan 1981). The bed velocity V_c 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_c .

Particle size distribution, density and shape, fluid density and viscosity, the diameter of the transfer pipe, and many other factors will impact the

FIGURE 6. Heterogeneous Slurry Flow Patterns

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
- 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 as "ballpark" estimates of 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 7. They are useful as "ballpark" estimates of the type of heterogeneous flow pattern that may exist for differing particle diameters and velocities.

Reference: (Newitt et al. 1955)

FIGURE 7. Heterogeneous Slurry Flow Patterns; Particle Diameter and Velocity Effects

Reference: (Nelson et al., 1985)

Figure 1. Homogeneous, Heterogeneous, and Flow with Stationary or Moving Bed Regions

3.0 PREPARATION OF SIMULATED NCRW AND RARE EARTH FLUORIDE-TRU SOLID SLURRIES

Cladding removal waste will be pretreated with a rare earth strike (primarily lanthanum and neodymium fluoride) and solids removal by centrifugation to segregate the TRU fraction from the non-TRU fraction of the waste. A process flow diagram for the CRW pretreatment process was depicted in Figure 1. The centrate exiting the centrifuge will be neutralized with sodium hydroxide and is expected to be suitable for grouting. The rare earth fluoride-TRU solids removed by centrifugation will be vitrified. The preparation of the simulated NCRW and rare earth fluoride-TRU solid slurries used during this development program will be described here.

3.1 ACQUISITION OF CRW AND RARE EARTH FLUORIDE-TRU SOLID SLURRIES

The simulated CRW and rare earth fluoride-TRU solid slurries used during this development program were prepared by Rockwell. The simulated CRW was prepared by dissolving strips of Zircaloy in an ammonium fluoride/ammonium nitrate (AFAN) solution. During dissolution, the Zirconium should react as follows:

The resulting solution was refluxed at its boiling point, cooled, and diluted with warm water. The composition of one 150-gallon sample of simulated CRW is shown in Table 4. This composition is considered typical for simulated CRW solutions.

The simulated rare earth fluoride-TRU solid slurry was prepared by adding rare earth nitrate to a solution of ammonium fluoride. The resulting mixture was centrifuged and the centrate was removed. The centrifuged solids were diluted with water to achieve a dilution factor of 18. A 5-gal sample of this slurry was provided by Rockwell.

TABLE 4. Composition of Simulated CRW Sample Received from Rockwell

Constituent	Concentration	Method of Analysis
NH_4^+	1.33 <u>M</u>	Titration
Zr^{3+}	0.46 <u>M</u>	Inductively Coupled Plasma
NO_3^-	0.073 <u>M</u>	Ion Chromatography
Total F ⁻	3.42 <u>M</u>	Ion Chromatography/ Specific Ion Electrode

3.2 NEUTRALIZATION OF SIMULATED CRW

Historically, CRW has been neutralized by direct and reverse strike methods. The direct strike method requires that sodium hydroxide be added to a vessel that contains CRW. During a reverse strike, sodium hydroxide is placed in a vessel, and CRW is added. A co-strike calls for the simultaneous addition of sodium hydroxide and CRW to an agitated vessel. During neutralization the following reactions are likely to occur:

The solids ($\text{ZrO}_2 \cdot 2\text{H}_2\text{O}$, NaF, NaNO_3) produced during the neutralization procedure induce the rheological properties that govern the fluid flow behavior of the NCRW slurry.

The nature of the solids produced during neutralization is determined by the neutralization procedure employed. The program described in this report was initially designed to assess the fluid flow properties of CRW slurries produced by two neutralization procedures. Schedule and cost constraints caused Rockwell to limit the program to an evaluation of one simulated CRW slurry. A slurry obtained by direct strike neutralization was considered to be the worst-case slurry. The solids in this slurry were known to settle at a faster rate, and to form a more concentrated sludge than the solids created during reverse

and to form a more concentrated sludge than the solids created during reverse and co-strike neutralizations. Consequently, equipment parameters based on results of work with a direct strike slurry should be able to handle the slurries resulting from reverse or co-strike neutralizations.

The direct strike procedure used by PNL to neutralize the simulated CRW solution was specified by Rockwell. The CRW solution to be neutralized was placed in a drum. The CRW was agitated and heated to 45-50°C. Technical grade sodium hydroxide solution (18-19M) was added to the CRW at a constant rate during a 20-minute interval. The stoichiometric amount of sodium hydroxide required to react with the CRW solution was added (see Equations 4, 5, and 6). An additional amount of sodium hydroxide was then added to assure that all reactions proceeded to completion.

The end point of the neutralization procedure was initially specified as a free hydroxide ion concentration of 0.1 M. Analytical chemists at Rockwell and PNL eventually determined that the procedures used to measure the free hydroxide ion concentration in a neutralized CRW slurry were not accurate or precise. As a result, Rockwell specified other methods to assure that the neutralization reactions were completed. The neutralization reaction was considered complete when 1) excess sodium hydroxide was added, 2) the final pH was greater than 13, 3) the settled solids concentration of the neutralized CRW was less than 45 volume percent, and 4) when the addition of more sodium hydroxide to the supernatant fraction of settled NCRW did not produce any visible particulates.

The CRW sample received from Rockwell was neutralized as shown in the schedule in Table 5. The initial neutralization of a 20-gal batch of CRW was witnessed and approved by Rockwell personnel. Subsequent neutralizations were conducted in a similar fashion. The neutralized slurry was then analyzed to determine its rheological properties. The laboratory rheological evaluations are described in the next section of this report.

TABLE 5. CRW Neutralization Schedule

<u>Batch</u>	<u>Quantity, gal</u>	<u>Date Neutralized</u>
0	20	February 11, 1985
1	40	March 7, 1985
2	40	March 19, 1985
3	40	March 28, 1985

4.0 LABORATORY RHEOLOGICAL EVALUATIONS

Laboratory rheological evaluations were conducted with samples of NCRW and rare earth fluoride-TRU solid slurries. The samples of NCRW analyzed were aliquots of the NCRW batches prepared for use during pilot-scale rheological and fluid flow evaluations (see Table 5). The sample of rare earth fluoride-TRU solid slurry analyzed was prepared by Rockwell.

The laboratory evaluations were conducted to 1) measure the physical properties of the slurries, 2) classify the rheological behavior of each slurry, 3) determine the effects of shear rate and temperature on the apparent viscosity of each slurry, and 4) provide background information needed to design and operate the pilot-scale pump-pipe test loop.

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 (see Figure 8). The measurement of viscosity with this instrument 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. 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 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 .

[®] Haake Buchler Instruments, Inc.

FIGURE 8. Schematic of a Haake Viscometer

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 9). When the shear stress surpasses the yield value τ_y , the rotor breaks loose from its "clamp." The rotor picks up speed, accelerating almost instantaneously to the value n_{tg} . The change in the behavior of the sample becomes apparent in the rapid 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

FIGURE 9. Flow Curve (Rheogram) for a Yield-Pseudoplastic Fluid

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.

The evaluation of the viscosity of NCRW samples was hindered by the rapid settling characteristics of the solids in the samples. The preparation of a rheogram (such as that shown in Figure 3a) takes approximately 10 minutes. The solids in the sample can settle appreciably during this time period. A series of seven replicate rheograms were prepared for a sample of NCRW Batch 0, heated to 50°C to determine the precision of viscometric procedures. The results obtained are summarized in Table 6. The 95% confidence bands straddle the mean values by ± 8 to 11 percent. This level of precision was considered adequate given the settling characteristics of NCRW slurries.

Standard laboratory techniques were used to measure the pH, density, dissolved solids, suspended solids and total solids content of each sample. The measurement of very alkaline pH values (greater than 13 units) is difficult;

TABLE 6. Replicate Rheograms for NCRW-Batch 0 at 50°C.

Shear Rate sec	Shear Stress, Pa							Ave	S.D.	95% Confidence Level		
	1	2	3	4	5	6	7			Max	Min	+/-%
27	0.13	0.12	0.11	0.13	0.13	0.14	0.16	0.131	0.0157	0.146	0.117	11.07
54	0.18	0.16	0.16	0.18	0.16	0.18	0.21	0.176	0.0181	0.192	0.159	8.54
81	0.26	0.22	0.22	0.23	0.21	0.23	0.26	0.233	0.0198	0.251	0.215	7.85
108	0.33	0.27	0.26	0.28	0.26	0.28	0.32	0.286	0.0282	0.312	0.260	9.13
135	0.37	0.32	0.31	0.33	0.30	0.32	0.39	0.334	0.0331	0.365	0.304	9.16
162	0.42	0.37	0.37	0.38	0.35	0.37	0.45	0.387	0.0350	0.419	0.355	8.36
189	0.48	0.43	0.42	0.44	0.39	0.41	0.52	0.441	0.0445	0.483	0.400	9.33
216	0.54	0.48	0.48	0.50	0.43	0.45	0.58	0.494	0.0516	0.542	0.447	9.65
243	0.59	0.53	0.53	0.56	0.47	0.49	0.64	0.544	0.0583	0.598	0.490	9.90
270	0.64	0.59	0.58	0.61	0.52	0.54	0.70	0.597	0.0607	0.653	0.541	9.41

the values obtained are not precise. Four pH instruments were used to measure the pH of each sample. A pH value of greater than 13 was reported when all of the pH instruments indicated this level of pH.

A series of selective filtration tests were conducted to obtain an estimate of the diameter of the solids in NCRW slurry. A sample of NCRW was passed through a screen with an opening of 38 microns. The fluid exiting the screen was applied to filter media with a known pore size. The results of these tests are reported in Section 4.3.1.

4.2 RHEOLOGICAL PROPERTIES

Laboratory evaluations were conducted to classify the rheological behavior of NCRW and rare earth fluoride-TRU solid slurries and to determine the effects of shear rate and temperature on the apparent viscosity of each slurry. These evaluations provided the background information needed to design and operate the pump-pipe test loop. The laboratory data were compared with pilot-scale information. Laboratory and pilot-scale data were scaled-up to predict the performance of the full-scale installation.

4.2.1 Classification of Slurries

An assumption implicit in this evaluation was that NCRW and rare earth fluoride-TRU solid slurries would be transported at velocities sufficient to prevent particles from settling in transfer piping. This assumption implies that very heterogeneous flow behavior (static bed, moving bed) cannot be tolerated. The objective was to create a pseudohomogeneous or nearly pseudohomogeneous flow regime in transfer piping.

A wide variety of pseudohomogeneous flow regimes is possible (see Section 2.2). The majority of slurries can be treated as if they were yield-pseudoplastic (Y-P) materials. The behavior of these materials can be defined by the following equations (Hershel and Bulkley 1926):

$$\tau = K\left(\frac{dv}{dy}\right)^n \quad \text{when } \tau_y = 0 \quad (7)$$

$$\tau = \tau_y + K\left(\frac{dv}{dy}\right)^n \quad \text{when } \tau_y > 0 \quad (8)$$

where: τ = shear stress, N/m^2 (Pascal)
 τ_y = yield stress, N/m^2
 K = consistency index, Ns/m^2
 $\frac{dV}{dy}$ = shear rate in y direction, sec^{-1}
 n = flow behavior index.

The yield-pseudoplastic model defined by Equations 7 and 8 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 mean values of the shear stress of NCRW-Batch 0 listed in Table 6 for each shear rate are plotted in Figure 10. These data were "fit" to the yield-pseudoplastic, pseudoplastic and Bingham plastic rheological models. The "goodness of fit" parameters obtained for each model are listed in Table 7. The regression coefficients indicate that the "goodness of fit" exceeded 0.999 in each instance (see Table 8).

