Simulation and Rheological Analysis of Hanford Tank 241-SY-101

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ABSTRACT

Rheological characterization and small scale simulation of Hanford Tank 241-SY-101 has been initiated to aid in the remediation efforts for the Department of Energy Hanford Site. The study has been initiated in response to growing concerns about the potential flammability hazard pertaining to the periodic release of up to 10000 cubic feet of hydrogen, nitrous oxide, nitrogen, and ammonia gasses. Various simulants emulating the radioactive waste stored in this tank have been used to ascertain the rheological parameters of the waste, simulate the ongoing processes of gas generation and release phenomenon inside the tank, and determine the feasibility of jet mixing to achieve a controlled release of the gas mixture.

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1. INTRODUCTION

Waste stored in Hanford Tank 241-SY-101 contains a highly radioactive mixture of chemicals which react to create hydrogen, nitrous oxide, nitrogen and ammonia gasses. The quantity of gasses generated represents a potential flammability hazard. These gasses form inside the slurry/sludge layer and accumulate in a sufficient volume to raise the overall tank liquid level by twelve inches. In intervals of approximately 110 days, a gas release occurs as part or all of the slurry layer overturns. The total time for an overturn is only a few minutes, during which time as much as 10,000 scf of gas has been released.

In order to prevent the almost instantaneous gas release, studies are in process at Hanford to mix the slurry by injection of supernate through nozzles near the tank bottom. Various studies have also been conducted at Los Alamos National Laboratory to determine to what degree this jet mixing will aid in the reduction of these violent gas releases. These studies have included overturn simulations to understand the dynamics, rheological measurements on various simulants to better understand the physical properties, and jet mixing simulations to determine the difficulties associated with mixing the Hanford waste. During these studies and in this report, the heaviest concentration was on determining the types of measurements required to characterize as accurately as possible the physical properties of the simulants and the actual contents of Hanford Tank 241-SY-101. Without accurate determination of the physical properties of simulants and tank contents, the effectiveness of any mixing technique in the actual tank would be questionable without expensive in-tank tests.

Before performing the overturn simulations, certain parameters had to be considered to facilitate gathering of accurate results. The first consideration was to determine relevant similarity parameters that allow for scaling from the full size tank to laboratory scale experiments and from laboratory scale experiments to the full size tank. The second consideration was to develop first order equations which predict the basic fluid dynamics and behavior of the actual tank and of the laboratory experiments.

Approximately fifty overturn simulations were performed on a small scale using various sizes of cylindrical glass containers. Using clear glass containers allowed three dimensional viewing of tank overturn events. Most of the tests were recorded on video tape and on thirty-five millimeter film. Many of these tests used simulants that generated gasses in a manner similar to the actual tank waste. These tests emulated various types of gas release events. Three different types of gas release events were observed; top peel, volcanic, and massive overturn. Top peel and volcanic events can be fairly localized and may or may not produce a surface disturbance or a noticeable level decrease;

however, these events can degas a significant portion of the slurry over an extended period of time.

Rheological parameters are those values that relate to the flow of matter. Fluids are separated into two main categories; Newtonian and Non-Newtonian. Newtonian fluids are those that have a linear shear stress-shear rate relationship. Non-Newtonian fluids do not display this linear relationship; therefore, the viscosity measured for a Non-Newtonian fluid is defined as the ratio of the shear stress to the shear rate and referred to as the apparent viscosity.

One type of Non-Newtonian fluid is a pseudoplastic fluid, an example of which is a Bingham plastic. This type of fluid is characterized by a finite yield stress. Shear stress increases non-linearly with increasing shear rate after the material has yielded. Non-radioactive Bingham plastic fluids were used to study the rheological characteristics of Hanford tank slurries.

The rheological properties of various simulants were extensively studied using six different types of viscometers. Over 200 different test sequences were conducted to explore the limitations associated with each viscometer. Of the six types of viscometers, the cylindrical spindle and the small sample adaptor configurations appear to provide the best characterizations of Non-Newtonian slurries containing precipitated salt crystals. The cone and plate viscometer has the limitation that for an accurate determination of the viscosity and shear stress of a salt-containing slurry, the crystal size must be less than the spacing between the cone and plate components of the spindle configuration. For the cone and plate used for these tests, the spacing between these two components was thirteen microns. Single crystal sizes of greater than forty microns were observed in some of the simulants.

Mixing of the sludge/slurry portion of Tank 241-SY-101 contents by means of injected jets of the overlying supernate has been proposed as a mechanism to control the release of gas as opposed to allowing the current overturn process to continue. The use of hydraulic jets for mixing and cutting is a concept originating over a century ago. Early applications were hydraulic mining and leveling, often on a very large and very destructive scale. At present, many jet concepts for mixing, cutting, and cleaning are commercially available. Prosser/Empo, Mass Transfer Systems, and NW Research Associates all have commercial products which could be incorporated into the Hanford concept. Integration of these devices would not only improve the effectiveness of the concept, but could also provide a slurry removal technique for removal of waste from this and other tanks.

At Los Alamos National Laboratory, various jet mixing parameters have been investigated. In most cases, the slurry/sludge fluid properties and the geometry of the jet and the tank govern the performance requirements of the pump. The effectiveness of stationary and moving jets were studied. Overall, the jet mixing concept appears to be a technique that should be capable of mixing tanks with the same geometric characteristics and contents as Tank 241-SY-101. There are, however, several design and engineering improvements that need to be addressed and incorporated into the concept before it will perform to its true potential.

2. OVERTURN SIMULATIONS

The purpose of this chapter is to present the methodology used to conduct simulations of the overturn process of Hanford Tank 241-SY-101.

2.1 HANFORD TANK 241-SY-101 SCALING

To accurately perform an overturn simulation, similarity parameters must be developed to relate laboratory experiments to the full size tank. Equations must also be formulated to predict the dynamics and behavior of the actual tank so that they may be applied in the laboratory. Parameters which must be considered to scale an overturn simulation include:

- The ratios of the depths of the convective and non-convective regions
- The ratio of the non-convective region depth to tank diameter
- The Reynolds number of the non-convective layer during rollover
- Ratios of accelerations, velocities, and length scales
- A scaled time that is a function of the fluid properties
- The ratios of viscous forces in terms of shear and yield strengths

2.1.1 Hanford Tank 241-SY-101 Characteristics

Gas production in the non-convective slurry/sludge layers proceeds at a constant rate of approximately 0.67 cf/day per 1,000 cf of slurry/sludge at an average non-convective layer pressure of 2.25 atm absolute. A mixture of approximately 36% hydrogen, 37% nitrogen, 28.5% nitrous oxide, 4% water vapor, 4% ammonia, and a combined total of 0.5% carbon dioxide, methane, and carbon monoxide is formed as a product of radiolysis and decomposition of the chemicals and water in the tank. The concentration of total organic carbon is 50% higher in the non-convective layer than in the convective layer.

Figure 2.1 portrays Hanford Tank 241-SY-101. The overall depth of the liquid/slurry/sludge/crust is approximately 408 inches. Hanford data list the viscosity of the sludge to be as great as $1.2(10^7)$ cP at 65° C. The high viscosity has been attributed to crystallization of the material which occurs when the material is heated to 50°-60° C. The viscosity of the convective layer is reported to be approximately 6 cP near the top of the tank. The uniform temperature of the convective layer suggests that it is thoroughly mixed and that an insignificant amount of gas is trapped in this region. The remaining portion of this section is devoted to summarizing tank characteristics as described in various Hanford reports referenced in chapter 7 of this document.

Figure 2.1: Hanford Tank 241-SY-101 Dimensions and Material Distribution

The slurry/sludge region has an almost parabolic temperature distribution which suggests three different types of activity. In the bottom 40 inches of the convective layer and in the top 20 inches of the slurry layer the temperature increases rapidly with depth below the convective layer. The degassed volume of this slurry region is approximately 7,360 cf. The average pressure in this region is 1.97 atm absolute. Crystallization in this region may not proceed at the same rate as in the remainder of the non-convective layer due to increased temperature. Another factor affecting crystallization may be the significant amount of mixing and degassing occurring in this region.

The middle region comprises the largest portion of the non-convective layer. This region is approximately 110 inches in depth. The volume of this region is approximately 40,500 cf, and the average pressure is 2.23 atm absolute. Gas does not rapidly move in this region until the entire layer reaches a density sufficient to allow buoyant force to overcome the yield strength of the layer and allow it to float to the top of the convective layer.

The third region is the bottom 30 inches of the tank. The volume of this region is approximately 11,000 cf. The average pressure in this region is 2.51 atm absolute. This sludge layer has a nearly uniform temperature distribution and temperatures which are slightly less than the layer above it. This layer appears to have a significant tensile strength. Hanford documents suggest that the tensile strength at this layer could be as high as 70,000 dynes/cm². This strength is sufficient to maintain the integrity of the sludge layer when the slurry layer above floats to the top of the convective layer. It appears that the sludge layer becomes loose on only every third or fourth overturn event. The largest gas release will occur when the sludge layer comes loose, due to the settling pressure at this greater depth and lower density due to the settling of a more dense layer above when the slurry layer overturns without the sludge layer. The maximum gas release, based upon an analysis of Hanford data and theoretical calculations, is estimated to be greater than 30,000 cf.

2.1.2 Scaling Parameters

The first scaling relationship to be discussed is the terminal velocity of a gas bubble moving under the action of gravity. For a bubble moving in a fluid with a viscosity near 1 cP, the terminal velocity is given by Equation 2.1:

$$v = \frac{g}{9} \left(\rho \frac{a^2}{\mu} \right) \quad (2.1)$$

Where:

g	=	Local gravity
ρ	=	Liquid density
a	=	Bubble radius
μ	=	Fluid viscosity

Equation 2.1 is valid for the convective region; however, this equation is not valid for the non-convective region due to the Non-Newtonian nature of the fluid. At a minimum, the constant would have a different value to compensate for the drag coefficient being a function of Reynolds number and the Reynolds

number being less than 1. This equation demonstrates how the high viscosity prevents the gas from moving a significant amount in the sludge/slurry layers. For the actual tank, the movement of gas bubbles in the non-convective layers in a 110 day period is insignificant.

Equation 2.2 shows the scaled time to rollover as a function of the properties of the fluid.

$$T = C \frac{V_s}{\left(\frac{dV_g}{dt}\right)} \quad (2.2)$$

Where:

C	=	A constant developed for the solution
V_s	=	Volume of the slurry
$\frac{dV_g}{dt}$	=	Rate of gas generation in the slurry

In general, scaled time was considered as a non-dimensional ratio relating Tank 241-SY-101 to the scaled experiments; as presented in Equation 2.3:

$$\frac{T_e}{T_{101}} = \frac{V_{s_e}}{V_{s_{101}}} \frac{\frac{dV_{g_{101}}}{dt}}{\frac{dV_{g_e}}{dt}} \quad (2.3)$$

The symbols used in Equation 2.3 are as defined previously. Characters with the subscript "e" denote experimental parameters; whereas characters with a "101" subscript represent Hanford Tank 241-SY-101 waste characteristics.

Graphical analysis of a modified curve fit of Hanford data provided an equation to obtain the pressure at any point in the tank as a function of the height, h, of the point from the bottom of the tank. The equation which provides this relationship is:

$$p = 37.877 - 0.06089(h) + 1.1024(10^{-5})h^2 \quad (2.4)$$

Where the units for P and h are psig and inches, respectively.

Another relationship is required to correlate the volume of gas generated to the increase in tank liquid depth. The relationship is obtained by Equation 2.5:

$$V_{gas} = \Delta h * A_{tank} = \frac{dV_g}{dt} * t * A_{tank} \quad (2.5)$$

In Equation 2.5:

V_{gas}	=	Actual volume of gas released by the slurry/sludge layers during an overturn event
Δh	=	The decrease in tank liquid height as a result of an overturn event
A_{tank}	=	Cross-sectional area of the tank

After an overturn event, the average pressure at the depth where the overturn originated can be obtained from Equation 2.6:

$$P_{avg} = \frac{V_{gr}}{V_{gas}} \quad (2.6)$$

In the previous equation:

V_{gr}	=	Measured volume of gas released at standard conditions
P_{avg}	=	Average pressure in standard atmospheres in the region where the gas originated

The initial thickness of slurry/sludge that overturned can be estimated by assuming that the density of the convective and non-convective layers can be approximated by constants. The average density of the convective layer, ρ_c , is approximately 1.51 g/cm³. The average initial degassed density of the non-convective layer, ρ_{nc} , is approximately 1.63 g/cm³. The buoyant force must equal the tensile strength of the slurry/sludge when the non-convective region overturns.

The equation which yields the vertical degassed dimension, h_i , of the region that has overturned is:

$$h_i = \frac{(\Delta h - \frac{\sigma}{\rho_l})}{(\frac{\rho_{sl}}{\rho_l} - 1)} \quad (2.7)$$

The actual thickness of the overturn layer, h_r , at rollover is approximated by Equation 2.8:

$$h_r = h_i + \Delta h \quad (2.8)$$

Equation 2.9 is used to calculate the density of the overturn layer at rollover, ρ_{sl} :

$$\rho_{sl} = \rho_{sl} \left(\frac{h_i}{h_r} \right) \quad (2.9)$$

As the void fraction of the sludge/slurry layer increases due to gas generation, the effective yield stress decreases due to a decrease in the cross-sectional area. Both the buoyant force and the effective yield strength are a function of the pressure distribution throughout the slurry/sludge region. From the assumptions of a constant gas generation rate and constant degassed densities in the convective and non-convective regions, the approximate separation point in the sludge/slurry region can be calculated.

2.2 SCALED SIMULATION

The main objectives of simulating the overturn event include:

- To observe the height increase of the slurry layer prior to overturn
- To observe the tank from all directions to note general three dimensional events
- To observe bubble formation
- To identify different types of gas release phenomena
- To observe the overturn event in three dimensions
- To observe settling of solids after an overturn
- To study crust formation

By using Equation 2.8, the importance of yield stress on an overturn event can be explored. For this example, two slurry overturn thicknesses have been calculated, 130 and 150 inches. The slurry is assumed to be uniformly gassed. For the purpose of comparison, and from data contained in the Hanford documents listed in Chapter 7, the largest observed gas release to date is approximately 10,000 scf. Figure 2.2 illustrates the relationship of the size of a gas release to the yield stress. Based on theoretical calculations, the yield stress of the material has to be relatively low at the time of an overturn event or much larger gas releases would be occurring. For the amount of gas being released, the yield stress is probably not greater than 2,000 dynes/cm², or 0.03 psi, at overturn. This leads to the assumption that yield stress does not appear to be a significant factor in the determination of the magnitude of gas being released at this time. As the sludge/slurry layer "ages" through such phenomena as cooling, crystallization, and settling; yield stress may eventually become the dominant factor in the amount of gas released.

In Tank 241-SY-101, increasing pressure at increasing depth creates the situation where the entire slurry/sludge layer does not overturn during every event. The volume of gas generated near the bottom of the tank is compressed to a greater degree than that near the top of the slurry layer. Buoyant forces generated by the gas tend to exceed the relatively low tensile strength at progressively deeper regions with subsequent overturns. It appears that the sludge/slurry layer detaches during every third or fourth overturn event. When this occurs, much of the slurry above it is not fully gassed. It also appears that part of the sludge has a yield strength large enough to prevent detachment.

Figure 2.2: Calculated Gas Release From Hanford Tank 241-SY-101 Versus Yield Stress Based on Level Decrease During an Overturn Event

To expedite testing processes, the gas generation rate per unit volume of a simulant would be increased by a factor of 100 to 1000, as given by Equation 2.3. Ideally, an overturn time of less than three hours is desirable to facilitate studying several overturn events per day.

Other scaling parameters of first order importance include the ratios of slurry/sludge depth to tank diameter, supernate depth to slurry/sludge depth, and supernate density to slurry density.

2.3 APPARATUS

A series of experiments were conducted to gain a qualitative understanding of gas release phenomena. The setup for an overturn simulation consisted of a glass container of up to sixteen inches in diameter filled with a suitable simulant material. The size of the container was dependant on the type of simulant used and the overturn phenomenon to be studied. Small containers were used when hazardous simulants were used to minimize disposal problems. For each simulation, a length scale was attached to the container to provide scaling parameters. The data recorded for the tests were primarily visual observations. Simulant behavior was documented in laboratory log books, and overturn events were recorded using a CCD/VCR setup and a thirty-five millimeter camera to record the time sequence of events before, during, and after an overturn event.

3. CHARACTERIZATION OF MEASUREMENT

Characterization of measurements involves selecting simulants and equipment which will provide the most accurate representation of the Hanford waste. Once the selection of simulants and equipment has been accomplished, tests must be performed to develop the methodology necessary to obtain a complete analysis of the fluids.

3.1 SIMULANTS

Based on the data previously released from PNL, simulants with very high viscosities and yield strengths were first selected. Initial tests were performed on two simulants. These mixtures were:

- Bentonite/Barium Sulfate/Water
- Polyacrylate/Water

Analysis of the data for these tests, and subsequent correlation of the results to Hanford data led to the testing of simulants with much lower viscosities. The mixtures used for these experiments were:

- Bentonite/Water and Bentonite/Barium Sulfate/Water
- Potassium Polyacrylate (Arigel)/Water
- Pacific Northwest Laboratory Based (Agnew 241-SY-101) Simulant

To aid in the analysis of simulants used in the jet mixing and overturn simulations, additional mixtures were tested. These included; sodium silicate/sodium carbonate/sodium sulfate, plaster/sand, and sand.

Before testing with a new simulant or hardware combination was initiated, calibration fluids were analyzed to insure the accuracy of the viscometer. These calibration fluids are Newtonian and have viscosities independent of shear rate; which, for rotational viscometers is dependent on the speed of rotation. The calibration fluids were tested at various temperatures, corresponding to those at which the fluids were certified.

Problems associated with the high viscosities of the initial simulants made it difficult to obtain accurate measurements of the rheological parameters. The most recent series of tests was used to determine the effects of crystal and particle size on the accuracy of the measurements. The formula for the PNL simulant used in this series of tests was obtained from Steve Agnew of INC-14 at LANL.

3.1.1 Bentonite/Water and Bentonite/Barium Sulfate/Water Mixtures

Bentonite is a colloidal clay that occurs naturally in a dry powdered form. When mixed with water the particles of bentonite absorb up to five times their own weight. The solution thickens with time and becomes a gel-like substance. As shown in Figure 3.1, no true crystalline structures are present in the mixture. The thickening process is accelerated when the mixture is exposed to the atmosphere. This type of mixture is Non-Newtonian and the viscosity decreases as shear rate increases. The yield stress of a bentonite/water solution is dependant on the ratio of the constituents in the mixture.

Barium sulfate was sometimes added to the mixture. The addition of barium sulfate caused the bentonite/water mixture to thicken in twelve to twenty-four hours. To ensure that the viscosity is the same as that of a bentonite/water mixture, the barium sulfate/bentonite/water mixture must be allowed to set for approximately twelve hours. The handling characteristics of a solution with barium sulfate are most useful during jet mixing experiments when the mixing cell is filled. Experimental bentonite/barium sulfate/water mixtures included 1:2.2:3.5, 1:3:9.3, and 1:1:7, barium sulfate:bentonite:water and 1:16, 1:10, and 1:7 mixtures of bentonite and water. The measurements were taken at room temperature, 45° C, or 60° C.

Figure 3.1: Bentonite/Water Mixture Physical Characteristics

Lines in this figure are 100 and 20 microns apart.

3.1.2 Polyacrylate/Water Mixtures

Potassium polyacrylate (arigel) and water mixtures were used for the majority of the polyacrylate experiments. Tests were also performed using sodium polyacrylate. Sodium polyacrylate mixtures absorbed more water than potassium polyacrylate, and therefore the high viscosities tested with arigel mixtures could not be as easily attained. One benefit of using polyacrylate mixtures is that they form a clear solution, so jet mixing experiments and flow tests are easily visualized.

When arigel is mixed with water the resultant mixture is a colorless, Non-Newtonian solution. As studied under a microscope, pure arigel powder does not possess crystalline structures, although individual particles of various sizes are present. The sizes of the particles are random and appear to be related to atmospheric moisture absorption. After the powder is mixed with water, no individual grains of arigel are observed. The individual formations seem to fuse together into an amorphous mass.

Two initial mixtures of potassium polyacrylate and water were analyzed. These mixtures were in ratios of 1:65 and 1:48. The 1:65 sample was tested twice, with a period of ten days in between tests. The ten day period between tests was to aid in analyzing the effects of time on polyacrylate mixtures. Tests were also conducted on 1:15 and 1:20 mixtures.

3.1.3 241-SY-101 Tank Simulant

Testing the viscosity of saturated solutions poses additional problems. In addition to problems inherent to Non-Newtonian fluids, these solutions generate crystalline structures. This saturated solution tends to thicken with time and crystallization and settling occur in different areas of the container at different rates. A thixotropic solution such as this is characterized by decreasing viscosity and shear stress when subjected to a constant shear rate.

Before any testing was performed, the material was mixed to ensure a uniform solution. At this point the density of the solution was measured to be 1.35 g/cm^3 . This mixing produces a highly disturbed, homogeneous material with physical properties such as viscosity, shear stress, and yield stress near the minimum possible. The mixing also prevented the buildup of large solid masses of material. The mixture was noticed to coagulate with time due to crystal formation. The majority of crystals in the solution were observed to be from 20 to 40 microns in size. The various crystal formations are depicted in Figure 3.2.

The chemical composition of the 241-SY-101 simulant is presented in Table 3.1.

Table 3.1: 241-SY-101 Simulant Chemical Constituents

Chemical Compound	Quantity (g/l)
Na ₄ EDTA	50.00
Na ₃ HEDTA	50.00
NaAlO ₂ + 0.21NaOH + 1.33H ₂ O	196.07
NaNO ₂	244.95
NaNO ₃	317.05
Na ₂ CO ₃	56.19
NaOH	139.60

Figure 3.2: Agnew 241-SY-101 Simulant Crystal Formations

Lines in this figure are spaced 100 microns apart.

3.1.4 Simulant Analysis

The calibration fluids were tested to establish a reference for testing of the simulant mixtures. Because the bentonite mixtures, arigel mixtures and the PNL simulant are Non-Newtonian fluids, they all have characteristics different from this standard. The different simulants allow for a comparison of the apparatus listed in sub-section 3.2.1 through the testing of materials with different physical and chemical characteristics. The bentonite is a particle solution in a gel form, while the 241-SY-101 simulant contains crystals that form with time.

3.2 MEASUREMENT

A number of different methods were used to measure the rheological properties of the different simulants. This section presents the methodology used in the collection of data for each instrument, descriptions of the apparatus, calibration procedures, data analysis, and the accuracy of each measurement.

3.2.1 Apparatus

With the exception of the capillary and the falling ball viscometers, all of the procedures rely on the principle of rotation to measure viscosity. In conjunction with DV-II+ version 1.0 software, the Brookfield viscometers measure percent torque, rotational speed, and temperature. These parameters are then manipulated in a series of equations to yield the viscosity, shear rate, and shear stress of the fluid.

3.2.1.1 LV Viscometer and Spindle Set

The LV viscometer used for the tests is a Brookfield Digital Viscometer Model LVDV-II+ . This viscometer is normally used in combination with a guard leg. Due to the types of materials tested, the guard leg has not been used; however, the removal of this component has been integrated into the calibration of the spindles.

The LV spindle set used with the LVDV viscometer consists of both disk and cylindrical spindles. The disc spindles return accurate results of apparent viscosity for most fluids; however, the cylindrical spindles are of specific importance when data are gathered on Non-Newtonian, shear thinning fluids. The geometry of the cylindrical spindles allows for the direct calculation of shear rate, shear stress, and viscosity.

Each LV viscometer is used with a constant temperature water bath. The bath is used to ensure that thermal equilibrium of the simulant is maintained. Since the viscosity of a fluid will change with a variation in temperature, it is critical that the temperature of the mixture be uniform. Temperature effects will be discussed in more detail in sub-sub-section 3.2.3.1.

3.2.1.2 Cone and Plate Viscometer

The cone and plate viscometer used to collect data is a Brookfield Digital Viscometer Model HBDV-II+.

The gap between the cone and the plate must be reset every time the spindle is removed. While a test is being performed, the gap thickness should be thirteen microns. For each spindle, a specific amount of fluid must be used. After the plate is attached to the viscometer, a minimum of one hour should be allowed for the sample to settle before measurements are conducted.

The plate or cup acts as a water jacket for the sample. It is connected externally to a water bath, which keeps the cup and the sample at a constant temperature. It is important to wait an hour before testing to ensure that the sample is at the desired temperature. It should be noted that at high temperatures (approximately 65°C or above) the thin film of fluid is severely chemically altered, resulting in surface charring of the plate.

3.2.1.3 LV Viscometer with Small Sample Adapter

The small sample adapter is used in conjunction with the LV viscometer described in sub-sub-section 3.2.1.1. The small sample adapter consists of a cylindrical sample chamber, water jacket, and spindle. Advantages of this system include:

- **Removable sample chamber:** Allows successive measurements without changing the operating conditions.
- **Limited sample volume:** A maximum of 16 ml of fluid is required for testing.
- **Temperature control:** A jacket surrounds the chamber so that precise temperature control can be maintained.

