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Development of an In Situ Method to Define the Rheological Properties of Slurries and Sludges Stored in Underground Tanks

W. O. Heath

April 1987

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ABSTRACT

A method for measuring the in situ flow properties of high-level radioactive waste (HLW) sludges has been developed at Pacific Northwest Laboratory, along with a preconceptual design for a shear vane device that can be installed in underground HLW storage tanks and used to make those measurements remotely. The data obtained with this device will assist in the design of mixing equipment used to resuspend and remove HLW sludges from their storage tanks for downstream processing. This method is also suitable for remotely characterizing other types of waste sludges and slurries. Commonly available viscometric methods were adapted to allow characterization of sludge samples in the laboratory such that the laboratory and in-tank data can be directly compared (scaled up). Procedures for conducting measurements and analyzing the results in terms of useful mathematical models describing both start-up and steady-state flow behavior are presented, as is a brief tutorial on the types of flow behavior that can be exhibited by tank sludges.

SUMMARY

Double-shell tanks (DST) are used to store nuclear wastes in the form of solutions and sludges at Hanford. Current plans include the retrieval of the high-level (HLW) and transuranic (TRU) fractions of these wastes and their processing to create immobile waste forms suitable for long-term storage in geologic repositories. Prior to their retrieval and subsequent processing, the properties (chemical, physical, and rheological) of these wastes must be determined. The goal of the Pacific Northwest Laboratory's (PNL) Double Shell Tank Sampling and Analysis Program, supported by the Department of Energy's Richland Operations Office (DOE-RL), is to characterize these properties.

The objective of one of the activities within this program was to develop methods for characterizing the rheological (flow behavior) properties of DST wastes. This report documents the adaptation of standard viscometric techniques to allow sludge characterization in the laboratory and describes the development of a novel method for measuring the in situ flow properties of DST contents. A preconceptual design is presented for a modified shear vane device that can be installed in DSTs and used to measure the following properties in situ:

- shear strength (sludge)
- apparent viscosity versus shear rate (slurry)
- yield strength (slurry)
- flow behavior index (slurry)
- consistency index (slurry).

These properties collectively determine the flow and dispersion behavior of settled tank sludges. Knowledge of them is essential to the design of mixing and pumping equipment that will be used to retrieve the DST contents. Shear strength is the most significant property used for sizing tank-mixing equipment; it provides a direct measure of the shear conditions that will be required to successfully break up and disperse settled sludge layers. Because many of the slurries and sludges in DSTs have remained substantially undisturbed for years and have settled into extremely durable layers, it is this initial dispersion that may prove to be the most difficult step involved in

waste retrieval. Therefore, accurate measurement of shear strength is especially critical to the success of waste retrieval operations. The remaining properties determine the flow behavior of the slurry formed after the sludge is dispersed. These properties and their engineering significance are fully described in the report.

Procedures are provided for measuring rheological properties: 1) in situ, using an in-tank shear vane device; and 2) in the laboratory, in conjunction with tank core samples. The in-tank shear vane must be used to obtain accurate measurements of the in-place sludge shear strength because it circumvents the disturbance and consequent weakening of the sludge caused by core sampling. If core samples cannot be taken (due to cost or other constraints), the shear vane can be used to measure all of the other needed sludge flow properties as well.

Shear vanes comprise a standard method for measuring the in situ shear strength of soils. The extension of traditional shear vane methods to allow measurement of apparent viscosity versus shear rate required a substantial testing and development effort. Most of this initial development was undertaken by PNL's West Valley Support Task sponsored by the West Valley Nuclear Services Co., Inc. (WVNS) for DOE. This report documents these developmental efforts so as to provide a complete overview of the research that culminated in the preconceptual in-tank shear vane design.

Procedures are described for analyzing the rheological data obtained by shear vanes and laboratory viscometers and reporting the data in terms of useful mathematical models. A calculator program was developed to assist in reducing the raw data. This program is provided as an appendix to the report.

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1.0 INTRODUCTION

Before the nuclear wastes stored in underground storage tanks can be retrieved and transferred to existing or new facilities (and finally immobilized), their chemical, physical, and rheological properties must be identified. The goal of the Double-Shell Tank (DST) Sampling and Analysis Program at the Pacific Northwest Laboratory (PNL) is to characterize these chemical, physical, and rheological properties. The Department of Energy's Richland Operations Office (DOE-RL) funds the program, which has been conducted in conjunction with related ongoing activities at Rockwell Hanford Operations. One objective of the program was the development of an in situ method to determine the rheological properties of neutralized cladding removal waste (NCRW) and other slurries and sludges contained in DSTs. Research at PNL culminated in a preconceptual design for a shear vane to be used in situ to identify the rheological properties of sludges and slurries in waste tanks.

Shear vane devices are not new; soil scientists have used them since the 1950s to test the shear strength of various soils. More recently, West Valley Nuclear Services, Inc. (WVNS), utilized shear vanes to measure the shear strengths of radioactive wastes contained in tanks at their site in West Valley, New York (Abdelhamid 1982). The work conducted by WVNS provided the baseline for the in situ shear vane development work described in this report.

Research at PNL focused on five objectives:

- modify the in situ methods developed by WVNS so that they could be used to determine the rheological properties of slurries and sludges contained in DSTs at Hanford
- investigate the scale-up of shear strength data to allow direct comparison between laboratory-scale data and full-scale data obtained in situ
- develop a method for using shear vanes to measure the viscosity of tank sludges as well as their shear strengths
- prepare a standard data analysis calculator program for shear vanes

- develop a preconceptual design for a shear vane that can be used in situ in the DSTs at Hanford.

Current plans are to install and operate in situ shear vane devices in waste tanks at both Hanford and West Valley, to obtain rheological data on the sludges stored at these sites. This data will be used in conjunction with FY 1987 scale-model DST mixing studies to assist in the development of DST retrieval systems to resuspend and remove DST sludges for downstream processing.

The format of this report follows the sequence in which the work was conducted. Initial activity was concerned with gaining an understanding of the theoretical foundation of non-Newtonian slurry/sludge flow systems, and Chapter 2 describes the physical properties that control the mobilization and dispersion of slurries and sludges. Classical mechanical and rheological models that can be used to characterize the flow behavior of slurries and sludges are discussed in Chapter 3. Laboratory-scale methods of measuring slurry/sludge flow parameters are presented in Chapter 4. Some details of the early developmental research are noted in Chapter 5, as are the further developments by PNL that enabled measurement of sludge viscosity and other rheological parameters. These methods and a modified shear vane design have resulted in a new technology for in-tank testing, which is summarized in Chapter 6. Appendix A provides an engineering sketch of a conceptual design for the modified shear vane device, and Appendix B presents the procedure by which a calculator program, VANE-2, can be used to reduce shear vane sludge and slurry data.

2.0 MOBILIZATION AND DISPERSION OF TANK SLUDGES

An in situ device designed to define the rheological behavior of slurries and sludges in underground tanks must provide information needed to design the process equipment that will be used to mobilize and retrieve the slurries and sludges. However, the mechanics of slurry/sludge mobilization must be understood before the nature of that information can be specified. A description of sludge dispersion mechanisms is provided in Section 2.1. The physical properties that control the mobilization and dispersion of sludges are discussed in Section 2.2.

2.1 SLUDGE DISPERSION MECHANISMS

The sludge layer at the bottom of a tank can be considered a cohesive solid. The word "cohesive" refers to the "self-stickiness" of the sludge material, which results from interparticle attractive forces. As an example, river clays and similar materials are cohesive solids, whereas dry sand and other materials that are not self-sticking are not cohesive. From a practical viewpoint, the sludge at the bottom of a tank can be considered a solid, or at least a "pseudo solid" (Rehbinder 1954).

When tank sludge is viewed as a solid, it becomes clear that its dispersion will involve two different physical processes in sequence:

- conversion of the solid sludge to a liquid slurry
- dispersion of the slurry particles throughout the tank.

The first process occurs in the elastic or solid regime, whereas the second process occurs in the plastic or viscous regime. Each regime has a separate set of parameters that determine the flow behavior and dispersion characteristics of the sludge layer.

For the first process to occur, local shear at the surface of the sludge layer is required. A certain magnitude of local shear stress will be required to overcome the cohesiveness of the sludge, which binds the sludge particles into a solid mass. If a sufficient level of shear can be developed, the sludge will fail, break up, and start to liquefy.

The second physical process is the actual dispersion of the slurry particles throughout the tank. The shear field developed by the mixing equipment must be sufficient to disperse them.

2.2 PHYSICAL PROPERTIES CONTROLLING THE MOBILIZATION AND DISPERSION CHARACTERISTICS OF SLURRIES AND SLUDGES

The ability of slurries and sludges to flow and be dispersed depends on their behavior in the elastic and viscous regimes. Important physical properties of sludges in these two regimes are described below.

2.2.1 The Elastic (or Solid) Regime: Stress-Strain Relationships

The reaction of nonbrittle solids to stress is characterized by reversible (elastic) deformation (strain) until failure occurs, whereupon further stress causes permanent (plastic) deformation. A typical stress-strain model for a nonbrittle solid is illustrated in Figure 2.1. In this model, increased stress causes increased strain, and the two vary linearly throughout the elastic regime up to the point of material failure. The ratio of stress to strain in the elastic regime is a characteristic of a given material and is known as Young's modulus of elasticity, E . It is defined by Van Vlack (1975) as

$$E = \frac{\sigma}{\epsilon} \quad (2.1)$$

where, in cgs units, E = Young's modulus, dyne/cm²

σ = applied stress, dyne/cm²

ϵ = strain, usually defined as the percentage of axial or cross-sectional deformation caused by stress, dimensionless.

The stress at which plastic deformation occurs (leading to failure), called the "yield strength" or "yield stress," is also a characteristic of a given material and is denoted by σ_y .

Analogous to the stress-strain behavior of nonbrittle solids, cohesive tank sludge will undergo shear-induced elastic strain until the yield strength

FIGURE 2.1. Stress-Strain Diagram for a Ductile Material with a Yield Point

is exceeded and plastic failure occurs. In sludge mobilization, the principal stresses will be in the direction of plane shear rather than axial compression or extension so that the shear modulus, G instead of E , is appropriate for describing the stress strain relationship in the elastic regime. The shear modulus is defined by Van Vlack (1975):

$$G = \frac{\tau}{\epsilon_s} \quad (2.2)$$

where, in egs units, G = shear modulus, dyne/cm²

τ = applied shear stress, dyne/cm²

ϵ_s = elastic shear strain, dimensionless.

The geometry of elastic shear strain is shown schematically in Figure 2.2.

The shear stress at which plastic deformation occurs (leading to failure) is denoted as the "shear strength," τ_s . Shear strength is a property exhibited by all cohesive materials, such as all clays, most or all tank sludges and sediments, and some slurries. In terms of sludge mobilization, the shear strength of the sludge will determine whether the available level of tank agitation can successfully break up the sludge. The relevance of shear strength is that in specifying a sludge mobilization (mixing) system, τ_s will determine the peak operating characteristics of the system. During startup

FIGURE 2.2. The Geometry of Elastic Shear Strain. Shear displaces atoms.

operations, the mixing system must produce enough local stress at the surface of the sludge layer to overcome shear strength, or "the sludge will not budge."

An important thing to remember from this discussion is that the resistance to flow of a sludge can be described by two parameters: the shear modulus and the shear strength. Only when local shear fields at the sludge/supernatant interface exceed τ_s will the sludge be transformed from a solid in the elastic regime to a viscous slurry in the plastic regime. In the plastic or viscous regime, viscosity is the appropriate quantity for describing stress-strain relationships.

2.2.2 The Plastic (or Viscous) Regime: Shear Stress, Shear Rate, and Viscosity Relationships

Viscosity is a physical property of fluids that determines how easily a fluid will flow. Consider two parallel plates, one on top of the other, separated by a fluid layer of uniform thickness, H . Assume that the plates each have an area equal to A . Suppose that the bottom plate is held fixed while the top plate is forced to slide at a constant speed, U , causing the intervening fluid to be sheared between the plates. The force, F , required to slide the top plate, is divided by the area of the plate, A , to obtain the shear stress, τ :

$$\tau = \frac{F}{A} \quad (2.3)$$

The rate at which the fluid is sheared by the sliding plates is called the shear rate, $\dot{S}$, defined as

$$\dot{S} = \frac{U}{H} \quad (2.4)$$

From this definition it can be seen that shear rate is independent of the fluid's properties. Viscosity, η , is defined as the ratio of shear stress to shear rate, or

$$\eta = \frac{\tau}{\dot{S}} \quad (2.5)$$

Viscosity is thus an indication of the amount of stress (force/area) required to cause a fluid to flow at a given rate.

Fluids for which the ratio $\tau/\dot{S}$ is constant for all values of $\dot{S}$ are called Newtonian fluids. A plot of shear stress versus shear rate for a Newtonian fluid results in a straight line through the origin with a slope equal to η . In general, sludges, sediments, and most slurries are non-Newtonian fluids in that the ratio $\tau/\dot{S}$ is not constant, but rather varies with shear rate. The behavior of non-Newtonian fluids is discussed in Chapter 3.

the rate at which the fluid is sheared by the rigid plates is called the shear rate, $\dot{\gamma}$, defined as

$$(2.4) \quad \dot{\gamma} = \frac{dv}{dy}$$

and this definition is seen that shear rate is independent of the fluid properties. viscosity, η , is defined as the ratio of shear stress to shear rate, or

$$(2.5) \quad \eta = \frac{\tau}{\dot{\gamma}}$$

viscosity is thus an indication of the amount of stress (pressure) required to cause a fluid to flow at a given rate.

Fluids for which the ratio η is constant for all values of $\dot{\gamma}$ are called Newtonian fluids. A plot of shear stress versus shear rate for a Newtonian fluid results in a straight line through the origin with a slope equal to η . In general, slurries, emulsions, and most slurries are non-Newtonian fluids in that the ratio η is not constant, but varies with shear rate. The behavior of non-Newtonian fluids is discussed in Chapter 3.

3.0 MECHANICAL AND RHEOLOGICAL MODELS FOR SLUDGE FLOW BEHAVIOR

The mobilization of slurries and sludges involves the transformation from a solid (or pseudo-solid) to a viscous fluid. Mathematical models that describe slurry/sludge flow behavior are discussed in this chapter. Flow behavior in the elastic regime is discussed in Section 3.1; the flow behavior present in the viscous regime, in Section 3.2. The relationship between an important elastic regime property, shear strength (τ_s), and a significant viscous regime property, yield stress (τ_y), is explored in Section 3.3.

3.1 FLOW BEHAVIOR IN THE ELASTIC REGIME

The simple physical model of a nonbrittle, elastic body was presented in Chapter 2. This model describes the cohesive behavior of a sludge in an undisturbed state. The idealized shear-stress/shear-strain relationship for this model was shown schematically in Figure 2.1 and is characterized by the parameters G and τ_s . The validity of this model depends on whether the sludge behaves elastically until the shear strength is exceeded. In reality, it has been shown that many cohesive solids, e.g. clays, exhibit irreversible strain, or creep, at constant stress (Evans, Hanley and Hess 1984; Vaid and Campanella 1977; Athanasopoulous and Richart 1983). Practically speaking, this means that rather than being elastic, clays often behave as extremely viscous fluids, with viscosity approaching infinity but still being finite as shear rate approaches zero (Tanner 1983; Reh binder 1954). However, the stress-strain behavior of such clays still reaches a peak value of stress beyond which viscosity rapidly decreases at constant shear rate. For our purpose, this peak stress can be considered the same as a yield stress; i.e., the question whether the path leading to failure involves reversible elastic strain or permanent plastic strain is not within the scope of this report.

3.1.1 Mises-Hencky Flow Condition for Plastic Materials

An interesting parameter sometimes used by rheologists to define the resistance of a cohesive solid to flow is the plastic resistance, E_p , defined by Reiner (1949) as

$$E_{pl} = \tau_s^2 / 2G \quad (3.1)$$

This equation is known as the Mises-Hencky flow condition, which, according to Mises (Reiner 1949) is the flow condition for any plastic material whether it obeys ideal elastic behavior in the elastic regime or not.

3.1.2 Effect of Settling Time on Shear Strength of Sample

There is one more complexity associated with time-dependent flow behavior, which appears to be the rule rather than the exception in both simulated and actual (Abdelhamid 1982) tank sludges. The shear strength of a material often depends on that material's shear history. For example, a non-radioactive sludge sample allowed to sit undisturbed in a viscometer for 18.5 h exhibited a shear strength of 24.6 dyne/cm², whereas initial measurements taken approximately 5 min after loading the sample in the viscometer indicated a maximum shear strength of only 8.2 dyne/cm² (data cited in Section 4.7). Therefore, for materials that form gels, shear strength depends on shear history.

3.2 FLOW BEHAVIOR IN THE VISCOUS REGIME

In the viscous regime, flow behavior is described by viscosity, which is the relationship between shear stress, τ , and shear rate, $\dot{\gamma}$. The ratio $\tau/\dot{\gamma}$ is equal to viscosity, η , and is constant over all shear rates for Newtonian fluids. In general, tank sludges and slurries are non-Newtonian in that the ratio $\tau/\dot{\gamma}$ is not constant over all values of $\dot{\gamma}$. For this reason, the viscosity of non-Newtonian fluids is referred to as "apparent viscosity," η_{app} .