The data in Table 8 indicate that the NCRW-Batch 0 sample can be described as either a pseudoplastic, Bingham plastic, or yield-pseudoplastic material. This inference arises from the fact that the precision of the shear stress data used to create Figure 10 is ± 8 to 11% (see Table 6). This degree of precision masks the effects of the low yield stress identified by the Bingham and yield-pseudoplastic models (see Table 7). Since NCRW-Batch 0 appears to have a small yield stress, it is likely that the fluid is a Bingham or yield-pseudoplastic material.

This "goodness of fit" procedure was used to classify samples of NCRW-Batches 1, 2, and 3. The regression coefficients and values of τ , τ_y , K and n measured for each slurry are summarized in Table 9. Yield-pseudoplastic rheograms for NCRW Batches 1, 2, and 3 are included as Figure 11. A combined rheogram for NCRW-Batches 1-3, prepared using average shear stress values at each shear rate, appears as Figure 12.

The NCRW slurries can clearly be classified as yield-pseudoplastic materials because 1) the rheograms "fit" the model with regression coefficients of

FIGURE 10. "Goodness of Fit" of Rheograms for NCRW-Batch 0 at 50°C to Pseudohomogeneous Flow Models

TABLE 7. Parameters for Fitting Data of Figure 10 to Three Pseudohomogeneous Flow Models

Model	Parameter	Value	Deviation	T-Value
Bingham Plastic	Yield Point, Pa	0.0758	0.0015	47.73
	Plastic Visc., Pa·s	0.0019	0.0000	203.59
Yield Pseudoplastic	Yield Point, Pa	0.0776	0.0042	18.20
	K, Pa·s	0.0018	0.0002	8.96
	n	1.0100		
Pseudoplastic (Power Law)	K, Pa·s	0.0083	0.0011	7.14
	n	0.7582	0.0266	28.49

TABLE 8. Analysis of Variance for Fitting Data of Figure 10 to Three Pseudohomogeneous Flow Models

Model	Source	Sum of Squares	Degrees of Freedom	Mean Square	F Value	Mult R-SQ
Bingham Plastic	Regression	0.2240	1	0.2240	41451	0.9998
	Residual	0.0000	8	0.0000		
Yield Pseudoplastic	Regression	0.2240	2	0.1120	19590	0.9998
	Residual	0.0000	7	0.0000		
Pseudoplastic (Power Law)	Regression	1.5362	2	0.7681	4593	0.9991
	Residual	0.0013	8	0.0001		

TABLE 9. Yield-Pseudoplastic Parameters for NCRW Slurries

Slurry	Yield Stress, τ_y (Pa)	Consistency Index, K (Pa·s)	Behavior Index, n	Regression Coefficient
NCRW-Batch 0	0.0777	0.0018	1.01	0.999
NCRW-Batch 1	0.0459	0.0011	1.07	0.999
NCRW-Batch 2	0.0142	0.0062	0.736	0.997
NCRW-Batch 3	0.0246	0.0039	0.801	0.997
NCRW-Batch 1-3	0.0363	0.0021	0.928

FIGURE 11. Yield-Pseudoplastic Rheogram for NCRW-Batches 1, 2, 3

FIGURE 12. Average Yield-Pseudoplastic Rheogram for NCRW-Batches 1-3

at least 0.997, 2) they exhibit yield stresses (not pseudoplastic or Newtonian), and 3) the flow behavior index is less than 1.0 (not Bingham plastic, dilatant, or Newtonian).

The rare earth fluoride-TRU solid slurries exhibited very different behavior than the NCRW slurries. The rare earth fluoride-TRU solid slurries contained very few solids (see Section 4.3). Two rheograms for this "slurry" are included in Figure 13. The shape of the rheograms (flow behavior index $n < 0$, $\tau_y = 0$) implies that rare earth fluoride-TRU solid "slurry" is a pseudoplastic material. A fit of the rheological data of Figure 13 to the pseudoplastic model (Equation 7) yields a flow behavior index n , of 0.79 to 0.88 and consistency index K , of 0.0015 to 0.0032 Pa·s. This range of parameters bracketed the rheological data obtained with rare earth fluoride-TRU solid slurry.

FIGURE 13. Rheogram for Rare Earth Fluoride-TRU Solids Slurry

4.2.2 Evaluation of Rheograms

The yield-pseudoplastic and pseudoplastic models (Equations 7 and 8) were used to evaluate the rheograms developed for NCRW (Figures 10, 11, 12) and rare earth fluoride-TRU solid slurries (Figure 13), respectively. This evaluation was designed to 1) develop the relationship between the apparent viscosity of each sample and shear rate, and 2) determine the effects of temperature on viscosity.

4.2.2.1 NCRW Slurry

A sample of NCRW-Batch 0 was used to assess the effects of temperature on the shear stress values measured with the Haake Rotovisco[®] viscometer. Rheograms for NCRW-Batch 0, prepared at 25, 30, 40 and 50°C are plotted in Figure 14. The solid lines through the actual data points (mean values) are based on the Bingham plastic model using the coefficients listed in Table 10. The Bingham plastic model was used in this instance because the value of n was equal to 1.0.

The coefficients in Table 10 were used to define the relationship between shear stress and shear rate at each temperature. For instance, at 25°C the relationship becomes:

$$\tau = 0.077 + 2.48 \left(\frac{dv}{dy} \right) \quad (9)$$

Values of shear stress τ are determined at the shear rate of interest. The apparent viscosity of the fluid is calculated by dividing the computed value of τ by the shear rate. Plots of apparent viscosity versus temperature for NCRW-Batch 0 are given on Figure 15. They reveal that NCRW-Batch 0 had a viscosity of 2 to 3.5 centipoise (CP) at temperatures of from 25°C to 50°C and shear rates of 70 to 500 sec^{-1} .

The viscosity of NCRW-Batch 0 increased as the shear rate decreased. This behavior is typical for all yield-pseudoplastic, Bingham plastic and pseudoplastic materials. Viscosity decreased as the temperature was increased. This behavior is typical for nearly all slurries. At a shear rate of 70 sec^{-1} (as

FIGURE 14. Rheogram for NCRW-Batch 0 as a Function of Temperature

TABLE 10. Coefficients of the Bingham Plastic Model
Used to Fit the Data of Figure 14

	Temperature, °C			
	25	30	40	50
Yield Point, Pa	0.077	0.067	0.071	0.061
Plastic Viscosity, cP	2.48	2.39	2.15	1.89
R squared	0.999	0.999	0.996	0.999

in the full-scale pump-pipe system) the viscosity decreased from about 3.6 to 2.7 cP as the temperature increased from 25 to 50°C. A similar decrease in viscosity with temperature was evident at other shear rates as well.

The viscosity calculations for NCRW-Batches 1, 2, and 3 were based on the yield-pseudoplastic coefficients included in Table 9. The coefficients define the relationship between shear stress and shear rate. A value of τ is determined at shear rates of interest. This value of τ is divided by the shear rate to yield the apparent viscosity at this shear rate. Plots of apparent viscosity versus shear rate for NCRW Batches 1, 2, and 3 at 50°C are given on Figure 16. At a shear rate of 70 sec^{-1} , the apparent viscosity ranged from about 2 to 2.3 cP. This narrow range of values (well within the ± 8 -11% precision of the viscometer) indicates that each batch of NCRW was prepared in a consistent manner.

4.2.2.2 Rare Earth Fluoride-TRU Solid Slurry

Viscosity calculations for rare earth fluoroide-TRU solid slurry are based on the pseudoplastic coefficients discussed in Section 4.2.1. These coefficients were used to construct the plots of apparent viscosity versus shear rate shown in Figure 17. Once again the apparent viscosity increased as the shear rate declined. At a shear rate of 100 sec^{-1} , the apparent viscosity of rare earth fluoride-TRU solid slurry was approximately 0.7 to 1.2 cP at 50°C. The viscosity decreased to about 0.7 to 0.8 cP at shear rates exceeding 500 sec^{-1} .

FIGURE 15. Apparent Viscosity of NCRW-Batch 0 as a Function of Temperature and Shear Rate

FIGURE 16. Apparent Viscosity of NCRW-Batches 1, 2, 3 as a Function of Shear Rate

FIGURE 17. Apparent Viscosity of Rare Earth Fluoride-TRU Solids Slurry as a Function of Shear Rate and Temperature

Because viscosities of 1 cP are at the limit of the useful range for Haake viscometers, it would be prudent to use an apparent viscosity of 1.5 cP during the design of the pump and transport system for rare earth fluoride-TRU solid slurry.

A plot of apparent viscosity versus shear rate at 25°C for rare earth fluoride-TRU solid slurry is also included on Figure 17. As expected, the calculated values of apparent viscosity at 25°C are larger than the corresponding values at 50°C.

4.3 PHYSICAL PROPERTIES

The rare earth fluoride-TRU solid and NCRW slurries were analyzed to measure macro-scale properties such as pH, total, suspended and dissolved solids content, solids settling rate, and slurry density. In addition, an attempt was made to measure the particle size distribution and shape of the NCRW solids.

4.3.1 NCRW Slurry

Standard laboratory procedures were used to measure the macro-scale physical properties of these slurries. The density, pH, and solids weight distribution results obtained for each batch of NCRW prepared (see Table 5) are summarized in Table 11. The results indicate, once again, that each batch of simulated NCRW was prepared in a consistent manner.

TABLE 11. Physical Properties of Simulated NCRW

<u>Property</u>	<u>Simulated NCRW</u>			
	<u>Batch 0</u>	<u>Batch 1</u>	<u>Batch 2</u>	<u>Batch 3</u>
Density, g/cc	1.14	1.16	1.15	1.18
pH	13.4	13.3	13.3	13.4
Dissolved Solids, wt%	4.9	5.1	4.7	4.8
Suspended Solids, wt%	12.1	13.7	13.7	14.3
Total Solids, wt%	17.0	18.8	18.4	19.1

Samples of simulated NCRW were shaken, placed in 100 ml graduated cylinders, and allowed to settle. The level of the solids-liquid interface was recorded as it descended in the cylinder. Plots of interface height versus time were prepared for each batch of NCRW (Figure 18). The settling rates for the linear portion of the curves were 0.14, 0.15, 0.11, and 0.12 cm/sec for NCRW-Batches 0, 1, 2, and 3, respectively, at 25°C. At a temperature of 50°C, the NCRW solids tended to settle more rapidly. For instance, NCRW-Batch 0 had a settling rate of 0.26 cm/sec at 50°C, nearly twice as high as the settling rate achieved at 25°C.

Selective filtration tests with NCRW revealed that greater than 99% of the flocs in the slurry had diameters smaller than 39 microns and larger than 8 microns. The solids present consisted of flocs or aggregates of individual particles. The mean size of these flocs was estimated to be 15 ± 5 microns.

4.3.2 Rare Earth Fluoride-TRU Solids Slurry

The rare earth fluoride-TRU solids sample provided by Rockwell displayed properties that were very different from the properties of NCRW slurry discussed in Section 4.3.1. The density, pH and solids weight distribution results obtained for the rare earth fluoride-TRU solids sample are summarized in Table 12. The low suspended solids concentration, 0.34 wt% of this sample, probably accounts for the fact that this slurry behaves as a nearly Newtonian fluid (see Section 4.2.1).

The small quantity of solids in the fluid settled as discrete particles, not as a flocculated mass that was typical for the NCRW samples. The particles settled at a rate of about 0.2 cm/sec.