3.2.1.4 LV Viscometer with T-Bar and Helipath

The helipath stand is also used with the LVDV-II+ viscometer. A configuration with the T-bar spindles is especially suited for materials having the consistency of a gel or paste. Unlike the cylindrical or disc spindle which may form a "channel" after a short period of time, the T-bar spindles and helipath stand operate in a helical pattern, thereby continuously testing undisturbed fluid. The difficulty with this system is that the complex geometry does not allow for the calculation of shear rate. Hence, data obtained from the T-bar configuration may not be compared to data acquired with other instruments, except as a function of RPM.

3.2.1.5 Capillary Viscometers

The capillary viscometers used in the collection of data were:

- Technical Glass Products Cross-Arm Viscometer # 9 and # 10
- Technical Glass Products Ubbelohde Viscometer # 5

Viscosity measurements acquired with these devices are based on constants developed for each particular viscometer. The appropriate constants are furnished by the manufacturer. The calculated viscosities are functions of flow time and temperature. These instruments may theoretically be used with Newtonian and Non-Newtonian fluids in the determination of viscosity, shear rate, and shear stress; however, many discrepancies in the data were observed when these devices were used to test Non-Newtonian, shear thinning fluids.

3.2.1.6 Falling Ball Viscometers

The falling ball viscometer used for these tests was:

- Gilmont Instruments Falling Ball Viscometer # 3

As with the capillary viscometers, the rheological parameters yielded by this instrument are based on constants provided by the manufacturer. This particular instrument is used with three different balls; glass, stainless steel, and tantalum. Each ball provides data for a particular viscosity range; with the maximum viscosity for this instrument being 2000 cP. When this viscometer was used to test the viscosity of Newtonian calibration fluids, the results were comparable to the certified values; however, when the instrument was used to test Non-Newtonian mixtures, no results could be obtained.

3.2.2 Calibration

Calibrations are performed to ensure accuracy of measurement. The accuracy is dependent upon the viscometer, the spindle used for the test, and a specific procedure followed by the individual making the measurements.

To calibrate the viscometers, the same procedure was followed as that to conduct a rheological test. The results from this calibration test were then compared to the certified standard of the calibration fluid. Any discrepancies in the two values were then investigated. Many factors may affect the viscosity measured by the viscometers; including but not limited to:

- Temperature of the sample
- Temperature uniformity
- Sample size
- Limitations of viscometer

Each viscometer had a specific range of viscosities for which accurate results could be obtained. Many also required that specific volumes of fluid be used. Any deviation from these stipulations were noted to result in data which deviated from the expected results.

The certified standards used in the calibration of the viscometers are presented in Table 3.2. All of the calibration fluids are traceable to a standard by the National Institute of Standards and Technology.

Table 3.2: Calibration Standards

Viscosity Standard	Manufacturer	Lot No.	Temp. (C)	Viscosity (cP)	Exp. Date
N2700000	CANNON	92102a	25.00	5827000.0	28-Feb-94
			60.00	375800.0	
N450000	CANNON	92202	25.00	1538000.0	30-Apr-94
			60.00	98790.0	
N190000	CANNON	91105	20.00	914500.0	28-Feb-94
			25.00	566700.0	
			40.00	152800.0	
			60.00	34700.0	
N62000	CANNON	92201a	25.00	202300.0	31-Mar-94
			60.00	17200.0	
100000	BROOKFIELD	121692	25.00	95680.0	
100000	BROOKFIELD	121692	25.00	95680.0	
100000	BROOKFIELD	111292	25.00	95520.0	
60000	BROOKFIELD	110292	25.00	55424.0	
60000	BROOKFIELD	110292	25.00	55424.0	
60000	BROOKFIELD	110292	25.00	55424.0	
30000	BROOKFIELD	103092	25.00	31560.0	
12500	BROOKFIELD	111792	25.00	12980.0	
5000	BROOKFIELD	061092	25.00	5080.0	
FM1500	VISCOMETERS (UK) Ltd	61231	25.00	1541.0	
FM1000	VISCOMETERS (UK) Ltd	20791	25.00	990.0	
1000	BROOKFIELD	052692	25.00	959.0	
FM500	VISCOMETERS (UK) Ltd	23491	25.00	538.0	
500	BROOKFIELD	052292	25.00	487.0	
VP160	CANNON	92101	20.00	431.7	31-May-93
			24.00	323.4	
			24.50	312.4	
			25.00	301.7	
			25.50	291.5	
			26.00	281.7	
FM100	VISCOMETERS (UK) Ltd	15292	25.00	104.0	
100	BROOKFIELD	062992	25.00	98.0	
50	BROOKFIELD	050492	25.00	49.3	

3.2.3 Procedure

Each viscometer used in the gathering of data had specific instructions on correct operation. The purpose of this sub-section is to present a brief overview of the methodology used in data collection.

3.2.3.1 Rotational Viscometers

For viscometers yielding data based upon rotation, the following parameters must be integrated into the data analysis:

- Temperature ($\pm 0.1^\circ$)
- Viscometer Model
- Spindle Used
- Rotational Speed or Speeds
- Length of Time (The manufacturers recommend that a minimum of 5 revolutions must occur between readings)
- Container Size
- Sample Volume

Each viscometer/spindle set may have specific guidelines regarding these parameters. Guidelines for specific viscometer configurations include the following:

LV and T-bar Arrangements: A 600 ml Low Form Griffin Beaker must be used. This beaker takes into account the given volume around the spindle accounted for in the equations for the viscometer.

Small Sample Adapter and Cone and Plate Configurations: The small sample adapter chamber and plate used with the cone and plate viscometer are specifically designed to be used with their counterparts. Each has a specific amount of fluid required for testing depending upon the spindle number. A syringe is used to accurately measure the amount of sample required. For the Agnew 241-SY-101 simulant the syringe has been altered to have a large inlet allowing for the crystals in solution.

As mentioned in sub-sub-section 3.2.1.1, sample temperature and thermal equilibrium greatly affect the viscosity of a material. Tests were performed to ascertain the effects of temperature variations on viscosity and the time required for thermal equilibrium when the fluids are exposed to increases or decreases in temperature. The results of these tests suggest that a minimum of three hours be allowed for the thermal equilibrium when a simulant is tested at an elevated temperature. Temperature effects, as well as results from the thermal equilibrium tests, are contained in sub-section 3.2.5.

3.2.3.2 Capillary Viscometers

For the capillary viscometers, the parameters that must be recorded include:

- Material density, ρ
- Local gravity, g
- Radius of capillary, r
- Driving head, H
- Length of capillary, L
- Volume of liquid used in the measurement, V
- Flow time, t
- Temperature, T

The viscosity results yielded by the capillary viscometers are dependent on the flow time of the fluid. The data recorded for the aforementioned parameters are then used in conjunction with the equations contained in sub-sub-section 3.2.4.2 to calculate viscosity, shear rate, and shear flow.

3.2.3.3. Falling Ball Viscometers

For the falling ball viscometer, viscosity is determined through the use of equations provided by the manufacturer. These equations, which are discussed in sub-sub-section 3.2.4.3, yield data based on the following parameters:

- Fluid density, ρ
- Ball density, ρ_b
- Time of descent, t
- Viscometer constant, K
- Temperature, T

Viscosity values obtained by the falling ball viscometers are a function of the geometry of the instrument and the time of descent. Theoretically, the shear rate may be changed by tilting the viscometer at different angles.

3.2.4 Data Analysis

The purpose of this sub-section is to present the methodology and equations used to calculate rheological properties of the simulants. The factors associated with each piece of equipment will be addressed individually, and all pertinent equations, reasons for discrepancies in the data, and necessary assumptions will be discussed.

3.2.4.1 Rotational Viscometers

During testing the rotational viscometers are connected to DVGather+ data acquisition software. Various rheological parameters are provided by the software or can be calculated using the measured torque and RPM. The data provided by the software differs for each spindle configuration; however, all necessary rheological parameters may be obtained either directly from the data acquisition software or by the following equations. Equations 3.1 through 3.3 are used to calculate the viscosity, shear rate, and shear stress.

$$\text{Viscosity (cP)} = \frac{100}{\text{RPM}} \cdot \text{TK} \cdot \text{SMC} \cdot \text{Torque} \quad (3.1)$$

$$\text{Shear Rate } \left(\frac{1}{\text{sec}} \right) = \text{RPM} \cdot \text{SRC} \quad (3.2)$$

$$\text{Shear Stress } \left(\frac{\text{Dynes}}{\text{cm}^2} \right) = \text{TK} \cdot \text{SMC} \cdot \text{SRC} \cdot \text{Torque} \quad (3.3)$$

Where:

RPM	=	Viscometer speed in revolutions per minute
TK	=	Viscometer torque constant
SMC	=	Spindle multiplier constant
SRC	=	Shear rate constant
Torque	=	Viscometer percent torque

The constants used in the previous equations are provided by the manufacturer and are based upon the geometry of the spindle. The constants for the spindles used are contained in Table 3.3.

Table 3.3: Spindle Constants

Spindle	SMC	SRC
LV2 cyl	32	0.212
LV3 cyl	128	0.210
CP41	1.228	2
CP52	9.83	2
SC4-31	32	0.34
SC4-34	64	0.28

The torque constants for the LV and HB model viscometers are 0.09373 and 8, respectively.

3.2.4.2 Capillary Viscometers

To calculate rheological properties using capillary viscometers, constants for each viscometer are provided by the manufacturer. Kinematic viscosity in centistokes is obtained by multiplying the appropriate constant by the flow time. The viscosity in centipoise may then be obtained by multiplying the kinematic viscosity by the density of the material. Viscosity, shear stress, and shear rate are given by Equations 3.4 through 3.6.¹

$$\text{Shear Stress } \left(\frac{\text{Dynes}}{\text{cm}^2} \right) = \frac{H \rho g}{2L} \quad (3.4)$$

¹ Equations for the capillary viscometers were received from Joseph Murray of Technical Glass Products.

$$\text{Shear Rate } \left(\frac{1}{\text{sec}} \right) = \frac{4V}{\pi r^3 t} \quad (3.5)$$

$$\text{Viscosity (cp)} = t \cdot K \quad (3.6)$$

In Equations 3.4 through 3.6:

K	=	Viscometer constant
ρ	=	Density of the material
g	=	Local gravity
r	=	Capillary radius
H	=	Capillary driving head
L	=	Capillary length
V	=	Volume of liquid
t	=	Flow time

The shear stress and shear rate for each capillary is fixed by the geometry of the viscometer and the density of the material. This makes it difficult to correlate the data obtained from these viscometers to data obtained from other testing methods.

As discussed previously, the constants used in Equation 3.6 to calculate viscosity are provided by the manufacturer. The constants for the viscometers are listed in Table 3.4.

Table 3.4: Capillary Viscometer Constants

Viscometer	Constant
TGP Viscometer # 9	30
TGP Viscometer # 10	100
TGP Ubbelohde Viscometer # 5	100

3.2.4.3 Falling Ball Viscometer

As in the case of the capillary viscometers, the calculated values of viscosity given by the falling ball viscometer are directly related to constants developed by the manufacturer which are based on the geometric characteristics of the instrument. The approximate constant for this viscometer was 35.

$$\text{Viscosity (cp)} = K \cdot (\rho_b - \rho) \cdot t \quad (3.7)$$

$$\text{Shear Rate } \left(\frac{1}{\text{sec}} \right) = \frac{2}{3} D_r (\rho_b - \rho) \sin \theta \quad (3.8)$$

Where:

K	=	Viscometer constant
ρ_b	=	Ball density
ρ	=	Fluid density
t	=	Descent time in minutes
D_r	=	Equivalent cylindrical length of sphere
θ	=	Angle of instrument from horizontal

For tests performed at angles other than 90°, the time used in Equation 3.7 must be corrected to obtain accurate results. Equation 3.9 provides the necessary correction.

$$t \text{ (sec)} = t' \cdot \sin \theta \quad (3.9)$$

Where:

t'	=	Descent of ball at angle θ from the horizontal
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By varying the angle at which the viscosity measurement is taken, a plot may be constructed similar to that obtained with the rotational viscometers. In theory, this concept may also be applied to the capillary viscometers; however, the applications of commercially available falling ball and capillary viscometers to Non-Newtonian fluids is limited.

3.2.5 Accuracy

Accuracy of measurement includes uncertainty and variation. For most of the apparatus used in the collection of data, the factors determining the accuracy were defined so that a numerical analysis could be performed. The purpose of this sub-section is to discuss the various parameters that affected the accuracy of the tests.

3.2.5.1 Rotational Viscometers

The following conditions affect the accuracy in measurement. This list is not necessarily inclusive of every factor affecting accuracy.

- Container size and geometry
- Temperature uniformity and maintainability
- Location of spindle in solution
- Slipping of spindle
- Presence of air bubbles in mixture
- Interference of temperature probe in solution
- Balancing of viscometer
- Particulate size and distribution

By controlling these factors the uncertainty and variation may be reduced to an acceptable level.

For the work relating to the Hanford experiment, low range speeds (0.3-2.0 RPM) are of main importance. To reduce errors and increase reliability, it is desirable to work with a viscometer/spindle combination that returns a percent torque close to 50. The closer to 100 percent torque the more accurate the reading, but any reading between 10 and 90 percent may be accepted as an accurate result.

Equation 3.10 is used to determine the viscosity range for a viscometer/spindle combination to provide accurate data. The constants are as defined in sub-section 3.2.4.1.

$$\text{Full Scale Viscosity Range (cP)} = TK + SMC + \frac{10000}{\text{RPM}} \quad (3.10)$$

A value of 1 percent of the full-scale viscosity range indicates a $\pm$ value within which the test results can be considered accurate.

If a Non-Newtonian, shear thinning fluid was tested at 0.3 RPM with an LV2 spindle and an LVDV viscometer and returned a measured viscosity of 35000 cP, the uncertainty would be calculated in the following manner. One percent of the full-scale viscosity range, which is based solely on the equipment used and the operating speed, returns a value of 1000 cP (from Eq. 3.10). This value is used in Equation 3.11 to determine the uncertainty. In this example, the uncertainty is $\pm 2.85\%$.

$$\text{Uncertainty} = \frac{0.01 * \text{Full Scale Viscosity Range}}{\text{Measured Viscosity}} \quad (3.11)$$

The readings taken from the viscometer also involve a measured accuracy, or precision, due to the number of readings. This parameter is referred to as variation. The variation is calculated using Equation 3.12:

$$\text{Variation} = \frac{\text{AVG (Range of Readings)} - \text{Specific Reading}}{\text{Specific Reading}} \quad (3.12)$$

This variation is the difference between the measured value and the average of the measured values. Using the same example, with an average viscosity of 35500 cP, the variation is equal to -1.42%. For the measured viscosity of 35000 cP, the value is accurate from -4.27% to +2.85% or 33505 cP to 35997 cP.

A numerical analysis could not be conducted to ascertain the effects of testing a sample in which thermal equilibrium had not been reached. Thermal tests were performed using two of the simulants; an arigel/water mixture and Agnew's 241-SY-101 simulant. Each of the tests consisted of placing the sample in a water bath and increasing the bath temperature. Six thermocouples were placed in the container to record the temperature variation from the outermost point to the center of the 600 ml low form beaker. The thermocouples were equidistance apart and positioned to record temperatures from the center of the beaker to the outermost point. Tests were performed with the thermocouples midway between the top of the mixture and the bottom of the container. The results of these tests are depicted in Figures 3.3 and 3.4.

Figure 3.3: Arigel Thermal Equilibrium Data

Figure 3.4: 241-SY-101 Simulant Thermal Equilibrium

The data from these tests served to reaffirm the procedure of allowing a minimum of three hours for the simulants to reach thermal equilibrium before a test is begun.

Several trials were also conducted to determine the residual torques present with the use of the LVII+ viscometer. Tests were performed using the 241-SY-101 simulant at two different temperatures. The tests consisted of operating the viscometer at a constant RPM and at zero RPM and taking data. Graphical results of these tests are presented in Figures 3.5 and 3.6.

Figure 3.5: 241-SY-101 Simulant Residual Torque

As illustrated in Figure 3.5, residual torques are present when tests are performed with the LVII+ viscometer. During the tests represented in these figures, data were gathered every thirty seconds. This was done to obtain a graphical representation of the differential viscosity of the material when subjected to a constant shear rate. The fluctuations of viscosity may be attributed to particle migration or a difference in material density in different sections of the solution. The data fluctuations inherent to the material cause minor discrepancies in the data presented in Chapter 5; however, the data may still be considered valid for comparison purposes. To provide further insight into the behavior of the 241-SY-101 simulant, a calibration fluid was tested in the same manner. A comparison of the two fluids is presented in Figure 3.6 on the following page.

Figure 3.6: Residual Torque Comparison

Figure 3.6 serves to illustrate the thixotropic nature of the 241-SY-101 simulant. At each point where the shear rate was altered, the percent torque gradually lessened until an equilibrium was reached. No such phenomenon was present with the calibration fluid. The percent torque values are directly related to the viscosity values, so the same trend towards an equilibrium is evident.

3.2.5.2 Capillary Viscometers

The main factors causing uncertainty in data yielded by the capillary viscometers are testing methodology and fluid characteristics. The values for viscosity are obtained by multiplying the observed flow time by an approximate constant provided by the manufacturer. Since the constant is approximate and the determination of the flow time is based on experimental observation, uncertainties in the viscosity values are difficult to analyze numerically. Furthermore, no documentation was furnished with the equipment regarding the uncertainties associated with the constant. It is therefore not feasible to assign a numerical value to the uncertainty of each reading.

The physical characteristics of the fluid being tested also cause uncertainty in the measurements. The calculations for viscosity and shear rate are dependent on the behavior of the fluid as it travels through the capillary. These calculations are valid only if the fluid travels through the capillary in a continuous manner. Tests were first performed on Newtonian calibration fluids, which flowed through the capillary in a uniform manner. When tests were

performed using Non-Newtonian, shear thinning fluids, it was observed that the behavior of the fluids when traveling through the capillaries was less uniform than that of the Newtonian fluids. The flow rate increased as the fluid traveled downward. Even when tests were repeated using the same simulant fluids under the same conditions, different viscosity values were calculated.

3.2.5.6 Falling Ball Viscometer

The falling ball viscometer used to test the simulants was greatly affected by the particular characteristics of each fluid. Since the results obtained by the falling ball viscometer are based on equations developed by the manufacturer, numerical uncertainties could not be calculated. The viscosity values for the calibration fluids were within acceptable ranges to the standards issued by the manufacturers; however, multiple tests performed using a potassium polyacrylate/water mixture yielded no results. The gel-like nature of the mixture prevented the ball from travelling through the tube, so data could not be taken.

3.2.6 Conclusions and Recommendations

Adhering to the procedures in sub-section 3.2.3 and controlling the additional parameters discussed in section 3.2.5, the measurements made with the rotational viscometers are acceptable for most fluids. Based on the data gathered from the calibration fluids, all of the rotational viscometers are calibrated within range for Newtonian fluids. The presence of crystals and particles limits the applicability of some rotational viscometers for use with some Non-Newtonian fluids.

Both the cone and plate and small sample adapter furnish reliable data for applications in which a limited volume and accurate temperature control of a sample are needed. The T-bar and helipath stand is best utilized in instances where the sample may be altered by the rotating effects of cylindrical spindles.

The measurements yielded by the capillary viscometers could not be compared to the data obtained with the other viscometers; therefore, these measurements could not support or refute the results gathered from the other techniques. This may be attributed to the fact that these viscometers are designed to be used in the testing of Newtonian fluids. The simulants used in this research are Non-Newtonian, shear thinning fluids which do not flow in the manner required for accurate results. Data from the falling ball viscometer was to be used as another comparison to the rheological characteristics provided by the rotational viscometers; however, the Non-Newtonian characteristics of the simulant fluids and the 2000 cP viscosity limit prevented any data from being recorded.

4. MIXING STUDIES

A jet mixing process has been chosen by Hanford as a potential means of mixing Tank 241-SY-101 in a controlled manner. A jet mixing system has been designed, fabricated, and installed in the tank. Experiments are in progress to determine the effectiveness of the jet mixing system.

At Los Alamos National Laboratory, parametric studies have been completed to gain an understanding of the importance of certain scaling parameters. Both open and closed loop tests were performed. In the closed loop tests the fluid was recirculated back into the system, whereas in an open loop test the fluid was discarded. The following parameters are considered when a jet mixing study is initiated:

- Required operating pressures
- Nozzle diameters
- Jet velocities
- Jet dynamic pressures
- Material properties of slurry simulants
- Penetration distances by jets into simulants

By understanding the importance of the aforementioned parameters and several non-dimensional scaling parameters, the potential effectiveness of the Hanford system and possible system improvements could be determined.

4.1 APPARATUS

The setup for a mixing study consists of a test cell containing tank simulant, several different sizes of nozzles, several different types of pumps, and instrumentation to measure and record desired flow and material parameters.

Both two and three dimensional (2-D and 3-D) test cells were studied. The 2-D cells were used with opaque simulants to allow for flow visualization studies. The test cells for the 2-D experiments had thicknesses of 1/8, 1/4, and 3/4 inches. For the 3-D experiments, a 16 inch diameter glass cylinder was primarily used.

Several different sizes of nozzles were used. With the 1/8 and 1/4 inch 2-D cells, the nozzles were typically square and built into the end walls. With the 3/4 inch 2-D and the 16 inch glass diameter cylinder, round nozzles with inside diameters of 0.07, 0.09, 0.13, and 0.19 inches were used.

Due to the tendency of the nozzles to plug, and due to the significant yield stresses of some of the simulants, three different types of pumps were considered for use. These pumps included; centrifugal, gear, and diaphragm. The limited head capability of the centrifugal pumps limited their application. High starting pressure transients were common, but did not occur on every test. Since the test requirements often needed a high transient pressure and a small flow rate, gear pumps were generally used for the tests. Diaphragm pumps should be used when the test environment encountered with closed loop systems presents the possibility of chunks of slurry plugging the pump or nozzle. Unfortunately, a diaphragm pump small enough for the laboratory experiments could not be obtained until it was too late to be utilized.

Many different types of simulants representing a wide variety of physical properties were used during the test program. Simulants used for jet mixing experiments included:

- Sand
- Ceramic slip
- Bentonite and barium sulfate mixtures
- Sodium and potassium polyacrylate mixtures
- Plaster/sand mixtures
- Sodium carbonate/sodium silicate/sodium sulfate mixtures

A data acquisition system was used to record the experimental parameters. Pressure transducers were used to measure the pressure just before the nozzle and the pressure differential across a Venturi meter. Experimental data were gathered on a MacIntosh computer in conjunction with a MacAdios IO board and a software package called SuperScope. The data acquisition system emulated an oscilloscope, and was configured to monitor the pump voltage, flow rate, and the nozzle pressure. The flow rate was calculated from the correlation of the differential pressure across the Venturi to a measured flow rate. Nozzle velocity was calculated by dividing the flow rate by the cross-sectional area of the nozzle. Velocity and pressure were then measured as functions of time.

4.2 PROCEDURE

A typical jet mixing test consists of some or all of the following steps:

- Equipment calibration
- Simulant preparation
- Measuring of simulant properties
- Preparation of test configuration
- Preparation of data acquisition system
- Initiating test
- Data acquisition
- Data analysis

Slight variations for each of the procedures occur based on the type of test and the nature of the simulant; however, the same general procedures are followed for any jet mixing experiment.

4.2.1 Simulant Preparation

For most of the jet mixing experiments, the simulants have been mixed in the following manner in an industrial strength mixer.

- Water is added
- Mixer is started
- Simulant is added slowly to allow for proper mixing
- Enough time is allowed for the solution to become thoroughly mixed

This procedure is repeated until a sufficient quantity of the simulant is produced. Enough must be produced to allow for testing of the rheological properties, in addition to the amount required for the mixing test.

4.2.2 Data Acquisition

Data were gathered in two ways. Numerical data were collected as stated in section 4.1. The other method of gathering data was through flow visualization. Both the 2-D and 3-D experiments were configured to optimize visual observation. Almost all of the tests were recorded on video tape. Thirty-five millimeter cameras were also used to document the tests.

5. RESULTS AND DISCUSSION

The purpose of this chapter is to discuss the three types of experiments performed to simulate the contents of Hanford Tank 241-SY-101.

5.1 OVERTURN SIMULATIONS

Over fifty tests were conducted to simulate Hanford Tank 241-SY-101 overturn phenomenon. The purpose of the tests was to develop an understanding of the different types of overturns which occur. Generally, the overturn events may be categorized as either top peel, volcanic, or total turnover.

In a top peel overturn, material from the top part of the slurry peels away in small pieces or sections. Some of this material floats to the top of the tank and becomes part of the crust, while some precipitates down to the top of the slurry layer. This type of slurry movement occurs at random, frequent intervals throughout the tank. Applying these characteristics to the tank described in sub-section 2.1.1, it is likely that top peeling occurs in the forty to sixty inches between the supernate and the top of the slurry. This type of phenomenon is one possible explanation of the temperature distribution in the top part of the slurry layer.