The flow behavior of time-independent, non-Newtonian fluids that display pseudoplastic properties is described in Section 3.2.1. The behavior of time-independent, non-Newtonian fluids that exhibit yield stresses is discussed in Section 3.2.2. Time-dependent, non-Newtonian flow systems are described in Section 3.2.3.

3.2.1 Flow Behavior of Non-Newtonian Fluids, the Power Law

The shear-stress/shear-rate relationships for several time-independent, non-Newtonian fluids are plotted in Figure 3.1. The pseudoplastic curve in

FIGURE 3.1. Rheograms for Time-Independent Non-Newtonian Fluids Not Exhibiting Yield Stress (McCarthy, Chan and Lokken 1985)

Figure 3.1 falls below the Newtonian line, indicating that at high shear rates, a pseudoplastic fluid "thins out" so that less stress is required to sustain fluid motion. Pseudoplastic behavior is for this reason also called "shear-thinning" behavior. Dilatant fluids on the other hand, exhibit "shear-thickening" behavior.

The shear-stress/shear-rate behavior of these non-Newtonian fluids has been successfully described by the power law equation (Merrington 1949; Govier and Aziz 1972):

$$\tau = k \dot{S}^n \quad (3.2)$$

where k = consistency index, $\text{dyne/cm}^2 \text{ s}^n$
 n = flow behavior index, dimensionless
 τ = shear stress, dyne/cm^2
 $\dot{S}$ = shear rate, s^{-1} .

The significance of the flow behavior index is that if $n = 1$, the fluid is Newtonian; if $n < 1$, the fluid is pseudoplastic or "shear thinning"; and if $n > 1$, the fluid is dilatant or "shear thickening."

For non-Newtonian fluids that obey the power law, the apparent viscosity, η_{app} , in centipoise at a specific shear rate, is defined by the expression

$$\eta_{app} = \frac{k\dot{S}^{n-1}}{100} \quad (3.3)$$

This expression is equivalent to the definition of viscosity given by Equation 2.5.

3.2.2 Flow Behavior of Non-Newtonian Fluids Exhibiting Yield Stress

Some non-Newtonian fluids that obey the power law can sustain a certain amount of shear stress before they flow. The stress required to initiate motion in such fluids is called the "yield stress," τ_y (Denn 1980). Flow curves for fluids exhibiting a yield stress are shown in Figure 3.2. Note that these curves have slopes identical to those in Figure 3.1 but are displaced from the origin by an amount equal to τ_y . The shear-stress/shear-rate behavior of these fluids is described by a modified form of the power law (Govier and Aziz 1972):

$$\tau = \tau_y + K\dot{S}^n \quad (3.4)$$

Note that Equation 3.4 reduces to Equation 3.2 when $\tau_y = 0$.

3.2.3 Time-Dependent Flow Behavior in Non-Newtonian Fluids, Thixotropy and Rheopexy

The flow behavior of many non-Newtonian fluids such as most sludges and some slurries can be time dependent. Fluids that become thinner with time when stirred at a constant rate are called thixotropic, those that thicken with time are called rheoplectic fluids (Blair 1949).

The characterization of time-dependent behavior in terms of a mathematical model for shear stress versus time and shear rate has been described by Ford and Steffe (1986). Measurements of shear vane torque versus time at several rates of revolution are required to develop the mathematical model. These data can be somewhat difficult to obtain because pre-shear conditions must be controlled prior to each measurement. Due to the difficulty involved, past

FIGURE 3.2. Rheograms for Time-Independent Non-Newtonian Fluids Exhibiting Yield Stress (McCarthy, Chan and Lokken 1985)

practice at PNL and elsewhere has been merely to note thixotropic behavior rather than to describe it in terms of a mathematical model. Reporting the shear stress required to initiate motion in undisturbed sludge, defined as shear strength, τ_s , is usually sufficient.

The viscosity corresponding to the peak value of stress (equivalent to shear strength) at which a material begins to fail through plastic deformation is called the maximum plastic viscosity, η_0 , defined by Rehbinder (1954) as

$$\eta_0 = \lim \left[\frac{\tau}{S} \right] \text{ as } \tau \rightarrow \tau_s \text{ (} S \rightarrow 0 \text{)} \quad (3.5)$$

Extremely high values of η_0 have been reported as a means of describing the creeping flow behavior of cohesive materials. In particular, Rehbinder reported, "...a peculiar creep in an undisturbed structure with a Newtonian viscosity of the order of 10^7 - 10^9 Poises, for dilute bentonite suspensions, which is 10^8 higher than the minimum viscosity of a disturbed structure." Values of η_0 are occasionally reported as "yield viscosity" or "start-up viscosity." Where possible (see discussion in Section 4.1), values of τ_s are reported instead of η_0 .

3.3 SHEAR STRENGTH AND YIELD STRESS

In the yield-pseudoplastic model for a viscous fluid, the yield stress will in general have a different value than the shear strength that appears in the elastic solid model (see Section 2.2). The difference, in terms of sludge mobilization, is that a sludge begins as an elastic solid with a shear strength τ_s , proceeds to a thixotropic fluid when τ_s is exceeded, and with time eventually achieves steady state and becomes a power law fluid that may exhibit a yield stress. Therefore, in this report, τ_y will be considered the time-independent yield stress exhibited in the steady-state viscous regime. The shear strength, on the other hand, is dependent upon shear history and, thus, upon time. It is exhibited during transient "start-up" shear, and marks the transition from a solid to a viscous slurry. Although the distinction between τ_y and τ_s is not often made, the values are fundamentally different. Figure 3.3 illustrates the locations of τ_y and τ_s on a plot of stress versus time at constant shear rate for a hypothetical tank sludge.

FIGURE 3.3. Plot of Shear Stress Versus Time at Constant Shear Rate for a Hypothetical Tank Sludge. The locations of yield stress (τ_y) and shear strength (τ_s) are shown.

4.0 MEASUREMENT OF SLUDGE PARAMETERS IN THE LABORATORY USING ROTATIONAL VISCOMETERS

This chapter describes how the parameters τ_s in the elastic regime and η_{app} , η_0 , τ_y , n , and K in the viscous regime can be measured in the laboratory by means of rotational viscometers. A rotational viscometer is a device that measures the torque required to rotate a spindle through a sample.

Brookfield® and Haake Rotovisco® rotational viscometers can be used to measure sludge parameters. Both operate according to the same basic principles. Figure 4.1 is a schematic of a Haake viscometer equipped with a concentric cylinder spindle arrangement. A motor rotates the inner cylinder

FIGURE 4.1. Schematic of a Haake® Viscometer
(adapted from Schramm 1981)

®Brookfield Engineering Laboratories, Inc., Stoughton, Massachusetts.
®Haake Mess-Technik GmbH and Company, Karlsruhe, West Germany.

(spindle) through a sample. A torque, caused by the resistance of the sample to shearing, acts on the spindle. This torque deflects a measuring spring placed between the motor and the spindle drive shaft. The spring deflection is transformed into an electrical signal, which is recorded on a chart or pen recorder. The magnitude of the spring deflection correlates linearly with the torque.

On a Brookfield viscometer, spindle speed is variable in eight discrete steps. The rate of spindle rotation is selected by rotating an eight-position knob on the left-hand side of the instrument body. Two Brookfield viscometers are available: the RVDT and the LVDT. The LVDT model has eight available speeds: 0.3, 0.6, 1.5, 3.0, 6.0, 12, 30, and 60 rpm. The RVDT model can be operated at several speeds: 0.5, 1.0, 2.5, 5.0, 10, 20, 50, and 100 rpm.

On Haake Rotovisco viscometers, rotational speed is continuously variable between 0.01 and 500 rpm. During testing, rotational speed can be programmed to increase, hold at a fixed rpm, and then decrease over selected time intervals. The speed signal (required for the determination of shear rate) does not come from the spindle directly but from a tacho-generator which sits above the motor and is mechanically linked to it. For slurries that do not exhibit a yield stress, the speeds of the tacho-generator, motor, and the spindle are identical so that the speed signal, n_{tg} , also defines the spindle speed, n_r . A slurry with a yield stress will "clamp" the spindle to the cup, until the torque applied is greater than the yield stress.

The following sections summarize the methodologies available to identify significant rheological parameters. Such parameters must be understood before equipment can be designed to mobilize sludges in underground storage tanks. Section 4.1 discusses the use of Brookfield disc and T-bar spindles to measure apparent and minimum plastic viscosities. Section 4.2 focuses on the measurement of apparent viscosity, shear stress, and shear rate by means of concentric cylinder spindles. An example calculation is provided. Section 4.3 examines the use of miniature shear vanes to measure apparent viscosity, shear stress, and shear rate, and provides two methods. Section 4.4 describes the measurement of steady-state yield stress by means of a rheogram and by torque decay. In Section 4.5, rheograms are used to determine power law coefficients. Two

examples illustrate the method. Section 4.6 contains tests for detection of time-dependent flow behavior in sludges, and Section 4.7 describes the measurement of non-steady-state shear strength.

4.1 MEASUREMENT OF APPARENT VISCOSITY AND MAXIMUM PLASTIC VISCOSITY BY MEANS OF STANDARD BROOKFIELD DISC AND T-BAR SPINDLES

Several types of spindles are available for use with Brookfield and Haake viscometers. The geometries of various Brookfield standard viscometer spindles are shown in Figure 4.2. Because of their shape, the T-bar and disc spindles allow measurement of viscosity, but at undefined shear rates. These spindles cannot compare shear stress and shear rate; they can measure only viscosity and spindle rotational speed. Values of viscosity are determined by recording the viscometer torque reading, R_t . A T-bar or disc spindle is rotated at a fixed rpm through a sample and R_t is multiplied by an empirical spindle factor to arrive at sample viscosity in centipoise (Brookfield 1984):

$$\eta = R_t \cdot M \quad (4.1)$$

where η = sample viscosity, centipoise

R_t = viscometer torque reading, 0 to 100 full-scale, dimensionless

M = empirical, rpm-dependent factor provided by Brookfield for each disc and T-bar spindle.

The data in Figure 4.3, a hypothetical plot of viscometer torque output reading versus time at constant RPM, was obtained by immersing a T-bar spindle in a gelled, cohesive sludge sample. The plot's peak occurs at the moment that the sludge's shear strength is exceeded. Consistent with the definition given by Equation (3.5), the viscosity calculated from the peak value of torque is the maximum plastic viscosity, η_0 .

FIGURE 4.2. Geometry of Various Brookfield Spindles

FIGURE 4.3. Plot of Viscometer Torque Output Versus Time at Constant RPM, Obtained with a T-Bar Spindle in a Gelled Sludge. The value of peak torque, $T_{\max}$, is used to calculate the maximum plastic viscosity, η_0 .

Because shear rate is not defined for T-bar spindles, the shear strength associated with this value of η_0 cannot be calculated. As discussed in Section 4.2, coaxial or concentric cylinder spindles for which shear rates are

defined should be used, if available, to characterize the flow behavior of non-Newtonian fluids. As described in Section 4.3, shear vanes may also be used, as shear vane rpm can be correlated with shear rate.

4.2 MEASUREMENT OF APPARENT VISCOSITY, SHEAR STRESS AND SHEAR RATE BY MEANS OF CONCENTRIC CYLINDER SPINDLES

Concentric cylinder or "Searle-type" rotational viscometers permit direct determination of shear rate versus shear stress and are therefore ideal for characterizing the flow behavior of non-Newtonian fluids. Haake Rotovisco viscometers are Searle types, featuring an inner cylinder (spindle) that rotates within a fixed outer cylinder (cup, see Figure 4.1). Brookfield provides a similar arrangement called the Brookfield UL adapter. Brookfield cylindrical spindles such as those shown in Figure 4.2, can also be used in a concentric cylinder arrangement if the fluid sample is contained in a cylindrical vessel. In this case the outer, fixed cylinder is the sample container itself.

For a concentric cylinder arrangement in which the inner cylinder rotates while the outer cylinder (which may be the inner wall of a sample container) is fixed, shear rate (in inverse seconds) is defined by Brookfield Engineering Laboratories (1984) as

$$\dot{\gamma} = \frac{2 \cdot \omega \cdot R_c^2 \cdot R_b^2}{x^2 (R_c^2 - R_b^2)} \quad (4.2)$$

where ω = angular velocity of spindle in rad/s equivalent to $(2\pi/60)$ (RPM)

R_c = radius of container, cm

R_b = radius of spindle, cm

x = radius at which shear rate is being calculated (usually taken as $x = R_b$).

Shear stress in dyne/cm is defined as

$$\tau = \frac{T}{2\pi \cdot R_b^2 \cdot L} \quad (4.3)$$

where T = torque measured by instrument, dyne-cm

L = effective length of spindle, cm.

Brookfield Engineering Laboratories (1984) calculates the value of T from the viscometer torque output, R_t , by

$$T = \frac{F \cdot R_t}{100} \quad (4.4)$$

where F = viscometer spring constant, dyne-cm

R_t = viscometer output reading, 0 to 100 full-scale, dimensionless.

The effective length, L , of a cylindrical spindle is different from the actual length and is a calculated value that accounts for spindle end effects. The actual and effective lengths, as well as radius, of Brookfield and Haake cylindrical spindles are provided in the viscometer's operating manual.

The output of a Haake viscometer equipped with a cylindrical spindle is shown in Figure 4.4. The figure shows two plots of the shear stress (S_τ -axis) developed at the wall of a cylinder rotated through a typical sludge sample as a function of shear rate (S_D -axis). Such plots are called "flow curves" or "rheograms." In this figure, shear rate was programmed to increase from 0 to 20 sec^{-1} , producing an "up-curve," was held at 20 sec^{-1} , and then was decreased to 0 sec^{-1} , producing a "down-curve." Note that the up-curve and down-curve do not coincide; i.e., they exhibit a hysteresis. As discussed in Section 4.6.2, such flow curve hysteresis is indicative of time-dependent, thixotropic flow behavior.

Values of shear stress, τ , versus shear rate, $\dot{S}$, can be determined from a Haake rheogram by reading values of S_τ (y-axis) and S_D (x-axis) from points taken on the flow curve, and calculating τ and $\dot{S}$ as

$$\tau = S_\tau \cdot \tau_{\max} \cdot 10, \text{ dyne/cm}^2 \quad (4.5)$$

$$\dot{S} = S_D \cdot \dot{S}_{\max}, \text{ sec}^{-1} \quad (4.6)$$

FIGURE 4.4. Rheogram of a Sludge Exhibiting Flow Curve Hysteresis

where $\tau_{\max}$ = full-scale shear stress, Pa
 $\dot{S}_{\max}$ = full-scale shear rate, sec^{-1} .

The values of $\tau_{\max}$ and $\dot{S}_{\max}$, indicated on each scale of the rheogram, are empirical values (provided by Haake) that depend on the geometry of the specific spindle assembly being used, the torque sensor being used, and the maximum test rpm.

A rheogram can also be produced using a Brookfield viscometer by plotting torque data obtained at several spindle speeds in terms of shear stress versus shear rate. Equations (4.2 and 4.3) are used to convert the data for torque versus rpm to values of shear stress versus shear rate. The following example illustrates how to calculate shear stress from data obtained with a Brookfield concentric cylinder apparatus.

Example Calculation of τ_s from Brookfield Concentric Cylinder Viscometer

Data. Figure 4.5, which is a plot of viscometer output, R_t , versus time at constant shear rate, shows a hypothetical sludge. The hypothetical test incorporates a Brookfield RVDT viscometer fitted with a concentric cylinder arrangement and run at a constant 0.5 rpm. In this arrangement, the effective spindle length is $L = 9.239$ cm, spindle radius is $R_b = 1.258$ cm, and cup radius is $R_c = 1.381$ cm (Brookfield 1982). By the shape of the plot, it is clear that this sludge exhibits a shear strength, as described in Sections 2.2.1 and 3.3. Equations (4.3 and 4.4) are used to calculate a shear stress of 24.6 dyne/cm^2 , which corresponds to the peak value of viscometer output, $R_t = 31.9$. This value of shear stress is equivalent to the shear strength of the hypothetical sludge: $\tau_s = 24.6 \text{ dyne/cm}^2$.

FIGURE 4.5. Plot of Viscometer Output Versus Time at Constant Spindle RPM for a Hypothetical Sludge Sample

4.3 MEASUREMENT OF APPARENT VISCOSITY, SHEAR STRESS AND SHEAR RATE BY MEANS OF MINIATURE SHEAR VANES

Shear vanes have been used for years by soil scientists to obtain convenient and reliable measurements of soil shear strength in the field. A standard shear vane (ASTM 1978) consists of a shaft to which four rectangular vanes or blades are attached as shown in Figure 4.6. Three shear vanes that have been used in testing at PNL are shown in Figure 4.7. As described in Chapter 5, shear vanes can be used to determine viscosity as well as shear strength. A correlation was developed between shear vane rotational speed and shear rate, allowing shear vanes to be used in conjunction with a rotational viscometer (or other torque-measuring device) to produce rheograms.