FIGURE 18. Simulated NCRW Solids Settling Rate at 25°C

TABLE 12. Physical Properties of Simulated Rare Earth
Fluoride-TRU Solids Slurry

<u>Property</u>	<u>Value</u>
Density, g/cc	1.00
pH	7.14
Dissolved Solids, wt%	0.03
Suspended Solids, wt%	0.34
Total Solids, wt%	0.36

Table 12. Physical Properties of Suspended and Settled Solids

Property	Value
Density, g/cc	1.00
Oil	7.14
Dissolved Solids, wt%	0.03
Suspended Solids, wt%	0.34
Total Solids, wt%	0.37

5.0 PILOT-SCALE RHEOLOGICAL AND TRANSPORT EVALUATIONS

A pilot-scale pump-pipe test loop provides a means to obtain rheological and transport information in a flow environment that simulates the environment in a full-scale pump-pipe network. The environment that exists in the viscometer during laboratory tests does not simulate the shear stress-rate of shear environment in a pipe network. As a result, it is usually more accurate to scale up pilot-scale pump-pipe data to predict full-scale performance than it is to scale up laboratory data.

A pilot-scale pump-pipe test loop was used to 1) classify the rheological behavior of simulated NCRW slurry, 2) develop correlations to predict the pressure drop in NCRW transfer piping, 3) identify critical transport requirements (minimum velocity, critical Reynolds number), and 4) verify line flushing requirements (velocity, volume needed). The results obtained with the pilot-scale pump-pipe loop are described in this section.

5.1 EXPERIMENTAL EQUIPMENT AND PROCEDURES

The pump-pipe test loop was installed in the High-Bay annex of Building 324 on the Hanford site. The loop was composed of 3/4- and 1-in. diameter, schedule 40 carbon steel pipe and pipe fittings. Dead spots and discontinuities were built into the loop to simulate the actual pipe arrangement that will be used to transfer NCRW and rare earth fluoride-TRU solid slurries from B-Plant to the tank farms. Figure 19 is a sketch of the piping arrangement that was installed in the High-Bay annex of Building 324.

The pressure drop developed in a pipe network will depend on the specific characteristics of the pipe runs, fittings and control elements in the network. Table 13 lists the pipe, fittings, and valves that were installed in the 3/4- and 1-in. pipe loop.

The classification of slurries based on pipe loop data requires the acquisition of pressure drop information in the laminar flow range. The solids in NCRW slurries tend to settle at the low velocities (less than about 0.5 fps) typical of laminar flow in 3/4- and 1-in. diameter pipes. The pressure drop developed in the pipe loop at laminar flow velocities can be less than one or

NCRW Test Loop

FIGURE 19. Pilot-Scale Piping Arrangement

TABLE 13. Pilot-Scale Pipe Network Material Listing

Item	3/4-in. Diameter Loop	1-in. Diameter Loop
Straight Pipe, ft		
Carbon Steel	200	336
Rubber Hose-Laminar	2	3
Rubber Hose-Turbulent	6	29
Standard Elbows-90°	5	5
Tees (Branch To Line)		
Laminar Flow	2	2
Turbulent Flow	3	3
Crosses	4	6
Flow Restrictors		
Laminar Flow	1	1
Turbulent Flow	3	3
Elbows (4 inch radius)	11	19
Pipe Entrance	1	1
Pipe Exit	1	1

two inches of water. Experimental equipment and procedures were developed to overcome the obstacles presented by settling solids and low pressure drops.

5.2 EXPERIMENTS WITH CLEAN WATER

Clean water was pumped through the pilot-scale pipe networks to 1) demonstrate the mechanical integrity of the system, 2) permit a determination of the accuracy and precision of data acquisition methods, and 3) identify baseline pressure drop requirements of the system.

5.2.1 Equivalent Length of Pilot-Scale Pipe Networks

Logistical considerations and design needs resulted in a pilot-scale pipe network that contained elbows, tees, crosses, flow restrictions, and other pipe fittings. The pressure drop due to these pipe fittings must be added to the pressure drop caused by flow through straight pipe segments to determine the

overall pressure drop in the pipe network. Traditionally, the pressure drop due to pipe fittings is expressed as:

$$\Delta P = K_1 \frac{V^2}{2g_c} \quad (10)$$

Where: ΔP = pressure loss, lb/ft²
 K_1 = number of velocity heads
 V = line velocity, ft/sec

Or:
$$\frac{L}{D} = \frac{K_1}{4f_f} \quad (11)$$

Where: L = length of pipe with ΔP Equal to ΔP of fitting, ft
 K_1 = number of velocity heads
 f = Fanning friction factor
 D = Diameter of Pipe, ft.

Unfortunately, the number of velocity heads K_1 , and the equivalent length L/D , for a fitting does not remain constant. The value of L/D will depend on the Reynolds number, pipe roughness, and fitting size and geometry. The value of K_1 is a function of the Reynolds number and the exact geometry of the fitting. The values of L/D and K_1 measured during the flow on non-Newtonian fluids can be different than corresponding values for Newtonian flow systems.

A review of technical literature dealing with measurements of L/D and K_1 was conducted. The material collected is listed in Section 8.1. Most experimental work was directed toward specific applications. The majority of investigators published their results without attempting to analyze the root problem or relate their results to an established or new theory.

Several investigators (Kittridge and Rowley 1957; Jamison and Villemonte 1971; Hooper 1981) present correlations that account for the fact that values of K_1 for pipe fittings increase as the Reynolds number decreases. A few researchers (Holmos et al. 1975; Cable and Boger 1978, 1979; Torrance 1963; Weltman and Keller 1957) have examined the effects of non-Newtonian rheology on measured values of K_1 or L/D . The general trend appears to indicate an

increase in K_1 and L/D , at a given Reynolds number, for pseudoplastic materials. This trend has not been examined in detail. Non-Newtonian effects on L/D and K_1 were not considered as values of L/D and K_1 were calculated.

We used the correlations of Kittridge and Rowley for pressure drop due to elbows, entrance and exit losses, and the correlations of Jamison and Villemonte for tees and crosses. The permanent pressure drop due to the flow restrictions caused by the quick disconnect hose couplings in the 3/4-in. line was estimated to be equal to 40% of the transient pressure drop caused by the equivalently sized square-edged orifice. The corresponding valve for the hose couplings installed in the 1-in. line was estimated as 60% of the transient pressure drop developed by an equivalently sized square-edged orifice. These correlations provide a means to approximate the pressure drop that occurred in pipe fittings during pilot-scale experiments. This approximation was considered adequate for the engineering design needs of the program. The computed value of the equivalent length of each pilot-scale pipe loop as a function of Reynolds number is summarized in Table 14.

TABLE 14. Equivalent Length of Pilot-Scale Pipe Loops as a Function of Reynolds Number

<u>Reynolds Number</u>	<u>Three Quarter Inch Diameter Loop,ft</u>	<u>One Inch Diameter Loop,ft</u>
100	243	405
200	243	403
300	243	415
400	247	414
500	251	416
600	253	426
700	256	433
800	259	440
900	261	443
1,000	264	447
2,000	298	502
5,000	256	477
10,000	263	495
15,000	260	464
20,000	263	471
25,000	267	476
30,000	267	478
35,000	270	483
45,000	265	466

5.2.2 Friction Factor Versus Reynolds Number Relationship

The pressure drop that results as incompressible fluids flow through circular pipes is a function of the characteristics of the fluid (density, viscosity, temperature) and of the pipe network (diameter, surface roughness). A relationship that correlates these characteristics is the Fanning friction factor. For Newtonian, steady flow in uniform circular pipes running full of liquid under isothermal conditions, the Fanning friction factor has been defined (Moody 1944) as:

$$f = \frac{D \Delta P}{4L} \frac{\rho V^2}{2g_c} \quad (12)$$

where: f = Fanning friction factor

D = inside diameter of pipe, ft

ΔP = pressure drop, lb_f/ft^2

L = equivalent length, ft

ρ = fluid density, lb_m/ft^3

V = bulk velocity, ft/sec

$g_c = 32.3 \text{ lb}_m \text{ ft}/\text{lb}_f \text{ sec}^2$.

The Fanning friction factor is a function of the Reynolds number and the surface roughness of the pipe. One representation of this relationship is depicted on Figure 20.

In the laminar flow region, the Fanning friction factor is equal to $16/\text{Re}$. The surface roughness of the pipe may be a consideration if the flow regime is turbulent (see Figure 20). In those instances where the pipe can be considered to be hydraulically smooth, and the flow regime is fully turbulent ($3000 < \text{Re} < 100,000$), f will equal (Govier and Aziz 1982):

$$f = 0.079 \text{ Re}^{-0.25} \quad (13)$$

FIGURE 20. Moody Diagram - Newtonian Fluids

The Reynolds number Re , equals:

$$Re = \frac{DV\rho}{\mu} \quad (14)$$

where: μ = viscosity, $lb_m/sec-ft$

Clean water was pumped through the pilot-scale test loops to identify the baseline pressure drop requirements of the system and to permit an assessment of the accuracy and precision of the data acquisition methods utilized. The temperature and flow rate of the water and the pressure drop resulting in the loop was recorded during each run. The temperature information was used to establish values of μ and ρ for water during the run. Equation 14 was used to calculate Re at each flow rate. The information in Table 11 defined the equivalent pipe length, L . Equation 12 was then used to calculate f . Typical f versus Re curves for the 3/4- and 1-inch pipe networks are depicted on Figures 21 and 22.

FIGURE 21. Friction Factor as a Function of Reynolds Number - Clean Water Tests: 3/4 Inch Pipe Network

The 3/4-inch pipe network exhibited friction factors in the laminar flow region that were generally 10% larger than the values predicted by the $f = 16/Re$ relationship. Nearly all the laminar flow data points described a line with a slope parallel to the line defined by $f = 16/Re$. This implies that the data collection procedures were precise. An accurate bucket-stop watch method was used to determine the line velocity, V . The pressure drop ΔP was measured by reading the miniscus height in a manometer. It is likely that the larger values of f are due to an erroneous value for equivalent length, L . The values of L listed in Table 12 for the laminar region are approximations (see

FIGURE 22. Friction Factor as a Function of Reynolds Number - Clean Water Tests: 1 Inch Pipe Network

Section 5.2.1). The data on Figure 21 indicate that these approximations are about 10% low for the 3/4-in. pipe network in the laminar region.

The friction factors calculated for the 3/4-in. pipe loop in the turbulent flow region closely approximated the values anticipated for a hydraulically smooth pipe. This result was not expected. The equivalent lengths, L , included in Table 12 for the turbulent range are based on well-established K_1 and L/D relationships. Flow rates and pressure drops were once again measured by the bucket-stop watch and manometer methods. The inside surface of the pipe was relatively smooth to the touch. The surface protuberances on the inside of the pipe were not examined under a microscope. They may have had a smaller

amplitude than is typical for carbon steel pipe. Replicate tests confirmed that the f versus Re relationship in the turbulent region closely approximated the values anticipated for a hydraulically smooth pipe (Equation 13).

The 1-in. diameter pipe network exhibited friction factors in the laminar range that were approximately 20% larger than those predicted by $f = 16/Re$. This 20% variance exceeded the variance experienced in the 3/4-in. pipe loop. This additional variance may be due to the fact that the estimates for equivalent length that were used for one inch pipe fittings (Kittridge and Rowley 1957; Jamison and Villemonte 1971) were developed for 1/2- and 3/4-in. pipe fittings. Extrapolation of these estimates to the 1-in. diameter case may have introduced the additional variance that was experienced.

The friction factors calculated for the 1-in. pipe loop in the turbulent flow region approximated the values anticipated for a hydraulically smooth pipe. The relatively smooth surface of the interior of the pipe may have contributed to this result.

The clean water pressure drop and flow rate data for the 3/4- and 1-in. pipe loops correlated relatively well with established relationships between friction factor and Reynolds number. The data obtained in the laminar region appear to be precise. These data indicate that published correlations for K_1 and L/D in the laminar range yield equivalent length estimates that are approximately 10 to 20% low for the pipe fittings used in this evaluation. The data obtained in the turbulent region closely approximated established correlations for hydraulically smooth pipe.