Volcanic type events occur when bubbles form at localized regions of the slurry. When bubble formation is sufficiently large, the bubbles break through the slurry layer. As the bubbles rise, material from the slurry layer is carried with them. The cavity created by this event is rapidly backfilled with surrounding slurry material. Volcanic overturns result from cracks or weaker regions of the slurry which allow gas to move and accumulate. Cracking or weak regions result from the swelling of the slurry caused by gas generation or non-uniformity of the redeposition process after an overturn. This type of event is also applicable in analyzing jet mixing due to the tendency of the slurry to crack or the jet to channel through the slurry. Volcanic overturn phenomenon and its relevance to jet mixing will be discussed further in section 5.3.

When bubble formation is uniformly dispersed, the entire slurry layer overturns. Bubbles formed in the slurry layer are generally smaller than those causing a volcanic overturn. On some occasions, the slurry layer drifted upward as a plug. The gap created by the plug tended to fill slowly with precipitates from the bottom of the floating slurry layer. In tests where the length scales discussed in section 2.2 were similar to the actual tank, the plug started to break apart before it floated to the top of the tank. During these simulations it was also noticed that all portions of the plug did not rise at the same time, but peeled off non-uniformly from the bottom of the tank.

In some tests the overturn was volcanic and localized. With such an overturn, the material from a small section erupted through a layer of slurry carrying debris with it. At other times, the slurry layer overturned as a unit. Significant factors which influenced observed processes include the viscosity of the slurry and the size and distribution of bubbles formed within the slurry. Higher viscosities, and the resulting higher yield stresses, in the slurry layer seemed to cause the slurry to form a plug that would rise as a whole, break apart at the surface, and then slowly precipitate back to the bottom of the tank. As observed, larger bubbles tended to increase the probability of volcanic type overturns. Bubbles close to the top of the slurry also tended to cause an increase in the number of volcanic type gas venting occurrences.

The experiments were documented and recorded with still photographs and on videotape. Photographs included in this section provide examples of the types of phenomenon previously discussed. It should be noted that the photographs were not taken from a single test. Figures 5.1 and 5.2 show the slurry in a nearly degassed state. In Figure 5.1, the surface of the slurry is not level. This resulted from uneven settling of the slurry after an overturn. Figure 5.2 was also taken after an overturn. In this event the finer material settled last, resulting in stratification throughout the slurry layer.

Figures 5.3 through 5.6 sequentially display a localized event. This event is most typical of surface peeling overturn. The gas accumulation located beneath and to the right of the overturn eventually resulted in a volcanic overturn. Other features of importance include the crust or foam layer on top of the liquid and the material on the sides of the container resulting from splashing. These key elements provide insight into the violent nature of the overturns.

A total overturn sequence is depicted in Figures 5.7 through 5.10. Figure 5.7 shows a massive separation occurring deep in the slurry layer. The separation has also initiated a release of material at the upper surface of the slurry. The widening gap between the slurry layers is shown in Figure 5.8. In Figure 5.9, the overturn has taken place and the slurry material is beginning to settle from the top of the liquid. Figure 5.10 shows most of the overturned material on the bottom of the tank and a thick crust/foam layer on the top of the liquid. Individual pieces of the crust may be seen breaking from the surface and beginning to fall toward the slurry.

Figure 5.1: Degassed slurry after overturn

Figure 5.2: Slurry stratification after overturn

Figure 5.3: Surface peeling overturn preliminary separation

Figure 5.4: Surface peeling overturn slurry behavior

Figure 5.5: Post surface peeling overturn slurry precipitation

Figure 5.6: Post surface peeling overturn material distribution

Figure 5.7: Start of total overturn separation

Figure 5.8: Total overturn slurry layer separation progressing

Figure 5.9: Post total overturn slurry precipitation

Figure 5.10: Post total overturn material distribution

5.2 RHEOLOGICAL CHARACTERIZATIONS

The measurements taken from the instrumentation described in previous chapters were obtained utilizing a number of different materials. The following fluids were used to compare the various apparatus:

- Newtonian Calibration Fluids
- Non-Newtonian, Shear Thinning Suspensions
- Non-Newtonian, Shear Thinning, Crystal Forming Fluids

Data and figures presented in this section are representative of the characteristics and testing results of a particular fluid. These data are not meant to be all-inclusive in that all testing produced the same data. They are meant to illustrate general trends in the behavior of the simulants and provide a comparison of one testing procedure to another.

Most of the comparisons are based on graphical analyses of data. Viscosity is plotted on log-log scales so that a more linear interpretation is portrayed. Shear stress is graphed as a function of shear rate. It is important to note that the point at which the shear stress intercepts the y-axis at shear rate equal to zero is the yield stress of the fluid. For all tests, a minimum of three data points are taken for each shear rate. These three points represent the variation, or scatter, discussed in sub-section 3.2.5. The variation listed in the spreadsheet data in the appendices is the difference between a point shown on the graph and the average of the data points at that specific shear rate. The accuracy of the measurements is represented as error bars above the highest point and below the lowest point. This technique was used at only a select number of shear rates to maintain the readability of the graphs.

Studying the variation provides the best comparison of one method to another because the uncertainty is independent of the type of material tested. In certain tests the data had higher uncertainty values due to the spindle chosen for testing with the particular fluid; however, the best choice of available equipment was used. If the equipment has been shown to be accurate when testing the calibration fluids, then it can be inferred that with the correct spindle/viscometer combination, a low uncertainty can be achieved. This low uncertainty, however, may not be used to denote accuracy for a particular reading. The uncertainty, when used in combination with the scatter for a particular shear rate, provides insight into the effectiveness of particular viscometer/simulant combinations.

5.2.1 Newtonian Calibration Fluids

Newtonian calibration fluids are used to verify viscometer accuracy. One such fluid was a viscosity standard from the Brookfield Corporation with a certified value of 55,424 cP at 25°C. Figures 5.11 and 5.12 present the viscosity and shear stress relationships, respectively. As illustrated by Figure 5.11, the viscosity for a Newtonian fluid is constant for a specific temperature and is independent of shear rate. The uncertainty is shown for each point in the form of error bars. Once a viscometer is proven to be within calibration, no further calibration is needed.

Figure 5.11: Viscosity of Calibration Standard at Twenty-Three Degrees Centigrade

The data obtained for the calibration fluid differs from the empirical results; however, this may be attributed to the fact that the calibration standard was certified at 25° C, whereas the test was performed at 23° C.

Figure 5.12: Shear Stress of Calibration Fluid at Twenty-Three Degrees Centigrade

To provide additional calibration verification, another test was performed using a different calibration fluid. The viscosity standard used in the 40°C test was certified at 152,660 cP for that temperature. As illustrated in Figures 5.13 and 5.14, the data yielded by the three methods corresponded to the accepted value to within approximately 15%, with high precision for each shear rate. Differences between the certified and experimental values may be attributed to difficulty in maintaining thermal equilibrium in the test sample.

Figure 5.13: Viscosity Comparison of Calibration Fluid at Forty Degrees Centigrade

Figure 5.14: Shear Stress Comparison of Calibration Fluid at Forty Degrees Centigrade

5.2.2 Non-Newtonian, Shear Thinning Suspensions

The Non-Newtonian, shear thinning suspensions used in this analysis were polyacrylate and bentonite mixtures. Various mixture ratios were used to test a broad range of viscosity values.

The first series of figures is presented to portray the results of tests performed using polyacrylate mixtures. Figures 5.15 and 5.16 display the range of viscosity as functions of time after mixing and shear rate. Figures 5.17 and 5.18 show the variation of shear stress as a function of shear rate. Table 5.1 lists the yield stress and density of potassium polyacrylate mixtures. The sample was expected to have increased in viscosity from the first test to the second test because of the reduced amount of air within the mixture; however, the viscosity decreased. This means that more drag is created in the solution with air bubbles than when most of the air bubbles have been removed. As depicted in Figure 5.17, the shear stress also decreased with time.

Figure 5.15: Potassium Polyacrylate Viscosity Relationships

Figure 5.16: Potassium Polyacrylate Shear Relationships

Table 5.1: Yield Stresses of Arigel Mixtures

Mixture Ratio (Arigel:Water)	Yield Stress (Dynes/cm ²)	Yield Stress (psi)
1:65	175	2.54(10 ⁻³)
1:15	550	7.98(10 ⁻³)
1:38	172	2.5(10 ⁻³)
1:20	400	5.8(10 ⁻³)

Figure 6.17: Potassium Polyacrylate Viscosity Variation With Shear Rate

Figure 6.18: Potassium Polyacrylate Shear Variations

Figures 5.19 and 5.20 illustrate the relationship of data obtained with different viscometers. As in previous diagrams, the full scatter of data is displayed. The uncertainty for this test was greatest with the cone and plate; approximately 15% for a shear rate of 0.880 per second. For each viscometer, the uncertainty decreased as shear rate increased.

Figure 5.19: Arigel Viscosity Relationship

Figure 8.20: Arigel Shear Stress Relationship

The Arigel tests provided data from all viscometers which was repeatable and showed little deviation from one instrument to another. The consistency of the material prevented cavitation from the spindles, therefore reducing the scatter at each shear rate.

Figure 5.21 displays the initial mixtures involving bentonite, water and barium sulfate in comparison with data received from Hanford. As these materials approached the viscosity of the Hanford data their consistency resembled that of nearly set plaster. Figure 5.22 displays the shear stress as a function of shear rate for these materials. When the shear stress/shear rate curve is extrapolated to a zero value, the yield strength for the Bingham plastic is attained. Table 5.2 summarizes the range of yield strengths and densities studied. The bentonite mixtures are not very sensitive to temperature variations in the range from 25°C to 45°C, as illustrated in Figure 5.23. At 60 °C crust formations created difficulties that have not yet been overcome.

Figure 5.21: Hanford Simulants Characteristics

Figure 5.22: Bentonite Mixture Analysis

Figure 5.23: Bentonite Mixture Temperature Effects

Table 5.2: Representative Bentonite Mixture Physical Parameters

Mixture (Barium Sulfate:Bentonite:Water)	Yield Stress (Dynes/cm ²)	Yield Stress (psi)	Density (g/cm ³)
0:1:16	69	0.001	1.12
0:1:10	207	0.003	1.26
0:1:7	1378	0.02	1.1
1:1:7	4135	0.06	1.30
2:2:1:3.5	18468	0.268	1.46
1:3:9:3	6691	0.10	1.25
Hanford Data	48237	0.7	1.7

. Density may have been affected by possible air entrapment.

To provide a basis for analysis of the data obtained from different techniques, bentonite mixtures were tested with different viscometer/spindle configurations. The results from these tests were used to study the effects of material characteristics on data output.

Figures 5.24 and 5.25 are representative of a 1:10 mixture of bentonite and water. For each test the full scatter of data points, or variation, is shown. The variation is best illustrated by the shear stress plot, Figure 5.25. The uncertainties for the data range from 1% for the Small Sample Adapter to 3% for the LV to 20% for the cone and plate. The viscosity test with each of the three methods shown in Figure 5.24 depicts a decreasing viscosity with increasing shear rate, typical characteristics of a Non-Newtonian, shear thinning fluid. The yield stress for this fluid is approximately 40 Dynes/cm². Although particles of dry bentonite are as large as 0.04 mm, this does not seem to effect the variation in the data. This is believed to be a result of the amorphous nature of the bentonite and water mixture. These non-crystalline particles seem to not offer significant resistance to the cone and plate thin film thickness.

Figure 5.24: Viscosity of a 1:10 Bentonite/Water Mixture

Figure 5.25: Shear Stress Relationship of a 1:10 Bentonite/Water Mixture

Capillary viscometers were also used to study the rheological characteristics of Non-Newtonian, shear thinning mixtures. Initial experimentation with the capillary viscometers involved calibration fluid; however, once the instrument provided accurate, repeatable results the focus was shifted to simulant materials. The simulant used in conjunction with the capillary viscometers was a 1:20 bentonite/water mixture.

A comparison of data obtained with the capillary viscometers to that obtained from other viscometers yielded inconclusive results. Figure 5.26 illustrates the data correlation for shear rate and viscosity. As depicted in this figure, the shear rates and viscosities yielded by the capillary viscometers did not correspond to the data provided by the Brookfield viscometer. As Figure 5.27 indicates, the data points for shear stress were so far removed from each other that no correlation between the two methods could be made. The tests performed with Non-Newtonian, shear thinning fluids served to question the viability of using capillary viscometers in determining the viscosity of these simulants.

**Figure 5.26: Viscosity Comparison of LV and Capillary Viscometers
For a 1:20 Bentonite/Water Mixture**

**Figure 5.27: Shear Stress Comparison of LV and Capillary Viscometers
For a 1:20 Bentonite/Water Mixture**

5.2.3 Non-Newtonian, Shear Thinning, Crystal Forming Fluids

After examination of the non-crystalline fluids discussed earlier, the saturated salt solution simulating the contents of the Hanford tank was studied. When this fluid was tested, a large variation in the testing results was observed. The data were taken at room temperature to reduce the effects caused by unequal temperatures. Figure 5.28 shows how much the scatter increased when the fluid is tested with the cone and plate apparatus. It is almost impossible to obtain specific values for the cone and plate viscometer. Even when trying to place some sort of fit to the data, as was done in Figure 5.29, there is no comparison to the LV cylindrical spindle set. Figure 5.30 shows that the typical scatter of the cone and plate viscometer is highly varied while that of the cylindrical spindle is not. Further examination of this scatter on a smaller time scale, as shown in Figures 5.31 and 5.32, shows a smooth increase in shear stress for the cylindrical spindle set but no such pattern for the cone and plate test. A possible reason for this high scatter could be the size of the crystals compared to the film thickness of the cone and plate viscometer. Other possible reasons include:

- Particle migration in shear flow
- Existence of air bubbles
- Particle size and distribution

Figure 5.28: 241-SY-101 Simulant Viscosity Comparison of LV and CP Spindles at Twenty-Three Degrees Centigrade

Figure 5.29: 241-SY-101 Simulant Shear Stress Comparison of LV and CP Spindles at Twenty-Three Degrees Centigrade

**Figure 5.30: Shear Stress Comparison of 241-SY-101 Simulant
Illustrating Cone and Plate Scatter**

**Figure 5.31: 241-SY-101 Simulant Cone and Plate Shear Stress Variance
With Time**

For the cone and plate configuration, the film thickness between the cone and the plate is 0.013 mm. Crystals as large as 0.04 mm have been observed in the Agnew 241-SY-101 simulant before testing. It is believed that these crystal sizes led to large discrepancies and poor repeatability in the cone and plate tests. The results of the large crystal size and thinner film thickness is the observed scatter.²

At this point there was still not a suitable comparison with the rotational viscometer to further support the data. Further tests were performed using the T-bar and small sample adapter. The results of these tests are depicted in Figures 5.32 through 5.35. It was a possibility that, with the cylindrical spindles, particles were actually being pushed out of the region where the fluid was being tested. The T-bar was used because it continuously examines new material in its helical path. Figures 5.34 and 5.35 show the comparison between the cylindrical spindles and the small sample adapter. The small sample adapter also prevents the problem of particle migration from the test area. The special geometry of the small sample adapter spindles and the small volume of the test chamber allow for a better mixing of the fluid while it is being tested.³

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2. Technical support personnel at Brookfield stated that since the cone and plate was the only viscometer which was characterized by such a large scatter in the data, that the crystalline nature of the particle and the size of the film thickness created the large variation in readings.
 3. The assumption that the small sample adaptor provides thorough mixing of the solution was taken from a conversation with David DiCorpo of Brookfield Engineering Laboratories on 12 May 1993. Mr. DiCorpo stated that particle migration from the spindle should be compensated by the relatively small sample size.

Figure 5.32: 241-SY-101 Simulant Shear Stress Variance With Time For LV Spindle

Figure 5.33: Viscosity Variation of 241-SY-101 Simulant With T-Bar Configuration

Figure 5.34: Viscosity Comparison of 241-SY-101 Simulant With LV and SSA Spindles

Figure 5.35: Shear Stress Comparison of 241-SY-101 Simulant With LV and SSA Spindles

5.2.4 Accuracy of Measurements

Table 5.3 summarizes the effects of accuracy on measurements in terms of uncertainty and variation. Comparing this with the figures discussed previously, a correlation between accuracy and the data scatter, or variation, becomes evident. The uncertainty is high in certain cases, due to the low percent torque and the particular spindle combination used for the test. At this time a spindle for the cone and plate was not available that would give a higher percent torque for the viscosity ranges of the bentonite mixtures tested.

Table 5.3: Typical Accuracy of Measurements Representative Values

Spindle	Fluid Tested	% Unc. ($\pm$)	% Variation
Cylindrical (LV)	Calibration Fluid	3.00	0.00
	241-SY-101 Simulant	3.75	2.00
	Bentonite/water mix	7.00	0.25
Cone and Plate (CP)	Calibration Fluid	4.00	0.00
	241-SY-101 Simulant	12.50	25.00
	Bentonite/water mix	18.00	10.00
Small Sample Adapter (SC4)	Calibration Fluid	2.50	0.20
	241-SY-101 Simulant	2.75	2.00
	Bentonite/water mix	12.50	0.00
T-bar	241-SY-101 Simulant	3.00	13.75

The values for uncertainty and variation presented in this table are obtained from equations provided by the manufacturer. Although particle size and migration have been discussed as probable factors affecting the data scatter for some tests, no analyses of these effects have been performed.

5.3 MIXING STUDIES

Of several proposed methods for controlling the gas release from tank 241-SY-101, the only concept that has been installed in the actual tank is a jet mixing apparatus. Unfortunately, it will be difficult to ascertain the success of this device in initial tests.

In order to examine the feasibility of the Hanford mixing experiments and to identify potential safety problems associated with the concept, small scale jet mixing experiments were conducted at Los Alamos National Laboratory. Water or supernate was injected into two-dimensional or three-dimensional test cells filled with various simulants. Sub-sections 5.3.1 and 5.3.2 contain examples of two-dimensional and three-dimensional tests that were conducted. In documenting these tests; steady state pressure, peak pressure, nozzle velocity, and pump voltage were measured. The experiments were also recorded on video tape and thirty-five millimeter film. Simulants used included sand, ceramic slip, barium sulfate/bentonite mixtures, plaster/sand mixtures, sodium and potassium polyacrylate mixtures, and saturated/slurry mixtures of sodium carbonate/sodium silicate/sodium sulfate. Viscosities of these mixtures varied from 70,000 cP to more than 15,000,000 cP at a shear rate of 0.063 sec^{-1} . The yield stresses varied from approximately 50 dynes/cm² to more than 20,000 dynes/cm², nozzle velocity varied from 4 to 48 ft/sec, and peak nozzle pressure varied from 3 to 30 psig.

In the initial stages of injection, the pump had to be capable of overcoming both the initial yield stress of the material and also the tendency of the nozzle to become clogged. Peak nozzle pressures up to three times the steady state values were observed. This was particularly evident of the slurry/saturated precipitate solutions. Mixing performance varied from nearly complete mixing to channelling without a significant amount of mixing. The effectiveness of mixing decreased with increasing simulant viscosity. As viscosity increased, yield stress also increased. In mixtures with viscosities above 100,000 cP, channelling was a significant factor in reducing the effectiveness of jet mixing. Once a channel was formed, the injected liquid followed the channel with little or no new mixing of the slurry occurring. With the saturated/slurry precipitate mixtures, even with channelling occurring the action of the moving stream of supernate tended to erode the slurry material. The erosion process of these simulants; however, proceeded at a much lower pace than that of mixtures with low viscosities.

One question which arises pertains to the results and effectiveness of the mixing experiment in the actual tank. The answer depends on what the actual physical properties of the sludge/slurry region in the tank are. If the high viscosity and yield stress values measured with the cone and plate viscometer

are correct, then the jet will make channels through the sludge/slurry region. Partial degassing will occur due to cracking, softening, and diffusion; characteristics of volcanic type gas releases. If the viscosity is less than 100,000 cP and the yield stress is less than 2,000 dynes/cm², then more widespread mixing is likely.

Several design improvements exist which could be incorporated into the jet mixing concept which would improve the effectiveness of the mixing process. First, due to a possible high yield stress and nozzle clogging issues, a pump capable of delivering a head pressure of up to 150 psig is desirable. Secondly, there are several companies that market jet mixing, cleaning, and mining equipment which have features that could enhance the effectiveness of the Hanford system.

Prosser/Enpo (a Burks Pumps, Inc. company) markets multi-jet equipment suitable for cleaning tanks up to eighty feet in diameter. The Prosser/Enpo rotational system for the nozzles would provide a delivery concept that would enhance the effectiveness of the Hanford system by sweeping over both the horizontal and vertical dimensions of the tank liquid from the end of a stationary pipe.⁴

Mass Transfer Systems, Inc. has a jet mixing nozzle configuration that enhances the effectiveness of the mixing concept by use of a concentric nozzle system that entrains tank liquids in addition to just injecting a primary liquid. One attribute of this system is that a more complete mixing is obtained in a shorter time.⁵

Another intriguing commercial concept is a jet mixing system marketed by NW Research Associates. This concept was developed as a technique for mining small deposits of ore with a minimum of surface disruption at the mining site. In this concept, a hole is bored into the ore body (typically less than eighteen inches in diameter). A concentric pipe configuration is then inserted into the hole. The injected liquid is pumped down through the outer channel, through cutting nozzles, and directed at the ore body to be removed. The entire drill system is rotated and moved up and down by a drilling rig. The resulting slurry

⁴ Additional information on the Prosser/Enpo system may be obtained by contacting Lee Lafond at (708) 357-9520 in Lisle, Illinois.

⁵ Information on the Mass Transfer Systems concept may be obtained by contacting Brian Wynn at (508) 679-6700 in Fall River, Massachusetts.

is removed through an inner pipe by means of a jet slurry pump. This concept has been used to mine a wide variety of ore deposits. Operating pressure of the jet nozzles is tailored to match the hardness of the ore deposit. Operating pressures have varied from approximately 200 to 3,000 psi depending on the yield strength of the rock.⁶

5.3.1 Two Dimensional Jet Mixing Tests

Values for various parameters obtained in the two-dimensional tests are contained in Table 5.4. Many of the two-dimensional tests were performed using the configuration depicted in Figure 5.36. In this cell, the injection nozzle is built into the sidewall. The active length of this cell is approximately 10 inches, and cell thickness is 0.25 inches. The nozzle is square with side lengths of 0.25 inches and is mounted 2.5 inches above the bottom of the test cell. Typical simulant fill height is approximately 8 inches. A second test cell used in two-dimensional tests is 10 inches long, has a simulant fill height of 11 inches, and a thickness of 0.125 inches. The nozzle used for this cell is square with side lengths of 0.125 inches and is mounted 3.0 inches above the bottom of the test cell. A third test cell has a total length of 16.5 inches, a fill depth of approximately 11 inches, and a thickness of 0.75 inches. For this test cell, the nozzles are inserted at the end of the supply tubing from the top of the cell. Nozzles with inside diameters of 0.07, 0.09, 0.13, and 0.19 inches were used. A benefit of this configuration is that the nozzle depth in the slurry simulant may be varied.

Figures 5.37 through 5.44 depict jet mixing performance as a function of increasing yield stress. Figure 5.37 shows a test of a simulant material with a yield stress of about 100 dynes/cm². The simulant material to the right of the channel in Figure 5.37 was eventually removed by the jet mixing and fluid removal process. The maximum jet penetration length, L, did not increase beyond that shown in the figure.

Figure 5.38 shows the results of the injection of a jet in a simulant having a yield stress of 965 dynes/cm². The nozzle was as close to the bottom of the test cell as was possible, about 0.25 inches above the bottom of the cell. Some of the jet fluid cut and cleared a region at the bottom of the tank. Most of the fluid returned to the surface of the simulant through the region disturbed by the insertion of the nozzle and nozzle supply tubing. After the test was

⁶ Additional information on the NW Research Associates concept may be obtained by contacting Stu Knoke at (206) 453-8184 in Bellevue, Washington.

started, the nozzle was raised to a centerline height of 2 inches. Figure 5.39 shows the results of the test. As in Figure 5.37, the jet eventually cut, mixed, and removed a significant portion of the simulant material.

Figure 5.40 illustrates the test results of a simulant with a yield stress of 1,610 dynes/cm². A transition from mixing to a channeling phenomenon seems to be occurring. Figure 5.41 shows a test of a simulant with a yield stress of 9,648 dynes/cm². Figure 5.42 shows a closer view of the same test. Note that very little material is removed once the channel has opened.

Figures 5.43 and 5.44 show jet mixing tests of plaster/sand and sodium carbonate/sodium sulfate/sodium silicate mixtures. The yield stresses were not measured; however, the plaster/sand mixture had a higher yield stress than the highest barium sulfate/bentonite/water mixture listed in Table 5.4. The sodium carbonate/sodium sulfate/sodium silicate mixture had a higher yield stress than the plaster/sand mixture. Note that to some degree channelling can be prevented if the velocity of the jet is kept low; thereby allowing the disturbed simulant region near the wall or supply tubing to gradually widen and serve as the fluid return path.