FIGURE 4.6. Shear Vane Geometry. Shearing involves one vertical cylindrical surface and two horizontal end surfaces (a). Twisting of the vane also induces normal stress, τ_n , on the shearing surface (b).

FIGURE 4.7. Three Shear Vanes Used During Testing at PNL

Shear vanes can be used with Brookfield, Haake, and other rotational viscometers. The two miniature shear vanes shown in Figure 4.7 were made by attaching blades to the end of a standard Brookfield spindle^(a) as shown in Figure 4.8. This allowed the miniature vanes to be attached to Brookfield viscometers and operated in the same way as standard Brookfield spindles. A coupling adapter (also fabricated at PNL) was used to attach them to Haake viscometers. The Haake sample cup (Figure 4.1) must be removed to accommodate a miniature shear vane.

FIGURE 4.8. Dimensions of Miniature Shear Vanes Used in Testing at PNL

(a) Brookfield spindle No. RV-7.

Shear vanes are operated in the same way as standard Brookfield and Haake spindles. When a shear vane is attached to a Brookfield viscometer, it is rotated at several speeds. The torque required to rotate the shear vane through a sample is measured at each speed. The calculational procedure outlined in Chapter 5 is used to calculate the viscosity, shear rate, and shear stress associated with each torque versus rpm data point. A rheogram is produced by plotting shear stress versus shear rate for several data points.

Used in conjunction with a Haake viscometer, a shear vane can either be rotated at a constant speed to produce one data point, or programmed to vary continuously in rotational speed from 0 to a maximum value and back down to 0, producing a complete flow curve (infinite number of data points). In either case, the calculation procedure outlined in Chapter 5 must be used to transform each data point from torque versus rotational speed to shear stress versus shear rate so that the data can be fit to the power law (Equation 3.2).

Two limitations apply to the use of shear vanes for obtaining viscosity data:

1. The test sludge/slurry must not be dilatant or "shear thickening."
2. The dimensionless Reynolds number characterizing flow patterns set up by a rotating shear vane must be less than 15.

The first criterion will usually be met because most sludges and slurries exhibit pseudoplastic or "shear thinning" behavior (with or without a yield stress) or approach ideal Newtonian or Bingham plastic behavior.

The correlation of shear vane torque with apparent sludge viscosity is based on a correlation between two dimensionless groups, the Reynolds number, N_{RE} , and the power number, N_p , where

$$N_{RE} = \frac{1.667 \rho D_v^2 N}{\eta_{app}} \quad (4.7)$$

$$N_p = \frac{22,620 T_v}{\rho D_v^5 N^2} \quad (4.8)$$

and where ρ = test fluid (sludge) density, g/cm³
 D_v = shear vane diameter, cm
 N = rate of shear vane rotation, rpm
 η_{app} = test fluid viscosity, cPs
 T_v = shear vane torque, dyne-cm.

This correlation, further discussed in Chapter 5, serves to relate values of shear vane torque through the power number to values of sludge viscosity through the Reynolds number. As discussed in Chapter 5, PNL test data confirms that the N_{RE} - N_p correlation is valid only for Reynolds numbers less than 15. Above $N_{RE} = 15$, the power number gradually becomes independent of the Reynolds number.

In practice, one cannot know whether the $N_{RE} < 15$ criterion has been met until the data have been analyzed. Table 4.1 can be used as a general guide for predicting maximum rotational speeds such that $N_{RE} < 15$ for a variety of test fluid viscosities, densities, and shear vane diameters.

A disadvantage of shear vanes for obtaining viscosity data is that analyzing the shear vane data involves more than multiplying viscometer output reading by an empirical spindle factor (as is the case with standard viscometer spindles). However, a calculator program designed for use with Hewlett-Packard® HP-41 series calculators greatly speeds up and simplifies data analysis. The program calculates viscosity, shear stress, shear rate, dimensionless Reynolds and Power numbers and includes a correction for shear vane shaft friction. This program, VANE-2, and instructions for using it are provided in Appendix B.

®Hewlett-Packard Company, San Diego, California.

TABLE 4.1. Maximum Shear Vane Rotational Speed ($N_{\max}$)^(a) for Apparent Viscosity Measurement

η_{app} (cPs)	D_v (cm)	ρ (g/cm ³)	$N_{\max}$ (rpm)
10	0.975	1.0	95
10	0.975	2.0	48
10	2.220	1.0	18
10	2.220	2.0	9
10	7.62	1.0	2
10	7.62	2.0	1
100	0.975	1.0	950
100	0.975	2.0	470
100	2.220	1.0	180
100	2.220	2.0	90
100	7.62	1.0	16
100	7.62	2.0	8
1000	0.975	1.0	9,500
1000	0.975	2.0	4,730
1000	2.220	1.0	1,830
1000	2.220	2.0	915
1000	7.62	1.0	155
1000	7.62	2.0	78
10,000	0.975	1.0	94,700
10,000	0.975	2.0	47,300
10,000	2.220	1.0	18,300
10,000	2.220	2.0	9,130
10,000	7.62	1.0	1,550
10,000	7.62	2.0	775

(a) Values of N at or below $N_{\max}$ assure that $N_{RE} < 15$.

4.4 MEASUREMENT OF STEADY-STATE YIELD STRESS

There are two general methods for determining yield stress, τ_y . The first involves extrapolation of a rheogram (plot of shear stress versus shear rate) to a shear rate of zero as discussed in Sections 4.4.1. An optimization procedure for this method is described in Section 4.4.2. The second method involves measuring residual torque on a spindle that has stopped rotating, and using the measured residual or decay torque to calculate a value of τ_y . This method, which can provide more precise data than the extrapolation procedures, is discussed in Section 4.4.3.

4.4.1 Extrapolation of Test Data to Zero Shear Rate

Figure 4.9 illustrates a Haake flow curve produced under steady-state conditions for a sludge that exhibits a yield stress. At low shear rates, the flow curve appears to be a straight line with a slope of about 4° off of vertical. The curve then abruptly changes (at about $\dot{S} = 5 \text{ s}^{-1}$) to a flow curve for a non-Newtonian fluid. Flow curves having this general shape, characterized by a marked deflection near a shear rate of zero, indicate the presence of a finite yield stress.

The elastic solid flow curve indicated in Figure 4.9 is produced when a spindle (concentric cylinder or shear vane) stops rotating at a finite level of torque. What happens mechanically is that at and below its yield stress, a

FIGURE 4.9. Flow Curve for a Typical Sludge, 0 to 468 s^{-1}

sludge behaves as a non-flowing solid and "clamps" the spindle, preventing rotation. While the spindle is still clamped and remains at a standstill, the motor rotation will cause some spring deflection and consequently a torque signal on the ordinate. For a slurry with a yield stress, a straight line, leaning off the vertical with an angle β , is recorded initially as shown in Figure 4.10. When the shear stress surpasses the yield value τ_y , the spindle breaks loose from its "clamp," and the rotor picks up speed, accelerating almost instantaneously from zero to the value indicated on the S_D scale (X-axis). Two regimes can be distinguished on the flow curve: the first is a segment of the "flow curve of a solid," while the second regime describes the flow of the material after it has been transformed into a liquid.

The torque at which a spindle begins rotating (up-curve) is indicated by a point of deflection in the overall flow curve near zero rpm. Depending on the test conditions selected, the flow curve may gradually change from one region to the other. The transition from a solid gel to an easy-flowing liquid may

FIGURE 4.10. Typical Flow Curve for a Pseudoplastic Fluid (adapted from Schramm 1981)

include 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 of the elastic and viscous branches of the rheogram.

If a Brookfield-type concentric cylinder arrangement is used to produce a flow curve, yield stress is calculated by

$$\tau_y = \frac{T}{2\pi R_b^2 L} \quad (4.9)$$

where T = torque measured by instrument, dyne-cm

L = effective length of spindle, cm

R_b = radius of spindle, cm.

The torque corresponding to the point of flow curve deflection is calculated by Brookfield Engineering Laboratories (1984) as

$$T = F \cdot \frac{R_t}{100} \quad (4.10)$$

where F = spring factor associated with viscometer, dyne-cm

R_t = viscometer torque reading, 0 to 100 full-scale, dimensionless.

Values of F for Brookfield and Haake viscometers are listed in Table 4.2. If a Haake viscometer is used, the torque at the point of flow curve deflection is calculated as

$$T = F \cdot S_\tau \cdot \frac{\% \tau}{100} \quad (4.11)$$

where S_τ = viscometer torque scale reading, 0 to 1 full-scale, dimensionless.^(a)

$\% \tau$ = torque reading scale factor, 1 to 100, dimensionless.^(a)

(a) Note that $S_\tau \cdot \% \tau = R_t$ = torque reading (regardless of viscometer used), 0 to 100 full scale, dimensionless.

TABLE 4.2. Viscometer Spring Constants

Torque Sensor System	F (dyne-cm)
Brookfield RVDT	7,187
Brookfield LVDT	673.7
Haake M1500	1,470,000
Haake M500	590,000
Haake M150	147,000
Load Cell Torque Apparatus	Torque corresponding to full-scale ($R_t = 100$) deflection

If a Haake concentric cylinder apparatus is used to produce the rheogram, the yield stress can be calculated directly (without having to calculate torque) via

$$\tau_y = S_\tau \cdot \tau_{\max} \cdot 10, \text{ dyne/cm}^2 \quad (4.12)$$

where $\tau_{\max}$ = full-scale shear stress, Pa.

Values of $\tau_{\max}$ and % τ are indicated on the S_τ scale of Haake rheograms.^(a)

If a miniature shear vane is used, in conjunction with a Brookfield or Haake viscometer, torque at the point of flow curve deflection is calculated by Equations (4.10 or 4.11), respectively. The following equation is then used to calculate yield stress (ASTM 1963):

$$\tau_y = \frac{T_v}{\pi} \left[\frac{H_v D_v^2}{2} + \frac{D_v^3}{6} \right]^{-1} \quad (4.13)$$

where T_v = torque applied to shear vane, dyne-cm

H_v = shear vane blade height, cm

D_v = shear vane blade diameter, cm.

(a) In Figure 4.9 for example, $\tau_{\max} = 14.49 \text{ Pa}$ ($= 144.9 \text{ dyne/cm}^2$), and % $\tau = 15$ as written in the upper left corner of the plot.

4.4.2 Optimizing the Extrapolation Method

If the presence of a yield stress is detected on a steady-state flow curve such as Figure 4.9, the following procedure can be used to obtain a more accurate value of τ_y .

Using a Haake viscometer equipped with a concentric cylinder spindle arrangement or a miniature shear vane, shear the sludge sample at a constant spindle speed (around 5 rpm or lower) until a constant (steady-state) reading is achieved. Then run a down-curve (from 5 to 0 rpm). If the flow curve plot is expanded in the low rpm range, the point of flow curve deflection is less ambiguous. For example, in Figure 4.11 (a flow curve of the sample represented in Figure 4.9), the low shear rate range is expanded, and the point of

FIGURE 4.11. Flow Curve for a Typical Sludge, 0 to 11.7 s⁻¹

deflection occurs at $S_\tau = 0.227$, $R_t = 3.41$. Using Equations (4.11 and 4.13), and assuming that a shear vane having $H_v = D_v = 2.220$ cm was used to make the measurement, one can calculate yield stress as $\tau_y = 220$ dyne/cm². The results of this calculation using Option 4 of the calculator program VANE-2 (described in Appendix B) are shown below.

$$\begin{aligned} F &= 147000.0 \text{ dyne-cm} \\ D_v &= 2.220 \text{ cm} \\ R_c &= 3.000 \text{ cm} \\ R_s &= 0.1588 \text{ cm} \\ T_c &= 0.000 \text{ dyne-cm} \\ R_t &= 3.410 \\ H_v &= 2.220 \text{ cm} \\ T_v &= 5012.7 \text{ dyne-cm} \\ \tau_s &= 218.8 \text{ dyne/cm}^2 \end{aligned}$$

If a Haake concentric cylinder spindle arrangement is used, the procedure is identical except that Equation (4.12) can be used to calculate τ_y directly from the expanded rheogram. This optimization procedure cannot be used with a Brookfield viscometer because it does not offer continuously variable spindle speeds.

Note that the slopes of the elastic solid flow curves in Figures 4.9 and 4.11 are different. These slopes, characterized by angle β measured from the vertical, have nothing to do with the flow behavior of the sludge sample. Instead, β is related to the speed at which the internal viscometer torque spring deflects at 0 rpm, which in turn depends on the rotational speed or shear rate range selected by the viscometer technician. It is therefore not necessary to report values of β .

4.4.3 Shear Vane Torque Decay at $N=\dot{S}=0$

The second method of determining sludge yield stress can be used with any torque-measuring device. Simply rotate a spindle through a sludge at a constant, low rpm (e.g., 0.5 rpm) until a stable viscometer output reading is obtained. Then turn off the viscometer drive motor. After the drive motor stops, the spindle will stop rotating. It will then rotate in the opposite direction, because of a force imposed by an internal viscometer spring as it

relaxes to zero deflection. If a yield stress exists, the sludge will clamp the spindle at a finite spring deflection corresponding to a finite torque reading. To calculate τ_y from this reading, Equations (4.9) through (4.13) can be used as appropriate, depending on the viscometer (Brookfield or Haake) and spindle (shear vane or concentric cylinder arrangement). Should the viscometer output signal decay to a torque output reading of zero, then the test material will not exhibit a true yield stress but may instead exhibit creeping (highly viscous) flow at very low shear rates. In cases where a sample fluid exhibits creep at constant stress, the final viscometer output will rapidly reach a certain value and then slowly reach zero as time goes to infinity. Figure 4.12 illustrates the difference in the two sets of behavior and indicates how τ_y should be specified in the case of plastic creep.

4.5 DETERMINING POWER LAW COEFFICIENTS FROM RHEOGRAMS

Power law parameters k and n are determined by plotting shear stress versus shear rate in terms of $\log (\tau - \tau_y)$ versus $\log (\dot{\gamma})$. The slope of such a plot is equivalent to n . The intercept (at $\log \dot{\gamma} = 0$) is equivalent to $\log k$. To prepare such a plot requires at least 5 and preferably 10 to 20 viscometer torque readings at as many spindle rotational speeds. The torque reading/rpm

FIGURE 4.12. Comparison of Elastic and Creep Behaviors as Shear Rate Approaches Zero

data are then reduced to shear-stress/shear-rate data by using the appropriate equations (depending on the viscometer/spindle arrangement) as described in Sections 4.1, 4.2, and 4.3.

When a Haake viscometer is used, shear the sample at a constant spindle rotational speed equal to $N_{\max}$ until a steady state-output is produced. Then ramp spindle rpm from $N_{\max}$ down to 0 over a period of at least 10 min (set $t_2 = 10$ min). Allow more time if the sample is very thixotropic and appears to require 5 min or more to achieve a steady-state output at $N_{\max}$. Down-curve time can be set at as little as 5 min if the sample is considered not very thixotropic or reaches steady state at $N_{\max}$ in less than 30 s. Read the values of S_τ and S_D off of the down-curve--between 10 and 20 points should be read at regularly spaced intervals. If a shear vane is used as the test spindle, convert values of S_τ to values of R_t by multiplying by $\% \tau$ (between 1 and 100). Convert values of S_D to rpm by multiplying by $N_{\max}$ (maximum shear vane rpm during the test). Then use VANE-2 (Appendix B) to calculate values of shear stress versus shear rate.

If a Brookfield viscometer is used, only eight discrete rotational speeds are available. To obtain a sufficient number of data points (between 10 and 20) use either one spindle with both an LVDT and an RVDT or two different spindles with one viscometer to obtain a maximum of 16 data points. Both Brookfield viscometers can be used with two different spindles for a total of 32 data points. If shear vanes are used, analyze the R_t versus N data using VANE-2. The following two examples pertain to cylindrical spindles. An example illustrating how n and k are determined from shear vane data is provided in Appendix B.