5.2.3 Shear Stress Versus Shear Rate Relationship

The relationship between shear stress and shear rate in a pipe for a given fluid defines its apparent viscosity. This relationship has been defined (Metzner and Reed 1955) for laminar flow of pseudoplastic materials as:

$$\tau_w = \frac{D\Delta P}{4L} = K' \left(\frac{8V}{D} \right)^n \quad (15)$$

where: τ_w = shear stress at wall, lb_f/ft^2
 D = inside diameter of pipe, ft

ΔP = pressure drop, lb_f/ft^2

L = equivalent length, ft

K' = consistency index, $\text{lb}_f \text{ sec}/\text{ft}^2$

V = velocity in pipe, ft/sec

n = flow behavior index

For Newtonian fluids, Equation 15 reduces ($n = 1$) to:

$$\frac{D\Delta P}{4L} = \mu \left(\frac{8V}{D} \right) \quad (16)$$

A logarithmic plot of Equation 15 (see Figure 23) for laminar flow data defines the values of n and K' . The flow behavior index n , is the slope of the line; while the intercept of the line at a shear rate of 1 sec^{-1} defines K' .

The onset of turbulence can be estimated by inspecting Figure 23 as well. Equation 15 was derived for laminar flow in a tube (Bird et al. 1960). It does not hold once turbulent flow begins. As a result, the point at which the slope

FIGURE 23. Logarithmic Plot of Shear Stress Versus Shear Rate

of the straight line through the data points changes markedly defines the shear rate at which the laminar flow regime collapses. For Newtonian fluids, the laminar region ends at a Reynolds number of about 2100. This Reynolds number, Equation 14, can occur at a variety of shear rate-diameter combinations. A higher shear rate is required for small diameter pipes than is required for larger diameter pipes. A plot of shear stress versus shear rate for a given fluid transported in pipes of different sizes will yield a series of laminar flow end points; one for each pipe size.

The shear stress-rate of shear relationship for clean water in the 3/4- and 1-in. pipe networks was defined. This relationship is depicted in Figure 24. The data collected during runs conducted with the 3/4-in. pipe network fit the Metzner and Reed model (Equation 15) very well. The flow behavior index n , was 0.98 and the consistency index K' , was $0.000030 \text{ lb}_f \cdot \text{s}/\text{ft}^2$ or 1.43 cP. As a Newtonian fluid, water should have an n equal to 1, and a consistency index equal to its viscosity. The average viscosity of the water during the laminar portion of the runs was about 1.25 cP. The fact that the measured K' exceeded the real K' by about 10%, lends additional credence to the presumption that the estimates of equivalent length L , are approximately 10% below actual values (see Section 5.3.1). If L were increased by 10%, the measured value of K' would have equaled 1.25 cP.

The shear stress-rate of shear relationship for clean water in the 1-in. diameter pipe network also fit the Metzner and Reed model well. The flow behavior index n was 0.99 and the consistency index K' was $0.000037 \text{ lb}_f \cdot \text{s}/\text{ft}^2$ or 1.77 cP. The average viscosity of the water during the laminar portion of the runs was 1.48 cP. The fact that the measured K' exceeded the real K' by 20% again supports the presumption that the estimates of equivalent length L are roughly 20% below actual values.

The transition from laminar to turbulent flow occurred at shear rates of approximately 50 and 38 sec^{-1} for the 3/4- and 1-in. diameter loops respectively. These shear rates correspond to Reynolds numbers of 2030 and 2230. These values are close approximations to the theoretical value of 2100 that is generally accepted for Newtonian fluids.

FIGURE 24. Shear Stress Versus Rate of Shear - Clean Water Tests

5.3 EXPERIMENTS WITH NCRW

The critical velocity (also known as the marginal, depositing, or minimum transport velocity) V_c , is the lowest permissible mean flow velocity that ensures the deposit-free transport of solids in a pipe. The NCRW slurry must be transported at a velocity larger than V_c . Diagrams of friction factor-Reynolds number and diagrams of shear stress-rate of shear provide information that helps to identify V_c . The preparation of these diagrams is complicated by the non-Newtonian character of NCRW slurries. Fortunately, rheological models for the pseudohomogeneous flow of non-Newtonian materials in pipes are available. These models (discussed in Section 5.3.1) permit the preparation of friction factor-Reynolds number (Section 5.3.2) and shear stress-rate of shear (Section 5.3.3) relationships for NCRW.

The actual NCRW pump-pipe system at Rockwell will experience outages periodically. The NCRW in the system will settle during these outages. This settled sludge must be resuspended and the lines flushed out before normal operations can resume. The amount of flushing water and the velocity at which it must be delivered to assure adequate cleaning of the transfer lines is discussed in Section 5.3.4.

5.3.1 Rheological Models for Pseudohomogeneous Non-Newtonian 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, Bingham plastic 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.

5.3.1.1 Pseudoplastic Fluids

The relationship between shear stress and rate of shear for pseudoplastic materials (see Figure 3) was defined as:

$$\tau = K \left(\frac{dv}{dy} \right)^n \quad (7)$$

Equation 7 reduces to:

$$\tau_w = \frac{D\Delta P}{4L} = K' \left(\frac{8V}{D} \right)^n \quad (15)$$

for the incompressible flow of time-independent pseudoplastic materials in circular pipes (Metzner and Reed 1955). The graphical procedures described in Section 5.2.3 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:

$$K' = K \left[\frac{3n+1}{4n} \right]^n \quad (17)$$

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

The Fanning friction factor was defined as:

$$f = \frac{D\Delta P}{4L} \frac{\rho V_c^2}{2g_c} \quad (12)$$

Metzner and Reed substituted the right side of Equation 15 into Equation 12 and obtained:

$$f = \frac{16\gamma}{D^n V_c^{2-n} \rho} \quad (18)$$

$$\text{where: } \gamma = g_c K' 8^{n-1} \quad (19)$$

They then let $f = 16/Re$, for the laminar flow of non-Newtonian fluids, and rearranged Equation 18 to yield a Reynolds number

$$(Re)_{M-R} = \frac{D^n V_c^{2-n} \rho}{\gamma}, \quad (20)$$

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 20 reduces to the traditional Newtonian Reynolds number (Equation 14).

Metzner and Reed believed that all pseudoplastic materials would follow the usual f versus Re relationship in the laminar region when Equation 20 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 12. Metzner and Reed used Equation 20 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.

Dodge and Metzner (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-independent, inelastic pseudoplastic slurries fit an empirical model:

$$\frac{1}{\sqrt{f}} = \frac{4.0}{n^{0.75}} \log (Re)_{M-R} f^{(1-n/2)} - \frac{0.40}{n^{1.2}} \quad (21)$$

This model is depicted graphically in Figure 25. This figure implies that the onset of turbulence occurs at $(Re)_{M-R}$ values greater than 2100, and tends to occur at increasing values of $(Re)_{M-R}$ as the value of n declines. Dodge and Metzner 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 20 to calculate Reynolds numbers in the turbulent flow range has been challenged recently (Hanks 1979a). Hanks points out that Equation 20 is only valid for laminar flow of true pseudoplastic materials (no yield stress, $n < 1$) in circular pipes with linear shear stress distributions. The Metzner and Reed approach was pursued here since NCFW is a yield-pseudoplastic material (Section 4) with a relatively small yield stress. The variance introduced by the small value of yield stress may not significantly affect the correlations proposed by Metzner, Reed, and Dodge.

FIGURE 25. Metzner and Reed Friction Factor - Re Relationships

5.3.1.2 Bingham Plastic and Yield-Pseudoplastic Fluids

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

$$\tau = K \left(\frac{dv}{dy} \right)^n \quad \text{when } \tau_y = 0 \quad (7)$$

$$\tau = \tau_y + \left(\frac{dv}{dy} \right)^n \quad \text{when } \tau_y > 0 \quad (8)$$

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 7 and 8 have been developed to permit the design of pipelines for the pseudo-homogeneous flow of yield-pseudoplastic fluids (Hanks 1978b). The equations merge with similar equations developed for pseudoplastic and Bingham plastic

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 Bingham and 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 Bingham or yield-pseudoplastic fluid than is required for a fluid without a yield stress. This additional shear rate requirement produces a higher value of Fanning friction factor at a given laminar Re 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 affects 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:

$$He = \frac{D^2 \rho \tau_y}{g K'^2} \quad (22)$$

where D = pipe diameter, m
 ρ = fluid density, kg/m^3
 τ_y = yield stress, Pa
 K' = flow consistency index, $Pa \cdot s$
 g = acceleration of gravity, 9.8 m/sec^2 .

The effects of He on f and Re_c have been examined in detail by Hanks (1978b), and are depicted in Figures 26-28. 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 (1978b) 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

FIGURE 26. Bingham Plastic Design Curve - f versus Re ($n = 1.0$)

FIGURE 27. Yield-Pseudoplastic Design Curve - f Versus Re ($n = 0.7$)

FIGURE 28. Yield-Pseudoplastic Design Curve - f Versus Re ($n = 0.5$)

summarized on Figure 29. The equations referred to on Figure 29 are listed in Table 15. Nomenclature for Table 15 is summarized in Table 16. These procedures are complex. A computer program is being prepared to perform the calculations.

5.3.2 Shear Stress-Shear Rate Relationships

The 3/4- and 1-inch diameter pump-pipe test loops were used to evaluate the rheological behavior of the four batches (see Table 5) of NCRW that were prepared. The initial batch of NCRW, Batch 0 was used to test sampling procedures and assess the accuracy and precision of the results obtained. The pressure drop data obtained with Batch 0 were not precise at low flow rates (less than one gpm). Sampling procedures were revised, to improve the precision of these measurements before tests with Batch 1 were initiated. Unfortunately, equipment failures during this series of tests compromised the results that were obtained. Tests conducted with Batches 2 and 3 proceeded smoothly. The results obtained during these tests will be reported.

5.3.2.1 Classification of Slurries

The pressure drop and flow rate information obtained during tests with NCRW Batches 2 and 3 was used to construct plots of shear stress versus rate of shear for these slurries. Logarithmic plots of the data obtained during tests (CRW1B2, CRW1B3) with NCRW Batches 2 and 3 in the one-inch pipe loop are depicted on Figures 30 and 31. A logarithmic plot of the data (CRW34B2) with NCRW Batch 2 in the 3/4 inch loop appears as Figure 32.

The data points on these figures appear to exhibit the properties of a pseudoplastic fluid (see Section 5.2.3). The point at which the slope of a straight line through the data points changes dramatically defines the shear rate at which the laminar flow regime collapses. This transition point occurred at a shear rate of approximately of $55\text{--}65 \text{ sec}^{-1}$ for NCRW in the 1-inch loop and at approximately 85 sec^{-1} for NCRW in the 3/4-inch diameter pipe loop.