Figure 5.36: Two-Dimensional Jet Mixing Configuration

Figure 5.37: Two-Dimensional 1:10 Bentonite/Water Jet Mixing Experiment

• Viscosity 155,000 cP

• Yield Stress 100 Dynes/cm²

• Jet Velocity 1.54 ft/sec

**Figure 5.38: Two-Dimensional 1:10 Bentonite/Water Jet Mixing
Nozzle Close To Cell Bottom**

- Mixture: 1:10 Bentonite/Water
- Nozzle Location: Close to bottom of test cell
- Viscosity: 1,540,000 cP at a shear rate of 0.063/sec
- Yield Stress: 965 dynes/cm²
- Jet Velocity: 6.0 ft/sec

Figure 5.39: Two-Dimensional 1:10 Bentonite/Water Jet Mixing
Nozzle Two Inches From Cell Bottom

- Mixture: 1:10 Bentonite/Water
- Nozzle Location: Two inches from bottom of test cell
- Viscosity: 1,540,000 cP at a shear rate of 0.063/sec
- Yield Stress: 965 dynes/cm²
- Jet Velocity: 9.67 ft/sec

Figure 5.40: Two-Dimensional 1:10 Bentonite/Water Jet Mixing Channelling Phenomenon

- Mixture: 1:10 Bentonite/Water
- Nozzle Location: Two inches from bottom of test cell
- Viscosity: 2,983,000 cP at a shear rate of 0.063/sec
- Yield Stress: 1,610 dynes/cm²
- Jet Velocity: 16.7 ft/sec

Figure 5.41: Two-Dimensional 3:1:9 Barium Sulfate/Bentonite/Water Jet Mixing
Nozzle Two Inches From Cell Bottom

- Mixture: 3:1:9 Barium Sulfate/Bentonite/Water
- Nozzle Location: Two inches from bottom of test cell
- Viscosity: 15,000,000 cP at a shear rate of 0.063/sec
- Yield Stress: 9,648 dynes/cm²
- Jet Velocity: 38.3 ft/sec

Figure 5.42: Two-Dimensional 3:1:9 Barium Sulfate/Bentonite/Water Jet Mixing Cutting and Channelling Phenomenon

- Mixture: 3:1:9 Barium Sulfate/Bentonite/Water
- Nozzle Location: Two inches from bottom of test cell
- Viscosity: 15,000,000 cP at a shear rate of 0.063/sec
- Yield Stress: 9.648 dynes/cm²
- Jet Velocity: 38.3 ft/sec

Figure 5.43: Plaster/Sand Two-Dimensional Jet Mixing
Jet Velocity of 2.2 Feet Per Second

Figure 5.44: Sodium Carbonate/Sodium Sulfate/Sodium Silicate Precipitated
Sludge/Slurry Mixture: Jet Velocity of 2.8 Feet Per Second

Table 5.4: 2D Tests

Material	Test Chamber (inch) L x H x T	Viscosity cP	Shear Rate sec ⁻¹	Yield Stress D/cm ² (psi)	Nozzle (inch)	Max Pressure psig	Steady Pressure psig	Flow gpm	Vel ft/sec	Max L (inch)	L/D	Nozzle Location (inch)
Hanford Data		6700 K	0.60	48,237 (0.7)								
Ceramic Slip	10 x 8 x 0.25				0.25 S		6.0	0.42	2.16	10.0	40.0	2.50
BaSO ₄ -Bent-H ₂ O 1:1:7	10 x 8 x 0.25	6000 K	0.063	4135 (0.06)	0.25 S		6.2	0.45	2.31	7.18	28.7	2.50
BaSO ₄ -Bent-H ₂ O 1:1:7	10 x 8 x 0.25	6000 K	0.063	4135 (0.06)	0.25 S		0.5	0.40	2.05	4.42	17.7	2.50
Bentonite-H ₂ O 1:10	10 x 8 x 0.25	155 K	0.063	100 (0.0015)	0.25 S	1.366	0.989	0.30	1.54	3.54	14.2	2.50
Bentonite-H ₂ O 1:10	10 x 8 x 0.25	155 K	0.063	100 (0.0015)	0.25 S	2.245	1.027	0.30	1.54	4.61	18.4	2.50
Bentonite-H ₂ O 1:10	10 x 8 x 0.25	155 K	0.063	100 (0.0015)	0.25 S	3.319	2.896	0.58	2.98	4.72	18.9	2.50
Sand	10 x 8 x 0.25	-	-	-	0.25 S	3.0	3.0	0.72	3.70	7.0	28.0	2.50
Plaster/Sand	10 x 8 x 0.25	-	-	-	0.25 S	-	-	0.42	2.16	2.12	8.5	2.50
Na ₂ CO ₃ -Na ₂ SO ₄ - Na ₂ SiO ₃	10 x 8 x 0.25	-	-	-	0.25 S	7.5	6.0	0.54	2.77	5.89	23.6	2.50
Na ₂ CO ₃ -Na ₂ SO ₄ - Na ₂ SiO ₃	10 x 11 x 0.125	-	-	-	0.125 S	30.0	2.0	0.52	10.7	8.31	66.5	3.0
BaSO ₄ -Bent-H ₂ O 3:1:9	16.5 x 11 x 0.75	15,000 K	0.063	968 (0.14)	0.07 D	19.0	6.0	0.46	38.3	14.2 split	203	1.75
Bentonite:H ₂ O 1:10	16.5 x 11 x 0.75	1,540 K	0.063	965 (0.014)	0.13 D	0.682	0.62	0.25	6.04	11.8	90.9	on bottom
Bentonite:H ₂ O 1:10	16.5 x 11 x 0.75	1,540 K	0.063	965 (0.014)	0.13 D	0.682	0.507	0.25	6.04	6.61	50.9	2.0
Bentonite:H ₂ O 1:10	16.5 x 11 x 0.75	1,540 K	0.063	965 (0.014)	0.13D	2.343	1.907	0.40	9.67	7.01	53.9	2.0
Bentonite:H ₂ O 1:10	16.5 x 11 x 0.75	2,983 K	0.063	1610 (0.023)	0.09 D	3.124	2.716	0.33	16.66	14.2 split	157.5	2.0
Bentonite:H ₂ O 1:10	16.5 x 11 x 0.75	2,983 K	0.063	1610 (0.023)	0.09 D	6.151	4.595	0.33	16.66	14.2 split	157.5	2.0
Bentonite:H ₂ O 1:10	16.5 x 11 x 0.75	1,213 K	0.063	945 (0.014)	0.19 D	0.878	0.560	0.38	4.30	14.2 split	74.7	2.0
Bentonite:H ₂ O 1:10	16.5 x 11 x 0.75	1,213 K	0.063	945 (0.014)	0.19 D	0.975	0.847	0.46	5.20	14.2 split	74.7	2.0
Bentonite:H ₂ O 1:10	16.5 x 11 x 0.75	1,213 K	0.063	945 (0.014)	0.19 D	3.124	2.679	0.65	7.35	10.6	55.9	2.0

5.3.2 Three-Dimensional Jet Mixing Tests

To gain further insight into the feasibility of the Hanford mixing experiments and to uncover potential safety problems with the concept, three-dimensional jet mixing experiments were performed. Dyed water was injected into three-dimensional test cells filled with two different simulants, examples of which are contained in the following pages. The simulants used in these experiments were sodium and potassium polyacrylate. Viscosity was varied from 70,000 to 1,021,000 cP at a shear rate of 0.063/sec, yield stress was varied from 34.5 dynes/cm² to 547 dynes/cm², nozzle velocity from 8.0 to 25.2 ft/sec, and peak nozzle pressure from 0.5 to 19.0 psig. Table 5.5 contains a summary of some of the tests performed. The injection nozzle had an inside diameter of 0.09 inches. The nozzle height above the bottom of the test cell was varied from near the bottom of the tank to near the top of the simulant material. The simulant fill height was typically 6.5 inches.

In the initial stages of injection, the pump had to be capable of overcoming both the initial yield stress of the material and also the tendency of the nozzle to clog. Peak nozzle pressures of greater than 2.5 times the steady state value were observed. As viscosity increased, yield stress also increased. Even with mixtures having viscosities as low as 70,000 cP, channelling was a significant factor in reducing the effectiveness of jet mixing. Once a channel was formed, the injected liquid followed the channel with little new mixing of the simulant occurring.

Figures 5.45 through 5.49 illustrate jet mixing performance for an arigel test. Viscosity was 1,021,000 cP and the yield stress was 547 dynes/cm² (0.0079 psi). Figure 5.45 depicts the test apparatus after a stationary nozzle test run. Figure 5.46 shows the jet impact region on the side of the glass container. Note that distinct channels were cut through the arigel. Near the glass surface, the channel is curved upward. Figure 5.47 shows the surface of the arigel after the test. Note the large bubble near the delivery tube. This bubble was formed as a result of the pressure relief action occurring early in the test. Rapid relieving of the jet pressure eliminated the transient pressure spike that often occurred in both two-dimensional and three-dimensional tests. Two additional tests were performed on the same mixture, and both tests exhibited a large pressure spike. Even with the pressure relief event, the jet still channelled rather than mixing the simulant.

Figures 5.48 and 5.49 display the results of a test where the nozzle was manually rotated and lifted to the surface and pushed back to the bottom of the test cell. Note that in Figure 5.48 there is extensive channelling and splitting of the simulant material, but little mixing. Figure 5.49 shows the surface after the test. The jet appears to have sliced through the arigel with no mixing having

occurred. With time, the blue dye used to aid in visualization diffused into the material surrounding the channels. Channels were observed to re-gel and close with time. The paths carved by the jet were observed to follow the weakest course away from the nozzle. One unexplained occurrence in the experiments was the near right angle path of the jet shown in Figure 5.49.

Figure 5.45: Three-Dimensional Jet Mixing Configuration

**Figure 5.46: Arigel Three-Dimensional Jet Mixing Experiment
Displaying Channelling**

Figure 5.47: Arigel Three-Dimensional Test Characterized By Pressure Relief

Figure 5.48: Three-Dimensional Arigel Movable Nozzle Jet Mixing Test

Figure 5.49: Surface Channelling During Three-Dimensional Arigel Movable Nozzle Test

Table 5.5: 3D Tests

Material	Test Chamber (inch) L x H x T	Viscosity cP	Shear Rate sec ⁻¹	Yield Stress D/cm ² (psi)	Nozzle (inch)	Max Pressure psig	Steady Pressure psig	Flow gpm	Vel ft/sec	Max L (inch)	L/D	Nozzle Location (inch)
Sodium Polyacrylate 1:206	7" OD 6.0" Deep	70,000	0.63	34.5 (0.0005)	0.09 D	19.0	6.0	0.46	23.2	7.00	77.8	0.5
Sodium Polyacrylate 1:206	12" OD 6.5" Deep	70,000	0.063	34.5 (0.0005)	0.09 D	2.2	1.0	0.25	12.6	9.82	109	0.5
Arigel-H ₂ O 1:20	16" OD 6.6" Deep	864,000	0.063	4967 (0.0072)	0.09 D	11.0	6.2	0.50	25.2	12.0	133.3	0.5
Arigel-H ₂ O 1:15	16" OD 6.5" Deep	1,021 K	0.063	547 (0.0079)	0.09 D	0.5	0.5	0.16	8.0	10.0 split	111.1	2.0
Arigel-H ₂ O 1:15	16" OD 6.5" Deep	1,021 K	0.063	547 (0.0079)	0.09 D	5.76	0.5	0.16	8.0	10.0 split	111.1	2.0

6. CONCLUSIONS AND RECOMMENDATIONS

Based upon a combined analysis of the three phases of testing performed to simulate and characterize the waste contained in Hanford Tank 241-SY-101, the following conclusions and recommendations have been formulated. Each of the three phases are discussed individually in this chapter.

6.1 OVERTURN SIMULATIONS

The overturn simulations provided insight into the physical occurrences inside Hanford Tank 241-SY-101. These small scale simulations accurately portrayed the gas formation and resulting layer interactions in the tank. Based on the data obtained from these simulations, it is recommended that further large scale simulations be performed to gain additional knowledge of the ongoing processes inside of the Hanford tank. It is further recommended that these tests be performed using simulants which possess chemical characteristics similar to those of the waste in the actual tank; therefore providing accurate data which may be directly related to characterization and analysis experiments.

6.2 RHEOLOGICAL CHARACTERIZATIONS

The measurements made with the rotational viscometers are acceptable for most Newtonian and Non-Newtonian fluids. Based on the data gathered from the calibration fluids, all of the rotational viscometers are calibrated within range for Newtonian fluids. In the case of the bentonite and water mixtures and arigel and water mixtures, it is concluded that similar, repeatable results of shear stress and viscosity are obtained. This conclusion is based on the low variation between readings and tests. Thus for a Newtonian or a Non-Newtonian, Non-Crystalline, shear thinning fluid, any of the rotational viscometers will yield repeatable results and still provide reasonable uncertainty.

For testing of the 241-SY-101 simulant the variation is too high for results from the cone and plate to be acceptable. Not only do the results not compare with those from other viscometers, but the data are not repeatable when tests are performed under identical conditions. The small sample adapter provides the most accurate and repeatable data because of the small volume and continuous mixing of the fluid. It is recommended that more tests be performed using the small sample adapter. If possible, actual tank material should be tested.

The fact that the capillary and falling ball viscometers used for this study are designed for use with Newtonian fluids, coupled with the fixed shear rate of the devices, leads to the conclusion that any data obtained from these viscometers may not be applied to this study. The geometry of the viscometers does not allow for effective comparative analyses of different shear rates; therefore, the results of the capillary and falling ball viscometer tests may not be correlated to data from other tests. These factors lead to the recommendation that further tests with these viscometers should not be pursued.

6.3 MIXING STUDIES

In mixtures with viscosities in excess of 100,000 cP, channelling can be a significant factor in reducing the effectiveness of jet mixing. Once a channel has formed in the solution, the injected liquid flows into the channel and little new mixing occurs. Although channelling did occur in the saturated/precipitated slurry solutions, the action of the jet of supernate has been observed to continue to erode the slurry material. This erosion process, however, proceeds at a much slower pace than with materials with low viscosities.

For the mixing process to be effective, the pump must overcome in the initial stages of injection, the yield stress of the material, and the tendency of the nozzle and pump to clog. This is of particular importance with saturated solutions, where the slurry material must be transported in liquid form to another location before re-crystallization occurs.

Based on the observations summarized in this report, the Hanford jet mixing experiment should, at a minimum, be at least partially effective in de-gassing the tank. One concern is that the pump being used may not have adequate head to overcome potential clogging and slurry yield strength problems. As mentioned in section 5.3, there are several commercial technologies which have features that would improve the effectiveness of the Hanford jet mixing concept.

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APPENDIX A: Calibration Fluid Raw Data

The purpose of this appendix is to present typical data obtained in the testing of calibration fluids to determine the accuracy of the viscometers used in the experimental analysis of Hanford Tank 241-SY-101 simulants.

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CP52 Spindles A.9**

**Small Sample Adaptor Residual Torque
Spindle SC4-34**

Data contained in the following spreadsheet were used to construct Figure 3.6.

CALCITE.XLS

DVGather V1.0 data Copyright 1992, Brookfield Engineering Labs

Date: 08/08/93

Model: LV

Time: 09:23

Spindle SC4-34

File: CALCITE

Sample: BROWNED-OATA Calibration Fluid

Speed RPM	Torque %	Viscosity cP	Shear Stress D/Cm2	Shear Rate 1/sec	Temperature °C	Time
2.0	47.4	14220.0	79.8	0.8	22.1	30
2.0	47.4	14220.0	79.8	0.8	22.3	60
2.0	47.4	14220.0	79.0	0.8	22.5	90
2.0	47.4	14220.0	79.8	0.8	22.8	120
2.0	47.3	14190.0	79.4	0.8	22.5	150
2.0	47.3	14190.0	79.4	0.8	22.4	180
2.0	47.3	14190.0	79.4	0.8	22.3	210
2.0	47.3	14190.0	79.4	0.8	22.2	240
2.0	47.2	14160.0	79.3	0.8	22.1	270
2.0	47.3	14190.0	79.4	0.8	22.1	300
2.0	47.3	14190.0	79.4	0.8	22.1	330
2.0	47.3	14190.0	79.4	0.8	22.1	360
2.0	47.3	14190.0	79.4	0.8	22.1	390
2.0	47.3	14190.0	79.4	0.8	22.1	420
2.0	47.3	14190.0	79.4	0.8	22.1	450
2.0	47.3	14190.0	79.4	0.8	22.1	480
2.0	47.3	14190.0	79.4	0.8	22.2	510
2.0	47.3	14190.0	79.4	0.8	22.2	540
2.0	47.3	14190.0	79.4	0.8	22.1	570
2.0	47.3	14190.0	79.4	0.8	22.1	600
2.0	47.3	14190.0	79.4	0.8	22.1	630
1.0	27.3	16380.0	45.9	0.3	22.1	660
1.0	24.6	14760.0	41.3	0.3	22.1	690
1.0	24.5	14700.0	41.2	0.3	22.1	720
1.0	24.2	14520.0	40.6	0.3	22.1	750
1.0	24.2	14520.0	40.6	0.3	22.1	780
1.0	24.2	14520.0	40.6	0.3	22.1	810
1.0	24.1	14480.0	40.5	0.3	22.1	840
1.0	24.2	14520.0	40.6	0.3	22.1	870
1.0	24.2	14520.0	40.6	0.3	22.1	900
1.0	24.2	14520.0	40.6	0.3	22.1	930
1.0	24.1	14480.0	40.5	0.3	22.1	960
1.0	24.2	14520.0	40.6	0.3	22.1	990
1.0	24.1	14480.0	40.5	0.3	22.1	1020
1.0	24.2	14520.0	40.6	0.3	22.1	1050
1.0	24.1	14480.0	40.5	0.3	22.1	1080
1.0	24.1	14480.0	40.5	0.3	22.1	1110
1.0	24.1	14480.0	40.5	0.3	22.1	1140
1.0	24.1	14480.0	40.5	0.3	22.1	1170
1.0	24.1	14480.0	40.5	0.3	22.1	1200
1.0	24.2	14520.0	40.6	0.3	22.1	1230
0.0	4.7	0.0	7.9	0.0	22.1	1260
0.0	4.5	0.0	7.6	0.0	22.1	1290
0.0	4.5	0.0	7.6	0.0	22.1	1320
0.0	4.5	0.0	7.6	0.0	22.1	1350
0.0	4.5	0.0	7.6	0.0	22.1	1380
0.0	4.4	0.0	7.4	0.0	22.1	1410
0.0	4.4	0.0	7.4	0.0	22.1	1440
0.0	4.5	0.0	7.6	0.0	22.1	1470
0.0	4.5	0.0	7.6	0.0	22.1	1500
0.0	4.4	0.0	7.4	0.0	22.1	1530
0.0	4.5	0.0	7.6	0.0	22.1	1560
0.0	4.4	0.0	7.4	0.0	22.1	1590
0.0	4.5	0.0	7.6	0.0	22.1	1620
0.0	4.5	0.0	7.6	0.0	22.1	1650
0.0	4.5	0.0	7.6	0.0	22.1	1680
0.0	4.5	0.0	7.6	0.0	22.1	1710
0.0	4.5	0.0	7.6	0.0	22.1	1740
0.0	4.5	0.0	7.6	0.0	22.1	1770
0.0	4.4	0.0	7.4	0.0	22.1	1800
0.0	4.4	0.0	7.4	0.0	22.1	1830
1.0	21.8	13080.0	36.6	0.3	22.1	1860
1.0	22.6	13560.0	38.0	0.3	22.1	1890
1.0	22.8	13680.0	38.3	0.3	22.1	1920
1.0	22.8	13680.0	38.3	0.3	22.1	1950

10	22.9	13740.0	38.5	0.3	22.1	1980
10	22.9	13740.0	38.5	0.3	22.1	2010
10	22.9	13740.0	38.5	0.3	22.1	2040
10	22.9	13740.0	38.5	0.3	22.1	2070
10	22.9	13740.0	38.5	0.3	22.1	2100
10	22.9	13740.0	38.5	0.3	22.1	2130
10	22.9	13740.0	38.5	0.3	22.1	2160
10	22.9	13740.0	38.5	0.3	22.1	2190
10	22.9	13740.0	38.5	0.3	22.1	2220
10	22.9	13740.0	38.5	0.3	22.1	2250
10	22.9	13740.0	38.5	0.3	22.1	2280
10	22.9	13740.0	38.5	0.3	22.1	2310
10	22.9	13740.0	38.5	0.3	22.1	2340
10	22.9	13740.0	38.5	0.3	22.1	2370
10	22.9	13740.0	38.5	0.3	22.1	2400
00	4.7	0.0	7.9	0.0	22.1	2430
00	4.6	0.0	7.7	0.0	22.1	2460
00	4.6	0.0	7.7	0.0	22.1	2490
00	4.5	0.0	7.6	0.0	22.1	2520
00	4.5	0.0	7.6	0.0	22.1	2550
00	4.5	0.0	7.6	0.0	22.1	2580
00	4.5	0.0	7.6	0.0	22.1	2610
00	4.5	0.0	7.6	0.0	22.1	2640
00	4.5	0.0	7.6	0.0	22.1	2670
00	4.5	0.0	7.6	0.0	22.1	2700
00	4.6	0.0	7.7	0.0	22.1	2730
00	4.5	0.0	7.6	0.0	22.1	2760
00	4.5	0.0	7.6	0.0	22.1	2790
00	4.5	0.0	7.6	0.0	22.1	2820
00	4.5	0.0	7.6	0.0	22.1	2850
00	4.6	0.0	7.7	0.0	22.1	2880
00	4.5	0.0	7.6	0.0	22.1	2910
00	4.5	0.0	7.6	0.0	22.1	2940
00	4.6	0.0	7.7	0.0	22.1	2970
00	4.6	0.0	7.7	0.0	22.1	3000
10	22.1	13280.0	37.1	0.3	22.1	3030
10	22.4	13440.0	37.6	0.3	22.1	3060
10	22.6	13680.0	38.3	0.3	22.1	3090
10	22.8	13680.0	38.3	0.3	22.1	3120
10	22.9	13740.0	38.5	0.3	22.1	3150
10	22.9	13740.0	38.5	0.3	22.1	3180
10	22.9	13740.0	38.5	0.3	22.1	3210
10	22.9	13740.0	38.5	0.3	22.1	3240
10	22.9	13740.0	38.5	0.3	22.1	3270
10	22.9	13740.0	38.5	0.3	22.1	3300
10	22.9	13740.0	38.5	0.3	22.1	3330
10	22.9	13740.0	38.5	0.3	22.1	3360
10	22.9	13740.0	38.5	0.3	22.1	3390
10	22.9	13740.0	38.5	0.3	22.1	3420
10	22.9	13740.0	38.5	0.3	22.1	3450
10	22.9	13740.0	38.5	0.3	22.1	3480
10	22.9	13740.0	38.5	0.3	22.1	3510
10	22.9	13740.0	38.5	0.3	22.1	3540
10	22.9	13740.0	38.5	0.3	22.1	3570
10	22.9	13740.0	38.5	0.3	22.1	3600
00	4.6	0.0	7.7	0.0	22.1	3630
00	4.6	0.0	7.7	0.0	22.1	3660
00	4.6	0.0	7.7	0.0	22.1	3690
00	4.6	0.0	7.7	0.0	22.1	3720
00	4.6	0.0	7.7	0.0	22.1	3750
00	4.6	0.0	7.7	0.0	22.1	3780
00	4.6	0.0	7.7	0.0	22.1	3810
00	4.5	0.0	7.6	0.0	22.1	3840
00	4.6	0.0	7.7	0.0	22.1	3870
00	4.5	0.0	7.6	0.0	22.1	3900
00	4.5	0.0	7.6	0.0	22.1	3930
00	4.5	0.0	7.6	0.0	22.1	3960
00	4.6	0.0	7.7	0.0	22.1	3990
00	4.5	0.0	7.6	0.0	22.1	4020
00	4.5	0.0	7.6	0.0	22.1	4050
00	4.5	0.0	7.6	0.0	22.1	4080
00	4.5	0.0	7.6	0.0	22.1	4110

CALCITE.XLS

00	45	00	78	00	22 1	4140
00	45	00	78	00	22 1	4170
00	45	00	78	00	22 1	4200
10	22 2	13320 0	37 3	03	22 2	4230
10	22 5	13500 0	37 8	03	22 1	4260
10	22 8	13680 0	38 3	03	22 1	4290
10	22 8	13680 0	38 3	03	22 2	4320
10	22 9	13740 0	38 5	03	22 2	4350
10	22 8	13680 0	38 3	03	22 1	4380
10	22 9	13740 0	38 5	03	22 1	4410
10	22 9	13740 0	38 5	03	22 1	4440
10	22 9	13740 0	38 5	03	22 2	4470
10	22 9	13740 0	38 5	03	22 2	4500
10	22 9	13740 0	38 5	03	22 1	4530
10	22 9	13740 0	38 5	03	22 1	4560
10	22 9	13740 0	38 5	03	22 2	4590
10	22 9	13740 0	38 5	03	22 1	4620
10	22 9	13740 0	38 5	03	22 1	4650
10	22 9	13740 0	38 5	03	22 1	4680
10	22 9	13740 0	38 5	03	22 1	4710
10	22 9	13740 0	38 5	03	22 1	4740
10	22 9	13740 0	38 5	03	22 1	4770
10	22 9	13740 0	38 5	03	22 1	4800
00	45	00	78	00	22 2	4830
00	45	00	78	00	22 1	4860
00	45	00	78	00	22 1	4890
00	45	00	78	00	22 1	4920
00	45	00	78	00	22 1	4950
00	45	00	78	00	22 1	4980
00	45	00	78	00	22 1	5010
00	45	00	78	00	22 1	5040
00	45	00	78	00	22 1	5070
00	45	00	78	00	22 1	5100
00	45	00	78	00	22 1	5130
00	45	00	78	00	22 1	5160
00	45	00	78	00	22 1	5190
00	45	00	78	00	22 1	5220
00	45	00	78	00	22 1	5250
00	45	00	78	00	22 1	5280
00	45	00	78	00	22 1	5310
00	45	00	78	00	22 1	5340
00	45	00	78	00	22 1	5370
00	45	00	78	00	22 1	5400
10	22 1	13200 0	37 1	03	22 1	5430
10	22 4	13440 0	37 6	03	22 1	5460
10	22 8	13680 0	38 3	03	22 1	5490
10	22 7	13620 0	38 1	03	22 1	5520
10	22 8	13680 0	38 3	03	22 1	5550
10	22 8	13680 0	38 3	03	22 1	5580
10	22 9	13740 0	38 5	03	22 1	5610
10	22 9	13740 0	38 5	03	22 1	5640
10	22 9	13740 0	38 5	03	22 1	5670
10	22 8	13680 0	38 3	03	22 1	5700
10	22 9	13740 0	38 5	03	22 1	5730
10	22 9	13740 0	38 5	03	22 1	5760
10	22 9	13740 0	38 5	03	22 1	5790
10	22 9	13740 0	38 5	03	22 1	5820
10	22 9	13740 0	38 5	03	22 1	5850
10	22 9	13740 0	38 5	03	22 1	5880
10	22 9	13740 0	38 5	03	22 1	5910
10	22 9	13740 0	38 5	03	22 1	5940
10	22 9	13740 0	38 5	03	22 1	5970
10	22 9	13740 0	38 5	03	22 1	6000

Combined Calibration Fluid Data For LV-2, SCA-21, and CP41 Spindles

**Data contained in the following spreadsheet were used to construct Figures
5.11 and 5.12**

DV-Gather+ V1.0 data Copyright 1992, Brookfield Engineering Labs.