4.5.1 Example: Determining Power Law Coefficients with a Brookfield Viscometer Fitted with a Concentric Cylinder Spindle Arrangement

Table 4.3 shows values of shear stress and shear rate obtained for a sludge sample. A Brookfield RVDT viscometer was fitted with the concentric cylinder UL adapter. This sludge was found to exhibit a yield stress (estimated by the torque decay method described in Section 4.4.3) of 2.66 dyne/cm^2 . Several replicate measurements were made by rotating the UL spindle at 0.3 rpm until the viscometer output reached a stable reading. The

TABLE 4.3. Values of Shear Stress and Shear Rate Obtained by Using a Brookfield RV Viscometer with a Brookfield UL Adapter

Shear Rate (S^{-1})	Shear Stress (dyne/cm ²)	Viscosity (cP)
0.0	2.66 ^(a)	--
0.61	9.21	1510.0
1.22	10.31	844.8
3.05	11.48	376.3
6.12	12.61	206.1
12.24	14.10	115.2
24.47	15.66	64.0
61.18	18.78	30.7
122.36	23.00	18.8

(a) Yield stress value measured using procedure described in Section 4.4.3.

spindle motor was then turned off, and the final viscometer output, R_t , was read. In all tests, R_t was found to be 3.40 ± 0.10 and τ_y was calculated by Equations (4.9) and (4.10) as

$$\tau_y = \frac{(7187)(3.40/100)}{2 \pi (1.258)^2 (9.239)} = 2.66 \text{ dyne/cm}^2 \quad (4.14)$$

The values in Table 4.3 were plotted as $\log (\tau - \tau_y)$ versus $\log (\dot{S})$, and produced a straight line. From the slope and intercept of this plot, the power law parameters in Equation (3.2) were calculated as $n = 0.19$ and $k = 7.27 \text{ dyne/cm}^2$. Since $n < 1$, this melter feed is considered a pseudoplastic power law fluid. Because this sludge sample exhibits a finite τ_y , and $n < 1$, it demonstrates yield-pseudoplastic behavior and is described, in cgs units, by

$$\tau = 2.66 + 7.27 \dot{S}^{0.19} \quad (4.15)$$

4.5.2 Example: Determining Power Law Coefficients with a Haake Rotovisco® Viscometer Fitted with a Concentric Cylinder Spindle Arrangement

Laboratory rheological data were also obtained for the same sludge as used in the previous example, except that measurements were made with a Haake

viscometer equipped with an M150 measuring/drive head and the MV II concentric cylinder spindle system. The resulting rheogram is shown in Figure 4.13. The yield-pseudoplastic model for this melter feed, based on the Haake rheogram, was calculated as

$$\tau = 2.54 + 7.74 \dot{\gamma}^{0.17} \quad (4.16)$$

Comparison of Equations (4.15) and (4.16) verify that data from both viscometers provide similar results. Table 4.4 shows values of shear stress and shear rate taken from the Haake rheogram.

FIGURE 4.13. Haake Rheogram of Melter Feed Sample Taken at t = 5 min

TABLE 4.4. Values of Shear Stress and Shear Rate Obtained by Using a Haake Rotovisco® RV-100 Viscometer with System M150, Sensor System MV II

Shear Rate (S^{-1})	Shear Stress (dyne/cm ²)	Viscosity (cP)
0.0	2.54 ^(a)	--
3.61	10.2	283.0
7.22	11.3	157.0
10.82	12.1	112.0
14.43	12.8	88.7
18.04	13.2	73.2
36.08	15.0	41.6
54.12	16.3	30.1
72.16	17.7	24.5
90.20	18.8	20.84
108.2	19.9	18.39
126.3	30.9	16.55
144.3	21.7	15.04
162.4	23.1	14.22

(a) Estimated from Haake rheogram.

Note that in Figure 4.13, there are two shear stress deflection points near zero shear rate. The start-up deflection point is related to shear strength, τ_s , which (as discussed in Section 3.3) is time-dependent for gel-forming materials. The deflection point on the lower curve is related to the steady-state yield stress, τ_y , and corresponds to the value of τ_y used in the power law Equation (4.16). Although the fluid represented in Figure 4.13 exhibits both, many fluids exhibit a τ_s but not a τ_y , indicating that once the gel structure is broken, these fluids obey the pseudoplastic model rather than the yield-pseudoplastic model.

4.6 TESTS FOR DETECTING TIME-DEPENDENT (THIXOTROPIC OR RHEOPECTIC) BEHAVIOR

There are two general methods for detecting time-dependent flow behavior in sludges. These methods are described below in Sections 4.6.1 and 4.6.2.

4.6.1 Constant Shear Rate Method

The first method is to run a spindle at a constant rpm for 5 to 10 min. Any viscometer/spindle arrangement may be used. If a sludge is thixotropic,

the viscometer torque reading will initially reach a maximum and with time will gradually fall off to a lower, steady-state value. A semi-quantitative method for reporting this type of data is to calculate a thixotropic breakdown coefficient, T_{BR} , defined by Brookfield Engineering Laboratories (1984) as

$$T_{BR} = \frac{\eta_{app1} - \eta_{app2}}{\ln \left[\frac{t_2 \text{ (min)}}{t_1 \text{ (min)}} \right]} \quad (4.17)$$

where η_{app1} = apparent sludge viscosity at time 1 (t_1)
 η_{app2} = apparent sludge viscosity at time 2 (t_2).

When reporting values of T_{BR} , pre-shear conditions should be described. If readings at constant rotational speed increase with time, then the sludge sample is rheopetic. Equation (4.17) can be used to report negative values of T_{BR} for rheopetic samples. A more-detailed quantitative method for describing time-dependent behavior is available (Ford and Steffe 1986).

4.6.2 Variable Shear Rate Flow Curve Hysteresis

The second method of characterizing time-dependent behavior is to measure spindle torque while ramping spindle rpm from 0 to N_{max} , holding at N_{max} until a steady-state torque reading is achieved, and then ramping shear vane rpm back down from N_{max} to 0. If a Haake viscometer is used, the test data will have the general appearance of Figure 4.14. The area of hysteresis between the up- and down-curves provides a semi-quantitative measure of time-dependent flow behavior. If the down-curve falls below the up-curve, the sample is thixotropic. If the down-curve rises above the up-curve, the sample is rheopetic.

The Haake-derived curves in Figure 4.14 are smooth because shear vane rpm during the test is varied continuously between 0 and N_{max} . By contrast, a Brookfield viscometer has discrete speeds that must be manually increased and decreased, resulting in a stepped output having the general appearance of Figure 4.15.

Since thixotropic behavior is time-dependent, the amount of time expended in ramping shear vane rpm up and down will influence the test results. If a

FIGURE 4.14. Flow Curve Hysteresis Indicating Sludge Thixotropy (adapted from Schramm 1981)

FIGURE 4.15. Up and Down Flow Curves Produced with Brookfield RVDT Viscometer

Haake viscometer is used, it is recommended that each curve be completed in 10 min. To ensure this time, set the programmable time parameters to $t_1 = t_2 = 10$ min. If a Brookfield viscometer is used, start at the lowest speed and progress to the highest speed, pausing about 1 min at each speed. Then, reduce the speed from maximum to minimum, pausing about 1 min at each speed, to produce the down-curve.

Between curves, allow sufficient time at a constant $N_{\max}$ for the viscometer torque output to fall to a steady-state (time invariant) value. Steady state is usually achieved within 10 min and often within 2 min. If a Haake viscometer is used, select a hold time of $t_3 = 10$ min. If steady state occurs sooner than 10 min, t_3 can be manipulated during the test to allow production of the down-curve without the full 10-min wait at $N_{\max}$. If a Brookfield viscometer is used, wait until the torque reading at $N_{\max}$ reaches a constant value, then shift to the next lowest speed, wait 1 min, shift down again, and so on until the curve is completed.

4.7 MEASUREMENT OF NON-STEADY-STATE SHEAR STRENGTH

Most sludges that exhibit thixotropy tend to form a gel that stiffens when left undisturbed. For example, Figure 4.16 is a Haake rheogram prepared 18.5 h after the rheogram shown in Figure 4.13 for the same sample using the same measuring system. The time dependency of τ_s is made evident by comparing these two figures.

Because the shear strength of a sludge is dependent on time (and shear history), it is recommended that samples be allowed to sit undisturbed for at least 48 h prior to τ_s determination. Test methods that require pre-shearing or disturbing a sludge sample just prior to measurement should be avoided. For example, the use of a concentric cylinder arrangement requires that the sample be poured into the gap between the two cylinders. This procedure causes the sample to be disturbed. If a concentric cylinder arrangement must be used, the sample should be loaded and then left undisturbed for 48 h.

FIGURE 4.16. Haake Rheogram of Melter Feed Sample Taken at $t = 18.5$ h

Miniature shear vanes provide an alternative method for shear strength determination because a shear vane is designed to be lowered into a sample without causing significant disturbance. The following sections describe the use of miniature shear vanes in conjunction with either Haake or Brookfield viscometers, in order to accurately measure τ_s , and the preparation of sludge samples for τ_s determination.

4.7.1 Sample Preparation

First, determine the volume of each sludge sample that will be required. Up to five replicate sludge samples should be examined to obtain a statistically meaningful body of data. Next, select sample vessels with inner diameters ($2R_c$) at least three times vane diameter (D_v), and with depths at least three

times vane height (H_v). For a given sample-volume/sample-vessel combination, select (or fabricate) a shear vane that will meet these geometric requirements. A Brookfield or Haake viscometer can be used to obtain a broad range of t_s data (see Table 4.5).

Thoroughly stir the sludge and pour it into sample containers, taking care to avoid forming bubbles or air pockets. Once in sample containers, the sludge should be stirred thoroughly to assure homogeneity.

To ensure that sufficient time has been allowed for a sludge to gel to full strength, it is best to measure τ_s as a function of gel time and report the value of τ_s associated with pseudo steady-state (>95% full strength) behavior. Where such tests cannot be afforded, select a gel time, allow all sludge samples to set for the same amount of time, ± 1 h, and report the gel time along with the τ_s data. There is no universal policy or rule of thumb regarding minimum gel time, but a minimum of 48 h is recommended between loading and testing the sample. In the interim, sample containers should be carefully sealed with PARAFILM® or in a plastic bag or other airtight enclosure to prevent evaporation, which can cause a significant increase in shear strength.

TABLE 4.5. Viscometer/Shear Vane Selection for Shear Strength Measurements

Torque Sensor System	Shear Vane Diameter (cm)	Maximum Measurable Torque (dyne-cm)	Maximum Measurable Shear Strength (dyne/cm ²)
Brookfield LVDT	0.975	673.7	350
	2.220	673.7	30
Brookfield RVDT	0.975	7187	3700
	2.220	7187	320
Haake RV-100/M150	0.975	147,000	75,730
	2.220	147,000	6,420
Haake RV-100/M500	0.975	490,000	252,420
	2.220	490,000	21,380

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4.7.2 Test Method for a Miniature Shear Vane

Once the shear vane is installed on the viscometer, obtain a medium sized laboratory apparatus support jack. Put a sludge sample on the jack; center the jack and sample directly under the shear vane. Zero the viscometer and recorder. Do not readjust them at any point during the test.

For best results, carefully raise the lab jack until the shear vane shaft is, immersed to a depth, L , equivalent to the vane height, H_v . The blades will be fully immersed. It is best to pre-mark the shaft at $L = H_v$ and then submerge the shaft to the mark; otherwise, it will be difficult to judge immersion depth.

Determine the speed, N , at which the shear vane should be rotated by selecting N from Table 4.6 relevant to the shear vane/viscometer combination used. As discussed later in Section 5.1.1, measured values of shear strength depend on shear vane rpm. With drive motor off, set the viscometer to a rotational speed selected from Table 4.6. When the viscometer drive motor is turned on, the shear vane will initially remain stationary as the internal viscometer torque spring gradually deflects, causing a steadily increasing torque output. As the torque increases, the shear vane should slowly, sometimes erratically, begin to turn. In the ensuing few seconds, the torque

TABLE 4.6. Viscometer RPM for Shear Strength Determination

Viscometer	Diameter (cm)	Suggested Test rpm ^(a)
Brookfield LVOT	0.975	0.3
	2.220	0.3
Brookfield RVDT	0.975	0.5
	2.220	--
Haake RV-100/M150	0.975	0.3
	2.220	0.2
Haake RV-100/M500	0.975	0.3
	2.220	0.2

(a) Based on a vane tip speed of 0.015 to 0.030 cm/s.

output should level off and begin to drop. Record the peak torque output reading as $R_t(\text{max})$. If a Brookfield viscometer is used, R_t will be between 0 and 100. If a Haake is used, record the peak value of S_T (between 0 and 1.0) and the output scale factor, $\% \tau$ (between 1 and 100). Multiply S_T by $\% \tau$ and record their product as $R_t(\text{max})$, which should be between 0 and 100. Figures 4.17 and 4.18 are typical Brookfield and Haake viscometer output plots obtained for τ_s determinations with shear vanes.

After peaking, the torque output should fall off to a lower, pseudo-steady-state value. The strength (dyne/cm^2) associated with this metastable output is known as the remolded strength; it may be worth recording but is optional. The phenomenon is fully discussed by Abdelhamid (1982).

FIGURE 4.17. Plot of Viscometer Output Versus Time at a Constant Shear Vane Rotation (0.3 rpm) for a Sample of Slurry

FIGURE 4.18. Plot of Viscometer Output Versus Time at a Constant Shear Vane Rotation (0.3 rpm) for a Sample of Radioactive NCRW Sludge

To analyze the $R_t(\text{max})$ test data in terms of τ_s , refer to the procedure in Appendix B. Use the torque correction for shaft friction if the apparent viscosity of the sludge exceeds approximately 10,000 cPs at very low shear rates ($\dot{S} < 0.1 \text{ s}^{-1}$). A method for calculating shaft friction is presented later in Section 5.2.3.

If a stratified sludge (containing multiple layers) is tested, the shear vane should be lowered to a depth that centers it in each layer during each test. Start with the uppermost layer and work vertically downward at the same horizontal (radial) location. For best results, the shear vane blade height should be smaller than the thickness of the smallest layer to be tested. Be

sure to record the length of shaft immersion (L in cm) associated with each test depth. If the dimensions of the strata are unknown, lower the shear vane in depth increments of $2 H_v$. Repeat the measurements at a second horizontal (radial) location, this time starting at a depth of $L = 1.5 H_v$ and descending in $2 H_v$ increments. If possible, a third set of measurements should also be performed, starting at $L = 2 H_v$. The combined data from all three tests will allow sludge layer characterization at depth increments of $0.5 H_v$. Figure 4.19 illustrates the location of a shear vane during the first two tests.

FIGURE 4.19. Location of Shear Vane During Determinations of Sludge Shear Strength

From one depth to the next, any residual torque (with viscometer drive motor off) should be dissipated by perturbing the sample up and down about 1 mm (use the lab jack). Take care to avoid sideways motion. It is usually possible to remove 50% to 80% of residual torque this way, but some will probably remain. Under no circumstances is it appropriate to readjust a viscometer or chart/pen recorder zero setting to achieve zero output in the middle of a test. Such adjustments can cause larger errors than those associated with undissipated residual torque.

4.7.3 Effect of Pore Pressure on Laboratory Shear Strength Measurements

When shear vane tests are conducted in soils, a correction usually must be made for pore pressure (Mesri and Godlewski 1977; British National Society 1961), also referred to as "capillary pressure" (van Olphen 1977). Capillary pressure occurs when water present in the soil is forced to flow through interparticle interstices (pores), creating a pressure drop because of surface tension at air/water interfaces. The net results can be erroneously high estimates of shear strength, depending on the soil's water content, void fraction and pore dimensions. In most in situ tank tests, capillary pressures will not occur because there are no air/water interfaces in the submerged sludge. However, laboratory tests may represent different conditions. It is therefore recommended that a liquid cover be placed over laboratory samples during miniature shear vane tests.

A word of caution: the sample cover liquid should have nearly the same chemistry and/or electrolytic strength as the real cover liquid (tank supernatant), to avoid peptization of the sample. Peptization, which can result in loss of cohesiveness and consequent reduction in shear strength of a sample, is discussed frequently in the literature of colloidal science, for example by van Olphen (1977).

From one depth to the next, any residual torque (with viscometer drive
stop off) should be registered by perching the sample up and down about 1 cm
on the lab jack. Take care to avoid sideways motion. It is usually
possible to remove 50% to 10% of residual torque this way, but some will
probably remain. Under no circumstances is it appropriate to transfer a
viscometer or chart to another room setting or remove into the
vicinity of a test. Such adjustments can cause larger errors than those
associated with unadjusted residual torque.

4.2 Effect of pore pressure on laboratory shear strength measurements

When shear zone tests are conducted in soils, a correction usually must be
made for pore pressure (Mair and Dobrowsky 1977, British National Society
1981), also referred to as "cellular pressure" (van Olphen 1977, Capillary
pressure occurs when water present in the soil is forced to flow through later-
filled interfaces (pores), causing a pressure drop because of surface ten-
sion at dispersed interfaces. The net result can be extremely high esti-
mates of shear strength, depending on the soil's water content, void fraction,
and pore dimensions. In most in situ tests, capillary pressures will not
occur because there are no oil-water interfaces in the saturated medium, how-
ever, laboratory tests may represent different conditions. It is therefore
recommended that a 10% cover be placed over laboratory samples during shear
zone shear tests.

A word of caution: the sample cover should have nearly the same
electrical and/or electrolytic strength as the test cover (plastic tank
electrode), to avoid penetration of the sample. Penetration, which can
result in loss of cohesion and consequent reduction in shear strength of a
sample, is discussed frequently in the literature on colloidal science, for
example by van Olphen (1977).

5.0 DEVELOPMENT OF A SHEAR VANE METHOD FOR IN-TANK MEASUREMENT OF SLUDGE FLOW PARAMETERS

A shear vane used in conjunction with torque instrumentation provides a convenient and reliable means of measuring the shear strength of cohesive materials (Terzaghi and Peck 1948; Krynnine 1947; Pyles 1984; ASTM 1978). Shear vanes have been used by soil scientists (ASTM 1978) because they offer the advantage of allowing soil shear strengths to be measured in the field. This obviates the need to remove core samples and subject them to laboratory testing. This removal step is undesirable because physical disturbances caused by the sampling operation tend to stress and weaken the samples. Consequently, shear strengths measured in the laboratory are often lower than the actual, in situ shear strength of the intact soil. Since shear vanes are designed to be positioned without causing disturbance along the cylindrical shearing surface (see Figure 4.6), they provide in situ soil strength data with engineering significance.