The data points obtained at shear rates below 55, 65, and 85 sec^{-1} for runs CRW1B2, CRW1B3, and CRW34B2, respectively, were fit to the pseudoplastic and yield-pseudoplastic rheological models. The results obtained are summarized in Table 17. The regression coefficients obtained for the least squares

E = Explicit Function
I = Implicit Function

FIGURE 29. Hanks' Calculation Procedure for the Flow of Yield-Pseudoplastic Fluids in Pipes(1978b)

TABLE 15. Hanks' Equations for the Flow of Yield-Pseudoplastic Fluids in Pipes (1978b)

$$\langle v_z \rangle = a \left(\frac{\tau_0}{\eta} \right)^{1/m} \left[\frac{m(1-\xi_0)^{(1+m)/m}}{\xi_0^{1/m}} \frac{(1-\xi_0)^2}{1+3m} + \frac{2\xi_0(1-\xi_0)}{1+2m} + \frac{\xi_0^2}{1+m} \right]^m \quad (23)$$

$$f = 16/\phi Re \quad (24)$$

$$Re = 8 \left(\frac{m}{1+3m} \right)^m \frac{a^m \langle v_z \rangle^2 \rho}{\eta} \quad (25)$$

$$\psi = (1+3m)^m (1+\xi_0)^{1+m} \left[\frac{(1-\xi_0)^2}{1+3m} + \frac{2\xi_0(1-\xi_0)}{1+2m} + \frac{\xi_0^2}{1+m} \right]^m \quad (26)$$

$$He = \frac{D^2 \rho (\tau_0)}{\eta} (2-m)/m = \frac{D^2 \rho}{\tau_0} \left(\frac{\tau_0}{\eta} \right)^{2/m} \quad (27)$$

$$Re_c = \frac{6464m}{(1+3m)^m} (2+m)^{\frac{2+m}{1+m}} \frac{\left[\frac{(1-\xi_{oc})^2}{1+3m} + \frac{2\xi_{oc}(1-\xi_{oc})}{1+2m} + \frac{\xi_{oc}^2}{1+m} \right]^{2-m}}{(1-\xi_{oc})^m} \quad (28)$$

$$He = \frac{3232}{m} (2+m)^{\frac{2+m}{1+m}} \left[\frac{\xi_{oc}}{(1-\xi_{oc})^{1+m}} \right]^{\frac{2-m}{m}} \left(\frac{1}{1-\xi_{oc}} \right)^m \quad (29)$$

$$R = \left(\frac{1+3m}{m} \right) \left[Re \left(\frac{f}{16} \right) \right]^{\frac{2-m}{m}}]^{1/m} \quad (30)$$

$$Re = (1-\xi_0)^{\frac{2-m}{m}} \left(\frac{m}{1+3m} \right) R^2 \left[\int_{\xi_0}^1 \xi^2 \xi(\xi, \xi_0, R) d\xi \right]^{2-m} \quad (31)$$

$$R^2 = 2He/\xi_0^{(2-m)/m} \quad (32)$$

TABLE 16. Nomenclature for Table 15

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/sec
$\langle v_z \rangle$	Area mean value of v_z	m/sec
$\langle v_z \rangle_c$	Laminar-turbulent transition value of $\langle v_z \rangle$	m/sec
z	Axial coordinate	--
η	Yield-power law consistency index	Pa·S
ζ	Dimensionless shear rate	--
ξ	Dimensionless radial coordinate, r/a	--
ξ_0	Dimensionless unsheared plug radius, τ_0/τ_w	--
ξ_{0c}	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
ψ	Laminar flow function	--

fit of the data to the pseudoplastic model all were 0.97. The regression coefficients for a fit to the yield-pseudoplastic model varied from 0.83 to 0.97. The very low values of τ_y (less than 0.08 Pa or 0.8 dynes/cm²) exhibited by the NCRW slurries contributed to the lower correlation coefficients obtained for the fit to the yield-pseudoplastic model. A τ_y of 0.08 Pa corresponds to a pressure of 0.0003 inches water gage. A small change in the values of n and K' will have a substantial impact on this value of τ_y ; and vice versa.

FIGURE 30. Shear Stress Versus Shear Rate - Pilot-Scale Run CRW1B2

FIGURE 31. Shear Stress Versus Shear Rate - Pilot Scale Run CRW1B3

FIGURE 32. Shear Stress Versus Shear Rate - Pilot-Scale Run CRW34B2

TABLE 17. Pseudoplastic and Yield-Pseudoplastic Parameters for NCRW Slurries

Run	Pseudoplastic Model				Yield-Pseudoplastic Model					Regression Coefficient
	n	K ¹		Regression Coefficient	n	τ_y		K ¹		
		lbm/ft-sec	Pa-s			lbm/ft-sec ²	Pa	lbm/ft-sec	Pa-s	
CRW1B2	0.696	0.0133	0.0198	0.97	0.771	0.0007	0.0103	0.0099	0.0147	0.83
CRW1B3	0.547	0.0141	0.0209	0.97	0.672	0.0202	0.0300	0.0068	0.0101	0.97
CRW34B2	0.417	0.0305	0.0453	0.97	0.758	0.0527	0.0783	0.0052	0.0077	0.90

5.3.2.2 Apparent Viscosity of Pilot-Scale NCRW Slurries

The coefficients summarized in Table 17 were used to define the relationship between apparent viscosity of the NCRW slurry used during each run and shear rate. The value of τ_w was determined at the shear rate of interest (using Equations 7 and 8). This value of τ_w was divided by the shear rate to determine the apparent viscosity. The apparent viscosity of NCRW at 50°C, at shear rates that will exist in the full-scale pipe network (70 sec⁻¹ at 50 gpm, 100 sec⁻¹ at 75 gpm) is summarized in Table 18.

The values of apparent viscosity computed with the yield-pseudoplastic parameters were very similar to the value obtained with the pseudoplastic parameters since the low value of τ_y included in the yield-pseudoplastic model had a negligible effect on calculated values of apparent viscosity.

5.3.3 Friction Factor-Reynolds Number Relationships

The shear stress-rate of shear data presented in Section 5.3.2 were used to calculate the value of the Fanning friction factor (Equation 12) at each shear rate evaluated during pilot-scale tests. The pseudoplastic and yield-pseudoplastic rheological models discussed in Section 5.3.1 were used to calculate a Reynolds number at each shear rate. The friction factor-Reynolds number relationship that results 1) provides an indication of the applicability of each rheological model to NCRW slurries, 2) identifies a predicted value of the critical Reynolds number Re_c and shear rate, and 3) provides a means to predict the pressure drop that will result in the full-scale NCRW pipe network.

5.3.3.1 Pseudoplastic Rheological Model

The rheological model developed by Metzner and Reed (1955) for the pseudohomogeneous flow of pseudoplastic fluids in pipes defines the Reynolds number by:

$$(Re)_{M-R} = \frac{D^n V^{2-n} \rho}{g_c K' 8^{n-1}} \quad (20)$$

Equation 20 was used to calculate the value of Re that corresponded to each value of Fanning friction factor observed during pilot-scale tests with NCRW Batches 2 and 3. The friction factor-Reynolds number relationships observed

TABLE 18. Apparent Viscosity of NCRW at 50°C Versus Shear Rate

Rheological Model	Pilot-Scale Run	Apparent Viscosity cP	
		Shear Rate 70 sec ⁻¹	Shear Rate 100 sec ⁻¹
Pseudoplastic	CRW1B2	5.4	4.9
	CRW1B3	3.1	2.6
	CRW34B2	3.8	3.1
Yield-Pseudoplastic	CRW1B2	5.7	5.2
	CRW1B3	2.9	2.5
	CRW34B2	3.9	3.3

during runs with NCRW Batches 2 and 3 (CRW1B2, CRW1B3) in the 1-in. pipe loop are depicted in Figures 33 and 34, respectively. The f versus $(Re)_{M-R}$ relationship observed during the run with NCRW-Batch 2 in the 3/4-in. diameter pipe loop (run CRW34B2) appears as Figure 35.

The friction factors observed in the laminar flow region correlated well with the theoretical value of $f = 16/(Re)_{M-R}$ during runs in the 3/4 and 1 inch pipe loops. The turbulent flow friction factors observed during runs CRW1B3 and CRW34B2 correlated well with the friction factors predicted by Equation 13. This equation was developed for the turbulent flow of Newtonian fluids in hydraulically smooth pipe.

Dodge and Metzner (1959) state that measured values of f will decrease as the pseudoplastic flow behavior index n , decreases. This prediction is embodied in Equation 21. The turbulent flow friction factors observed during run CRW1B2 ($n = 0.697$) correlated well with Equation 21. The turbulent flow friction factors observed during runs CRW1B3 ($n = 0.547$) and CRWB4B2 ($n = 0.417$) exceeded the values predicted by Equation 21 and were in line with values associated with Newtonian fluids in smooth pipes. The majority of turbulent flow pilot scale data were clustered near the line defined by Equation 13. The friction factors predicted by this equation should be used to calculate the pressure drop anticipated in the full-scale system, if the pseudoplastic model is chosen to scale-up pilot-scale data. The pressure drop in the full-scale system would be calculated by rearranging Equation 12, to yield

FIGURE 33. Friction Factor Versus Reynolds Number $(Re)_{M-R}$: Pilot-Scale Run CRW1B2

FIGURE 34. Friction Factor Versus Reynolds Number $(Re)_{M-R}$: Pilot Scale Run CRW1B3

FIGURE 35. Friction Factor Versus Reynolds Number $(Re)_{M-R}$: Pilot-Scale Run CRW34B2

$$\Delta P = \frac{4Lf}{D} \frac{\rho V^2}{2g_c} \quad (33)$$

Dodge and Metzner (1959) have suggested that the onset of turbulence increases above an Re of 2100 as the flow behavior index, n , decreases. Their predictions (Figure 25) of $(Re_c)_{M-R}$ are compared with the experimental values indicated on Figures 33-35 in Table 19.

The predicted values of $(Re_c)_{M-R}$ do not correlate well with actual values observed during pilot-scale tests. This lack of correlation could be due to non-linear stress distributions in the pipe loops (Equation 20 does not apply), the presence of a yield stress, a lack of sufficient experimental data in the $(Re_c)_{M-R}$ range of 2,000 to 3,000, or other unknown factors.

The friction factor-Reynolds number relationships in Figures 33-35 provide an indication of the shear rate needed to assure a turbulent flow regime in each pipe network. The maximum value of $(Re)_{M-R}$ that correlates well with the laminar friction factor equation identifies the highest rate that was achieved during laminar flow. These maximum laminar flow shear rates are listed in Table 20.

The maximum measured value of shear rate exceeded the laminar-turbulent transitional shear rates indicated by Figures 30-32 during each pilot scale run. This may be another indication that the predictions of Re_c provided by the Metzner, Reed, and Dodge approach are not accurate for NCRW slurries. They appear to provide conservative predictions of Re_c .

5.3.3.2 Yield-Pseudoplastic Rheological Model

The calculation procedure outlined on Figure 29 was used to determine the Reynolds number $(Re)_H$, that corresponded to each value of Fanning friction

TABLE 19. Predicted Versus Actual Values of $(Re_c)_{M-R}$

Pilot-Scale Run	Predicted Value $(Re_c)_{M-R}$	Actual Value $(Re_c)_{M-R}$
CRW1B2	2500	Insufficient data
CRW1B3	2700	2100-2900
CRW34B2	2900	1900

TABLE 20. Maximum Laminar Flow Shear Rates; Metzner and Reed Predictions Versus Observed Values

Pilot-Scale Run	Maximum Laminar Flow Value Shear Rate		Figures 30-32 Shear Rate, sec ⁻¹
	(Re) _{M-R}	sec ⁻¹	
CRW1B2	1400	73	55
CRW1B3	2100	67	65
CRW34B2	1900	99	85

factor observed during pilot-scale tests. The friction factor-Reynolds number relationships observed during runs CRW1B2 and CRW1B3 in the 1-in. pipe loop are depicted in Figures 36 and 37, respectively. Figure 38 shows the f versus $(Re)_H$ relationship observed during run CRW34B2 in the 3/4-in. pipe loop.

The friction factors observed in the laminar flow region during run CRW1B2 correlated well with the theoretical value of $f = 16/Re$. The friction factors observed during runs CRW1B3 and CRW34B2 were up to 50% larger than the theoretical value. This result was expected since the Reynolds number calculations for the yield-pseudoplastic model is dependent on the Hedstrom number of the fluid (see Figure 29). The pilot-scale Hedstrom values used to compute the Reynolds numbers were 31, 687, and 2796 for runs CRW1B2, BRW1B3, and CRW34B2, respectively. The "excess" value of the friction factor implied by Figures 37 and 38 is proportional to the value of He (equation 22) used in the Reynolds number calculation. The values of He determined by the pilot-scale unit are probably too large (see Section 5.4). These large values of He probably caused the "excess" friction factors indicated on Figures 37 and 38.