Date: 06/09/99_06/15/99

Time: 16:35

File: C:\LVBK\CALCF68\CALSSA\CAL68

Model: LV/HBALV

Spindle: LV2/CP41/SC4.0

Sample: Calibration Fluid

55424 cP

A.8

Speed RPM	Torque %	Viscosity cP	Shear Stress D/Cn2	Shear Rate 1/Sec	Temp. °C	Uncertainty +/-	Variation
0.3	53.2	53190.0	33.8	0.064	25.0	2.92%	0.00%
0.3	53.2	53190.0	33.8	0.064	25.0	2.92%	0.00%
0.5	88.4	53030.0	56.2	0.106	25.0	2.18%	0.17%
0.5	88.1	52850.0	56.0	0.106	25.0	2.18%	0.17%
0.3	16.4	53780.0	322.2	0.600	24.0	7.13%	0.00%
0.3	16.4	53780.0	322.2	0.600	24.0	7.13%	0.00%
0.6	32.8	53780.0	644.5	1.200	24.1	4.06%	0.00%
0.6	32.8	53780.0	644.5	1.200	24.1	4.06%	0.00%
1.0	54.7	53740.0	1075.0	2.000	24.1	2.86%	0.00%
1.0	54.6	53640.0	1073.0	2.000	24.1	2.86%	0.00%
0.3	56.7	56690.0	57.8	0.102	25.4	2.74%	1.00%
0.3	57.9	57890.0	59.0	0.102	25.1	2.64%	1.04%
0.5	90.6	56150.0	95.5	0.170	25.3	2.06%	0.21%
0.5	94.0	56390.0	95.9	0.170	25.4	2.05%	0.21%

Combined Calibration Fluid Data For LV-4, SCA-21, and CP52 Spindles

Data contained in the following spreadsheet were used to construct Figures 5.13 and 5.14.

Combined Calibration Fluid Data
 Cannon 152660 cP @ 40 Degrees C
 Edward G. Sarris
 Created 15 July 1993

Speed RPM	Lv4 Spindle			Numerical Uncertainties		Lv4 Spindle		
	viscosity cP	viscosity kg/m ² s	Uncertainty	High (cP)	Low (cP)	Shear Stress D Gm/2	Shear Stress Pascals	Shear Rate 1/2sec
0.5	160000.0	160.0000	12.50%	179995.75	140004.27	100.5000	10.0600	0.066
0.5	166000.0	166.0000	12.07%	185992.75	146004.27	104.5800	10.4580	0.063
0.5	172000.0	172.0000	11.63%	191992.75	152004.27	108.6600	10.8560	0.060
0.5								0.066
0.5								0.066
0.5								0.066
0.6	175000.0	175.0000	5.78%	182997.87	169002.13	217.9600	21.7960	0.126
0.6	175000.0	175.0000	5.78%	182997.87	169002.13	217.9600	21.7960	0.126
0.6	171000.0	171.0000	5.67%	180997.87	161002.13	213.4900	21.3490	0.125
0.6								0.132
0.6								0.132
0.6								0.132
1.0	169000.0	169.0000	5.53%	175158.72	169001.28	356.5500	35.6550	0.210
1.0	169000.0	169.0000	5.53%	175158.72	169001.28	356.5500	35.6550	0.210
1.0	169000.0	169.0000	5.53%	175158.72	169001.28	356.5500	35.6550	0.210
1.0								0.220
1.0								0.220
1.0								0.220
2.0	166000.0	166.0000	1.76%	171599.96	167600.04	706.1200	70.6120	0.420
2.0	166000.0	166.0000	1.79%	170999.96	167000.04	705.6000	70.5600	0.420
2.0	167700.0	167.7000	1.79%	170659.96	164700.04	704.5400	70.4540	0.420
2.0								0.440
2.0								0.440
2.0								0.440
2.5								0.550
2.5								0.550
2.5								0.550
3.5								0.800
3.5								0.800
3.5								0.800
5.0	166500	166.5000	1.20%	168739.57	164300.43	1045.3560	104.5356	0.650
5.0	166500	166.5000	1.20%	168739.57	164300.43	1045.3560	104.5356	0.650
5.0	166500	166.5000	1.20%	168739.57	164300.43	1044.5620	104.4562	0.650
0.5								1.200
0.5								1.200
0.6								1.200
1								2
1								2
1								2
2.0								4.000
2.0								4.000
2								4
4.0								8.000
4.0								8.000
4.0								8.000

Speed RPM	Cone and Plate		Small Sample Adaptor		Shear Rate 1/2 π c
	Shear Stress D/Gm ²	Shear Stress Pascals	Shear Stress D/Gm ²	Shear Stress Pascals	
0.3					0.083
0.3					0.083
0.3					0.083
0.3			106.50	10.3600	0.086
0.3			106.50	10.3600	0.086
0.3			106.70	10.3700	0.086
0.6					0.138
0.6					0.128
0.6					0.128
0.6			212.50	21.3300	0.132
0.6			212.50	21.3300	0.132
0.6			212.20	21.2200	0.132
1.0					0.210
1.0					0.210
1.0					0.210
1.0			352.80	35.2800	0.220
1.0			352.80	35.2800	0.220
1.0			352.80	35.2800	0.220
1.0					0.420
2.0					0.420
2.0					0.420
2.0			706.50	70.6500	0.440
2.0			706.50	70.6500	0.440
2.0			706.50	70.6500	0.440
2.0			962.80	96.2800	0.530
2.3			962.80	96.2800	0.530
2.3			962.80	96.2800	0.530
0.3	1065.0	106.500			0.600
0.3	1065.0	106.500			0.600
0.3	1065.0	106.500			0.600
0.3					0.627
3.0					0.627
3.0					0.627
3.0					0.627
0.6	2060.4	206.040			1.200
0.6	2060.4	206.040			1.200
0.6	2060.4	206.040			1.200
0.6	2060.4	206.040			1.200
1	3997.2	399.720			2
1	3997.2	399.720			2
1	3997.2	399.720			2
2.0	6700.1	670.010			4.000
2.0	6712.9	671.290			4.000
2.0	6700.1	670.010			4
2					
4.0	13461.2	1346.120			8.000
4.0	13461.2	1346.120			8.000
4.0	13418.0	1341.800			8.000

Small Sample Adaptor						
Speed	viscosity	viscosity,	Uncertainty,	Numerical Uncertainty		Shear Rate
RPM	CP	kg/m ² s		High (CP)	Low (CP)	1/Sec
0.3						0.088
0.3						0.088
0.3						0.088
0.3	188400.0	188.4000	8.81%	182366.56	190408.41	0.088
0.3	188400.0	188.4000	8.81%	182366.56	190408.41	0.088
0.3	184900.0	184.9000	8.71%	180788.56	188908.41	0.088
0.8						0.128
0.8						0.128
0.8						0.128
0.8	181800.0	181.8000	4.85%	189298.29	153801.71	0.182
0.8	181800.0	181.8000	4.85%	189298.29	153801.71	0.182
0.8	180800.0	180.8000	4.97%	188798.29	152801.71	0.182
1.0						0.210
1.0						0.210
1.0						0.210
1.0	180300.0	180.3000	2.99%	185098.98	155301.02	0.220
1.0	180300.0	180.3000	2.99%	185098.98	155301.02	0.220
1.0	180300.0	180.3000	2.99%	185098.98	155301.02	0.220
2.0						0.420
2.0						0.420
2.0						0.420
2.0	180800.0	180.8000	1.50%	182898.48	158100.51	0.440
2.0	180300.0	180.3000	1.50%	182898.48	157900.51	0.440
2.0	180300.0	180.3000	1.50%	182898.48	158100.51	0.440
2.5	180300.0	180.3000	1.20%	182418.58	158580.41	0.500
2.5	180300.0	180.3000	1.20%	182418.58	158580.41	0.500
2.5	180800.0	180.8000	1.20%	182418.58	158580.41	0.500
0.3						0.800
0.3						0.800
0.3						0.800
3.0						0.880
3.0						0.880
3.0						0.880
0.8						1.200
0.8						1.200
0.8						1.200
1						2
1						2
1						2
2.0						4.000
2.0						4.000
2						4
4.0						8.000
4.0						8.000
4.0						8.000

COOK AND PLAIN						
Speed RPM	Viscosity	Viscosity	Uncertainty	Numerical Uncertainties		Shear Rate 1/Sec
	cP	dIN/100g		High (cP)	Low (cP)	
0.3						0.088
0.3						0.088
0.3						0.088
0.3						0.088
0.3					4.1	0.088
0.3					4.7	0.088
0.3					4.1	0.088
0.8						0.128
0.8						0.128
0.8						0.128
0.8						0.182
0.8						0.182
0.8						0.182
1.0						0.210
1.0						0.210
1.0						0.210
1.0						0.220
1.0						0.220
1.0						0.220
2.0						0.420
2.0						0.420
2.0						0.420
2.0					5.1	0.440
2.0					4.9	0.440
2.0						0.440
2.5						0.300
2.5					1.7	0.300
2.5						0.300
0.3	173008.0	173.0080	15.16%	156231.88	146734.87	0.800
0.3	173015.8	173.0158	14.86%	1501240.48	143475.87	0.800
0.3	173029.0	173.2090	15.17%	1260231.83	144784.87	0.800
8.0						0.880
8.0						0.880
8.0						0.880
0.8	171687.3	171.6873	7.83%	164908.37	163580.89	1.200
0.8	171687.3	171.6873	7.83%	164908.37	163580.89	1.200
0.8	171687.3	171.6873	7.83%	164908.37	163580.89	1.200
1	165682.4	165.6824	6.83%	177728.40	161888.40	2
1	165682.4	165.6824	4.83%	177728.40	161888.40	2
1	165682.4	165.6824	4.83%	177728.40	161888.40	2
2.0	167503.5	167.5035	5.83%	171419.50	163571.50	4.000
2.0	167503.4	167.5034	5.84%	171419.40	163564.40	4.000
2	167616.2	167.6162	2.83%	171489.30	166871.30	4
4.0	167616.4	167.6164	1.17%	163280.43	166330.43	8.000
4.0	167616.4	167.6164	1.17%	163280.43	166330.43	8.000
4.0	167616.4	167.6164	1.17%	163280.43	166330.43	8.000

APPENDIX B: Potassium Polyacrylate (Arigel) Raw Data

The purpose of this appendix is to present representative raw data used to construct the arigel graphs contained in this document.

TABLE OF CONTENTS

Arigel Thermal Equilibrium Test Data B.3

Arigel/Water 1:65 Mixture LV1 Spindle Data B.5

**Combined 1:135 Arigel/Water Mixture For LV3, SC4-34, and
CP41 Spindles B.8**

Arigel Thermal Equilibrium Test Data

The data contained in the following spreadsheet were used to construct Figure 3.3.

Temperature Variation Across An Air-Glass-Water Mixture
 COMBINED DATA FROM PILES ACROSS AND AVERAGE
 Temperature Increase From 0 degrees C to 65 degrees C
 Elmer C. Sims
 March 17, 1940

Weight of Water 18 500.37
 Weight of Airgel 1.67
 Weight of Diamond Mixture 42.10
 Weight of Sample 544.14 Grams of Water - 0.02 degrees at 0.01%

Raw Data									
Time	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp
minutes	1	2	3	4	5	6	7	8	9
0	22	22	22	22	22	22	22	22	22
10	23	23	23	23	23	23	23	23	23
20	24	24	24	24	24	24	24	24	24
30	25	25	25	25	25	25	25	25	25
40	26	26	26	26	26	26	26	26	26
50	27	27	27	27	27	27	27	27	27
60	28	28	28	28	28	28	28	28	28
70	29	29	29	29	29	29	29	29	29
80	30	30	30	30	30	30	30	30	30
90	31	31	31	31	31	31	31	31	31
100	32	32	32	32	32	32	32	32	32
110	33	33	33	33	33	33	33	33	33
120	34	34	34	34	34	34	34	34	34
130	35	35	35	35	35	35	35	35	35
140	36	36	36	36	36	36	36	36	36
150	37	37	37	37	37	37	37	37	37
160	38	38	38	38	38	38	38	38	38
170	39	39	39	39	39	39	39	39	39
180	40	40	40	40	40	40	40	40	40
190	41	41	41	41	41	41	41	41	41
200	42	42	42	42	42	42	42	42	42
210	43	43	43	43	43	43	43	43	43
220	44	44	44	44	44	44	44	44	44
230	45	45	45	45	45	45	45	45	45
240	46	46	46	46	46	46	46	46	46
250	47	47	47	47	47	47	47	47	47
260	48	48	48	48	48	48	48	48	48
270	49	49	49	49	49	49	49	49	49
280	50	50	50	50	50	50	50	50	50
290	51	51	51	51	51	51	51	51	51
300	52	52	52	52	52	52	52	52	52
310	53	53	53	53	53	53	53	53	53
320	54	54	54	54	54	54	54	54	54
330	55	55	55	55	55	55	55	55	55
340	56	56	56	56	56	56	56	56	56
350	57	57	57	57	57	57	57	57	57
360	58	58	58	58	58	58	58	58	58
370	59	59	59	59	59	59	59	59	59
380	60	60	60	60	60	60	60	60	60
390	61	61	61	61	61	61	61	61	61
400	62	62	62	62	62	62	62	62	62
410	63	63	63	63	63	63	63	63	63
420	64	64	64	64	64	64	64	64	64
430	65	65	65	65	65	65	65	65	65
440	66	66	66	66	66	66	66	66	66
450	67	67	67	67	67	67	67	67	67
460	68	68	68	68	68	68	68	68	68
470	69	69	69	69	69	69	69	69	69
480	70	70	70	70	70	70	70	70	70
490	71	71	71	71	71	71	71	71	71
500	72	72	72	72	72	72	72	72	72

Arigel/Water 1:65 Mixture LV1 Spindle Data

The data contained in the following spreadsheet were used to construct Figures 5.15 and 5.17.

DV3athert+ V1.0 data Copyright 1992 Brookfield Engineering Labs
 Date 01/22/92 Model HE
 Time 14:03 Spindle LV1
 File 0PLC Sample 1.65 Angel Water

							Calculated Values	
Speed	Torque	Viscosity	Shear Stress	Shear Rate	Temperature	Time	Shear Stress	Shear Rate
RFM	%	cP	Dy/Cm ²	1/Sec	°C	Sec	Dy/Cm ²	1/Sec
0.3	29.5	503500.0	0.0	0.0	28.4	0	332.31	0.07
0.3	26.7	455700.0	0.0	0.0	28.9	1024	300.76	0.07
0.3	23.2	397200.0	0.0	0.0	28.5	1033	261.29	0.07
0.6	31.2	266200.0	0.0	0.0	28.4	559	351.39	0.13
0.6	30.2	257700.0	0.0	0.0	28.4	557	340.16	0.13
0.6	29.5	251700.0	0.0	0.0	28.5	555	332.24	0.13
1.0	35.2	197600.0	0.0	0.0	28.3	325	430.32	0.22
1.0	37.7	193000.0	0.0	0.0	28.3	301	424.60	0.22
1.0	37.2	190500.0	0.0	0.0	28.2	315	412.10	0.22
2.0	51.7	132400.0	0.0	0.0	28.2	197	532.56	0.44
2.0	50.6	129500.0	0.0	0.0	28.3	172	509.90	0.44
2.0	48.8	127500.0	0.0	0.0	28.2	179	561.00	0.44
4.0	67.4	96270.0	0.0	0.0	28.2	66	759.16	0.86
4.0	66.3	94630.0	0.0	0.0	28.2	51	753.54	0.86
4.0	64.7	92620.0	0.0	0.0	28.2	112	729.82	0.86
10.0	92.6	47410.0	0.0	0.0	28.2	104	1043.02	2.20
10.0	87.0	44540.0	0.0	0.0	28.1	244	973.36	2.20
10.0	85.8	43930.0	0.0	0.0	28.2	35	986.46	2.20

CV3aure+ V1.0 data Copyright 1992, Brookfield Engineering Labs

Date 02/02/92

Model HE

Time 10:01

Spindle LV1

File 3PLCA

Sample 1 6C Angel Water

Speed	Torque	Viscosity	Shear Stress	Shear Rate	Temperature	Time	Shear Stress	Shear Rate
RPM	%	cP	Dy/Cm ²	1/Sec	°C	Sec	Dy/Cm ²	1/Sec
0.3	22.2	378000.0	0.0	0.0	25.1	2	250.07	0.066
0.3	21.9	372100.0	0.0	0.0	25.0	1030	245.53	0.066
0.3	20.9	355000.0	0.0	0.0	25.0	1040	234.30	0.066
0.6	27.9	239100.0	0.0	0.0	25.0	500	314.29	0.132
0.6	27.2	232100.0	0.0	0.0	25.0	500	306.37	0.132
0.6	26.6	227000.0	0.0	0.0	25.0	500	299.64	0.122
1.0	34.3	175600.0	0.0	0.0	25.0	300	366.22	0.220
1.0	33.5	171500.0	0.0	0.0	25.0	300	377.30	0.220
1.0	33.0	163000.0	0.0	0.0	25.0	307	371.60	0.220
2.0	44.3	114700.0	0.0	0.0	25.0	560	505.56	0.440
2.0	44.3	113400.0	0.0	0.0	25.0	151	498.96	0.440
2.0	44.0	112600.0	0.0	0.0	25.1	150	495.44	0.440
4.0	60.3	77150.0	0.0	0.0	25.0	105	673.15	0.550
4.0	59.9	76740.0	0.0	0.0	25.0	105	673.55	0.560
4.0	59.4	76030.0	0.0	0.0	25.0	105	669.06	0.560
10.0	85.4	43720.0	0.0	0.0	25.0	50	961.84	2.200
10.0	85.1	44060.0	0.0	0.0	25.0	45	969.76	2.200
10.0	85.7	43660.0	0.0	0.0	25.0	56	965.36	2.200
30.0	99.0	99.0	99.0	0.0	25.0	17	6.53	6.600

**Combined 1:135 Arigel/Water Mixture For LV3, SC4-34, and
CP41 Spindles**

**The data contained in the following spreadsheet were used to construct Figures
5.19 and 5.20.**

B.10

Speed RPM	Uncertainty	Numerical Uncertainty		LMI Spindle		Cone and Plate		Small Sample Adaptor		Shear Rate 1/Sec
		High (cP)	Low (cP)	Shear Stress D/Cm 2	Shear Stress Pascals	Shear Stress D/Cm 2	Shear Stress Pascals	Shear Stress D/Cm 2	Shear Stress Pascals	
0.0				54 6500	5 4650					0.003
0.0				54 1670	5 4167					0.003
0.0				54 4110	5 4411					0.003
0.0				72 3110	7 2311					0.126
0.0				71 5550	7 1555					0.126
0.0				71 5550	7 1555					0.126
1.0				92 2110	9 2211					0.210
1.0				92 4630	9 2463					0.210
1.0				92 4630	9 2463					0.210
2.0				12 46900	12 4690					0.420
2.0				12 9420	12 9420					0.420
2.0				12 9340	12 9340					0.420
0.0						12 10	12 100			0.400
0.0						127 7	12 770			0.400
0.0						129 7	12 970			0.400
4.0				170 1000	17 0000					0.000
4.0				102 6900	10 2630					0.000
4.0				100 0200	10 0020					0.000
4.0	1.0%	16700 74	14000 20					117 30	10 7300	0.000
4.0	7.75%	16670 74	14200 20					130 70	10 8200	0.000
4.0	7.75%	16670 74	14200 20					130 70	10 8200	0.000
0.0						104 7	10 470			1.200
0.0						100 6	10 060			1.200
0.0						100 6	10 060			1.200
10.0	4.67%	10700 00	9700 10					225 10	22 5000	2.200
10.0	5.00%	9933 00	8974 10					200 00	20 0000	2.200
10.0	5.00%	9741 00	8702 10					203 00	20 3000	2.200
2.0						357 0	35 700			4.000
2.0						301 5	30 150			4.000
2.0						359 0	35 900			4.000
20.0	2.00%	5694 97	5175 03					305 30	30 5300	6.600
20.0	2.00%	5750 97	5439 03					309 50	30 9500	6.600
20.0	2.00%	5694 97	5175 03					305 30	30 5300	6.600
4.0						524 0	52 400			0.000
4.0						520 5	52 050			0.000
4.0						520 5	52 050			0.000
60.0	2.00%	4070 00	3719 02					527 10	52 7100	10.200
60.0	2.04%	3900 00	3639 02					517 30	51 7300	10.200
60.0	2.17%	3070 00	2719 02					501 10	50 1100	10.200
10.0						027 0	02 700			20.000
10.0						025 2	02 520			20.000
10.0						025 2	02 520			20.000
100.0	1.70%	2074 00	2179 01					021 10	02 1000	22.000
100.0	1.74%	2006 00	2111 01					007 10	00 7100	22.000
100.0	1.79%	2700 00	2675 01					510 20	50 0200	22.000
30.0						1230 0	120 000			60.000
30.0						1234 1	123 410			60.000
30.0						1232 1	123 210			60.000

APPENDIX C: Bentonite Mixtures Raw Data

The purpose of this appendix is to present typical data obtained by tests performed on Bentonite/Water mixtures.