Shear vanes offer similar advantages for in-tank testing of high-level liquid waste (HLLW) sludges. The first use of shear vanes for measuring the shear strength of an HLLW tank sludge was described by Abdelhamid (1982). A shear vane of 3-in. dia, mounted on a shaft 40 ft long was lowered to different depths within the tank sludge and rotated at 0.017 rpm (one revolution per hour) as stated in the above-mentioned ASTM procedure. The amount of torque required to initiate vane rotation (start-up torque, $T_{\max}$) was used to calculate sludge shear strength via Cadling's Equation (ASTM 1963):

$$T_{\max} = \pi \left[H_v \frac{D_v^2}{2} + \frac{D_v^3}{6} \right] \tau_s \quad (5.1)$$

Following this initial extension of the shear vane method to the measurement of the shear strength of tank sludges, PNL embarked on a WVNS-sponsored program to further develop the use of shear vanes for in situ sludge testing.

The next three sections summarize the developments made during this program. Section 5.1 discusses scale-up of shear strength data. Section 5.2 focuses on the development of a method for measuring apparent viscosity using shear vanes. Section 5.3 describes attempts to correlate shear vane rpm with shear rate.

5.1 SCALE-UP OF SHEAR VANE SHEAR STRENGTH DATA

Shear vanes can be used to evaluate the shear strength, τ_s , of a sludge by submerging the vane portion in the sludge, rotating it at a constant speed, and measuring the amount of torque required to initiate vane rotation. Equation (5.1) is used to relate the measured start-up torque to sludge shear strength.

The procedure (§4.7) for using the PNL miniature shear vanes to measure the shear strength of laboratory sludge samples differs from the ASTM soil test procedure in both the size of shear vane used and the rotational speed during testing. The ASTM procedure D2573-72/78 (ASTM 1978) specifies the use of shear vanes having diameters between 3.8 and 9.2 cm, whereas the two miniature shear vanes used at PNL (tank sludge testing) have diameters of 0.975 cm and 2.220 cm. The ASTM procedure also specifies an upper limit in the rate of vane rotation during testing of 0.017 rpm (one revolution per hour). In contrast, most viscometers have a minimum rotational speed of 0.3 to 0.5 rpm.

During initial testing at PNL, it was determined that when rotated at 0.05 rpm, several measurements of sludge start-up torque using the different-sized miniature shear vanes all resulted in the same values of shear strength as calculated by Equation (5.1.) Measured values of shear strength are apparently independent of shear vane diameter within the range of 0.975 cm $< D_v < 2.220$ cm. The following section describes tests that were conducted to determine whether measured values of sludge shear strength are dependent on the rotational speed of the shear vanes. From these tests, a vane tip speed criterion was developed to allow in-tank shear vane data to be compared directly with laboratory-scale, miniature shear vane data.

Effect of Vane RPM on Shear Strength Measurement. To investigate the effect of vane rotational speed on shear strength measurements, the two miniature shear vanes were rotated at various speeds through iron-based and silica-based tank sludge simulants. The range of speed investigated was 0.017 rpm to 0.5 rpm, corresponding to the maximum speed recommended by ASTM (1978) for soil shear strength testing and the minimum speed available on a Brookfield RVDT viscometer. A Haake viscometer, capable of a minimum speed of 0.05 rpm, was used in conjunction with the two shear vanes to perform the shear strength measurements. The results for the 0.975-cm shear vane are shown in Figure 5.1. Each plotted point represents the average of one to three data points, exhibiting minimal scatter.

As can be seen from the plotted test data, shear strength appears to be independent of shear vane rotational speed in the range of 0.3 rpm to 0.5 rpm. Below this range, shear strength appears to vary as a function of vane rpm as well as test material (as evidenced by the two differently shaped curves). An initial conclusion might be that the in-tank and in-cell shear vanes should be rotated at the same speed to ensure that the two procedures generate directly comparable data. However, an assumption implicit in shear vane testing is that the material behaves as an elastic solid being sheared along the outer edges of the vane. The rate of elastic strain is related to vane tip speed, suggesting that vane tip speed may be a more appropriate test parameter to hold constant in the in-tank and in-cell tests. This rationale suggests that an in-tank shear vane of 8.9 cm (3.5 in.) dia should be rotated at 0.032 rpm (1.9 revolutions per hour) during shear strength testing to achieve the same tip speed (0.015 cm/s) as that of a 0.975-cm viscometer shear vane rotated at 0.3 rpm. Furthermore, rotation at this higher speed should produce data that are less sensitive to small variations in the rate of shear vane rotation. On the basis of available test data, therefore, it is recommended that the in-tank shear vane be rotated at 0.032 rpm. However, this recommendation should be verified during additional laboratory- and field-scale tests.

FIGURE 5.1. Effect of Shear Vane RPM on Sludge Shear Strength Measurement

5.2 MEASUREMENT OF APPARENT VISCOSITY USING SHEAR VANES

The main uncertainty associated with use of a shear vane to obtain viscosity data is whether the measured variable, shear vane torque, will vary as a predictable function of shear vane rate of revolution. To investigate the torque versus rpm response of a shear vane over a wide set of operating conditions encompassing both laboratory-scale and full-scale (in-tank) testing, the effects of following variables were studied:

- shear vane diameter, D_v
- test fluid viscosity, η
- test vessel radius, R_c .

The following sections describe the equipment, procedure, calculations, and results of this experiment.

5.2.1 Test Equipment

Three shear vanes were tested; their diameters were 0.975 cm (shear vane No. 1), 2.220 cm (shear vane No. 2), and 7.557 cm (shear vane No. 3). All three vanes heights (H_v) equaled the overall diameters (D_v). All fluids used, except glycerol and corn syrup, were Brookfield viscosity standards, having the stated viscosity $\pm 1\%$ at 25°C. The viscosities of corn syrup and glycerol were determined with a Haake rotovisco viscometer, Model RV-100, fitted with sensor system M-150. The densities of the test fluids were measured as 1.26 g/cm³ for glycerol, 1.41 g/cm³ for corn syrup, and 0.97 for all of the Brookfield viscosity standards. The test fluids were poured into containers of various radii for shear vane testing. Table 5.1 lists the specific configurations tested.

TABLE 5.1. Shear Vane/Tank/Test Fluid Configurations Investigated

Tank Radius	Shear Vanes			Test Fluids CP	Shear Vanes		
	No. 1	No. 2	No. 3		No. 1	No. 2	No. 3
1.68	X	X		5.4		X	
2.95	X	X		50.5		X	
4.20	X	X		475	X	X	
14.0			X	1,037 ^(a)			X
				1,237	X	X	
				12,000	X	X	
				14,650 ^(b)	X	X	X
				29,700			

(a) Glycerol at test conditions (15°C).

(b) Corn syrup at test conditions (12°C).

5.2.2 Experimental Procedure

In a procedure common to all test configurations, a measured volume of test fluid was carefully poured into a test container to avoid bubbles; the test fluid temperature was monitored and in most cases remained constant, $\pm 1^\circ\text{C}$; a test shear vane was installed and rotated at several rpm; and torque readings were recorded at each rpm setting.

The torque required to rotate shear vanes 1 and 2 was measured with two Brookfield viscometers, an LVDT model and an RVDT model. The viscometer output reading is related to shear vane torque in dyne-cm by Equation 4.4.

Shear vane 3 was tested in conjunction with a 0.25-hp agitator motor mounted on a freely swiveling base that was prevented from rotating by a metal rod linked to a strain gauge load cell device for torque instrumentation. The load cell readings in grams were converted to values of torque in dyne-cm via the following expression (Haliday and Resnik 1981):^(a)

$$T_o = (a) (R_t - R_o)(r)(\sin\theta) \quad (5.2)$$

where: T_o = overall shear vane torque, dyne-cm

R_t = load cell reading, g

R_o = constant subtracted from load cell reading to account for agitator motor torque (constant), equal to 13.25 g for glycerol tests and 16.5 g for corn syrup tests

r = length of metal rod linking freely rotating agitator motor base to fixed-mounted load cell, 10 in.

θ = angle between metal linkage rod and line drawn radially from center of agitator shaft, 90°

a = conversion factor equal to $2.49 \times 10^3 \text{ cm}^2/\text{s}^2\text{in.}$

$$\left(\frac{980 \text{ cm}}{\text{s}^2} \times \frac{2.54 \text{ cm}}{\text{in.}} \right)$$

(a) P. 179, Equation 12.2a, where $F = (a)(R_\tau - R_o)$

This test apparatus was used to vary the rotational speed of shear vane No. 3 continuously from 40 rpm to 300 rpm. Values of rpm were recorded by a digital tachometer, accurate to the nearest 0.5 rpm.

5.2.3 Shaft Friction Correction

The overall torque data, T_0 , for each test was corrected to account for shaft torque, T_s , caused by frictional losses to the test fluid. The following expression for a cylinder rotating within a cylindrical container was used to calculate the shaft torque (Brookfield 1984):^(a)

$$T_s = \eta \cdot R_b^2 \cdot L \cdot \frac{8\pi^2}{60} \cdot \frac{NR_c^2}{R_c^2 - R_b^2} \quad (5.3)$$

where T_s = torque caused by shaft friction, dyne-cm

η = fluid viscosity, Poise (1 Poise = 100 cP)

R_b = shaft radius, cm

L = shaft length, cm

N = rate of shaft rotation, rpm

R_c = radius of mixing vessel, cm.

This expression does not account for shaft end effects, which can be assumed to be negligible.

The calculated values of shaft torque were subtracted from the overall torque measurements to yield values of vane torque, T_v , or

$$T_v = T_0 - T_s \quad (5.4)$$

Values of T_v , not T_0 , are used in all subsequent calculations.

(a) Page 18: Combine Equations 5.4, 5.5, and 5.6 and solve for M where M is equivalent to T_s .

5.2.4 Correlation of Test Data Via Reynolds Number/Power Number Relationship

Based on common industrial practices (Bates, Fondy and Fenic 1966; Calderbank and Moo-Young 1961; Metzner and Otto 1957), the test data values of T_v and N were plotted in terms of the dimensionless groups N_{RE} and N_p :

$$N_{RE} = \frac{\rho D^2 N}{\eta} \quad (5.5)$$

$$N_p = \frac{P}{\rho D^5 N^3} \quad (5.6)$$

where N_{RE} = Reynolds number, ratio of inertial forces to viscous forces, dimensionless

N_p = Power number, ratio of pressure differences producing flow to inertial forces, dimensionless

ρ = test fluid density, g/cm³

D = shear vane diameter, cm

N = shear vane rate of rotation, rev/s
(not radians/s or degrees/s)

η = test fluid viscosity, Poise (1 Poise = 100 cP)

P = shear vane power applied to test fluid, dyne-cm/s.

Shear vane power, P , is calculated as (Halliday and Resnick 1981).

$$P = T_v \cdot \omega \quad (5.7)$$

where T_v = vane torque, dyne-cm

ω = vane angular velocity, radians/s

Using the relation

$$\omega = \frac{2\pi \cdot N}{60} \quad (5.8)$$

Equation 5.7 becomes

$$P = T_v \cdot \frac{2\pi}{60} \cdot N, \text{ dyne-cm/s} \quad (5.9)$$

An example of plots of N_p versus N_{RE} for various turbine agitator geometries is provided in Figure 5.2, which is abstracted from Bates, Fondy and Fenic (1966). Note that the plots are approximately linear in the laminar flow regime, defined by Bates, Fondy and Fenic as $N_{RE} < 10$, and by Oldshue (1983) as $N_{RE} < 15$.

Figure 5.3 is a plot of the PNL shear vane test data in terms of N_p versus N_{RE} . All of the test data are plotted. As can be seen, there is remarkably little scatter in the data, which indicates a linear relationship between N_p and N_{RE} independent of test fluid viscosity from 5.4 to 29,700 cP, independent of shear vane diameter from 0.975 cm to full scale, and independent of

FIGURE 5.2. Plots of N_p and N_{RE} for Some Turbine Agitator Geometries

FIGURE 5.3. Plot of Power Number (N_p) Versus Reynolds Number (N_{RE}) from the Shear Vane Test Data

container radius from 1.68 cm to 14.0 cm. From the test data, the relationship between N_p and N_{RE} for a shear vane is calculated as

$$\log N_p = -(0.977)\log N_{RE} + (2.190) \quad (5.10)$$

which is valid from Reynolds numbers ranging from 10^{-5} (lowest tested) to about 10. The viscosity of a fluid can be measured with a shear vane by calculating a power number based on torque measurements, identifying the corresponding Reynolds number (from Figure 5.3), and back-calculating the viscosity, η .

5.2.5 Discussion of Experimental Results

The data presented in Figure 5.3 indicate that the torque-versus-rpm response of a shear vane such as that planned for use in both scale-model and full-scale, in-tank tests is a predictable function of two dimensionless groups, the Reynolds number, N_{RE} , and the power number, N_p . For a shear vane operated in the laminar regime ($N_{RE} < 10$), the relationship between $\log N_{RE}$ and $\log N_p$ is linear as described by Equation 5.10.

Plots of $\log N_p$ versus $\log N_{RE}$ for all types of turbine agitators have been found (Bates, Fondy and Fenic 1966) to have a slope equal to -1, which compares favorably to PNL's empirically determined slope of -0.977. This is as expected: a shear vane can be categorized as a turbine agitator by its geometry.

The Froude number,

$$N_{FR} = \frac{DN^2}{g}, \quad (5.11)$$

representing the ratio of inertial to gravitational forces, can also be important in describing mixing phenomenon and can be factored in by plotting $\log N_p/N_{FR}$ versus N_{RE} . However, the Froude number is considered insignificant in mixing power correlations for baffled tanks, and also for unbaffled tanks except when an appreciable vortex is formed (Bates, Fondy and Fenic 1966). In PNL tests, vortex formation was not appreciable; therefore, N_{FR} was not factored into the data correlation.

The utility of the N_{RE} - N_p correlation developed for the shear vane is that with this correlation, shear vane torque measurements can be used to estimate tank sludge viscosity, both in the scale model and in the full-scale tank.

5.3 RELATIONSHIP BETWEEN VANE RPM AND SHEAR RATE

As described in Section 5.2.4, shear vanes were found to exhibit N_{RE} - N_p behavior representative of impeller mixers operated at Reynolds numbers in the laminar range. The most generally accepted empirical correlation between rate of revolution and shear rate for impellers has the form $\dot{S} = KN$, where $\dot{S}$ is

shear rate in s^{-1} and N is rotational speed in revolutions per second. The proportionality constant, K , is usually assigned a numerical value of 10 (Bates, Fondy and Fenic 1966), although a value of 13 is recommended by some authors (Oldshue 1983).

To investigate the relationship between N and $\dot{S}$, shear vanes were used to measure the apparent viscosity of two non-Newtonian (pseudoplastic) liquids at several rpms. The fluids were also tested with a Haake viscometer to produce rheograms. The rheogram viscosities were compared with those calculated by using the N_{RE}/N_p correlation. Then, the shear rates corresponding to those viscosities were determined from the rheogram. This procedure was based on the general method developed by Metzner and Otto (1957). The results are presented in Table 5.2. The data were all taken at a shear vane rotational speed of 100 rpm.

If the values of shear rate are averaged as they appear in the table, K is calculated to be 11.1. Note that this value falls within the range of values recommended in the literature (10 to 13).

TABLE 5.2. Shear Rate Data (at 100 rpm) as a Function of Shear Vane Diameter and Sludge Type

Sample Material	Shear Vane Diameter (cm)	Shear Rate (s^{-1})
Iron-based sludge simulant #1	2.220	19.7
Iron-based sludge simulant #1	2.220	20.8
Iron-based sludge simulant #1	0.975	15.6
Silica-based sludge simulant #1	0.975	32.4
Silica-based sludge simulant #2	0.975	17.8
Silica-based sludge simulant #4	0.975	5.5

On the basis of the data in Table 5.2, it is recommended that the following equation be used to estimate shear rates:

$$\dot{S} = (11.1) N \quad (5.12)$$

where $\dot{S}$ = shear rate, inverse seconds

N = shear vane rotational speed, revolutions per second.

However, because of the large amount of scatter in the test data, additional baseline data are required to verify the shear rate equation given by Equation (5.12).

where $\dot{\gamma}$ = shear rate, inverse seconds
 $\dot{\gamma} = 2\pi \text{ (rotational speed, revolutions per second)}$
However, because of the large amount of scatter in the test data, additional
baseline data are required to verify the shear rate equation given by
Equation (2.12).

6.0 CONCEPTUAL DESIGN OF FULL-SCALE IN-SITU SHEAR VANE DEVICE

An objective of the current DST Sampling and Analysis program is to design an apparatus for performing in-situ tank sludge rheology characterization. Chapter 6 presents a conceptual design for a modified shear vane device and describes how it can be used to accomplish in-tank rheological characterization of DST sludge.