Hanks (1978b) states that measured values of f in the turbulent region will decrease as n decreases, and increase as the value of He increases (Figures 26-28). The turbulent flow friction factors observed during pilot-scale tests exceeded the values predicted by Hanks. The majority of turbulent flow pilot-scale data were clustered near the line defined by Equation 13. The friction factors predicted by this equation should be used to calculate the pressure drop anticipated in the full-scale system, when the yield-pseudoplastic model is used to scale-up pilot-scale data.

FIGURE 36. Friction Factor Versus Reynolds Number $(Re)_H$: Pilot-Scale Run CRW1B2

FIGURE 37. Friction Factor Versus Reynolds Number $(Re)_H$: Pilot-Scale Run RW1B3

FIGURE 38. Friction Factor Versus Reynolds Number $(Re)_H$: Pilot-Scale Run CRW34B2

The Hanks calculation procedure (Figure 29) permits the determination of critical values of Reynolds number without the need for actual friction factor information. These predictions of critical $(Re_c)_H$ values are summarized in Table 21.

The value of $(Re_c)_H$ that results from the Hanks procedure is dependent of the value of the Hedstrom number. The magnitude of this number varied widely during the test series. This variation was caused by the lack of precision associated with estimates of the yield stress of NCRW slurries. The critical shear rates predicted for the 1-in. test loops would have been approximately the same if measured values of yield stress were identical. The data in Table 21 imply that the Hanks calculation procedure provides conservative estimates of critical shear rate values for NCRW slurries.

5.3.4 Line Flushing Requirements

The full-scale pump-pipe network will be subject to process upsets. These upsets could cause NCRW slurry to remain in the transfer piping for extended periods of time. The NCRW solids will settle from the suspension during this time period. The full-scale pump must be able to resuspend settled NCRW solids and clean the pipe network after each slurry transfer and after an equipment malfunction.

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 5.3.4.1.

TABLE 21. Critical Reynolds Numbers and Shear Rates:
Hanks Prediction Versus Observed Values

Pilot-Scale Run	Hedstrom Number	Hanks Prediction		Figure 30-32 Shear Rate, sec ⁻¹
		$(Re_c)_H$	Shear Rate sec ⁻¹	
CRW1B2	31	2290	120	55
CRW1B3	687	2780	73	65
CRW34B2	2796	3020	126	85

The current Rockwell design for the full-scale pump-pipe system specifies that one pipe volume of water be used for flushing, and that this water be delivered at a rate of 75 gpm (3.3 fps). These design criteria were applied to the pilot-scale pump-pipe system. The results obtained are described in Section 5.3.4.2.

5.3.4.1 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 39. Incipient motion is achieved at point A on Figure 39. 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 development of a curve like Figure 39 for NCRW was beyond the scope of this work since specific flush water quantities and velocities were specified by Rockwell. The aim was to determine if these specifications would be adequate for the resuspension of NCRW. An attempt was made to estimate the critical resuspension velocity for NCRW in order to provide background information that could be useful if the design flushing specifications changed in the future.

FIGURE 39. Effects of Applied Pressure and Fluid Velocity on the Resuspension of Settled Solids

The critical flushing velocity must be greater than the critical deposition velocity V_c , indicated by point C in Figure 39. Many empirical methods have been developed to estimate V_c (Wiedenoth and Kirchner 1972; Govier and Aziz 1981). These methods were developed for specific solid-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 NCRW slurry.

Pilot-scale pressure drop-flow rate information is available for NCRW. A plot of pressure drop versus fluid velocity provides an indication of the type of flow pattern that exists in the pipe (see Section 2.3.1). These plots were prepared for tests conducted in the 1-in. and 3/4-in. systems and are included as Figure 40 and 41, respectively. Homogeneous flow is believed to begin at the point at which the slope of the slurry curve matches the slope of the curve

FIGURE 40. Pressure Drop-Velocity Relationship - 1-In. Pipe Network

for clean water. This point occurred at approximately 1.3 fps during tests in the 3/4-in. pipe network and 1.2 to 1.5 fps during tests in the one-inch pipe network.

The estimates of the velocity necessary for a homogeneous suspension provided by Figures 40 and 41 were checked during screening tests conducted in a 10-ft section of clean 1-in. diameter Lexan pipe. This section of pipe was connected to a positive displacement pump and a recycle drum. Neutralized CRW (Batch 3) was circulated in this loop at a number of velocities. The flow patterns developed in the pipe at different fluid velocities were recorded. These flow patterns are summarized in Table 22. The onset of a homogeneous

FIGURE 41. Pressure Drop-Velocity Relationship - 3/4-In. Pipe Network

TABLE 22. Heterogeneous Flow Patterns for NCRW - 1-In. Pipe

Flow Pattern Description	Fluid Velocity, fps
Moving Bed (3/16 in. high by 3/4 in. wide)	0.65
Moving Bed (1/8 in. high by 3/4 in. wide)	0.90
Moving Bed (1/32 in. high by 1/8 in. wide)	1.10
Heterogeneous Flow (no moving bed)	1.20

flow pattern occurred at a velocity of approximately 1.2 fps. This result matches the velocity predicted by inspecting Figure 40. A velocity of 1.2 fps is 1.8 times the velocity V_c , at which the flow regime changed from a laminar to a turbulent condition (see Section 5.3) in the 1-in. pilot-scale system.

The velocity necessary to resuspend settled NCRW will exceed 1.2 fps. The pressure necessary to resuspend NCRW is likely to exceed the pressure drop associated with a flow rate of 1.2 fps (see Figure 39). The specific values of the required resuspension pressure and velocity are unknown. The experiments described in Section 5.3.4.2 identified one set of operating conditions that were able to resuspend NCRW and flush transfer lines.

5.3.4.2 Experiments with NCRW

The 3/4-in. pilot-scale pipe network was used to conduct line flushing tests. This network contained dead spots, low spots and other discontinuities that were expected to be present in the full-scale system (see Figure 19). The network held six gallons of NCRW. Each flushing test was conducted by 1) allowing NCRW to remain in the network overnight 2) metering 6 gallons of clean water into the suction side of the positive displacement pump 3) pumping the clean water through the pipe network at a rate of 5 gpm (3.1 fps), 4) collecting the fluid discharged from the network during the pumping period, 5) stopping the pump when the last element of clean water entered the suction of the pump, 6) slowly draining the fluid remaining in the pipe network, 7) disassembling and inspecting the pipe network. Line flushing tests were conducted on three occasions. Pertinent information associated with each test is summarized in Table 23.

The pressure drop surge column of Table 23 identifies the maximum pressure surge observed when flush water was just introduced to the pipe network. The maximum pressure-normal pressure ratio provides an indication of the maximum pressure characteristic that will be required of the full-scale flush water pump. The relative similarity of the total solids contents listed in columns 7 and 8 is an indication that nearly all of the solids were removed from the pipe network during the flush. The "in pipe" total solids content is the solids content of the NCRW that was placed in the pipe. The "flushed slurry" total

TABLE 23. Summary of 3/4-In. Pipe Loop Line Flushing Tests

Test Date	NCRW Batch	Flush Water		Pressure Drop Surge $\Delta P_{max}/\Delta P_{norm}$	Total Solids Content	
		Quantity, gal.	Rate, fps		In Pipe wt. %	Flushed Slurry wt. %
March 13, 1985	1	6	3.1	1.3	18.8	17.2
March 21, 1985	2	6	3.1	1.3	18.4	14.6
April 4, 1985	0	6	3.1	1.5	n.a.	25.9

solids content is the solids content of a composite sample of the six gallons of slurry that was flushed from the pipe.

Visual inspections of the pipe network after it was flushed confirmed that nearly all of the NCRW was removed by the flush water. Straight horizontal runs of pipe were generally free of NCRW after each flushing test. A deposit of "frothy" NCRW usually collected in the dead legs of the crosses in the line. This deposit was approximately 1/4 inch deep.

The horizontal leg of the "U" low spot in the loop (see Figure 19) was replaced with a clean Lexan pipe element prior to the flush test conducted on April 4. This element became full of NCRW solids as the slurry settled. The element was unplugged during the flush test. A deposit of NCRW approximately 1/16 inch deep remained in the element at the conclusion of the flush.

The flushing regime specified by Rockwell was effective in cleaning the 3/4-in. pipe network and is expected to be effective in flushing the full-scale system.

5.4 COMPARISON OF PILOT-SCALE AND LABORATORY RESULTS

A Haake Rotovisco® viscometer was used to obtain the rheological information reported in Section 4. This device does not closely simulate the conditions that the NCRW slurry will encounter as it is pumped from B-Plant to the tank farms. Results obtained from lab and field equipment will only be analogous when the devices are geometrically, kinematically, and dynamically similar. Geometric similarity requires that all corresponding dimensions in

systems of different size bear the same ratio to each other. A concentric cylinder viscometer bears little resemblance to a pump-pipe flow system.

Systems are dynamically similar when the ratio of all corresponding forces are equal. Kinematic similarity requires that velocities at corresponding points be in the same ratio. For pump-pipe flow the Reynolds number, Hedstrom number, the pump impeller tip speed, the shear rate in the pipe, and the pump specific speed are indicators of dynamic and kinematic similarity.

The NCRW slurry transportation system will consist of a cantilevered centrifugal pump, a run of 3-in. diameter pipe, and the ancillary equipment needed to monitor and control the performance of the system. The system is being designed to handle 50 to 75 gpm of NCRW. These flow rates correspond to shear rates of 70 and 100 sec^{-1} in the pipe. The Haake viscometer operates in the laminar range at shear rates up to 1000 sec^{-1} . The viscometer appears to be kinematically similar to the flow regime that will exist in the full-scale NCRW transportation system.

The large differences in geometry between the rotational viscometer, a centrifugal pump and a 3-in. diameter pipe induce a substantial degree of dissimilarity in the dynamic conditions existent in each system. Design limitations arising from non-isothermal conditions, wall effects, pulsating flow, and the presence of piping discontinuities can cause laboratory and pilot-scale evaluations to yield different results.

Laboratory and pilot-scale data will be compared in this section. These data were previously used to 1) classify NCRW slurries, 2) determine the relationship between apparent viscosity and shear rate, and 3) predict critical transport properties. This comparison will be based on the rheological properties of NCRW Batches 2 and 3, since these slurries were the only ones to undergo a complete series of laboratory and pilot-scale tests.

5.4.1 Classification of NCRW Slurries

The Haake® viscometer and pump-pipe test loop experiments identified NCRW slurry as a pseudoplastic or yield-pseudoplastic fluid. A comparison of computed values of the parameters that define this pseudoplastic or yield-pseudoplastic behavior is provided in Tables 24 and 25.

TABLE 24. Comparison of Pilot-Scale and Laboratory Yield-Pseudoplastic Parameters

NCRW Batch	Laboratory Parameters				Pilot-Scale Parameters				
	n	τ_y (Pa)	K' (Pa·s)	R	Pipe Diameter inches	n	τ_y (Pa)	K' (Pa·s)	R
2	0.736	0.0142	0.0066	0.99	3/4	0.758	0.0783	0.0077	0.90
					1	0.771	0.0103	0.0147	0.83
3	0.801	0.0246	0.0041	0.99	1	0.672	0.0300	0.0101	0.97

TABLE 25. Comparison of Pilot-Scale and Laboratory Pseudoplastic Parameters

NCRW Batch	Laboratory Parameters			Pilot-Scale Parameters			
	n	K' (Pa·s)	R	Pipe Diameter inches	n	K' (Pa·s)	R
2	0.66	0.0119	0.99	3/4	0.417	0.0453	0.97
				1	0.696	0.0198	0.97
3	0.72	0.0061	0.99	1	0.547	0.0209	0.97

The laboratory and pilot-scale estimates of yield-pseudoplastic parameter n , were consistent. The pilot-scale estimate exceeded the laboratory estimate by 3 to 19%. The variation in estimates of τ_y were much larger. The pilot-scale estimate of τ_y varied from 38% below to 450% greater than the laboratory estimate of this parameter. One reason for the breadth of this range is the difficulty encountered during pilot-scale measurements of very small yield stresses. The pilot-scale estimates of K' varied from 17 to 145% larger than the laboratory estimates. These variances will impact estimates of the apparent viscosity of NCRW at low shear rates.