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Bentonite/Water 1:10 Mixture Data For LV3, CP41, and SC4-34
 Spindles C.3

Bentonite/Water 1:20 Mixture Data For LV2 Spindle and
 Capillary Viscometers C.5

**Bentonite/Water 1:10 Mixture Data For LV3, CP41, and SC4-34
Spindles**

**The data contained in the following spreadsheets were used to construct
Figures 5.24 and 5.25**

DV Gather+ V1.0 data Copyright 1992, Brookfield Engineering Labs
 Date: 06/16/93 Model: LV/BB/LV
 Time: 07:57 Spindle: LV3/CP41/SC1-34
 File: SPL24LV3/SPL24CP3/SPL24SS2/SPL24__3 Sample: Bentonite Water Mix 1:10

Speed RPM	Torque %	Viscosity cP	Shear Stress D/Cm2	Shear Rate 1/Sec	Temp. °C	Uncertainty	Variation
0.3	19.7	78780	49.6	0.063	20.3	5.08%	-5.92%
0.3	19.5	77980.0	49.1	0.063	20.3	5.13%	-4.95%
0.3	16.4	65590.0	41.3	0.063	20.3	6.10%	13.00%
0.3	26.6		53190.0	44.7	0.084	3.76%	-1.88%
0.3	26.1		52190.0	43.8	0.084	3.83%	0.00%
0.3	25.6		51190.0	43.0	0.084	3.91%	1.95%
0.6	19.7	39390.0	49.6	0.126	20.4	5.08%	-7.45%
0.6	18.1	36190.0	45.6	0.126	20.4	5.53%	0.74%
0.6	16.9	33790.0	42.6	0.126	20.5	5.92%	7.89%
0.6	26.8		26790.0	45.0	0.168	3.73%	-2.61%
0.6	25.7		25690.0	43.2	0.168	3.89%	1.56%
0.6	25.8		25790.0	43.3	0.168	3.88%	1.16%
1.0	20.1	24110.0	50.6	0.210	20.5	4.98%	-1.31%
1.0	19.5	23400.0	49.1	0.210	20.5	5.13%	1.68%
1.0	19.9	23870.0	50.1	0.210	20.6	5.03%	-0.32%
1.0	31.6		18960.0	53.1	0.280	3.16%	2.74%
1.0	31.9		19140.0	53.6	0.280	3.13%	1.78%
1.0	33.9		20340.0	56.9	0.280	2.95%	-4.23%
2.0	23.6	14160.0	59.5	0.420	20.6	4.24%	1.69%
2.0	24.0	14400.0	60.5	0.420	20.6	4.17%	0.00%
2.0	24.4	14640.0	61.5	0.420	20.6	4.10%	-1.64%
2.0	37.8		11340.0	63.5	0.560	2.64%	4.85%
2.0	40.4		12120.0	67.9	0.560	2.47%	-1.90%
2.0	40.7		12210.0	68.4	0.560	2.46%	-2.62%
0.3	4.7	15390.0	92.3	0.600	23.2	21.28%	-2.84%
0.3	4.6	15060.0	90.4	0.600	23.1	21.74%	-0.71%
0.3	4.4	14410.0	86.5	0.600	23.1	22.72%	3.77%
4.0	28.8	8638.0	72.6	0.840	20.6	3.47%	-3.70%
4.0	27.4	8218.0	69.0	0.840	20.6	3.65%	1.22%
4.0	27.0	8098.0	68.0	0.840	20.6	3.70%	2.72%
4.0	53.9		8083.0	90.5	1.120	1.86%	0.00%
4.0	54.7		8203.0	91.9	1.120	1.83%	-0.67%
4.0	54.4		8158.0	91.4	1.120	1.84%	-0.12%
0.6	4.6	7532.0	90.4	1.200	23.0	21.74%	0.00%
0.6	4.6	7532.0	90.4	1.200	23.0	21.74%	0.00%
0.6	4.6	7532.0	90.4	1.200	23.0	21.74%	0.00%
1.0	5.0	4912.0	98.2	2.300	23.0	20.00%	-5.33%
1.0	4.9	4814.0	96.3	2.000	23.0	20.41%	-3.41%
1.0	4.3	4224.0	84.5	2.000	23.0	23.26%	10.09%
10.0	34.4	4127.0	86.7	2.100	20.6	2.91%	-0.58%
10.0	34.1	4091.0	85.9	2.100	20.6	2.93%	0.29%
10.0	34.1	4091.0	85.9	2.100	20.6	2.93%	0.29%
2.0	8.7	4273.0	170.9	4.000	23.0	11.50%	-0.76%
2.0	9.1	4470.0	178.8	4.000	23.0	10.99%	-5.13%
2.0	8.1	3979.0	159.1	4.300	22.9	12.34%	6.58%
4.0	8.9	2136.0	174.9	8.000	23.0	11.24%	6.27%
4.0	9.4	2109.0	184.7	8.000	23.0	10.64%	0.71%
4.0	10.1	2481.0	198.4	8.000	23.0	9.90%	-6.27%
10.0	9.1	894.0	172.8	20.000	23.1	10.39%	0.37%
10.0	9.1	894.0	178.8	20.000	23.1	10.99%	0.37%
10.0	9.2	903.8	180.8	20.000	23.1	10.87%	0.00%

C.4

**Bentonite/Water 1:20 Mixture Data For LV2 Spindle and
Capillary Viscometers**

**The data contained in the following spreadsheets were used to construct
Figures 5.26 and 5.27.**

Date: 06/21/93

Model: LV

Time: 08:11

Spindle: LV2

File: SPL23

Sample: BENTONITE-DATA 2011 Bentonite - Water

Speed RPM	Torque %	Viscosity cP	Viscosity kg/m ² s	Shear Stress Pascals	Shear Stress Dyn/cm ²	Shear Rate 1/Sec	Temperature °C	Time Sec	Uncertainty	Variation
3.3	21.0	21000.0	21.0000	1.3356	13.3560	0.0636	21.2	1088	4.76%	-5.87%
3.3	19.4	19400.0	19.4000	1.2338	12.3384	0.0636	21.6	1093	5.15%	1.89%
3.3	18.9	18900.0	18.9000	1.2020	12.0204	0.0636	21.4	1082	5.29%	4.59%
3.6	23.2	11600.0	11.6000	1.4755	14.7552	0.1272	21.4	519	4.31%	2.01%
3.6	23.7	11850.0	11.8500	1.5073	15.0732	0.1272	21.4	537	4.22%	-0.14%
3.6	24.1	12050.0	12.0500	1.5328	15.3276	0.1272	21.5	507	4.15%	-1.86%
1.0	27.7	8308.0	8.3080	1.7613	17.6130	0.2120	21.4	326	3.61%	-1.93%
1.0	27.7	8308.0	8.3080	1.7613	17.6130	0.2120	21.5	331	3.61%	-1.93%
1.0	26.1	7929.0	7.9290	1.6535	16.5354	0.2120	21.5	330	3.31%	4.24%
2.0	24.8	5219.0	5.2190	2.2129	22.1296	0.4240	21.5	177	2.87%	-0.21%
2.0	32.7	4904.0	4.9040	2.0793	20.7930	0.4240	21.5	152	3.36%	1.11%
2.0	24.5	5174.0	5.1740	2.1938	21.9378	0.4240	21.5	153	2.90%	-1.41%
4.0	44.2	3014.0	3.0140	2.9100	28.1027	0.8480	21.5	108	2.26%	-0.41%
4.0	43.4	3254.0	3.2540	2.7544	27.5939	0.8480	21.5	76	2.30%	-0.61%
4.0	41.8	3124.0	3.1240	2.6576	26.5763	0.8480	21.5	79	2.39%	3.14%
10.0	75.6	2268.0	2.2680	4.8082	48.0816	2.1200	21.5	76	1.32%	2.69%
10.0	74.0	2220.0	2.2200	4.7064	47.0640	2.1200	21.5	31	1.35%	4.91%
10.0	83.3	2493.0	2.4990	5.2979	52.9788	2.1200	21.5	32	1.20%	-6.86%

Regression Analysis For Intersect Point For Cross-Arm Viscometer

28210 170.63
28210 126.2
23500 72.976

Regression Output:

Constant
Std Err of Y Est. 0.00332144
R Squared 0.995049554
No. of Observations 3
Degrees of Freedom 2

X Coefficient(s) 0.004705773124
Std Err of Coef. 0.000821311331

Cross-Arm Viscometer Test: 1000 Bentonite Solution

10 Viscometer

Apparent Viscosity 1000
Flow Time(s) 10
Density (g/cm³) 1.00
Volume (cm³) 4.3

OUTPUT
Kinematic Viscosity 1000
Viscosity 1000
Shear Rate 170.63
Shear Stress 2821

10 Viscometer

Approximate Constant: 100
Flow Time(s) 20
Density (g/cm³) 1.03
Volume (cm³) 7.1

OUTPUT
Kinematic Viscosit 2000
Viscosity 2060
Shear Rate 126.2
Shear Stress 2821

9 Viscometer

Approximate Constant: 30
Flow Time(s) 41
Density (g/cm³) 1.03
Volume (cm³) 4.7

OUTPUT
Kinematic Viscosit 1200
Viscosity 1236
Shear Rate 72.96
Shear Stress 2350

APPENDIX D: Agnew 241-SY-101 Simulant Raw Data

The purpose of this appendix is to present typical data obtained by tests performed on the Agnew 241-SY-101 simulant.

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Temperature Distribution Data: Bath Increase From 23° to 50° C

Data contained in the following spreadsheet were used to construct Figure 3.4.

Temperature Variation Across GY 101 Simulant Mixture 22

Temperature Increase From 23 degrees C to 50 degrees C

Edward C Sams

Created 1 June, 1993

K type Thermocouple Standard Limits of Error: ± 2.2 degrees or 0.75%

RAW DATA

Time (minutes)	Gage 1 (C)	Gage 2 (C)	Gage 3 (C)	Gage 4 (C)	Gage 5 (C)	Gage 6 (C)	Bath (C)
0	23	23	23	23	23	23	23
10	29	25	24	24	24	23	36.1
20	37	30	27	26	25	24	46.3
30	43	36	32	30	29	28	50
40	45	40	36	35	33	32	50
50	46	42	39	38	37	36	50
60	47	44	41	41	39	38	50
70	47	45	43	43	42	41	50
80	48	46	44	44	43	42	50
90	48	47	45	45	44	44	50
100	48	47	46	46	45	45	50
110	49	48	47	47	46	46	50
120	49	48	47	47	47	46	50
130	49	48	48	48	47	47	50
140	49	48	48	48	48	47	50
150	49	49	48	48	48	47	50
160	50	49	48	48	48	48	50
170	50	49	49	48	48	48	50
180	50	50	49	48	48	48	50

Small Sample Adaptor Residual Torque Test: Spindle SC4-34

Data contained in the following spreadsheet were used to construct Figure 3.5.

DVOther V1.0 data Copyright 1992, Brookfield Engineering Labs

Date 08/31/03

Model LV

Time 08:18

Spindle SC4-34

File SPL21CTC

Sample UNKNOWN-BAY Agynous Simulant

Speed RPM	Torque %	Velocity dP	Shear Stress D/Cm2	Shear Rate 1/sec	Temperature °C	Time s
100	88.0	3858.0	110.9	2.800	21.1	30
100	87.4	4043.0	113.2	2.800	21.1	60
100	88.2	4181.0	116.2	2.800	21.1	90
100	87.7	4081.0	113.7	2.800	21.1	120
100	87.7	4081.0	113.7	2.800	21.1	150
100	87.0	4019.0	112.5	2.800	21.1	180
100	71.1	4285.0	119.4	2.800	21.1	210
100	88.3	4087.0	114.7	2.800	21.1	240
100	88.0	3858.0	110.9	2.800	21.1	270
100	87.3	4037.0	113.0	2.800	21.1	300
100	88.7	3841.0	110.4	2.800	21.1	330
100	88.8	3886.0	111.9	2.800	21.1	360
100	87.3	4037.0	113.0	2.800	21.1	390
100	88.9	4133.0	115.7	2.800	21.1	420
100	88.1	3886.0	111.0	2.800	21.1	450
100	87.0	4019.0	112.5	2.800	21.1	480
100	87.2	4031.0	112.9	2.800	21.1	510
100	88.0	3886.0	110.9	2.800	21.1	540
100	88.8	3838.0	110.2	2.800	21.1	570
100	88.3	3877.0	111.4	2.800	21.1	600
100	87.7	4081.0	113.7	2.800	21.1	630
40	40.0	9888.0	87.2	1.120	21.1	660
40	38.7	9884.0	86.7	1.120	21.1	690
40	38.1	9884.0	86.7	1.120	21.1	720
40	38.8	9838.0	86.5	1.120	21.1	750
40	40.2	8029.0	87.5	1.120	21.1	780
40	41.3	8184.0	88.4	1.120	21.1	810
40	38.2	9879.0	86.8	1.120	21.1	840
40	38.5	9824.0	86.3	1.120	21.1	870
40	38.5	9824.0	86.3	1.120	21.1	900
40	38.2	9879.0	86.8	1.120	21.1	930
40	38.8	9884.0	87.0	1.120	21.1	960
40	40.7	8104.0	88.4	1.120	21.1	990
40	41.8	8288.0	70.2	1.120	21.1	1020
40	40.3	8044.0	87.7	1.120	21.1	1050
40	38.8	9884.0	87.0	1.120	21.1	1080
40	40.0	9888.0	87.2	1.120	21.1	1110
40	40.5	8074.0	88.0	1.120	21.0	1140
40	40.3	8044.0	87.7	1.120	21.1	1170
40	40.8	8119.0	88.5	1.120	21.1	1200
40	41.1	8184.0	88.0	1.120	21.1	1230
00	8.1	00	13.8	0.000	21.0	1260
00	7.8	00	12.8	0.000	21.1	1290
00	7.8	00	12.8	0.000	21.1	1320
00	7.8	00	12.8	0.000	21.1	1350
00	7.5	00	12.8	0.000	21.1	1380
00	7.5	00	12.8	0.000	21.1	1410
00	7.5	00	12.8	0.000	21.0	1440
00	7.5	00	12.8	0.000	21.0	1470
00	7.5	00	12.8	0.000	21.1	1500
00	7.5	00	12.8	0.000	21.0	1530
00	7.5	00	12.8	0.000	21.1	1560
00	7.5	00	12.8	0.000	21.0	1590
00	7.5	00	12.8	0.000	21.1	1620
00	7.5	00	12.8	0.000	21.1	1650
00	7.5	00	12.8	0.000	21.1	1680
00	7.5	00	12.8	0.000	21.0	1710
00	7.5	00	12.8	0.000	21.0	1740
00	7.5	00	12.8	0.000	21.0	1770
00	7.5	00	12.8	0.000	21.0	1800
00	7.5	00	12.8	0.000	21.0	1830
40	43.2	8479.0	72.6	1.120	21.0	1860
40	41.8	8284.0	70.4	1.120	21.1	1890
40	40.4	8088.0	87.8	1.120	21.1	1920
40	40.3	8044.0	87.7	1.120	21.1	1950

40	412	81790	88 2	1 120	21 1	1980
40	404	80880	87 9	1 120	21 0	2010
40	421	83140	70 7	1 120	21 0	2040
40	405	80740	88 0	1 120	21 0	2070
40	412	81790	88 2	1 120	21 0	2100
40	402	80280	87 5	1 120	21 1	2130
40	431	84840	72 4	1 120	21 0	2160
40	428	84180	71 9	1 120	21 0	2190
40	428	84180	71 9	1 120	21 0	2220
40	425	83740	71 4	1 120	21 1	2250
40	408	81180	88 5	1 120	21 0	2280
40	408	80880	88 2	1 120	21 0	2310
40	412	81790	88 2	1 120	21 0	2340
40	408	81180	88 5	1 120	21 0	2370
40	408	80880	88 2	1 120	21 0	2400
40	418	82380	88 9	1 120	21 0	2430
00	38 4	00	84 5	0 000	21 0	2460
00	82	00	13 8	0 000	21 0	2490
00	78	00	13 3	0 000	21 0	2520
00	78	00	13 3	0 000	21 0	2550
00	78	00	13 3	0 000	21 0	2580
00	78	00	13 3	0 000	21 0	2610
00	78	00	13 3	0 000	21 0	2640
00	78	00	13 1	0 000	21 0	2670
00	78	00	13 3	0 000	21 0	2700
00	78	00	13 1	0 000	21 0	2730
00	78	00	13 3	0 000	21 0	2760
00	78	00	13 3	0 000	21 0	2790
00	78	00	13 1	0 000	21 0	2820
00	78	00	13 1	0 000	21 0	2850
00	78	00	13 1	0 000	21 0	2880
00	78	00	13 3	0 000	21 0	2910
00	78	00	13 1	0 000	21 0	2940
00	78	00	13 1	0 000	21 0	2970
00	78	00	13 1	0 000	21 0	3000
00	78	00	13 1	0 000	21 0	3030
40	415	82240	88 7	1 120	21 0	3060
40	422	83290	70 9	1 120	21 0	3090
40	46 4	88080	78 3	1 120	21 0	3120
40	438	85880	73 6	1 120	21 0	3150
40	431	84840	72 4	1 120	21 0	3180
40	409	81340	88 7	1 120	21 0	3210
40	420	82880	70 5	1 120	21 0	3240
40	411	81840	88 0	1 120	21 0	3270
40	422	83290	70 9	1 120	21 0	3300
40	431	84840	72 4	1 120	21 0	3330
40	419	82840	70 4	1 120	21 0	3360
40	43 4	85080	72 9	1 120	21 0	3390
40	419	82840	70 4	1 120	21 0	3420
40	411	81840	88 0	1 120	21 0	3450
40	428	83880	71 8	1 120	21 0	3480
40	42 3	83440	71 0	1 120	21 0	3510
40	42 4	83580	71 2	1 120	21 0	3540
40	418	82880	70 2	1 120	21 0	3570
40	40 9	81340	88 7	1 120	21 0	3600
00	91	00	15 3	0 000	21 0	3630
00	77	00	12 9	0 000	21 0	3660
00	78	00	12 8	0 000	21 0	3690
00	78	00	12 8	0 000	21 0	3720
00	78	00	12 8	0 000	21 0	3750
00	78	00	12 8	0 000	21 0	3780
00	75	00	12 8	0 000	21 0	3810
00	75	00	12 8	0 000	21 0	3840
00	75	00	12 8	0 000	21 0	3870
00	75	00	12 8	0 000	21 0	3900
00	75	00	12 8	0 000	21 0	3930
00	75	00	12 8	0 000	21 0	3960
00	75	00	12 8	0 000	21 0	3990
00	75	00	12 8	0 000	21 0	4020
00	75	C0	12 8	0 C00	21 0	4050
00	75	00	12 8	0 000	21 0	4080
00	75	00	12 8	0 000	21 0	4110

0.0	7.5	0.0	12.8	0.000	21.0	4140
0.0	7.5	0.0	12.8	0.000	21.0	4170
0.0	7.5	0.0	12.8	0.000	21.0	4200
4.0	44.1	8614.0	74.1	1.120	21.0	4230
4.0	42.5	8374.0	71.4	1.120	21.0	4260
4.0	42.7	8404.0	71.7	1.120	21.0	4290
4.0	43.0	8449.0	72.2	1.120	21.0	4320
4.0	42.2	8329.0	70.9	1.120	21.0	4350
4.0	41.8	8289.0	70.2	1.120	21.0	4380
4.0	41.8	8289.0	70.2	1.120	21.0	4410
4.0	40.8	8119.0	68.5	1.120	21.0	4440
4.0	41.5	8224.0	69.7	1.120	21.0	4470
4.0	41.8	8289.0	70.2	1.120	21.0	4500
4.0	43.3	8484.0	72.7	1.120	21.0	4530
4.0	41.8	8289.0	70.2	1.120	21.0	4560
4.0	43.4	8509.0	72.9	1.120	21.0	4590
4.0	43.0	8449.0	72.2	1.120	21.0	4620
4.0	42.6	8389.0	71.6	1.120	21.0	4650
4.0	43.6	8539.0	73.2	1.120	21.0	4680
4.0	44.2	8629.0	74.2	1.120	21.0	4710
4.0	43.8	8589.0	73.6	1.120	21.0	4740
4.0	44.8	8719.0	75.2	1.120	21.0	4770
4.0	42.2	8329.0	70.9	1.120	21.0	4800
0.0	11.1	0.0	18.6	0.000	21.0	4830
0.0	10.0	0.0	18.8	0.000	21.0	4860
0.0	9.9	0.0	18.6	0.000	21.0	4890
0.0	9.8	0.0	18.5	0.000	21.0	4920
0.0	9.7	0.0	18.3	0.000	21.0	4950
0.0	9.6	0.0	18.1	0.000	21.0	4980
0.0	9.6	0.0	18.1	0.000	21.0	5010
0.0	9.5	0.0	18.0	0.000	21.0	5040
0.0	9.5	0.0	18.0	0.000	21.0	5070
0.0	9.5	0.0	18.0	0.000	21.0	5100
0.0	9.4	0.0	15.8	0.000	21.0	5130
0.0	9.4	0.0	15.8	0.000	21.0	5160
0.0	9.4	0.0	15.8	0.000	21.0	5190
0.0	9.4	0.0	15.8	0.000	21.0	5220
0.0	9.4	0.0	15.8	0.000	21.0	5250
0.0	9.4	0.0	15.8	0.000	21.0	5280
0.0	9.4	0.0	15.8	0.000	21.0	5310
0.0	9.4	0.0	15.8	0.000	21.0	5340
0.0	9.4	0.0	15.8	0.000	21.0	5370
0.0	9.4	0.0	15.8	0.000	21.0	5400
4.0	43.0	8449.0	72.2	1.120	21.0	5430
4.0	45.6	8839.0	78.6	1.120	21.0	5460
4.0	41.2	8179.0	69.2	1.120	21.0	5490
4.0	43.6	8539.0	73.2	1.120	21.0	5520
4.0	42.6	8389.0	71.6	1.120	21.0	5550
4.0	43.0	8449.0	72.2	1.120	21.0	5580
4.0	43.3	8484.0	72.7	1.120	21.0	5610
4.0	44.6	8689.0	74.9	1.120	21.0	5640
4.0	41.3	8194.0	69.4	1.120	21.0	5670
4.0	43.1	8484.0	72.4	1.120	21.0	5700
4.0	41.3	8194.0	69.4	1.120	21.0	5730
4.0	40.4	8059.0	67.9	1.120	21.0	5760
4.0	42.8	8419.0	71.9	1.120	21.0	5790
4.0	42.9	8434.0	72.1	1.120	21.0	5820
4.0	43.2	8479.0	72.6	1.120	21.0	5850
4.0	41.1	8164.0	69.0	1.120	21.0	5880
4.0	42.9	8434.0	72.1	1.120	21.0	5910
4.0	45.0	8749.0	75.6	1.120	21.0	5940
4.0	43.4	8509.0	72.9	1.120	21.0	5970
4.0	43.7	8554.0	73.4	1.120	21.0	6000

DVGather+ V1.0 date Copyright 1992, Brookfield Engineering Labs

Date 08/31/83

Model LV

Time 15:37

Spindle SC4-34

File SPL21CTD

Sample UNFORMED-DATA Agnew Simulant

Speed RPM	Torque %	Viscosity 50 Degrees C	Shear Stress D/Cm2	Shear Rate 1/sec	Temperature °C	Time sec
100	19.9	1194.0	33.4	2.800	49.9	30
100	19.9	1194.0	33.4	2.800	49.9	60
100	20.3	1218.0	34.1	2.800	49.9	90
100	20.2	1212.0	33.9	2.800	49.9	120
100	20.1	1206.0	33.8	2.800	49.9	150
100	20.2	1212.0	33.9	2.800	49.9	180
100	20.3	1218.0	34.1	2.800	49.9	210
100	20.1	1206.0	33.8	2.800	49.9	240
100	20.2	1212.0	33.9	2.800	49.9	270
100	20.2	1212.0	33.9	2.800	50.0	300
100	20.2	1212.0	33.9	2.800	50.0	330
100	20.3	1218.0	34.1	2.800	49.9	360
100	20.1	1206.0	33.8	2.800	49.9	390
100	20.4	1224.0	34.3	2.800	49.9	420
100	20.3	1218.0	34.1	2.800	50.0	450
100	20.3	1218.0	34.1	2.800	49.9	480
100	20.3	1218.0	34.1	2.800	50.0	510
100	20.3	1218.0	34.1	2.800	50.0	540
100	20.4	1224.0	34.3	2.800	50.0	570
100	20.2	1212.0	33.9	2.800	50.0	600
40	15.0	2250.0	25.2	1.120	50.0	630
40	15.3	2295.0	25.7	1.120	50.0	660
40	15.3	2295.0	25.7	1.120	50.0	690
40	15.3	2295.0	25.7	1.120	50.0	720
40	15.4	2310.0	25.9	1.120	50.0	750
40	15.3	2295.0	25.7	1.120	50.0	780
40	15.4	2310.0	25.9	1.120	50.0	810
40	15.7	2355.0	26.4	1.120	50.0	840
40	15.4	2310.0	25.9	1.120	50.0	870
40	15.5	2325.0	26.0	1.120	50.0	900
40	15.4	2310.0	25.9	1.120	50.0	930
40	15.4	2310.0	25.9	1.120	49.9	960
40	15.5	2325.0	26.0	1.120	49.9	990
40	15.6	2340.0	26.2	1.120	50.0	1020
40	15.5	2325.0	26.0	1.120	50.0	1050
40	15.3	2295.0	25.7	1.120	50.0	1080
40	15.5	2325.0	26.0	1.120	50.0	1110
40	15.4	2310.0	25.9	1.120	50.0	1140
40	15.4	2310.0	25.9	1.120	50.0	1170
40	15.4	2310.0	25.9	1.120	50.0	1200
00	4.6	0.0	7.7	0.000	50.0	1230
00	4.6	0.0	7.7	0.000	50.0	1260
00	4.6	0.0	7.7	0.000	50.0	1290
00	4.6	0.0	7.7	0.000	50.0	1320
00	4.6	0.0	7.7	0.000	49.9	1350
00	4.6	0.0	7.7	0.000	50.0	1380
00	4.6	0.0	7.7	0.000	50.0	1410
00	4.6	0.0	7.7	0.000	49.9	1440
00	4.6	0.0	7.7	0.000	50.0	1470
00	4.6	0.0	7.7	0.000	49.9	1500
00	4.6	0.0	7.7	0.000	49.9	1530
00	4.6	0.0	7.7	0.000	49.9	1560
00	4.5	0.0	7.6	0.000	50.0	1590
00	4.5	0.0	7.6	0.000	50.0	1620
00	4.6	0.0	7.7	0.000	50.0	1650
00	4.5	0.0	7.6	0.000	49.9	1680
00	4.6	0.0	7.7	0.000	50.0	1710
00	4.5	0.0	7.6	0.000	50.0	1740
00	4.5	0.0	7.6	0.000	50.0	1770
00	4.5	0.0	7.6	0.000	49.9	1800
40	16.7	2505.0	28.1	1.120	50.0	1830
40	15.7	2355.0	26.4	1.120	49.9	1860
40	15.9	2385.0	26.7	1.120	50.0	1890
40	15.8	2370.0	26.5	1.120	50.0	1920
40	15.7	2355.0	26.4	1.120	50.0	1950