Figure 6.1 shows the conceptual design of a shear vane device recommended for in-tank use. An engineering sketch is provided in Appendix A. The device is designed to be installed, as shown, through an existing tank riser having inner diameter of 10 cm (4 in.) or greater. To allow operation at up to 300 rpm, an outer shaft support structure was designed. This structure, consisting of a fixed 3-in. schedule 80 pipe, imparts sufficient rigidity to prevent the inner, rotating shear vane shaft from whipping at high rates of rotation. Spherical bearings and roller bearing bushings (not shown) permit the inner shaft to rotate within the fixed support structure. Spherical bearings were used rather than thrust bearings (employing roller bearings) because the former can better tolerate small shaft deflections, providing better stability at high speeds.

To simplify installation, removal, and decontamination, the shear vane shaft was designed to be disassembled in 3-m sections. The couplers used to attach the sections are designed to be easy to engage and disengage for minimal personal exposure or even adaptation to entirely remote handling. These couplers are off-the-shelf items that are slightly modified to clear the inner diameter of the tank riser. The polar moment of inertia associated with rotation at 300 rpm is calculated to be insufficient to cause the couplers to disengage during testing.

The shear vane at the bottom of the rotating shaft has a vane diameter and height equal to 8.9 cm (3.5 in.) and is of the same general shape as those used in testing at PNL. The recommended material of construction is carbon steel, the same material used to fabricate the tank.

FIGURE 6.1. Conceptual Design of a Shear Vane Installed in a Double-Shell Tank

Instrumentation requirements consist of a tachometer to measure shear vane rpm (0-300) and a load cell to measure shear vane torque (a measuring capability of 0 to 20 ft-lb_f should be adequate). The load cell is linked to the shear vane drive motor, which must be mounted on a freely swiveling base. If the load cell is mounted on a fixed platform and linked to the motor, the torque applied to the motor can be measured. This measured torque, T_o , is the sum of three torques:

- T_v , torque applied directly to the rotating vanes
- T_s , torque applied to the exposed rotating shaft portion of the shear vane
- T_c , torque associated with frictional losses within the shaft structure.

The torque applied to the vanes, T_v , is calculated as

$$T_v = T_o - (T_s + T_c) \quad (6.1)$$

Values of T_s can be calculated via Equation (5.3). The correction torque, T_c , must be empirically determined prior to testing by rotating the shear vane in air and calculating a correction torque from the in-air readings. This calculated value, usually approximately independent of rotational speed, is then subtracted, along with calculated values of T_s (rpm dependent), from each overall shear vane torque measurement (Equation 6.1).

6.1 CONDUCTING IN-TANK SHEAR VANE MEASUREMENTS

The use of shear vanes to make in-situ rheological measurements of sludge in underground HLLW storage tanks involves procedures similar to those described in Chapter 4 for miniature shear vanes. Characterization of tank sludge rheology should proceed, as closely as is possible or practicable, as follows:

1. The location of the sludge layer/supernatant interface should be accurately measured with respect to a reference point above the tank riser. [An in-tank density probe (Abdelhamid 1982) can be used to locate this interface.]
2. The shear vane segments should be assembled, positioned above the tank riser, and rotated at several rpms in air. Use the in-air torque readings to calculate T_C , which is caused by internal friction in the shear vane shaft and drive motor.
3. Carefully (slowly) lower the shear vane shaft through the riser and into the tank until the bottom of the shear vane shaft is immersed in sludge to a depth of 8.9 cm. (3.5 in.), equivalent to $1 H_V$ (see Figure 4.20).
4. Initiate vane rotation at 0.032 rpm. A plot of torque versus time should be produced, having the general appearance of Figure 3.3. Use the peak value of the torque reading [$R_t(\max)$] to calculate sludge shear strength (τ_s) using option #4 of VANE-2 (Appendix B).
5. Prepare an "up-curve" and a "down-curve" by ramping vane speed from 0.032 rpm to 50 rpm, holding at 50 rpm until a steady-state reading is achieved, and then ramping back down to 0 rpm. Hold at 0 rpm until the torque reading decays to a steady-state value. At each rpm, hold for approximately 1 min before proceeding to the next rpm. Ramping in increments of 2 to 3 rpm is recommended so that 15 to 25 data points are obtained on the up- and down-curves. A maximum speed of 50 rpm is recommended because axial mixing set up by the rotating vane is negligible at this speed. Axial mixing, which becomes appreciable at around 100 rpm, should be avoided during initial rheological measurements.
6. Compare the up- and down-curves to determine whether time-dependent behavior (thixotropy or rheopexy) is exhibited (see Sections 3.2.3 and 4.6).
7. Using Option #1 of VANE-2, analyze the down-curve data in terms of shear stress versus shear rate as discussed in Section 4.3 and in Appendix B.

8. Determine whether a yield stress exists by the final torque reading at 0 rpm at the conclusion of the down-curve test. Using the torque decay method presented in Section 4.4.3, calculate the yield stress based on the final torque decay reading. Option #4 of VANE-2 can also be used to calculate τ_y .
9. Fit the steady-state down-curve data, analyzed in steps 7 and 8, to the yield-pseudoplastic power law equation discussed in Section 4.5 and in Appendix B.
10. Lower the shear vane shaft an additional 18 cm to a shaft depth of $L = 3H_v = 26.7$ cm. Repeat steps 4 through 9 at this depth. (A depth increment equal to $2 H_v$ provides a vertical distance of $1 H_v$ between tests. This is recommended to minimize the effect of disturbances on subsequent tests. Because H_v , in this case, equals 8.9 cm (3.5 in.), a depth increment of 18 cm (7 in.) is recommended between tests.)
11. Repeat step 10 at lower depths in depth increments of 18 cm.
12. Complete the analysis of the data (can be done in 1 or 2 d) to determine whether further tests at the current tank riser location are warranted.
13. Slowly raise the shear vane shaft up through the tank sludge. It is a good idea to pause at various heights, separated by a vertical distance of 18 cm (7 in.), and run high-rpm tests, for instance at 100, 150, 200 and 250 rpm. Do not exceed 300 rpm, or excessive shaft whipping could cause damage. Incorporate the high-rpm shear vane data in the analyses done in steps 7, 8, and 9 for low-rpm data taken at the same or similar sludge depths.
14. Carefully raise the shear vane assembly completely out of the tank. Partial decontamination can be accomplished by rinsing the assembly with water as it raised. If this is an acceptable approach, a jig (involving spray nozzles) may be required to assure that the contaminated rinse water drains into the tank.
15. If possible, lower the shear vane assembly through other risers to obtain sludge data at other locations within the same tank.

16. Disengage the shaft couplers and place the disassembled shaft portions in a 10-ft cask. Transport the shaft sections in the cask to a decontamination facility, or to a suitable burial site for final disposal.

If these steps are followed, it should be possible to conduct all tests necessary to characterize the rheology of a tank sludge within a 1-week period. It is important, of course, that the entire operation be thoroughly planned and test personnel have the opportunity to acquire experience through cold testing with appropriate mock-ups of a tank, shear vane, shear vane handling equipment, and so on. The following example shows how measured values of shear vane torque and rotational speed are analyzed to determine the apparent viscosity of a tank sludge. The example uses one data point for torque versus rpm.

6.2 EXAMPLE CALCULATION: ESTIMATION OF SLUDGE VISCOSITY FROM IN-TANK SHEAR VANE DATA

Assume that a stable (steady-state) shear vane torque of approximately 1.96×10^7 dyne-cm (17.3 in.-lb_f) was measured during the test. This value of T_0 will be used in this example. Assume further that the torque associated with shaft motor-bearing friction was measured, by rotating the shear vane in air, as 9.0×10^5 dyne-cm (0.8 in.-lb_f). Finally, assume that the shear vane has diameter and vane height equal to 8.89 cm (3.5 in.) and that the shear vane rate of rotation was held constant at approximately 50 rpm throughout the test. Figure 6.2 illustrates the placement of such a shear vane in the sludge layer at the bottom of a tank.

First, the component of overall shear vane torque attributable to the portion of the shear vane shaft contacting the tank supernatant is calculated as $T_s = 400$ dyne-cm (3.5×10^{-4} in.-lb_f) via Equation (5.3):

$$T_s = \eta \cdot R_b^2 \cdot L \cdot \frac{8\pi^2}{60} \cdot \frac{NR_c^2}{R_c^2 - R_b^2} \quad (6.2)$$

FIGURE 6.2. In-Tank Test Configuration Assumed in Example Calculation

where η = assumed supernatant viscosity, 2.6 cP = 0.026 Poise

R_b = shear vane shaft radius, 1/4-in. = 0.635 cm

L = length of shaft immersed in supernatant, 19 ft = 580 cm

N = shear vane rate of rotation, 50 rpm

R_c = tank radius, 35 ft = 1069 cm.

In this case, T_s is negligible and $T_v = T_o - T_c = 16.5 \text{ in.-lb}_f$. Next, the power number, N_p , is calculated. To convert the units of T_v from in.-lb_f to dyne-cm,

$$T_v = 16.5 \text{ in.-lb}_f \times \frac{32.17 \text{ lb}_m\text{-ft}}{\text{lb}_f\text{-s}^2} \times \frac{2.54 \text{ cm}}{\text{in.}} \times \frac{30.5 \text{ cm}}{\text{ft}} \quad (6.3)$$

$$\times \frac{453.6 \text{ g}}{\text{lb}_m} = 1.86 \times 10^7 \text{ dyne-cm}$$

Power, P , is calculated via Equation (5.9) as

$$\begin{aligned} P &= T_v \times \frac{2\pi N}{60} \\ &= (1.86 \times 10^7) \left(\frac{2\pi}{60}\right) (50) \\ &= 9.7 \times 10^7 \text{ dyne-cm/s } (1.30 \times 10^{-2} \text{ H}_p) \end{aligned}$$

The power number, N_p , is then calculated via Equation (5.6) as

$$N_p = \frac{P}{D^5 N^3 \rho}$$

where D = shear vane diameter, 8.89 cm (3.5 in.)

ρ = assumed hard layer sludge density, 2.49 g/cm³

and

$$N_p = \frac{(9.7 \times 10^7) \text{ dyne-cm/s}}{(8.89 \text{ cm})^5 (50 \text{ rpm})^3 \left(\frac{1 \text{ min.}}{60 \text{ sec}}\right)^3 (2.49 \text{ g/cm}^3)} = 1.22 \times 10^3$$

Using Equation (5.10), developed empirically as described in Section 5.2.4, estimate the Reynolds number associated with this shear vane test case by

$$\log [1.217 \times 10^3] = -0.977 \log [N_{RE}] + 2.190$$

$N_{RE} = 1.214 \times 10^{-1}$, which is well into the laminar regime. The definition of the Reynolds number is then used to estimate the sludge viscosity at 50 rpm:

$$N_{RE} = \frac{\rho D^2 N}{\eta}$$

or

$$1.21 \times 10^{-1} = \frac{(2.49 \text{ g/cm}^3)(8.89 \text{ cm})^2(50 \text{ rpm})(\frac{1 \text{ min}}{60 \text{ sec}})}{\eta \text{ (Poise)}}$$

and $\eta = 1.35 \times 10^3$ Poise or roughly 135,000 cP.

By this initial calculation, the apparent viscosity of the sludge layer is large enough that the portion of the shear vane shaft submerged in the sludge layer may experience a large friction loss which should be considered. The average depth of the shear vane during the test is such that about 41.9 cm (16.5 in.) of the shaft was submerged in sludge. Assuming the sludge layer to be homogeneous--not a generally valid assumption but made to simplify this example calculation--a new estimate of T_s is made, this time using $L = 41.9$ cm and $\eta = 135,000$ cP. Now T_s is calculated as 1.50×10^6 dyne-cm, resulting in a corrected T_v of 1.71×10^7 dyne-cm. Based on this value of T_v , a new, overall sludge viscosity (average viscosity of sludge layer) is calculated as 124,000 cP. Iterative calculations are then performed in which the average sludge viscosity is guessed, and new values of T_s and T_v are calculated. New values of P , N_p , and N_{RE} are also calculated, as is a new estimate of the average sludge viscosity. The iterations are performed until the estimated and calculated values of viscosity converge. In this case, after three iterations the values of sludge viscosity converge at a value of 126,000 cP.

Further, more-detailed examples are provided in Appendix B along with a calculator program for quickly analyzing the raw torque and rotational speed shear vane data.

7.0 NOMENCLATURE

D_v	= diameter of shear vane, cm
E	= Young's modulus of elasticity, dyne/cm ²
E_{pl}	= plastic resistance, dyne/cm ²
ϵ	= axial strain, dimensionless
ϵ_s	= shear strain, dimensionless
F	= spring factor associated with viscometer, dyne-cm
G	= shear modulus, dyne/cm ²
H_v	= height of shear vane blades, cm
k	= power law consistency index, dyne/cm ² s ⁿ
L	= length of shear vane shaft immersed in test fluid, cm
n	= power law flow behavior index, dimensionless
n_{tg}	= spindle speed signal transmitted by Haake tachogenerator, dimensionless
n_r	= actual Haake spindle speed
N	= rate of shear vane rotation, rpm or rps as specified
N_p	= power number, ratio of pressure differences producing flow to inertial forces, dimensionless
N_{RE}	= Reynolds number, ratio of inertial forces to viscous forces, dimensionless
η_{app}	= apparent viscosity, centipoise
η_0	= maximum plastic viscosity, centipoise
η_s	= viscosity of fluid in contact with shear vane shaft, centipoise
η_v	= viscosity of fluid in contact with vanes, centipoise
σ	= applied stress, dyne/cm ²
σ_s	= yield strength, dyne/cm ²
P	= shear vane power applied to test fluid, dyne-cm/s
ρ	= density of test fluid, g/cm ³
R_c	= radius of mixing vessel/sample container, cm
R_o	= torque reading offset (correction value, dimensionless)
R_s	= radius of shear vane shaft, cm
R_t	= viscometer/apparatus torque reading, dimensionless
T_c	= torque caused by friction in apparatus, dyne-cm

$\dot{S}$	= shear rate, s^{-1}
T_O	= overall shear vane torque, dyne-cm
T_S	= torque caused by shaft friction, dyne-cm
T_V	= net torque applied by vane, dyne-cm
τ	= shear stress, dyne/cm^2
τ_s	= shear strength, dyne/cm^2
τ_y	= yield stress, dyne/cm^2

8.0 REFERENCES

- Abdelhamid, M. S. 1982. "Test Results and Evaluation Tank 8D-2 Sludge Characterization Study West Valley Demonstration Project." Job No. 10805-108-23, West Valley Nuclear Services Company.
- American Society for Testing and Materials (ASTM). 1963. Laboratory Shear Testing of Soils. ASTM STP No. 316, pp. 377-385, Philadelphia, Pennsylvania.
- American Society for Testing and Materials (ASTM). 1978. Standard Test Method for Field Vane Shear Test in Cohesive Soil. ASTM D2573-72/78, Philadelphia, Pennsylvania.
- Athanasopoulos, G. A., and F. E. Richart, Jr. 1983. "Effect of Creep on Shear Modulus of Clays." J. Geotech. Eng. 109(10):1217-1232.
- Bates, R. L., P. L. Fondy and J. G. Fenic. 1966. "Impeller Characteristics and Power," pp. 111-175, Mixing Theory and Practice, Academic Press Publications Co., New York.
- Blair, G. W. S. 1949. A Survey of General and Applied Rheology. Sir Isaac Pitman and Sons, Ltd., London.
- British National Society of the International Society of Soil Mechanics and Foundation Engineering. 1961. Conference on Pore Pressure and Suction in Soils at the Institution of Civil Engineers, held on March 30-31, 1960. Butterworths, London.
- Brookfield Engineering Laboratories, Inc. 1982. UL Adapter Assembly and Operating Instructions. Brookfield Engineering Laboratories, Inc., Stoughton, Massachusetts.
- Brookfield Engineering Laboratories, Inc. 1984. More Solutions to Sticky Problems - A Guide to Getting More From Your Brookfield Viscometer. Brookfield Engineering Laboratories, Inc., Stoughton, Massachusetts, pp. 17-25.
- Calderbank, P. H. and M. B. Moo-Young. 1961. Transactions of the Institution of Chemical Engineers. (London), 39(22).
- Denn, M. M. 1980. Process Fluid Mechanics. Prentice-Hall, Inc., Englewood Cliffs, New Jersey.
- Evans, D. J., H. J. M. Hanley, and S. Hess. 1984. "Non-Newtonian Phenomena in Simple Fluids." Phys. Today 37(1):26-33.
- Ford, E. W. and J. F. Steffe. 1986. "Quantifying Thixotropy in Starch-Thickened, Strained Apricots Using Mixer Viscometry Techniques." J. Texture Stud. 17:71-85.