The pilot-scale estimates of pseudoplastic parameter n , were up to 37% lower than corresponding laboratory estimates. These lower estimates of n were balanced by higher estimates of the consistency index K' . Pilot-scale estimates of K' were from 66 to 280% higher than laboratory estimates. The regression coefficients R , obtained during pilot-scale and laboratory tests were all at least 0.97. This regression coefficient implies that the parameters listed in Table 25 are accurate estimates for the slurries that were tested. The NCRW appears to have exhibited different rheological behavior in the pipe loop than it did in the laboratory rotational viscometer.

5.4.2 Apparent Viscosity of NCRW Slurries

The parameters in Tables 24 and 25 were used to estimate the apparent viscosity of NCRW slurry as it travels in the full-scale pump-pipe system. The slurry will be pumped at flow rates of 50 to 75 gpm in a 3-in. diameter pipe network. These flow rates correspond to shear rates of approximately 70 and 100 sec^{-1} . The predicted values of apparent viscosity at these shear rates are summarized in Table 26.

The estimates of apparent viscosity provided by the pilot-scale unit were approximately 50% larger than the values estimated with the parameters determined in the laboratory. This variance will impact the values of Re_c predicted by each set of data.

5.4.3 Critical Transport Velocities

The pseudoplastic and yield-pseudoplastic rheological models can be used to scale up data obtained in the laboratory to predict the value of the critical Reynolds number and shear rate. Each procedure relies on available estimates for n and K' . An additional estimate for τ_y is required for the yield pseudoplastic model. The pseudoplastic model relies on the estimates of $(Re_c)_{M-R}$ provided by Figure 25. The yield-pseudoplastic model employs the calculation approach described on Figure 29. The predicted values of Re_c and critical shear rate obtained with laboratory and pilot-scale rheological parameters are summarized in Table 27.

The pilot-scale predictions of the critical shear rate provided by the pseudoplastic and yield-pseudoplastic models are similar (see Section 5.3). Each model predicts a critical shear rate that exceeds the actual critical shear rate experienced during the pilot-scale tests. This shear rate was estimated as the point of inflection of the curves in Figures 30-32.

The laboratory-scale prediction of the critical shear rate based on yield-pseudoplastic rheological parameters are in very good agreement with the actual values experienced during pilot-scale tests. This result may be due to the fact that the yield-pseudoplastic flow behavior index n , measured during laboratory and pilot-scale tests were in good agreement. This fact together with

TABLE 26. Comparison of Pilot-Scale and Laboratory Predictions of Apparent Viscosity (cP)

NCRW Batch	Laboratory Prediction				Pipe Diameter (inch)	Pilot-Scale Predictions			
	Pseudoplastic		Yield-Pseudoplastic			Pseudoplastic		Yield-Pseudoplastic	
	70 sec ⁻¹	100 sec ⁻¹	70 sec ⁻¹	100 sec ⁻¹		70 sec ⁻¹	100 sec ⁻¹	70 sec ⁻¹	100 sec ⁻¹
2	2.8	2.5	2.4	2.1	3/4	3.8	3.1	3.9	3.3
					1	5.4	4.9	5.7	5.2
3	1.9	1.7	2.1	1.9	1	3.1	2.6	2.9	2.5

TABLE 27. Comparison of Pilot-Scale and Laboratory Predictions of Critical Transport Velocities

NCRW Batch	Laboratory Predictions						Pilot-Scale Prediction						Actual Critical Shear Rate (sec ⁻¹)
	Pseudoplastic		Yield-Pseudoplastic				Pseudoplastic		Yield-Pseudoplastic				
	(Re _c) _{M-R}	Shear Rate ₁ (sec ⁻¹)	Pipe Diameter (Inches)	He	(Re _c) _H	Shear Rate ₁ (sec ⁻¹)	(Re _c) _{M-R}	Shear Rate ₁ (sec ⁻¹)	Pipe Diameter (Inches)	He	(Re _c) _H	Shear Rate ₁ (sec ⁻¹)	
2	2450	102	3/4	293	2233	76	2900	128	3/4	2796	3020	126	85
	2450	70	1	477	2304	53	2500	118	1	31	2290	120	55
3	2550	52	1	3022	2725	51	2700	79	1	687	2780	73	65

the potential for more accurate estimates of τ_y in the laboratory may have contributed to the excellent correlation of the data that was obtained.

Laboratory predictions of the critical shear rate based on pseudoplastic rheological parameters were 20-27% higher than actual values for Batch 2 and 25% lower than the actual value for Batch 3. This variance is smaller than the variance obtained when the pseudoplastic model was used to correlate pilot-scale data.

The rheological parameters determined in the laboratory provided a more accurate estimate of the critical shear rate in most instances than did the estimates obtained with pilot-scale parameters. This result may not occur with slurries that exhibit rheological properties that differ from those displayed by NCRW. The NCRW slurry is a time-independent fluid. Thixotropic and rheopectic fluids are likely to exhibit markedly different behavior in a pipeline environment than they do in a viscometer. Neutralized CRW is composed of solids that settle rapidly. These solids degrade the precision and accuracy of pressure drop measurements obtained at low shear rates. The low yield stress exhibited by NCRW was difficult to measure in the pump-pipe test loop. Fluids with larger yield stresses will be easier to define.

6.0 DESIGN REQUIREMENTS FOR THE FULL-SCALE SYSTEM

One goal of the Rheological Evaluation of Pretreated Cladding Removal Waste Program was to evaluate those rheological and transport properties critical to assuring the successful handling of processed CRW streams. The approach taken to achieve this goal included laboratory (Section 4) and pilot-scale (Section 5) evaluations of the physical and rheological properties of NCRW and rare earth fluoride-TRU solid slurries. The purpose of this section is to scale up pilot-scale and laboratory results, where possible, to establish the process design needs of the full-scale pump-pipe network that will transport NCRW and rare earth fluoride-TRU solid slurries from B-Plant to the tank farms.

The full-scale pump-pipe network must transport NCRW and rare earth fluoride-TRU solid slurries at velocities that prevent the deposition of solids in the transfer lines. Pilot-scale critical transport property estimates will be scaled up to predict full-scale performance in Section 6.1. The centrifugal pump used to transport NCRW must be sized to deliver NCRW and rare earth fluoride-TRU solid slurries through approximately 8400 ft of 3-in., schedule 40, carbon steel pipe. The pressure drop that can be expected to occur in this pipe will be estimated in Section 6.2. The pump used to flush settled NCRW from transport lines must be sized to deliver the pressure and fluid velocity needed to resuspend settled solids. This pressure and fluid velocity will be identified in Section 6.3.

6.1 SCALE-UP OF PILOT-SCALE CRITICAL TRANSPORT PROPERTIES

The pseudoplastic (Metzner and Reed 1955) and yield-pseudoplastic (Hanks 1978b) rheological models were used to scale-up laboratory data so that these data could be compared with results obtained during pilot-scale experiments. This comparison is documented in Section 5.4. The critical Reynolds number predicted by the pseudoplastic model is only a function of the flow behavior index, n (see Figure 25). For instance, for an n of 0.8, the pseudoplastic model will predict an Re_c of about 2550 for any pipe diameter and any yield stress.

The yield-pseudoplastic model accounts for the effects of τ_y and pipe diameter on Re_c and provides a precise way to predict Re_c for various combinations of τ_y , n , K' , and pipe diameter. A semi-empirical method developed by Bowen (1961a-f) accounts for the effects of pipe diameter on $(Re_c)_{M-R}$. The pseudoplastic, yield-pseudoplastic and Bowen approaches to the scale-up of pump-pipe test loop data are discussed in this section.

6.1.1 Pseudoplastic Model

The pseudoplastic n and K' parameters determined for the laboratory and full-scale NCRW data summarized in Table 25, and the $(Re_c)_{M-R}$ values summarized in Table 27 were used to estimate critical pipeline velocities for NCRW in the full-scale system. These estimates are summarized in Table 28.

The variance in the predicted values of critical velocity arises from the fact that larger values of K' were determined during pilot-scale tests than were determined during laboratory tests. All of the predicted values of $(Re_c)_{M-R}$ are well below the design velocity in the full-scale pipe network (2.1 fps).

The rare earth fluoride-TRU solid slurry was a pseudoplastic material with an n of 0.9 and a K' of 0.00219 Pa·s at 25°C. The pseudoplastic model predicts an $(Re_c)_{M-R}$ of 2250 for a n equal to 0.9 (Figure 25). This $(Re_c)_{M-R}$ is equivalent to a line velocity of 0.18 fps in a 3-in. diameter line. The suspended solids concentration of rare earth fluoride-TRU solid slurry is 0.34 wt% (Table 10). This "slurry" will not tend to clog transportation lines.

6.1.2 Yield-Pseudoplastic Model

The yield-pseudoplastic model relies on the approach summarized in Figure 29. 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 calculate this value of τ_y/τ_w .

TABLE 28. Predictions of Full-Scale $(Re_c)_{M-R}$: Pseudoplastic Model

NCRW Batch	Laboratory Predictions		Pilot-Scale Predictions		
	$(Re_c)_{M-R}$	Velocity (ft/sec)	Pipe Diameter (inches)	$(Re_c)_{M-R}$	Velocity (ft/sec)
2	2450	0.41	3/4	2900	0.76
			1	2500	0.71
3	2550	0.31	1	2700	0.56

The yield-pseudoplastic rheological parameters obtained during laboratory and pilot-scale tests (Table 24) were used to predict values of Re_c for NCRW in a 3-in. diameter, schedule 40, carbon steel pipe. These predictions are summarized in Table 29. The values of τ_y and He derived from laboratory data are probably more accurate than those obtained during pilot-scale tests with NCRW. The laboratory rheological data accurately predicted the Re_c measured during pilot-scale tests. The laboratory predictions may also be more accurate in this instance. All of the predicted values of Re_c are well below the design velocity of 2.1 fps (50 gpm) envisioned for the full-scale system.

6.1.3 Bowen's Method

The scale-up method developed by Bowen (1961a-f) modifies the correlations developed by Dodge and Metzner (1959) for pseudoplastic fluids to account for the effects of pipe diameter on the Re_c . The model is based on the assumption

TABLE 29. Predictions of Full-Scale $(Re_c)_H$: Yield-Pseudoplastic Model

NCRW Batch	Laboratory Predictions			Pilot-Scale Predictions			
	He	$(Re_c)_H$	Velocity, fps	Pipe diameter, inches	He	$(Re_c)_H$	Velocity, fps
2	4198	2907	0.40	3/4	39983	4774	0.68
				1	271	2447	0.69
3	26490	4063	0.37	1	6024	3502	0.54

that the relationship between friction factor and Reynolds number for pseudo-plastic materials (for $Re < 100,000$) can be expressed as

$$f = 0.079 Re^{-0.25} \quad (13)$$

or, more generally;

$$f = a/Re^b \quad (34)$$

where a, b = constants for a given fluid

If Equation 20 for $(Re)_{M-R}$, and equation 12 for f are substituted into equation 34 and rearranged, the following expression results.

$$\frac{D(1+bn)}{L} \Delta P = k V^{(2-2b + bn)} = k V^c \quad (35)$$

The values of n, b and c can be obtained from logarithmic plots of shear stress $(D\Delta P/4L)$ versus rate of shear $(8V/D)$ for pilot-scale pump-pipe data. The flow behavior index n equals the slope of the laminar portion of the curve defining the shear stress-rate of shear relationship (Figure 23). The slope of the turbulent branches of the shear stress-rate of shear plot for each pipe diameter defines c . Once c is known b is easily calculated. The relationship given by equation 34 now defines shear stress as a function of velocity for any pipe diameter. The pipe diameter and line velocities of interest in the full-scale system are entered into equation 34. These values define the turbulent branch of the shear stress-rate of shear diagram for the pipe diameter of the full-scale system.