40	156	2340 0	26.2	1 120	48 9	1980
40	155	2325 0	26 0	1 120	48 9	2010
40	155	2325 0	26 0	1 120	48 9	2040
40	156	2340 0	26.2	1 120	48 9	2070
40	155	2325 0	26 0	1 120	48 9	2100
40	154	2310 0	25.9	1 120	48 9	2130
40	157	2355 0	26.4	1 120	48 9	2160
40	155	2325 0	26 0	1 120	48 9	2190
40	154	2310 0	25.9	1 120	48 9	2220
40	154	2310 0	25.9	1 120	50 0	2250
40	154	2310 0	25.9	1 120	50 0	2280
40	153	2295 0	25.7	1 120	48 9	2310
40	154	2310 0	25.9	1 120	48 9	2340
40	153	2295 0	25.7	1 120	48 9	2370
40	156	2340 0	26.2	1 120	48 9	2400
00	51	00	8.6	0 000	48 9	2430
00	50	00	8.4	0 000	48 9	2460
00	49	00	8.2	0 000	48 9	2490
00	50	00	8.4	0 000	48 9	2520
00	50	00	8.4	0 000	48 9	2550
00	50	00	8.4	0 000	48 9	2580
00	50	00	8.4	0 000	48 9	2610
00	49	00	8.2	0 000	48 9	2640
00	49	00	8.2	0 000	48 9	2670
00	49	00	8.2	0 000	50 0	2700
00	49	00	8.2	0 000	48 9	2730
00	49	00	8.2	0 000	48 9	2760
00	49	00	8.2	0 000	48 9	2790
00	49	00	8.2	0 000	48 9	2820
00	49	00	8.2	0 000	48 9	2850
00	49	00	8.2	0 000	50 0	2880
00	49	00	8.2	0 000	50 0	2910
00	49	00	8.2	0 000	50 0	2940
00	49	00	8.2	0 000	48 9	2970
00	61	00	10.2	0 000	48 9	3000
40	159	2385 0	26.7	1 120	48 9	3030
40	158	2370 0	26.5	1 120	50 0	3060
40	154	2310 0	25.9	1 120	50 0	3090
40	153	2295 0	25.7	1 120	50 0	3120
40	152	2280 0	25.5	1 120	50 0	3150
40	153	2295 0	25.7	1 120	50 0	3180
40	152	2280 0	25.5	1 120	48 9	3210
40	153	2295 0	25.7	1 120	50 0	3240
40	154	2310 0	25.9	1 120	48 9	3270
40	157	2355 0	26.4	1 120	48 9	3300
40	152	2280 0	25.5	1 120	50 0	3330
40	154	2310 0	25.9	1 120	50 0	3360
40	153	2295 0	25.7	1 120	50 0	3390
40	152	2280 0	25.5	1 120	50 0	3420
40	151	2265 0	25.4	1 120	50 0	3450
40	153	2295 0	25.7	1 120	50 0	3480
40	153	2295 0	25.7	1 120	50 0	3510
40	151	2265 0	25.4	1 120	50 0	3540
40	156	2340 0	26.2	1 120	50 0	3570
40	152	2280 0	25.5	1 120	50 0	3600
00	49	00	8.2	0 000	48 9	3630
00	48	00	8.1	0 000	48 9	3660
00	47	00	7.9	0 000	48 9	3690
00	47	00	7.9	0 000	50 0	3720
00	47	00	7.9	0 000	50 0	3750
00	47	00	7.9	0 000	48 9	3780
00	47	00	7.9	0 000	50 0	3810
00	47	00	7.9	0 000	50 0	3840
00	47	00	7.9	0 000	50 0	3870
00	47	00	7.9	0 000	50 0	3900
00	47	00	7.9	0 000	48 9	3930
00	47	00	7.9	0 000	50 0	3960
00	47	00	7.9	0 000	50 0	3990
00	47	00	7.9	0 000	48 9	4020
00	47	00	7.9	0 000	50 0	4050
00	47	00	7.9	0 000	48 9	4080
00	47	00	7.9	0 000	48 9	4110

SPL21CTD XLS

00	47	00	79	0 000	50 0	4140
00	47	00	79	0 000	49 9	4170
00	42	00	71	0 000	49 9	4200
40	158	2370 0	26 5	1 120	49 9	4230
40	154	2310 0	25 9	1 120	49 9	4260
40	153	2295 0	25 7	1 120	49 9	4290
40	153	2295 0	25 7	1 120	49 9	4320
40	154	2310 0	25 9	1 120	49 9	4350
40	152	2280 0	25 5	1 120	49 9	4380
40	151	2265 0	25 4	1 120	49 9	4410
40	155	2325 0	26 0	1 120	49 9	4440
40	147	2205 0	24 7	1 120	49 9	4470
40	149	2235 0	25 0	1 120	49 9	4500
40	150	2250 0	25 2	1 120	49 9	4530
40	148	2220 0	24 9	1 120	49 9	4560
40	146	2190 0	24 5	1 120	49 9	4590
40	149	2235 0	25 0	1 120	49 9	4620
40	149	2235 0	25 0	1 120	49 9	4650
40	147	2205 0	24 7	1 120	49 9	4680
40	148	2220 0	24 9	1 120	49 9	4710
40	148	2220 0	24 9	1 120	49 9	4740
40	146	2190 0	24 5	1 120	50 0	4770
00	48	00	81	0 000	49 9	4800
00	46	00	77	0 000	49 9	4830
00	46	00	77	0 000	49 9	4860
00	46	00	77	0 000	49 9	4890
00	46	00	77	0 000	49 9	4920
00	46	00	77	0 000	49 9	4950
00	45	00	76	0 000	49 9	4980
00	45	00	76	0 000	49 9	5010
00	45	00	76	0 000	49 9	5040
00	45	00	76	0 000	49 9	5070
00	45	00	76	0 000	49 9	5100
00	45	00	76	0 000	49 9	5130
00	45	00	76	0 000	49 9	5160
00	45	00	76	0 000	49 9	5190
00	45	00	76	0 000	49 9	5220
00	45	00	76	0 000	49 9	5250
00	45	00	76	0 000	49 9	5280
00	45	00	76	0 000	49 9	5310
00	45	00	76	0 000	49 9	5340
00	45	00	76	0 000	49 9	5370
00	45	00	76	0 000	49 9	5400
00	45	00	76	0 000	49 9	5430
00	45	00	76	0 000	49 9	5460
00	45	00	76	0 000	49 9	5490
00	45	00	76	0 000	49 9	5520
00	45	00	76	0 000	49 9	5550
00	45	00	76	0 000	49 9	5580
00	45	00	76	0 000	49 9	5610
00	45	00	76	0 000	49 9	5640
00	45	00	76	0 000	49 9	5670
00	45	00	76	0 000	49 9	5700
00	45	00	76	0 000	49 9	5730
00	45	00	76	0 000	49 9	5760
00	45	00	76	0 000	49 9	5790
00	45	00	76	0 000	49 9	5820
00	45	00	76	0 000	49 9	5850
00	45	00	76	0 000	49 9	5880
00	45	00	76	0 000	49 9	5910
00	45	00	76	0 000	49 9	5940
00	45	00	76	0 000	49 9	5970
00	45	00	76	0 000	49 9	6000

Combined Data For LV2 and CP41 Spindles

The data contained in the following spreadsheets were used to construct Figures 5.28, 5.29, and 5.30.

DV Gather+ V1.0 data Copyright 1992, Brookfield Engineering Labs

Date: 05/10/93

Model: LV/BB

Time: 08:07:17

Spindle: LV2/CP41

File: SPL21LVW/SPL21CPH/SPL21T23

Sample: Agnew's Simulant

Speed RPM	Torque %	Viscosity cP	Shear Stress psi	Shear Rate 1/Sec	Temp. °C	Uncertainty +/-	Variation
0.3	22.1	12300.0	2.06E-04	0.064	22.5	4.48%	45.11%
0.3	31.3	31290.0	2.89E-04	0.064	22.3	3.20%	3.42%
0.3	43.5	43400.0	4.01E-04	0.064	21.7	2.30%	-25.59%
0.6	25.3	12650.0	2.33E-04	0.127	22.6	3.95%	1.38%
0.6	25.5	12750.0	2.35E-04	0.127	22.6	3.92%	1.18%
0.6	26.6	13300.0	2.45E-04	0.127	22.6	3.76%	-3.01%
1.0	31.2	9358.0	2.88E-04	0.212	22.8	3.21%	-1.60%
1.0	30.2	9058.0	2.78E-04	0.212	22.7	3.31%	1.66%
1.0	30.7	9208.0	2.83E-04	0.212	22.7	3.26%	0.00%
2.0	39.9	5984.0	3.68E-04	0.424	22.8	2.51%	3.63%
2.0	41.8	6269.0	3.85E-04	0.424	22.8	2.39%	-1.04%
2.0	42.4	6359.0	3.91E-04	0.424	22.8	2.36%	-2.44%
0.3	21.9		71720.0	6.24E-03	0.6	4.57%	0.30%
0.3	21.6		70730.0	6.15E-03	0.6	4.63%	1.70%
0.3	22.4		73350.0	6.38E-03	0.6	4.46%	-1.93%
4.0	51.6	3869.0	4.76E-04	0.848	22.9	1.94%	0.78%
4.0	52.7	3952.0	4.84E-04	0.848	22.9	1.90%	-1.33%
4.0	51.7	3877.0	4.77E-04	0.848	22.9	1.92%	0.58%
0.6	21.2	18500.0		3.22E-03	1.2	8.85%	127.75%
0.6	29.7	48630.0		8.46E-03	1.2	3.37%	-13.36%
0.6	36.2	59270.0		1.03E-02	1.2	2.76%	-25.31%
1.0	7.8	7663.0		2.22E-03	2.0	12.82%	-11.54%
1.0	7.0	6877.0		1.99E-03	2.0	14.29%	-1.43%
1.0	5.9	5796.0		1.68E-03	2.0	16.95%	16.95%
10.0	76.6	2298.0	7.06E-04	2.120	22.8	1.31%	1.22%
10.0	77.5	2325.0	7.15E-04	2.120	22.8	1.29%	0.04%
10.0	73.5	2355.0	7.24E-04	2.120	22.9	1.27%	-1.23%
2.0	4.1	2014.0		1.17E-03	4.0	24.39%	4.88%
2.0	4.1	2014.0		1.17E-03	4.0	24.39%	4.88%
2.0	4.7	2309.0		1.34E-03	4.0	21.27%	-8.52%

DV7ather V1.0 data Copyright: 1992, Brookfield Engineering Labs
 Date: 05/12/93 Model: LV/HB
 Time: 13:43/12:17 Spindle: LV2/CP41
 File: SPL21LVL/SPL21CPL Sample: Agnew's Simulant

Speed RPM	Torque %	Viscosity cP	Shear Stress psi	Shear Rate 1/Sec	Temp. °C	Uncertainty	Variation
				0.064			
				0.064			
				0.064			
				0.127			
				0.127			
				0.127			
1.0	27.5	8079.0	2.34E-04	0.212	22.6	3.62%	-0.99%
1.0	27.0	8048.0	2.49E-04	0.212	22.6	3.70%	-1.85%
1.0	24.9	7458.0	2.37E-04	0.212	22.6	4.02%	6.43%
2.0	37.6	5639.0	3.47E-04	0.424	22.6	2.66%	0.44%
2.0	37.3	5684.0	3.49E-04	0.424	22.6	2.64%	-0.35%
2.0	37.8	5669.0	3.49E-04	0.424	22.6	2.65%	-0.04%
				0.6			
				0.6			
				0.6			
4.0	53.3	3997.0	4.91E-04	0.843	22.6	1.88%	1.00%
4.0	54.1	4057.0	4.99E-04	0.848	22.6	1.85%	-0.49%
4.0	54.1	4057.0	4.99E-04	0.848	22.6	1.85%	-0.49%
0.5	16.2	26520.0	4.62E-03	1.2	22.2	6.17%	93.65%
0.6	40.2	65820.0	1.15E-02	1.2	22.2	2.49%	-21.97%
0.6	37.7	61730.0	1.07E-02	1.2	22.3	2.65%	-16.80%
1.0	6.1	5993.0	1.74E-03	2.0	22.3	16.38%	93.53%
1.0	9.0	8842.0	2.56E-03	2.0	22.2	11.11%	27.78%
1.0	19.4	19060.0	5.52E-03	2.0	22.3	5.15%	-43.72%
10.0	88.3	2648.0	8.14E-04	2.120	22.6	1.15%	-1.02%
10.0	97.3	2513.0	8.95E-04	2.120	22.6	1.15%	0.11%
10.0	95.0	2597.0	7.33E-04	2.120	22.6	1.15%	0.92%
2.0	7.7	3782.0	2.19E-03	4.0	22.2	12.99%	-14.71%
2.0	4.1	2014.0	1.17E-03	4.0	22.2	24.39%	60.16%
2.0	7.9	3881.0	2.25E-03	4.0	22.2	12.56%	-16.84%
4.0	12.4	3291.0	3.82E-03	8.0	22.2	7.45%	-12.10%
4.0	7.4	1817.0	2.11E-03	8.0	22.2	13.52%	21.94%
4.0	6.5	1536.0	1.95E-03	8.0	22.3	15.39%	-0.02%

Cone and Plate Scatter Data

Data contained in the following spreadsheet were used to construct Figure 15.31.

Date: 05/20/93
Time: 12:58
File: SP22TMS
Model: BB
Spindle: CP41
Sample: Agave's Simulant

Time	Temp	Shear Rate	Shear Stress	Viscosity	CP	D/Out	psi	1/Sec	Sec
1	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
2	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
3	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
4	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
5	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
6	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
7	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
8	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
9	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
10	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
11	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
12	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
13	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
14	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
15	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
16	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
17	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
18	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
19	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
20	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
21	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
22	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
23	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
24	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
25	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
26	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
27	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
28	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
29	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
30	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
31	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
32	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
33	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
34	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
35	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
36	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
37	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
38	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
39	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
40	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
41	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
42	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
43	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
44	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
45	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
46	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
47	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
48	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
49	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
50	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3
51	23.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.3

0.3	3.6	11790.0	70.7	1.03E-03	0.6	23.1	52
0.3	3.4	11130.0	66.8	9.69E-04	0.6	23.1	53
0.3	3.4	11130.0	66.8	9.69E-04	0.6	23.1	54
0.3	3.4	11130.0	66.8	9.69E-04	0.6	23.1	55
0.3	3.4	11130.0	66.8	9.69E-04	0.6	23.1	56
0.3	3.3	10010.0	64.8	9.40E-04	0.6	23.1	57
0.3	3.3	10010.0	64.8	9.40E-04	0.6	23.1	58
0.3	3.4	11130.0	66.8	9.69E-04	0.6	23.1	59
0.3	3.4	11130.0	66.8	9.69E-04	0.6	23.1	60
0.3	3.6	11790.0	70.7	1.03E-03	0.6	23.1	61
0.3	3.4	11130.0	66.8	9.69E-04	0.6	23.1	62
0.3	3.7	12120.0	72.7	1.05E-03	0.6	23.1	63
0.3	3.7	12120.0	72.7	1.05E-03	0.6	23.1	64
0.3	4.1	13430.0	90.6	1.17E-03	0.6	23.1	65
0.3	9.4	30790.0	194.7	2.69E-03	0.6	23.1	66
0.3	11.5	37640.0	226.0	3.20E-03	0.6	23.1	67
0.3	11.5	37640.0	226.0	3.20E-03	0.6	23.1	68
0.3	11.5	37640.0	226.0	3.20E-03	0.6	23.1	69
0.3	19.9	65170.0	391.0	5.67E-03	0.6	23.1	70
0.3	19.9	65170.0	391.0	5.67E-03	0.6	23.1	71
0.3	19.9	65170.0	391.0	5.67E-03	0.6	23.1	72
0.3	26.3	86120.0	516.7	7.49E-03	0.6	23.1	73
0.3	27.8	91040.0	546.2	7.92E-03	0.6	23.1	74
0.3	27.8	91040.0	546.2	7.92E-03	0.6	23.1	75
0.3	9.1	29920.0	178.9	2.59E-03	0.6	23.1	76
0.3	8.8	28820.0	172.3	2.51E-03	0.6	23.1	77
0.3	10.0	32750.0	196.5	2.85E-03	0.6	23.1	78
0.3	12.1	43120.0	273.1	3.73E-03	0.6	23.1	79
0.3	12.1	43120.0	273.1	3.73E-03	0.6	23.1	80
0.3	13.9	45120.0	273.1	3.96E-03	0.6	23.1	81
0.3	15.9	52170.0	312.4	4.53E-03	0.6	23.1	82
0.3	15.9	52170.0	312.4	4.53E-03	0.6	23.1	83
0.3	13.1	42920.0	257.4	3.73E-03	0.6	23.1	84
0.3	13.1	42920.0	257.4	3.73E-03	0.6	23.1	85
0.3	21.3	69750.0	418.5	6.07E-03	0.6	23.1	86
0.3	21.3	69750.0	418.5	6.07E-03	0.6	23.1	87
0.3	21.3	69750.0	418.5	6.07E-03	0.6	23.1	88
0.3	27.0	84420.0	533.5	7.69E-03	0.6	23.1	89
0.3	27.0	84420.0	533.5	7.69E-03	0.6	23.1	90
0.3	5.8	18970.0	114.7	1.35E-03	0.6	23.1	91
0.3	4.1	13430.0	80.6	1.17E-03	0.6	23.1	92
0.3	4.1	13430.0	80.6	1.17E-03	0.6	23.1	93
0.3	4.2	13750.0	82.5	1.20E-03	0.6	23.1	94
0.3	4.2	13750.0	82.5	1.20E-03	0.6	23.1	95
0.3	3.9	12770.0	76.6	1.11E-03	0.6	23.0	96
0.3	3.9	12770.0	76.6	1.11E-03	0.6	23.0	97
0.3	3.9	12770.0	76.6	1.11E-03	0.6	23.0	98
0.3	7.4	24220.0	145.4	2.11E-03	0.6	23.0	99
0.3	6.7	21940.0	131.6	1.91E-03	0.6	23.0	100
0.3	6.7	21940.0	131.6	1.91E-03	0.6	23.0	101
0.3	6.3	20960.0	122.9	1.83E-03	0.6	23.0	102
0.3	6.4	20960.0	125.7	1.82E-03	0.6	23.0	103
0.3	6.4	20960.0	125.7	1.82E-03	0.6	23.0	104
0.3	6.4	20960.0	125.7	1.82E-03	0.6	23.0	105
0.3	7.0	22420.0	137.5	1.99E-03	0.6	23.0	106
0.3	15.0	49120.0	294.7	4.27E-03	0.6	23.0	107
0.3	18.3	59930.0	359.6	5.21E-03	0.6	23.0	108
0.3	19.3	63270.0	379.2	5.52E-03	0.6	23.0	109

0.3	20.4	66800.0	400.8	5.81E-03	0.6	23.0	110
0.3	23.6	77200.0	463.7	6.72E-03	0.6	23.0	111
0.3	26.5	86700.0	520.7	7.55E-03	0.6	23.0	112
0.3	26.5	86700.0	520.7	7.55E-03	0.6	23.0	113
0.3	10.1	33070.0	198.4	2.88E-03	0.6	23.0	114
0.3	10.1	33070.0	198.4	2.88E-03	0.6	23.0	115
0.3	10.1	33070.0	198.4	2.88E-03	0.6	23.0	116
0.3	2.7	8842.0	53.0	7.69E-04	0.6	23.0	117
0.3	2.7	8842.0	53.0	7.69E-04	0.6	23.0	118
0.3	2.7	8842.0	53.0	7.69E-04	0.6	23.0	119
0.3	3.4	11130.0	66.3	9.63E-04	0.6	23.0	120
0.3	3.6	11790.0	70.7	1.01E-03	0.6	23.0	121
0.3	4.4	14410.0	86.5	1.25E-03	0.6	23.0	122
0.3	4.4	14410.0	86.5	1.25E-03	0.6	23.0	123
0.3	4.4	14410.0	86.5	1.25E-03	0.6	23.0	124
0.3	4.4	14410.0	86.5	1.25E-03	0.6	23.0	125
0.3	4.4	14410.0	86.5	1.25E-03	0.6	23.0	126
0.3	7.9	25870.0	155.2	2.25E-03	0.6	23.0	127
0.3	7.9	25870.0	155.2	2.25E-03	0.6	23.0	128
0.3	7.9	25870.0	155.2	2.25E-03	0.6	23.0	129
0.3	10.8	35270.0	210.2	3.08E-03	0.6	23.0	130
0.3	12.8	41920.0	251.5	3.65E-03	0.6	23.0	131
0.3	12.8	41920.0	251.5	3.65E-03	0.6	23.0	132
0.3	13.9	45520.0	273.1	3.96E-03	0.6	23.0	133
0.3	9.9	32030.0	192.6	2.79E-03	0.6	23.0	134
0.3	9.0	29470.0	176.8	2.56E-03	0.6	23.0	135
0.3	8.8	28820.0	172.9	2.51E-03	0.6	23.0	136
0.3	9.5	31110.0	186.7	2.71E-03	0.6	23.0	137
0.3	13.4	43880.0	263.3	3.82E-03	0.6	23.0	138
0.3	13.4	43880.0	263.3	3.82E-03	0.6	23.0	139
0.3	13.4	43880.0	263.3	3.82E-03	0.6	23.0	140
0.3	22.1	75640.0	453.9	6.58E-03	0.6	23.0	141
0.3	22.1	75640.0	453.9	6.58E-03	0.6	23.0	142
0.3	23.1	75640.0	453.9	6.58E-03	0.6	23.0	143
0.3	23.1	75640.0	453.9	6.58E-03	0.6	23.0	144
0.3	31.8	104100.0	624.8	9.06E-03	0.6	22.9	145
0.3	31.8	104100.0	624.8	9.06E-03	0.6	22.9	146
0.3	32.9	107700.0	646.4	9.37E-03	0.6	22.9	147
0.3	37.2	121800.0	730.9	1.06E-02	0.6	22.9	148
0.3	41.5	135900.0	815.4	1.18E-02	0.6	22.9	149
0.3	42.5	139200.0	835.0	1.21E-02	0.6	22.9	150
0.3	42.5	139200.0	835.0	1.21E-02	0.6	22.9	151
0.3	42.6	142800.0	856.7	1.24E-02	0.6	22.9	152
0.3	6.2	20300.0	121.8	1.77E-03	0.6	22.9	153
0.3	4.9	16050.0	96.3	1.40E-03	0.6	22.9	154
0.3	4.1	13430.0	80.6	1.17E-03	0.6	22.9	155
0.3	4.2	13750.0	82.5	1.20E-03	0.6	22.9	156
0.3	4.8	15720.0	94.2	1.37E-03	0.6	22.9	157
0.3	5.1	16700.0	100.2	1.45E-03	0.6	22.9	158
0.3	5.2	17030.0	102.2	1.49E-03	0.6	22.9	159
0.3	5.2	17330.0	104.2	1.53E-03	0.6	22.9	160
0.3	5.1	16900.0	101.1	1.51E-03	0.6	22.9	161
0.3	5.1	16900.0	101.1	1.51E-03	0.6	22.9	162
0.3	6.2	20300.0	121.8	1.77E-03	0.6	22.9	163
0.3	6.2	20300.0	121.8	1.77E-03	0.6	22.9	164
0.3	6.2	20300.0	121.8	1.77E-03	0.6	22.9	165
0.3	9.2	33450.0	192.7	2.65E-03	0.6	22.9	166
0.3	10.2	33730.0	202.4	2.82E-03	0.6	22.9	167

0.3	10.3	33730.0	202.4	2.938-03	0.6	22.9	168
0.3	11.4	37330.0	224.0	3.258-03	0.6	22.9	169
0.3	11.4	37330.0	224.0	3.258-03	0.6	22.9	170
0.3	11.4	37330.0	224.0	3.258-03	0.6	22.9	171
0.3	12.4	40250.0	241.5	5.248-03	0.6	22.9	172
0.3	12.4	40250.0	241.5	5.248-03	0.6	22.9	173
0.3	13.4	43250.0	261.5	5.248-03	0.6	22.9	174
0.3	14.4	46330.0	281.2	5.538-03	0.6	22.9	175
0.3	14.4	46330.0	281.2	5.538-03	0.6	22.9	176
0.3	15.4	49490.0	301.5	7.568-03	0.6	22.9	177
0.3	16.2	108700.0	652.3	9.468-03	0.6	22.9	178
0.3	16.2	112000.0	672.0	9.748-03	0.6	22.9	179
0.3	16.2	112000.0	672.0	9.748-03	0.6	22.9	180

LV2 Spindle Scatter Data

Data contained in the following spreadsheet were used in Figure 5.32

DV-2000 data Copyright 1992, Brookfield Engineering Labs
 Date: 06/01/93 Model: LV
 Time: 10:20 Spindle: LV2
 File: SPL217W6 Sample: Agnew's Simulant

Speed RPM	Torque %	Viscosity cP	Shear Stress D/Cm ²	Shear Rate 1/Sec	Temperature °C	Time Sec
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	1
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	2
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	3
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	4
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	5
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	6
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	7
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	8
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	9
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	10
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	11
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	12
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	13
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	14
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	15
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	16
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	17
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	18
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	19
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	20
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	21
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	22
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	23
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	24
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	25
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	26
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	27
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	28
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	29
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	30
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	31
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	32
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	33
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	34
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	35
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	36
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	37
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	38
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	39
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	40
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	41
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	42
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	43
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	44
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	45
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	46
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	47
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	48
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	49
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	50
0.0	18.8	0.0	0.000 0.00E+00	0.000	22.7	51