- Govier, G. W., and K. Aziz. 1972. The Flow of Complex Mixtures in Pipes. Robert E. Krieger Publishing Company, Malabar, Florida.
- Halliday, D. and R. Resnick. 1981. Fundamentals of Physics, 2nd Edition, Extended Version. John Wiley and Sons, New York.
- Krynine, D. P. 1947. Soil Mechanics - Its Principles and Structural Applications. McGraw-Hill Book Company, Inc., New York.
- McCarthy, D., M. K. C. Chan and R. O. Lokken. 1985. Rheological Evaluation of Pretreated Cladding Removal Waste. PNL-5589, Pacific Northwest Laboratory, Richland, Washington.
- Merrington, A. C. 1949. Viscometry. Arnold Publishers, London.
- Mesri, G., and P. M. Godlewski. 1977. "Time- and Stress-Compressibility Interrelationship." J. Geotech. Eng. Div. 103:417-435
- Metzner, A. B. and R. E. Otto. 1957. "Agitation of Non-Newtonian Fluids," AIChE 3:1, 3.
- Oldshue, J. Y. 1983. Fluid Mixing Technology. McGraw-Hill Publications Company, New York.
- Pyles, M. R. 1984. "Vane Shear Data on Undrained Residual Strength." J. Geotech. Eng. 110(4):543-547.
- Reh binder, P. 1954. "Coagulation and Thixotropic Structures." Discuss. Faraday Soc. 18:151-160.
- Reiner, M. 1949. Deformation and Flow - An Elementary Introduction to Theoretical Rheology. H. K. Lewis, Co. Ltd., London.
- Schramm, G. 1981. Optimization of Rotovisco Tests. Gebrüder Haake GmbH, Karlsruhe, West Germany.
- Tanner, R. I. 1983. "Recent Progress in Rheology." J. of Appl. Mech. 50:1181-1190.
- Terzaghi, K., and R. B. Peck. 1948. Soil Mechanics Engineering Practice. John Wiley and Sons, Inc., New York.
- Vaid, Y. P., and R. G. Campanella. 1977. "Time-Dependent Behavior of Undisturbed Clay." J. Geotech. Eng. Div. 103:693-709.
- Van Olphen, H. 1977. An Introduction to Clay Colloid Chemistry. 2nd ed. John Wiley and Sons, New York.
- Van Vlack, L. H. 1975. Elements of Materials Science and Engineering, 3rd edition. Addison-Wesley Publishing Company, Reading, Massachusetts.

APPENDIX A

CONCEPTUAL DESIGN OF FULL SCALE,
IN-SITU SHEAR VANE DEVICE

SHEAR VANE ASSEMBLY
SCALE 1/2"=1'-0"

MATL: CLESON STEEL

NOTE: SHAFT - 300 RPM (MAX)

CONCEPTUAL
COMMENT PRINT
NOT APPROVED FOR CONSTRUCTION

FIGURE A.1.
Conceptual Design
of Full Scale,
In-Situ Shear
Vane Device

U. S. Department Of Energy Richland Operations Office PACIFIC NORTHWEST LABORATORY OPERATED BY BATTTELLE MEMORIAL INSTITUTE	
SHEAR VANE	
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APPENDIX B

PROCEDURE FOR USING CALCULATOR PROGRAM "VANE-2" FOR REDUCING SHEAR VANE SLUDGE AND SLURRY DATA

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APPENDIX B

PROCEDURE FOR USING CALCULATOR PROGRAM "VANE-2" FOR REDUCING SHEAR VANE SLUDGE AND SLURRY DATA

INTRODUCTION

This procedure employs an HP-41 calculator program for analyzing sludge shear strength and apparent viscosity data obtained using shear vanes. This program, VANE-2, was developed to simplify the calculations and to allow shear vane data to be rapidly analyzed as it becomes available. This program will provide feedback to test personnel while they are performing in-tank and laboratory shear vane tests. It should result in better and more informed responses to decisions that arise during testing, and more assurance that sufficient data are obtained. Sludge shear strength and viscosity data can be obtained using shear vanes in conjunction with a torque-measuring device, such as a viscometer, by following procedures outlined in Chapters 4 and 5.

VANE-2 is a user-interactive calculator program that asks the user questions and then performs the desired calculations. Familiarity with an HP-41 calculator is not required to use this program. Before proceeding, however, it is best to obtain an HP-41 calculator loaded with VANE-2 and an HP 82143A printer.

For VANE-2 to calculate sludge/slurry shear strength, the following data must be input by the user: F , D_v , R_c , R_s , T_c , R_t , and H_v . The program then calculates T_o , T_v , and τ_s . For the program to calculate sludge/slurry viscosity, the following input data are required: F , D_v , R_c , R_s , T_c , R_t , N , L , η_s , and ρ . The program then calculates T_o , T_s , T_v , P , N_p , N_{RE} , η_v , $\dot{\gamma}$ and τ .

The following instructions explain how to use VANE-2 for analyzing shear vane data.

SETTING UP THE CALCULATOR AND PRINTER

First, hook up the HP 82143A printer by plugging the printer cable into one of four ports at the front of the HP-41 calculator. Assure that calculator and printer are off during the hook up. Turn on the calculator and set it in "user mode" by pushing the user switch until the word "USER" shows up in the lower left corner of the calculator display. Each time the program is restarted, User mode must be reactivated. The calculator must not be in "program mode" (the phrase "PRGM" shows up in the lower right corner of the calculator display). Get out of it by pushing the "PRGM" switch, which is to the right of the "ON" switch. Next, assure sufficient storage register space by performing the following keystrokes: press "XEQ"; press "ALPHA"; press the buttons "8," "COS," "1," "LN" to spell the word "SIZE"; press "ALPHA"; key in "030." There are now 30 storage registers available for program use. Now turn on the printer and set the mode switch to "MAN." Calculator and printer are now on and ready to go.

INPUTTING INITIAL DATA AND STARTING THE PROGRAM

With the calculator in User mode, press the " Σ +" button (top left button on calculator keypad). This starts the program. The phrase "FACTOR=?" should appear on the calculator display. The program is asking for a spring factor, which corresponds to the full-scale torque, in dyne-cm, that the viscometer (or load cell) is capable of measuring. Select the appropriate spring factor from Table B.1 and key it into the calculator. Use the "+" button to correct any incorrect digits. After the correct spring factor is keyed in, press "R/S," which advances the program to the next step.^(a)

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- (a) Whenever the "R/S" button is pushed, the phrase "PRGM" will appear in the lower right corner of the calculator display, indicating that the program is running. Pushing any button on the calculator keypad will interrupt (stop) the program. Program operation can be resumed by pushing "R/S." When the program has finished running, the phrase "PRGM" will disappear.

TABLE B.1. Viscometer Spring Factor

Torque Sensor System	F (dyne-cm)
Brookfield RVDT	7,187
Brookfield LVDT	673.7
Haake M1500	1,470,00
Haake M500	490,000
Haake M150	147,000
Load Cell	Torque corresponding to full-scale ($R_t = 100$) deflection

The calculator display now asks for the diameter, D_v , of the shear vane. Input D_v in cm and press "R/S" to proceed.

The program now asks for the radius, R_c , of the test container. Input R_c in cm and press "R/S" to proceed.

The program now asks for the radius, R_s , of the shaft portion of the shear vane. The miniature shear vanes used in lab testing have a shaft radius of 0.1588 cm. Input R_s (in cm) and push "R/S" to proceed.

The program now asks for T_c (correction for torque zero offset caused by bearing friction, etc. in torque instrumentation). If the shear vane data were obtained using a Brookfield or Haake viscometer, $T_c = 0$. If other torque instrumentation was used, such as an agitator motor linked to a load cell, a nonzero value for T_c must be determined empirically. This is done by rotating the shear vane in air at the test rpm, reading the load cell output, and calculating the torque associated with the in-air reading. Input this zero offset torque in dyne-cm and press "R/S" to proceed.

The program has now received all initial data and automatically prints out a list of the input values as they were keyed in, as shown in Figure B.1. If an error occurs in the printout, start over by pushing the USER switch and then " Σ ," and input the correct values. After the program becomes familiar, all of these steps will take less than one minute.

F=4,900.0 DYNE-CM
D-V=2.220 CM
R-C=3.000 CM
R-S=0.1500 CM
T-C=0.800 DYNE-CM

FIGURE B.1. Printout of Initial Value Data

USING THE PROGRAM

VANE-2 contains several subroutines for calculating various parameters pertaining to sludge flow properties and shear vane test conditions. Which subroutines are used depends on what parameters are to be calculated. The input values of the four variables F, L, R_t , and N (R_t , and N are described later) control the calculation process and determine the parameters to be calculated. Depending on whether each variable is input as zero or some non-zero value, different subroutines are activated and different parameters are calculated. By controlling the values for F, L, R_t , and N, six different calculation options are available. Table B.2 describes these options and indicates how they are selected by appropriate zero or non-zero inputs of F, L, R_t , and N. Use Table B.2 to select the appropriate option on the basis of the parameters to be calculated. Figure B.2 is a flow chart of VANE-2 that illustrates how the program uses this initial value data to determine which subroutines are activated. The equations employed by VANE-2 are listed in Table B.3. The following sections provide general information on how and when to use the six available calculation options.

INPUTTING TORQUE READING AND SHEAR VANE RPM DATA

After the initial values for F, D_v , R_c , R_s , and T_c are keyed in and printed out as described earlier, the program asks for a viscometer/load cell torque reading (R_t). If a Brookfield viscometer (digital or dial reading) was used, R_t is equivalent in magnitude to the viscometer output signal that varies from 0 to 100. If a Haake Rotovisco viscometer was used, R_t equals the torque output reading, S_t , which varies from 0 to 1.0, multiplied by an output scale factor, $\% \tau$, which varies from 0 to 100. For example, if the Haake output (S_t) reads 0.8 and the scale factor ($\% \tau$) is 50%, $R_t = (0.8) (50) = 40.0$.

TABLE B.2. VANE-2 Subroutine Options and How to Control Them

Option #	Conditions	Inputs Required	Calculated Parameters
1	$F \neq 0$ $R_t \neq 0$ $N \neq 0, L \neq 0$	$F, D_v, R_c, R_s, T_c, R_t, N,$ L, η_s, ρ	$T_o, T_s, T_v, P, N_p,$ N_{RE}, η_v, S, τ
2	$F \neq 0$ $R_t \neq 0$ $N \neq 0, L = 0$	$F, D_v, R_c, R_s, T_c, R_t, N,$ $L = 0, \rho$	$T_o, T_s = 0, T_v, P, N_p,$ $N_{RE}, \eta_v, \dot{S}, \tau$
3	$F \neq 0$ $R_t = 0$ $N = 0$	$F, D_v, R_c, R_s, T_c, N, L$ η_s	T_s
4	$F \neq 0$ $R_t \neq 0$ $N = 0$	$F, D_v, R_c, R_s, T_c, R_t,$ H_v	T_o, T_v, τ_s
5	$F = 0$ $N \neq 0, L \neq 0$	D_v, N, T_v, ρ	$P, N_p, N_{RE}, \eta_v, \dot{S}, \tau$
6	$F = 0$ $N = 0$	D_v, T_v, H_v	τ_s

If other torque instrumentation is used, such as a load cell connected to a free-swiveling motor base, R_t equals the torque output reading expressed as a percentage of full-scale output. For example, if the output scale reads from 0 to 1000, and a particular reading is 469.0, then $R_t = (469/1000) \times (100) = 46.9$. After inputting an appropriate value of R_t , press "R/S" to proceed.

The program now asks for the rate of shear vane rotation, N , in revolutions per minute. Key in rpm and press "R/S" to proceed.

FIGURE B.2. VANE-2 Flow Chart

TABLE B.3. Equations Employed by VANE-2(a)

$$T_o = F \cdot \frac{R_t}{100} \quad (1)$$

$$T_s = \frac{\eta_s}{100} \cdot R_s^2 \cdot L \cdot \frac{8\pi^2}{60} \cdot \frac{N R_c^2}{R_c^2 - R_s^2} \quad (2)$$

$$T_v = T_o - T_s - T_c \quad (3)$$

$$P = T_v \cdot \frac{2\pi}{60} \cdot N \quad (4)$$

$$N_p = \frac{P}{\rho D_v^5 (N/60)^3} \quad (5)$$

$$\log N_p = -(0.977) \log N_{RE} + (2.190) \quad (6)$$

$$N_{RE} = \frac{P D_v^2 (N/60)}{(\eta_v/100)} \quad (7)$$

$$\dot{S} = (11.1) \frac{N}{60} \quad (8)$$

$$\tau = (\eta_v/100) (\dot{S}) \quad (9)$$

$$\tau_s = \frac{T_v}{\pi} \left[\frac{H_v D_v^2}{2} + \frac{D_v^3}{6} \right]^{-1} \quad (10)$$

(a) All of these equations are obtained from the literature except for (6), and (9), which are developed by Heath in unpublished documents.

INPUTTING REMAINING TEST PARAMETERS

The program now asks for the length, L , of the shaft portion of the shear vane (above the blades) that was submerged in the test fluid during the test. Input L (in cm) and press "R/S" to proceed. If no part of the shaft was submerged, input $L = 0$.

If F , R_t , N , and L were all assigned nonzero values (Option #1) or if $R_t = 0$ (Option #3), the program now asks for the viscosity (η) of the fluid in contact with the shaft portion of the shear vane. The input value of η_s is used to calculate a correction for shaft friction, T_s . Enter η_s in centipoise and press "R/S" to proceed.

The program now asks for the density of the sludge in g/cm^3 . Input sludge density and press "R/S" to proceed.

ANALYZING SLUDGE VISCOSITY DATA

In analyzing sludge viscosity data, Options #1, #2, #3, and #5 are involved. For tests in which the vanes and part of the shaft are immersed in the same test fluid (sludge), use Option #1 of Table B.2. In this case, first input the initial data (F through T_c) as described in preceding section. Then input R_t , N , and L as described above. The program now asks for the viscosity, η_s , of the fluid in contact with the shaft portion of the shear vane. Generally, η_s will not be known beforehand, so estimate a value, enter it, and press "R/S" to proceed. Now input ρ in g/cm^3 and press "R/S" to proceed. The program will now calculate and print out the parameters listed in Table B.2 under Option #1.

Following this step, the program is ready to analyze additional data, having new values for R_t , N , L , η_s , and ρ , but with the same initial values for F , D_v , R_c , R_s , and T_c . The program will request new values for R_t , N , L , η_s , and ρ , which should be input as described above. If one or more of the initial values of F , D_v , R_c , R_s , or T_c change, start the program over by pressing "USER" and " Σ ", and input the new initial value data.

Procedure When Vanes and Shaft Are in Contact with the Same (Unknown) Fluid

In cases where the fluid contacting the shear vane shaft is the same as that contacting the blades, η_v must, by definition, be equivalent to η_s . In general, the estimated value of η_s used to calculate shaft friction will differ from the value of η_v calculated by VANE-2. Since $\eta_s = \eta_v$ is known, an iterative procedure must be followed wherein the calculated value of η_v is used as a better estimate of η_s , allowing a new value of η_s to be calculated. This procedure is repeated until the values of η_s and η_v converge such that $\eta_s = \eta_v = \eta_{app}$, where η_{app} is the apparent viscosity of the sludge in centipoise. The calculation shown in Figure B.3 illustrates this iterative procedure.

Even though the initial estimated value of η_s in the sample calculation was low by a factor of 50, note that only three iterations were required for η_s and η_v to converge. The procedure does not generally require a large number of iterations.

F=4,900.0 DYNE-CM D-V=2.220 CM R-C=3.000 CM R-S=0.1500 CM T-C=0.000 DYNE-CM	RT=40.0 N=10.0 RPM L=1.000 CM VISC-S=100.0 CPS DENS=1.250 G/CM ³ T-O=1,960.0 DYNE-CM T-S=0.3 DYNE-CM T-V=1,959.7 DYNE-CM RE=2.150E-2 NP=6.594E3 VISC-V=4,774.9 CPS RATE=1.850 INV SEC TAU=80.34 DYNE/CM ²	RT=40.0 N=10.0 RPM L=1.000 CM VISC-S=4,775.0 CPS DENS=1.250 G/CM ³ T-O=1,960.0 DYNE-CM T-S=15.9 DYNE-CM T-V=1,944.1 DYNE-CM RE=2.160E-2 NP=6.542E3 VISC-V=4,736.1 CPS RATE=1.850 INV SEC TAU=87.62 DYNE/CM ²	RT=40.0 N=10.0 RPM L=1.000 CM VISC-S=4,736.5 CPS DENS=1.250 G/CM ³ T-O=1,960.0 DYNE-CM T-S=15.0 DYNE-CM T-V=1,944.2 DYNE-CM RE=2.160E-2 NP=6.542E3 VISC-V=4,736.5 CPS RATE=1.850 INV SEC TAU=87.62 DYNE/CM ²
(a)	(b)	(c)	(d)

FIGURE B.3. Example Calculation of Apparent Sludge Viscosity from Shear Vane R_t Versus N Data.

- (a) Initial value data
- (b) Iteration #1, η_s guessed as 100 cP, η_v calculated as 4775 cP
- (c) Iteration #2, η_v used as new estimate for η_s
- (d) Iteration #3, values of η_s and η_v converge; $\eta_{app} = \eta_s = \eta_v = 4740$ cP.