This procedure was applied to NCRW pilot-scale data (Figures 30, 31, 32). The regressed lines that represent this data are identified on Figure 42. The values of n, c and b obtained during the pilot-scale runs are summarized in Table 30.

The average values of n, c and b were 0.553, 1.59, and 0.290 respectively. The Bowen method assumes that the slope of the turbulent branch for a 3-in. diameter pipe will equal the average slope obtained during tests

FIGURE 42. Rheogram Scale-up: Bowen's Method

TABLE 30. Bowen's Method Data Summary

NCRW Run	n	c	b
CRW34B2	0.417	1.60	0.253
CRW1B2	0.696	1.43	0.437
CRW1B3	0.547	1.74	0.179

with the 3/4- and 1-in. diameter pipe loops on a slope of 1.59. When this value of the slope c , and average values of n and b are substituted into equation 34, the following relationship results:

$$\frac{D^{1.16} \Delta P}{4L} = k V^{1.59} \quad (36)$$

The NCRW pilot-scale data was fit to equation 35. The data fit equation 35 for $k = 0.00933$ with a regression coefficient of 0.98. The full-scale turbulent branch was defined by solving equation 35 for three arbitrary fluid velocities in the full-scale pipe. This calculation is summarized in Table 31.

The fluid velocities selected are used to calculate $D^{1.16} \Delta P / 4L$ ($0.00933 V^{1.59}$). This value is normalized to yield a traditional shear stress value ($D \Delta P / 4L$) for NCRW in a 3-in. diameter pipe. These shear stress values and their corresponding velocities define the full-scale turbulent branch on Figure 42. The intersection of this branch with the laminar curves for each pilot-scale run is the predicted value of the critical shear rate derived from the data of that run. All of the predicted values of the critical velocity are well below the design velocity in the full-scale network.

TABLE 31. Prediction of Full-Scale Critical Velocity: Bowen's Method

Operating Condition		Parameters		Predicted Critical Values		
Shear Rate, sec ⁻¹	Velocity, fps	$\frac{D^{1.16} \Delta P}{4L},$ lb _f /ft ²	$\frac{D \Delta P}{4L},$ lb _f /ft ²	Pilot- Scale Run	Shear Rate, sec ⁻¹	Velocity, fps
50	1.60	0.20	0.024	CRW34B2	13.0	0.42
100	3.20	0.059	0.072	CRW1B2	10.0	0.32
200	6.4	0.178	0.218	CRW1B3	8.5	0.27

6.2 PRESSURE DROP EXPECTED IN THE FULL-SCALE SYSTEM

The pressure drop in the full-scale system can be estimated by solving equation 33:

$$\Delta P = \frac{4 L f}{D} \frac{\rho V^2}{2 g_c} \quad (33)$$

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.

The pressure drop estimates discussed in this section are all based on assumptions listed in Table 31. These assumptions reflect the current design parameters for the full-scale system.

6.2.1 NCRW Slurry

The relationship between f and Re depends on the rheological model used to calculate Re . The pseudoplastic and yield-pseudoplastic models were used to evaluate NCRW.

6.2.1.1 Pseudoplastic Model

The Reynolds number for pseudoplastic fluids was given by equation 20:

$$(Re)_{M-R} = \frac{\rho^n V^{2-n}}{g_c K' 8^{n-1}} \quad (20)$$

The parameters n and K' obtained during laboratory and pilot-scale tests were used to calculate $(Re)_{M-R}$ for the normal and maximum fluid velocities indicated in Table 32. This value of $(Re)_{M-R}$ was used to establish the friction factor, f . The f versus $(Re)_{M-R}$ relationship for hydraulically smooth pipe (Figures 33-35) fit pilot-scale NCRW data. This relationship was used to estimate f for the full-scale system. The predicted values of pressure drop for the full-scale system are summarized in Table 33.

TABLE 32. Assumptions in Full-Scale Pressure Drop Calculations

Item	Symbol	Value
Equivalent length	L	8400 feet
Pipe roughness	ϵ	same as pilot-scale unit
Temperature	-	50°C
Pipe diameter	D	3.068 inches
Line velocities	V	2.17 fps normal 3.31 fps maximum

The predicted values of pressure drop range from 29 to 36 psig for the normal flow case, and from 61 to 73 psig for the maximum flow case. The average of the predicted values of pressure drop is 32 psig for the normal flow rate and 65 psig for the maximum flow rate anticipated in the full-scale system.

6.2.1.2 Yield Pseudoplastic Model

The Reynolds number for yield-pseudoplastic fluids is calculated by the iterative procedure summarized on Figure 29. The parameters n , K' and τ_y obtained during laboratory and pilot-scale tests were used to calculate $(Re)_H$ for the normal and maximum fluid velocities indicated in Table 31. The f versus $(Re)_H$ relationship obtained during pilot-scale tests (Figures 36-38) was used to estimate f for the full-scale system. The predicted values of pressure drop for the full-scale system are summarized in Table 34.

The predicted values of pressure drop range from 27 to 36 psig for the normal flow case and from 60 to 75 psig for the maximum flow case. The average of the predicted value of pressure drop is 30 psig for the normal flow rate and 64 psig for the maximum flow rate anticipated in the full-scale system. These pressure drops are very similar to the pressure drop predicted by the pseudoplastic model. Pilot-scale data yielded higher pressure drop predictions than laboratory data for both the yield-pseudoplastic and pseudoplastic models. Rheological data obtained in the laboratory provided more accurate estimates of pilot-scale critical shear rates than pilot-scale rheological data (Section 5.4). The pressure drop estimates provided by the laboratory data summarized in Tables 33 and 34 may also provide more accurate estimates of full-scale pressure drop.

TABLE 33. Prediction of Full-Scale Pressure Drop: Pseudoplastic Model

Item	Laboratory Data				Pilot-Scale Run		
	Batch 0	Batch 1	Batch 2	Batch 3	CRW34B2	CRW1B2	CRW1B3
n	0.76	0.87	0.66	0.72	0.417	0.696	0.547
$g_c K' \text{ (lb}_m\text{/ft-sec)}$	0.00604	0.00232	0.00803	0.00410	0.0305	0.0133	0.0141
$\rho \text{ (lb}_m\text{/ft}^3\text{)}$	71.1	73.4	71.8	73.6	71.6	71.6	71.9
$(Re)_{M-R}\text{-normal}$	17700	30400	20500	32400	15520	10740	19100
$(Re)_{M-R}\text{-maximum}$	29900	49000	36200	52700	29700	18630	35240
f-normal	0.0069	0.0060	0.0066	0.0059	0.0070	0.0076	0.0066
f-maximum	0.0060	0.0054	0.0058	0.0053	0.0059	0.0066	0.0058
$\Delta P \text{ normal (psig)}$	32.8	29.4	31.6	29.1	33.5	36.4	31.8
$\Delta P \text{ maximum (psig)}$	66.9	61.4	64.9	60.7	65.8	73.6	64.9

TABLE 34. Prediction of Full-Scale Pressure Drop: Yield-Pseudoplastic Model

Item	Laboratory Data				Pilot-Scale Run		
	Batch 0	Batch 1	Batch 2	Batch 3	CRW34B2	CRW1B2	CRW1B3
n	1.01	1.07	0.736	0.801	0.758	0.771	0.672
$g_c K'$ (lb _m /ft-sec)	0.0012	0.0007	0.0045	0.0027	0.0052	0.0099	0.0068
τ_y (lb _m /ft-sec ²)	0.0523	0.0309	0.0007	0.0166	0.0527	0.0007	0.0202
ρ (lb _m /ft ³)	71.1	73.4	71.8	73.6	71.6	71.6	71.9
(Re) _H -normal	19000	27800	24400	27900	14800	10100	19600
(Re) _H -maximum	33600	47300	43000	49220	27300	17300	35700
f -normal	0.0066	0.0061	0.0065	0.0061	0.0071	0.0080	0.0066
f -maximum	0.0058	0.0053	0.0055	0.0053	0.0061	0.0068	0.0057
ΔP -normal (psig)	29.3	27.9	29.1	28.0	31.8	35.8	29.6
ΔP -maximum (psig)	63.6	60.0	60.9	60.1	67.5	75.0	63.2

6.2.2 Rare Earth Fluoride-TRU Solids Slurry

The rare earth fluoride-TRU solids slurry received from Rockwell was a pseudoplastic fluid with n equal to 0.884 and K' equal to 0.0015 Pa·s at a temperature of 50°C (see Section 4.2.1). The pseudoplastic f versus Re procedures described in Section 6.2.1.1 were used to predict the pressure drop that would develop if rare earth fluoride-TRU solids slurry were pumped through the full-scale system defined by Table 31. The predicted pressure drop is 21 psig for a flow rate of 50 gpm and 43 psig for a flow rate of 75 gpm. These pressure drops are smaller than those calculated for the transport of NCRW since the density and viscosity of rare earth fluoride-TRU solids slurries are lower than corresponding values for NCRW. The lower viscosity produces a higher calculated value of $(Re)_{M-R}$ and a lower value of f . The lower values of density and friction factor produce reduced estimates of line pressure drop (see Equation 33).

6.3 FULL-SCALE LINE FLUSHING REQUIREMENTS

The current RHO design for the full-scale pump-pipe system specifies that one pipe volume of water be used for flushing, and that this water be delivered at a rate of 75 gpm (3.3 fps). These criteria were applied to NCRW slurry that was allowed to settle in the 3/4-in. diameter pilot-scale unit. The pipe loop was effectively cleaned during each flushing test.

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. During the pilot-scale tests, the pressure gradient applied equaled about 1.3 times the normal pressure drop associated with a flow velocity of 3.3 fps (see Table 23). If this criterion is applied to the full-scale system, a pressure drop of from 75 to 95 psig (see Tables 33, 34) would result during flushing.

The resuspension velocity of 3.3 fps was approximately three times the velocity needed to achieve a homogeneous flow regime in the 3/4-in. system (1-1.2 fps) and 4.3 times the velocity, V_c , at which the flow pattern in the 3/4-in. pipe changed from a laminar to a turbulent condition. The velocity V_c

in the full-scale system will probably be in the 0.4 to 0.7 fps range (see Section 6.1.2). The pressure drop developed in the full-scale system at line velocities of 1.7 to 3.0 fps will range from 19-25 psig to 51-68 psig based on the data summarized in Table 32. If the necessary pressure gradient remains at 1.3 times the pressure developed during normal flow, the flushing pump would have to develop a pressure of 25-33 psig to 66-88 psig at flushing velocities of 1.7 to 3.0 fps.

The duration of the flush will affect the amount of solids ultimately removed from the line. One flush volume was satisfactory during pilot-scale tests, and should be satisfactory during full-scale tests, if line velocities of 3.3 fps are maintained during the flush.

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

The rare earth fluoride-TRU solids slurry contains 0.36 wt% total solids. This low solids loading will not lend to clog transfer lines. It is not likely that the rare earth fluoride-TRU solids slurry line will have to be flushed.

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