Procedure when Vanes and Shaft Are in Contact with Different (Unknown) Fluids

A similar but somewhat more involved procedure must be used to calculate the apparent sludge viscosity (η_{app}) when the fluid contacting the shaft is different from that contacting the vanes. For example, when tests are conducted in multi-layered sludges, it is possible for the shaft to be in contact with several fluids where flow properties all differ from those of the material in contact with the vanes. In this case, a shaft friction loss torque correction (T_s) must be calculated for each layer, using Option #3 in Table B.2. As an example, consider a three-layered sludge in which the apparent viscosities of the top two layers have been determined, but that of the bottom layer is unknown. Refer to Figure B.4, which provides a basis for an illustrative example calculation.

FIGURE B.4. Example Calculation Test Configuration

First, press "USER" and " $\Sigma+$," and input $F = 673.7$ dyne-cm, $D_v = 0.975$ cm, $R_c = 2.0$ cm, $R_s = 0.1588$ cm, and $T_c = 0.0$ dyne-cm, which are the values indicated in Figure B.4. Calculate the shaft torque associated with friction losses to the water layer by keying in $R_t = 0$ (to activate Option #3), $N = 10$ rpm, $L = 1.0$ cm, and $\eta_s = 1.04$ cp. Shaft torque (τ_s) due to friction losses in the top water layer is calculated as 3.5×10^{-3} dyne-cm. To calculate T_s for sludge #1, key in $R_t = 0$, $N = 10$ rpm, $L = 1.2$ cm, and $\eta_s = 850$ cp, resulting in $T_s = 3.4$ dyne-cm. The frictional losses for sludge #2 are similarly calculated as $T_s = 5.8$ dyne-cm. The total shaft friction losses above the bottom sludge layer, at 10 rpm, are $(3.5 \times 10^{-3}) + 3.4 + 5.8 = 9.204$ dyne-cm.

Now, the apparent viscosity of the bottom sludge layer can be calculated by pressing " $\Sigma+$," which starts the program over, and inputting the appropriate values of F , D_v , R_c , and R_s . This time, instead of keying in $T_c = 0.0$, key in $T_c = 9.204$ dyne-cm. This correction torque, in this case attributed to shaft friction losses in the top layer of the sample, will be used to adjust the overall torque, T_p , in calculating the net torque applied by the vanes, T_v . Input $R_t = 63.7$, $N = 10$ rpm, and $L = 0.5$ cm corresponding to the length of the shaft submerged in sludge #3 at the bottom of the test container. As described earlier, use an iterative procedure to guess η_s ; calculate η_v ; use η_v as a better guess for η_s ; and so on until $\eta_s = \eta_v = \eta_{app}$. In each case, input $\rho = 1.5$ g/cm³. The final value of η_{app} is calculated as 12,150 cPs at 10 rpm, corresponding to a shear rate ($\dot{\gamma}$) of 1.850 s⁻¹. With an initial estimate of $\eta_s = 1200$ cPs, four iterations were required for η_s and η_v to converge.

Using Option #2 to Save Time when Shaft Friction Is Negligible

In cases where shaft friction is negligible ($T_s = 0$), use Option #2 by keying in $L = 0$. Option #2 can also be used in cases where T_s is known beforehand by inputting $L = 0$ and $T_c = T_s$. The option is further useful for obtaining a quick estimate of apparent sludge viscosity without accounting for shaft friction losses. For the three-layered sludge data depicted in Figure B.4, an apparent viscosity of 13,065 cP is calculated using Option #2. As expected, this value is higher than the more-accurate value of 12,150 cP, which took shaft friction into account.

Using Option #5 to Save Time when Vane Torque Is Already Known

Option #5 (Table B.2) is provided to save time when a value of T_v is already known. This would occur, for example, if Option #2 were used to calculate T_v and the other parameters neglecting shaft friction losses, and if Option #3 were used to calculate only the shaft friction losses. In this case T_s of Option #3 would be subtracted from T_v of Option #2; and the resulting T_v , corrected for shaft friction losses, would be input directly by using Option #5. Repeated use of VANE-2 will demonstrate the practicality of these options.

FITTING NON-NEWTONIAN VISCOSITY DATA TO THE POWER LAW MODEL FOR YIELD-PSEUDOPLASTIC MATERIALS

The preceding section described how data for shear vane torque, T_v , versus rotational speed, N , can be reduced to data for shear stress, τ , versus shear rate, $\dot{S}$, by means of VANE-2. The relationship between τ and $\dot{S}$ uniquely defines the flow behavior of viscous fluids.

For Newtonian fluids the ratio $\tau/\dot{S}$ is constant over all shear rates and is equal to viscosity, η . In general, melter feeds and tank sludges are non-Newtonian in that the ratio $\tau/\dot{S}$ is not constant over all values of $\dot{S}$. The shear stress-shear rate behavior of these fluids has been successfully described by the power law Equation 4:

$$\tau = k\dot{S}^n \quad (11)$$

where k = consistency index, dynes/cm²

n = flow behavior index, dimensionless.

This expression can be used to calculate values of shear stress as a function of shear rate. Values of apparent viscosity, η_{app} in centipoise, can then be calculated by the expression

$$\eta_{app} = \frac{\tau}{\dot{S}} \quad (12)$$

The values of k and n for a given fluid are determined experimentally by measuring shear stress at several different shear rates and plotting the data as $\log \tau$ vs $\log \dot{S}$. The slope and intercept of such a plot, which is usually approximately linear, correspond to values of n and k , respectively. The significance of the flow behavior index is that if $n = 1$, the fluid is Newtonian; if $n < 1$, the fluid is "shear thinning" or pseudoplastic; and if $n > 1$, the fluid is shear thickening or dilatant. Melter feeds and sludges are typically found to be pseudoplastic as n is usually less than unity. Note that sludges and slurries must be pseudoplastic (not dilatant) in order for the shear vane method to work properly. If a pseudoplastic is found to exhibit a yield stress, τ_y , then it is termed a "yield-pseudoplastic" and is described by

$$\tau - \tau_y = k\dot{S}^n \quad (13)$$

Figure B.5 schematically represents the various types of rheological behavior in qualitative shear stress and shear rate curves.

FIGURE B.5. Rheograms for Time-Independent Non-Newtonian Fluids

Example: Determining Power Law Parameters from Shear Vane Data. By operating a viscometer equipped with a shear vane at different rates of vane rotation, sufficient data to produce a rheogram or plot of shear stress versus shear rate can be obtained. Measurements of shear vane torque must be made at several rotational speeds (e.g., more than 5) to provide sufficient data to analyze the power law coefficient, k , and exponent, n .

Table B.4 shows values of shear stress and shear rate that represent data obtained for a "typical" melter feed slurry. Each row in Table B.4 represents a single data point for shear vane torque versus rpm. Note that this melter feed was found to exhibit a yield stress of 2.66 dyne/cm² (estimated by the torque decay method described in Section 4.4.3). To determine k and n , first plot the $\dot{S}$ vs τ data (first two columns of Table B.4 in terms of $\ln(\dot{S})$ versus $\ln(\tau - \tau_y)$ as shown in Figure B.6. For this data, the plot intercepts the line $\dot{S} = 1$ ($\ln \dot{S} = 0$) at a value of $\ln k = 1.98$. The power law coefficient k is thus $\exp(1.98) = 7.24$ dyne/cm². The slope of the plot, n , is found to be 0.19. Because $n < 1$, this melter feed is considered a pseudoplastic power law fluid. Therefore, this melter feed slurry exhibits yield-pseudoplastic behavior and is described by the following power law expression, in cgs units:

TABLE B.4. Values for Shear Stress and Shear Rate Obtained for a Sample of Melter Feed Slurry

$\dot{S}$ (sec ⁻¹)	τ (dyne/cm ²)	$\tau - \tau_y$	$\ln \dot{S}$	$\ln(\tau - \tau_y)$	η_{app} (cP)
0.0	2.66	0	--	--	--
0.61	9.21	6.55	-0.49	1.87	1510.0
1.22	10.31	7.65	0.20	2.04	844.8
3.05	11.48	8.82	1.12	2.18	376.3
6.12	12.61	9.95	1.81	2.30	206.1
12.24	14.10	11.44	2.51	2.44	115.2
24.47	15.66	13.00	3.20	2.57	64.0
61.18	18.78	16.12	4.11	2.78	30.7

FIGURE B.6. Plot of $\log \dot{\gamma}$ Versus $\log \tau$ for Typical Melter Feed

$$\tau - 2.66 = 7.2 \dot{\gamma}^{0.19} \quad (14)$$

Apply this same procedure for calculating the power law coefficient k and exponent n regardless of whether the τ versus $\dot{\gamma}$ data of interest were obtained using a shear vane or any other viscometric method. The resultant power law expression adequately describes the flow behavior of pseudoplastic ($\tau_y = 0$) and

yield-pseudoplastic fluids. Such an expression allows non-Newtonian flow behavior to be entered into engineering calculations and is thus a great practical utility.

ANALYZING SLUDGE SHEAR STRENGTH DATA

Note that yield stress, τ_y , in the yield-pseudoplastic model (previous section) will in general be different than the shear strength τ_s , which is a property of elastic solids. The difference, in terms of sludge mobilization, is that a sludge begins as an elastic solid having a shear strength, τ_s , proceeds to a thixotropic fluid when τ_s is exceeded, and with time eventually achieves steady state and becomes a power law fluid that may exhibit a yield stress, τ_y . Therefore, τ_y should be considered the time-independent yield stress exhibited in the steady-state viscous regime. In contrast, shear strength, τ_s , is shear history-dependent and thus time-dependent. It is exhibited during transient "startup" shear, and it marks the transition from an elastic solid to a viscous slurry. Although the distinction between τ_y and τ_s is not made often enough, both values are fundamentally different, and both are amenable to measurement as described in Sections 4.4 and 4.7, respectively.

Sludge shear strength data is much simpler to analyze than sludge viscosity data. First, press "R/S" and input the initial values of F , D_v , R_c , R_s , and T_c . If shaft friction is suspected of being significant, use Option #3 to calculate T_s (described in preceding section) and add this value of T_s to T_c . After F , D_v , R_c , R_s , and T_c have been entered, the program will ask for R_t . Enter R_t as described in preceding sections and press "R/S." The program now asks for N . For shear strength calculations, key in a value of 0.0 for N and press "R/S" to proceed. (The parameter N does not enter into shear strength calculations.) This initializes Option #4. The program now asks for the height, H_v , of the shear vane blades submerged in the slurry during the tests. Input H_v (in cm) and press "R/S" to proceed. The program now calculates vane torque and sludge shear strength.

Using Option #6 to Save Time when Vane Torque Is Already Known. If T_v is known ahead of time, use Option #6 as described in Table B.2 to speed up the calculation process. To use Option #6, input $F = 0$, input D_v , input $N = 0$, input T_v , input H_v , and the program will calculate τ_s .

"VANE-2" PROGRAM LISTING AND STORAGE REGISTER DESCRIPTION

Table B.5 provides a description of the contents of the storage registers used in VANE-2. Table B.6 provides a program listing of VANE-2. Both tables are provided for the reader's use.

TABLE B.5. Storage Register Description

<u>Parameter</u>	<u>Register Number</u>
ρ	04
D	05
η_s	06
N	07
R_E	08
T_o	09
N_p	10
R_c	11
L	12
R_b	14
T_s	15
T_v	16
P	17
H_v	18
τ	19
R_t	20
S	21
η_v	22
F	23
T_c	24
τ_s	25

TABLE B.6. VANE-2 Program Listing

81 LBL "VANE-2"	64 "RT="	127 RCL 14	198 *	253 RVIEW
82 ADV	65 ARCL 20	128 X12	191 RCL 07	254 GTO 01
83 ADV	66 RVIEW	129 *	192 *	255 LBL 02
84 CF 27	67 RCL 20	130 RCL 06	193 60	256 RCL 23
85 SF 21	68 RCL 23	131 *	194 /	257 X=0?
86 FIX 3	69 *	132 100	195 100	258 GTO 07
87 "FACTOR=?"	70 100	133 /	196 *	259 RCL 09
88 PROMPT	71 /	134 STO 15	197 RCL 08	260 RCL 24
89 STO 23	72 STO 09	135 LBL 03	198 /	261 -
90 "D-VANE=?"	73 LBL 04	136 RCL 20	199 STO 22	262 STO 16
91 PROMPT	74 RCL 23	137 X=0?	200 RCL 23	263 LBL 09
92 STO 05	75 X=0?	138 GTO 05	201 X=0?	264 "H-VANE=?"
93 RCL 23	76 ADV	139 RCL 12	202 GTO 08	265 PROMPT
94 X=0?	77 "N=?"	140 X=0?	203 "T-O="	266 STO 18
95 GTO 06	78 PROMPT	141 STO 15	204 ARCL 09	267 FIX 3
96 "R-C=?"	79 STO 07	142 RCL 09	205 "I DYNE-CM"	268 "H="
97 PROMPT	80 X=0?	143 RCL 15	206 RVIEW	269 ARCL 18
98 STO 11	81 GTO 02	144 -	207 LBL 05	270 "I CM"
99 "R-S=?"	82 "N="	145 RCL 24	208 "T-S="	271 RVIEW
100 PROMPT	83 ARCL 07	146 -	209 ARCL 15	272 FIX 1
101 STO 14	84 "I RPM"	147 STO 16	210 "I DYNE-CM"	273 RCL 05
102 "T-C=?"	85 RVIEW	148 LBL 10	211 RVIEW	274 X12
103 PROMPT	86 RCL 23	149 "DEMS=?"	212 RCL 20	275 RCL 18
104 STO 24	87 X=0?	150 PROMPT	213 X=0?	276 *
105 LBL 06	88 GTO 07	151 STO 04	214 GTO 01	277 2
106 FIX 1	89 "L=?"	152 FIX 3	215 "T-V="	278 /
107 "F="	90 PROMPT	153 "DEMS="	216 ARCL 16	279 RCL 05
108 ARCL 23	91 STO 12	154 ARCL 04	217 "I DYNE-CM"	280 3
109 "I DYNE-CM"	92 RCL 12	155 "I G/CM13"	218 RVIEW	281 Y1X
110 RVIEW	93 X=0?	156 RVIEW	219 LBL 08	282 6
111 FIX 3	94 GTO 03	157 FIX 1	220 RCL 07	283 /
112 "D-V="	95 FIX 3	158 RCL 16	221 60	284 +
113 ARCL 05	96 "L="	159 .105	222 /	285 1/X
114 "I CM"	97 ARCL 12	160 *	223 11.1	286 RCL 16
115 RVIEW	98 "I CM"	161 RCL 07	224 *	287 *
116 RCL 23	99 RVIEW	162 *	225 STO 21	288 PI
117 X=0?	100 FIX 1	163 STO 17	226 RCL 22	289 /
118 GTO 04	101 "VISC-S=?"	164 RCL 17	227 100	290 STO 25
119 "R-C="	102 PROMPT	165 2.16 E05	228 /	291 "TORQUE="
120 ARCL 11	103 STO 06	166 *	229 RCL 21	292 ARCL 16
121 "I CM"	104 "VISC-S="	167 RCL 07	230 *	293 "I DYNE-CM"
122 RVIEW	105 ARCL 06	168 3	231 STO 19	294 RVIEW
123 FIX 4	106 "I CPS"	169 Y1X	232 SCI 3	295 "STRENGTH="
124 "R-S="	107 RVIEW	170 /	233 "RE="	296 ARCL 25
125 ARCL 14	108 RCL 11	171 RCL 05	234 ARCL 08	297 "I DYNE/CM12"
126 "I CM"	109 X12	172 5	235 RVIEW	298 RVIEW
127 RVIEW	110 RCL 07	173 Y1X	236 "HP="	299 GTO 01
128 FIX 3	111 *	174 /	237 ARCL 10	300 LBL 07
129 "T-C="	112 RCL 11	175 RCL 04	238 RVIEW	301 "T-V=?"
130 ARCL 24	113 X12	176 /	239 FIX 1	302 PROMPT
131 "I DYNE-CM"	114 RCL 14	177 STO 10	240 "VISC-V="	303 STO 16
132 RVIEW	115 X12	178 RCL 10	241 ARCL 22	304 FIX 1
133 LBL 01	116 -	179 LOG	242 "I CPS"	305 "T-V="
134 FIX 3	117 /	180 2.190	243 RVIEW	306 ARCL 16
135 RCL 23	118 0	181 -	244 FIX 3	307 "I DYNE-CM"
136 X=0?	119 *	182 .977	245 "RATE="	308 RVIEW
137 GTO 04	120 PI	183 /	246 ARCL 21	309 RCL 07
138 ADV	121 X12	184 CMS	247 "I INV SEC"	310 X=0?
139 "RT=?"	122 *	185 101X	248 RVIEW	311 GTO 09
140 PROMPT	123 60	186 STO 08	249 FIX 2	312 GTO 10
141 STO 20	124 /	187 RCL 04	250 "TAU="	313 END
142 X=0?	125 RCL 12	188 RCL 05	251 ARCL 19	
143 GTO 04	126 *	189 X12	252 "I DYNE/CM12"	

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