0.3	73.8	73730.0	46.924 6.808-04	0.064	22.7	51
0.3	73.9	73880.0	46.988 6.818-04	0.064	22.7	53
0.3	74.0	73980.0	47.051 6.828-04	0.064	22.7	54
0.3	74.2	74180.0	47.178 6.848-04	0.064	22.7	55
0.3	74.2	74180.0	47.178 6.848-04	0.064	22.7	56
0.3	74.2	74180.0	47.178 6.848-04	0.064	22.7	57
0.3	74.2	74180.0	47.178 6.848-04	0.064	22.7	58
0.3	74.2	74180.0	47.178 6.848-04	0.064	22.7	59
0.3	74.7	74680.0	47.496 6.898-04	0.064	22.7	60
0.3	74.8	74780.0	47.560 6.908-04	0.064	22.7	61
0.3	75.0	74980.0	47.687 6.918-04	0.064	22.7	62
0.3	75.0	74980.0	47.687 6.918-04	0.064	22.7	63
0.3	75.0	74980.0	47.687 6.918-04	0.064	22.7	64
0.3	75.0	74980.0	47.687 6.918-04	0.064	22.7	65
0.3	75.5	75480.0	48.005 6.968-04	0.064	22.7	66
0.3	75.7	75680.0	48.132 6.978-04	0.064	22.7	67
0.3	75.8	75780.0	48.196 6.998-04	0.064	22.7	68
0.3	75.8	75780.0	48.196 6.998-04	0.064	22.7	69
0.3	75.8	75780.0	48.196 6.998-04	0.064	22.7	70
0.3	75.8	75780.0	48.196 6.998-04	0.064	22.7	71
0.3	76.4	76380.0	48.579 7.048-04	0.064	22.7	72
0.3	76.5	76480.0	48.641 7.058-04	0.064	22.7	73
0.3	76.6	76580.0	48.705 7.068-04	0.064	22.7	74
0.3	76.6	76580.0	48.705 7.068-04	0.064	22.7	75
0.3	76.6	76580.0	48.705 7.068-04	0.064	22.7	76
0.3	76.6	76580.0	48.705 7.068-04	0.064	22.7	77
0.3	77.3	77280.0	49.150 7.138-04	0.064	22.7	78
0.3	77.5	77480.0	49.277 7.158-04	0.064	22.7	79
0.3	77.6	77580.0	49.341 7.158-04	0.064	22.7	80
0.3	77.6	77580.0	49.341 7.158-04	0.064	22.7	81
0.3	78.0	77980.0	49.595 7.198-04	0.064	22.7	82
0.3	78.1	78080.0	49.659 7.208-04	0.064	22.7	83
0.3	78.3	78280.0	49.786 7.228-04	0.064	22.7	84
0.3	78.5	78480.0	49.912 7.248-04	0.064	22.7	85
0.3	78.7	78680.0	50.040 7.268-04	0.064	22.7	86
0.3	78.7	78680.0	50.040 7.268-04	0.064	22.7	87
0.3	79.0	78980.0	50.201 7.288-04	0.064	22.7	88
0.3	79.2	79180.0	50.358 7.308-04	0.064	22.7	89
0.3	79.4	79380.0	50.486 7.328-04	0.064	22.7	90
0.3	79.5	79480.0	50.549 7.338-04	0.064	22.7	91
0.3	79.5	79480.0	50.549 7.338-04	0.064	22.7	92
0.3	79.5	79480.0	50.549 7.338-04	0.064	22.7	93
0.3	79.7	79680.0	50.676 7.358-04	0.064	22.7	94
0.3	79.7	79680.0	50.676 7.358-04	0.064	22.7	95
0.3	80.0	79980.0	50.867 7.388-04	0.064	22.7	96
0.3	80.0	79980.0	50.867 7.388-04	0.064	22.7	97
0.3	80.0	79980.0	50.867 7.388-04	0.064	22.7	98
0.3	80.0	79980.0	50.867 7.388-04	0.064	22.7	99
0.3	80.3	80280.0	51.058 7.408-04	0.064	22.7	100
0.3	80.4	80380.0	51.122 7.418-04	0.064	22.7	101
0.3	80.6	80580.0	51.249 7.438-04	0.064	22.7	102
0.3	80.6	80580.0	51.249 7.438-04	0.064	22.7	103
0.3	80.6	80580.0	51.249 7.438-04	0.064	22.7	104
0.3	80.6	80580.0	51.249 7.438-04	0.064	22.7	105
0.3	81.1	81080.0	51.567 7.488-04	0.064	22.7	106
0.3	81.3	81280.0	51.694 7.508-04	0.064	22.7	107
0.3	81.3	81280.0	51.694 7.508-04	0.064	22.7	108
0.3	81.3	81280.0	51.694 7.508-04	0.064	22.7	109

0.3	81.3	81280.0	51.694	7.50B-04	0.064	22.7	110
0.3	81.7	81630.0	51.943	7.52B-04	0.064	22.7	111
0.3	81.8	81780.0	52.012	7.54B-04	0.064	22.7	112
0.3	81.8	81780.0	52.012	7.54B-04	0.064	22.7	113
0.3	81.8	81780.0	52.012	7.54B-04	0.064	22.7	114
0.3	81.8	81780.0	52.012	7.54B-04	0.064	22.7	115
0.3	81.8	81780.0	52.012	7.54B-04	0.064	22.7	116
0.3	82.0	81980.0	52.139	7.56B-04	0.064	22.7	117
0.3	82.1	82030.0	52.203	7.57B-04	0.064	22.7	118
0.3	82.1	82080.0	52.203	7.57B-04	0.064	22.7	119
0.3	82.1	82080.0	52.203	7.57B-04	0.064	22.7	120
0.3	82.1	82080.0	52.203	7.57B-04	0.064	22.7	121
0.3	82.4	82380.0	52.394	7.60B-04	0.064	22.7	122
0.3	82.4	82380.0	52.394	7.60B-04	0.064	22.7	123
0.3	82.5	82430.0	52.457	7.61B-04	0.064	22.7	124
0.3	82.5	82430.0	52.457	7.61B-04	0.064	22.7	125
0.3	82.5	82430.0	52.457	7.61B-04	0.064	22.7	126
0.3	82.5	82480.0	52.457	7.61B-04	0.064	22.7	127
0.3	82.7	82680.0	52.584	7.62B-04	0.064	22.7	128
0.3	82.8	82780.0	52.648	7.63B-04	0.064	22.7	129
0.3	82.8	82780.0	52.648	7.63B-04	0.064	22.7	130
0.3	82.8	82780.0	52.648	7.63B-04	0.064	22.7	131
0.3	82.8	82780.0	52.648	7.63B-04	0.064	22.7	132
0.3	82.8	82780.0	52.648	7.63B-04	0.064	22.7	133
0.3	82.8	82780.0	52.648	7.63B-04	0.064	22.7	134
0.3	83.0	82980.0	52.775	7.65B-04	0.064	22.7	135
0.3	82.9	82880.0	52.712	7.64B-04	0.064	22.7	136
0.3	83.0	82980.0	52.775	7.65B-04	0.064	22.7	137
0.3	83.0	82980.0	52.775	7.65B-04	0.064	22.7	138
0.3	82.9	82880.0	52.712	7.64B-04	0.064	22.7	139
0.3	82.9	82880.0	52.712	7.64B-04	0.064	22.7	140
0.3	82.8	82780.0	52.648	7.63B-04	0.064	22.7	141
0.3	82.8	82780.0	52.648	7.63B-04	0.064	22.7	142
0.3	82.8	82780.0	52.648	7.63B-04	0.064	22.7	143
0.3	82.5	82480.0	52.457	7.61B-04	0.064	22.7	144
0.3	82.6	82580.0	52.521	7.62B-04	0.064	22.7	145
0.3	82.6	82580.0	52.521	7.62B-04	0.064	22.7	146
0.3	82.6	82580.0	52.521	7.62B-04	0.064	22.7	147
0.3	82.6	82580.0	52.521	7.62B-04	0.064	22.7	148
0.3	82.6	82580.0	52.521	7.62B-04	0.064	22.7	149
0.3	82.6	82580.0	52.521	7.62B-04	0.064	22.7	150
0.3	82.6	82580.0	52.521	7.62B-04	0.064	22.7	151
0.3	82.6	82580.0	52.521	7.62B-04	0.064	22.7	152
0.3	82.7	82680.0	52.584	7.62B-04	0.064	22.7	153
0.3	82.7	82680.0	52.584	7.62B-04	0.064	22.7	154
0.3	82.7	82680.0	52.584	7.62B-04	0.064	22.7	155
0.3	82.7	82680.0	52.584	7.62B-04	0.064	22.7	156
0.3	82.7	82680.0	52.584	7.62B-04	0.064	22.7	157
0.3	82.3	82380.0	52.648	7.63B-04	0.064	22.7	158
0.3	82.8	82780.0	52.648	7.63B-04	0.064	22.7	159
0.3	82.8	82780.0	52.648	7.63B-04	0.064	22.7	160
0.3	82.3	82380.0	52.648	7.63B-04	0.064	22.7	161
0.3	82.6	82580.0	52.521	7.62B-04	0.064	22.7	162
0.3	82.6	82580.0	52.521	7.62B-04	0.064	22.7	163
0.3	82.7	82680.0	52.584	7.62B-04	0.064	22.7	164
0.3	82.7	82680.0	52.584	7.62B-04	0.064	22.7	165
0.3	82.7	82680.0	52.584	7.62B-04	0.064	22.7	166
0.3	82.7	82680.0	52.584	7.62B-04	0.064	22.7	167

0.3	82.7	82680.0	52.584	7.628-04	0.364	22.7	163
0.3	82.8	82780.0	52.648	7.638-04	0.364	22.7	169
0.3	82.8	82780.0	52.648	7.638-04	0.364	22.7	170
0.3	83.1	83080.0	52.839	7.668-04	0.364	22.7	171
0.3	83.2	83180.0	52.902	7.678-04	0.364	22.7	172
0.3	83.2	83180.0	52.902	7.678-04	0.364	22.7	173
0.3	83.3	83280.0	52.966	7.688-04	0.364	22.7	174
0.3	83.5	83480.0	53.093	7.708-04	0.364	22.7	175
0.3	83.5	83480.0	53.093	7.708-04	0.364	22.7	176
0.3	83.5	83480.0	53.093	7.708-04	0.364	22.7	177
0.3	83.5	83480.0	53.093	7.708-04	0.364	22.7	178
0.3	84.1	84080.0	53.675	7.758-04	0.364	22.7	179
0.3	84.2	84180.0	53.538	7.768-04	0.364	22.7	180

DV Gather+ V1.0 data Copyright 1992, Brookfield Engineering Labs
 Date: 06/01/93 Model: LV
 Time: 13:39 Spindle: LV2
 File: SPL217M7 Sample: Agnew's Simulant

Speed RPM	Torque g	Viscosity cP	Shear Stress D/Cm2 psi	Shear Rate 1/Sec	Temperature °C	Time Sec
0.0	11.7	0.0	0.000 0.00E+00	0.000	22.7	1
0.0	11.4	0.0	0.000 0.00E+00	0.000	22.7	2
0.0	11.4	0.0	0.000 0.00E+00	0.000	22.7	3
0.0	11.4	0.0	0.000 0.00E+00	0.000	22.7	4
0.3	17.1	17100.0	10.876 1.58E-04	0.064	22.7	5
0.3	18.8	18800.0	11.957 1.70E-04	0.064	22.7	6
0.3	21.2	21200.0	13.493 1.96E-04	0.064	22.7	7
0.3	21.2	21200.0	13.493 1.96E-04	0.064	22.7	8
0.3	21.2	21200.0	13.493 1.96E-04	0.064	22.7	9
0.3	21.2	21200.0	13.493 1.96E-04	0.064	22.7	10
0.3	29.1	29090.0	18.531 2.68E-04	0.064	22.7	11
0.3	30.8	30790.0	19.582 2.84E-04	0.064	22.7	12
0.3	32.5	32490.0	20.684 3.00E-04	0.064	22.7	13
0.3	33.6	33590.0	21.363 3.10E-04	0.064	22.7	14
0.3	33.6	33590.0	21.363 3.10E-04	0.064	22.7	15
0.3	33.6	33590.0	21.363 3.10E-04	0.064	22.7	16
0.3	33.6	33590.0	21.363 3.10E-04	0.064	22.7	17
0.3	37.9	37890.0	24.098 3.49E-04	0.064	22.7	18
0.3	38.8	38790.0	24.670 3.58E-04	0.064	22.7	19
0.3	39.4	39390.0	25.052 3.63E-04	0.064	22.7	20
0.3	39.4	39390.0	25.052 3.63E-04	0.064	22.7	21
0.3	39.4	39390.0	25.052 3.63E-04	0.064	22.7	22
0.3	39.4	39390.0	25.052 3.63E-04	0.064	22.7	23
0.3	40.5	40490.0	27.024 3.92E-04	0.064	22.7	24
0.3	40.4	40390.0	27.596 4.00E-04	0.064	22.7	25
0.3	44.0	43390.0	27.378 4.06E-04	0.064	22.6	26
0.3	45.2	45190.0	28.741 4.17E-04	0.064	22.7	27
0.3	45.2	45190.0	28.741 4.17E-04	0.064	22.7	28
0.3	45.2	45190.0	28.741 4.17E-04	0.064	22.7	29
0.3	45.2	45190.0	28.741 4.17E-04	0.064	22.7	30
0.3	47.5	47490.0	30.004 4.38E-04	0.064	22.7	31
0.3	48.4	48390.0	30.776 4.46E-04	0.064	22.7	32
0.3	49.5	49490.0	31.476 4.56E-04	0.064	22.6	33
0.3	49.5	49490.0	31.476 4.56E-04	0.064	22.6	34
0.3	49.5	49490.0	31.476 4.56E-04	0.064	22.6	35
0.3	49.5	49490.0	31.476 4.56E-04	0.064	22.6	36
0.3	51.5	51490.0	32.748 4.75E-04	0.064	22.7	37
0.3	52.2	52190.0	33.193 4.81E-04	0.064	22.7	38
0.3	52.7	52690.0	33.511 4.86E-04	0.064	22.7	39
0.3	53.5	53490.0	34.020 4.93E-04	0.064	22.7	40
0.3	53.5	53490.0	34.020 4.93E-04	0.064	22.7	41
0.3	53.5	53490.0	34.020 4.93E-04	0.064	22.7	42
0.3	53.5	53490.0	34.020 4.93E-04	0.064	22.7	43
0.3	55.9	55890.0	35.546 5.15E-04	0.064	22.7	44
0.3	56.5	56490.0	35.928 5.21E-04	0.064	22.6	45
0.3	57.0	56990.0	36.246 5.26E-04	0.064	22.7	46
0.3	57.0	56990.0	36.246 5.26E-04	0.064	22.7	47
0.3	57.0	56990.0	36.246 5.26E-04	0.064	22.7	48
0.3	57.0	56990.0	36.246 5.26E-04	0.064	22.7	49
0.3	59.2	59190.0	37.045 5.46E-04	0.064	22.7	50
0.3	59.7	59690.0	37.453 5.50E-04	0.064	22.7	51

0.3	59.7	59690.0	37.963	5.50E-04	0.064	22.7	52
0.3	59.7	59690.0	37.963	5.50E-04	0.064	22.7	53
0.3	59.7	59690.0	37.963	5.50E-04	0.064	22.7	54
0.3	61.4	61390.0	39.044	5.66E-04	0.064	22.6	55
0.3	62.0	61990.0	39.426	5.72E-04	0.064	22.6	56
0.3	62.3	62290.0	39.616	5.74E-04	0.064	22.7	57
0.3	62.3	62290.0	39.616	5.74E-04	0.064	22.7	58
0.3	62.3	62290.0	39.616	5.74E-04	0.064	22.7	59
0.3	62.3	62290.0	39.616	5.74E-04	0.064	22.7	60
0.3	64.0	63990.0	40.698	5.92E-04	0.064	22.7	61
0.3	64.0	64290.0	40.833	5.93E-04	0.064	22.7	62
0.3	64.9	64890.0	41.270	5.98E-04	0.064	22.7	63
0.3	65.0	65090.0	41.524	6.02E-04	0.064	22.7	64
0.3	65.0	65290.0	41.524	6.02E-04	0.064	22.7	65
0.3	65.0	65290.0	41.524	6.02E-04	0.064	22.7	66
0.3	65.0	65290.0	41.524	6.02E-04	0.064	22.7	67
0.3	66.9	66890.0	42.542	6.17E-04	0.064	22.7	68
0.3	67.4	67390.0	42.850	6.21E-04	0.064	22.7	69
0.3	67.9	67890.0	43.173	6.26E-04	0.064	22.7	70
0.3	67.9	67890.0	43.173	6.26E-04	0.064	22.7	71
0.3	68.9	68890.0	43.814	6.35E-04	0.064	22.7	72
0.3	69.1	69090.0	43.941	6.37E-04	0.064	22.7	73
0.3	69.2	69190.0	44.005	6.38E-04	0.064	22.7	74
0.3	69.3	69290.0	44.063	6.39E-04	0.064	22.7	75
0.3	69.6	69590.0	44.259	6.42E-04	0.064	22.7	76
0.3	69.6	69590.0	44.259	6.42E-04	0.064	22.7	77
0.3	70.2	70190.0	44.641	6.47E-04	0.064	22.7	78
0.3	70.3	70290.0	44.704	6.48E-04	0.064	22.7	79
0.3	70.6	70590.0	44.895	6.51E-04	0.064	22.7	80
0.3	70.8	70790.0	45.016	6.53E-04	0.064	22.7	81
0.3	70.9	70890.0	45.142	6.55E-04	0.064	22.7	82
0.3	71.0	70990.0	45.142	6.55E-04	0.064	22.7	83
0.3	71.4	71290.0	45.339	6.58E-04	0.064	22.6	84
0.3	71.6	71590.0	45.525	6.60E-04	0.064	22.6	85
0.3	71.9	71890.0	45.715	6.63E-04	0.064	22.6	86
0.3	72.1	72090.0	45.843	6.65E-04	0.064	22.7	87
0.3	72.1	72090.0	45.843	6.65E-04	0.064	22.7	88
0.3	72.8	72790.0	46.289	6.71E-04	0.064	22.7	89
0.3	72.8	72790.0	46.288	6.71E-04	0.064	22.7	90
0.3	72.9	72890.0	46.415	6.72E-04	0.064	22.6	91
0.3	72.9	72890.0	46.479	6.74E-04	0.064	22.7	92
0.3	73.1	73090.0	46.479	6.74E-04	0.064	22.7	93
0.3	73.1	73090.0	46.479	6.74E-04	0.064	22.7	94
0.3	73.1	73090.0	46.479	6.74E-04	0.064	22.7	95
0.3	73.1	73090.0	46.479	6.74E-04	0.064	22.7	96
0.3	73.5	73480.0	46.733	6.78E-04	0.064	22.6	97
0.3	73.7	73680.0	46.860	6.79E-04	0.064	22.6	98
0.3	73.9	73880.0	46.988	6.81E-04	0.064	22.7	99
0.3	73.9	73880.0	46.988	6.81E-04	0.064	22.7	100
0.3	74.0	74090.0	47.099	6.82E-04	0.064	22.7	101
0.3	74.1	74190.0	47.115	6.82E-04	0.064	22.6	102
0.3	74.2	74290.0	47.178	6.84E-04	0.064	22.6	103
0.3	74.3	74390.0	47.242	6.85E-04	0.064	22.6	104
0.3	74.4	74390.0	47.306	6.86E-04	0.064	22.7	105
0.3	74.4	74390.0	47.306	6.86E-04	0.064	22.7	106
0.3	74.4	74390.0	47.306	6.86E-04	0.064	22.7	107
0.3	74.4	74390.0	47.306	6.86E-04	0.064	22.7	108
0.3	74.7	74680.0	47.496	6.89E-04	0.064	22.7	109

0.3	74.7	74680.0	47.496 6.89E-04	0.064	22.7	110
0.3	74.8	74780.0	47.560 6.90E-04	0.064	22.7	111
0.3	74.8	74780.0	47.560 6.90E-04	0.064	22.7	112
0.3	74.8	74780.0	47.560 6.90E-04	0.064	22.7	113
0.3	74.8	74780.0	47.560 6.90E-04	0.064	22.7	114
0.3	74.8	74780.0	47.560 6.90E-04	0.064	22.7	115
0.3	74.8	74780.0	47.560 6.90E-04	0.064	22.7	116
0.3	74.9	74880.0	47.624 6.91E-04	0.064	22.7	117
0.3	74.9	74880.0	47.624 6.91E-04	0.064	22.7	118
0.3	74.9	74880.0	47.624 6.91E-04	0.064	22.7	119
0.3	74.9	74880.0	47.624 6.91E-04	0.064	22.7	120
0.3	75.2	75180.0	47.814 6.93E-04	0.064	22.7	121
0.3	75.2	75180.0	47.814 6.93E-04	0.064	22.7	122
0.3	75.2	75180.0	47.878 6.94E-04	0.064	22.7	123
0.3	75.2	75180.0	47.878 6.94E-04	0.064	22.7	124
0.3	75.2	75180.0	47.878 6.94E-04	0.064	22.7	125
0.3	75.2	75180.0	47.878 6.94E-04	0.064	22.7	126
0.3	75.2	75180.0	47.878 6.94E-04	0.064	22.7	127
0.3	75.3	75880.0	48.260 7.00E-04	0.064	22.7	128
0.3	75.3	75880.0	48.260 7.00E-04	0.064	22.7	129
0.3	75.3	75880.0	48.260 7.00E-04	0.064	22.7	130
0.3	76.1	76080.0	48.387 7.02E-04	0.064	22.7	131
0.3	76.1	76080.0	48.387 7.02E-04	0.064	22.7	132
0.3	76.2	76180.0	48.450 7.03E-04	0.064	22.7	133
0.3	76.4	76380.0	48.578 7.04E-04	0.064	22.7	134
0.3	76.4	76380.0	48.578 7.04E-04	0.064	22.7	135
0.3	76.4	76380.0	48.578 7.04E-04	0.064	22.7	136
0.3	76.7	76680.0	48.768 7.07E-04	0.064	22.7	137
0.3	76.8	76780.0	48.832 7.08E-04	0.064	22.7	138
0.3	77.0	76980.0	48.959 7.10E-04	0.064	22.7	139
0.3	77.0	76980.0	48.959 7.10E-04	0.064	22.7	140
0.3	77.0	76980.0	48.959 7.10E-04	0.064	22.7	141
0.3	77.0	76980.0	48.959 7.10E-04	0.064	22.7	142
0.3	77.4	77380.0	49.214 7.14E-04	0.064	22.7	143
0.3	77.5	77480.0	49.277 7.15E-04	0.064	22.7	144
0.3	77.6	77580.0	49.341 7.15E-04	0.064	22.7	145
0.3	77.6	77580.0	49.341 7.15E-04	0.064	22.7	146
0.3	77.6	77580.0	49.341 7.15E-04	0.064	22.7	147
0.3	77.6	77580.0	49.341 7.15E-04	0.064	22.7	148
0.3	77.6	77580.0	49.341 7.15E-04	0.064	22.7	149
0.3	77.7	77680.0	49.404 7.16E-04	0.064	22.7	150
0.3	77.7	77680.0	49.404 7.16E-04	0.064	22.7	151
0.3	77.7	77680.0	49.404 7.16E-04	0.064	22.7	152
0.3	77.7	77680.0	49.404 7.16E-04	0.064	22.7	153
0.3	77.9	77980.0	49.532 7.18E-04	0.064	22.7	154
0.3	77.9	77980.0	49.532 7.18E-04	0.064	22.7	155
0.3	77.9	77980.0	49.532 7.18E-04	0.064	22.7	156
0.3	78.2	78180.0	49.722 7.21E-04	0.064	22.7	157
0.3	78.2	78180.0	49.722 7.21E-04	0.064	22.7	158
0.3	78.2	78180.0	49.722 7.21E-04	0.064	22.7	159
0.3	78.2	78180.0	49.722 7.21E-04	0.064	22.7	160
0.3	78.1	78080.0	49.659 7.20E-04	0.064	22.7	161
0.3	78.1	78080.0	49.659 7.20E-04	0.064	22.7	162
0.3	78.0	77980.0	49.595 7.19E-04	0.064	22.7	163
0.3	78.0	77980.0	49.595 7.19E-04	0.064	22.7	164
0.3	77.9	77880.0	49.532 7.18E-04	0.064	22.7	165
0.3	77.8	77780.0	49.468 7.17E-04	0.064	22.7	166
0.3	77.6	77580.0	49.341 7.15E-04	0.064	22.7	167

0.3	77.6	77500.0	49.341	7.138-04	0.064	22.7	168
0.3	77.4	77300.0	49.214	7.148-04	0.064	22.7	169
0.3	77.3	77200.0	49.150	7.138-04	0.064	22.7	170
0.3	77.2	77100.0	49.086	7.128-04	0.064	22.7	171
0.3	77.2	77100.0	49.086	7.128-04	0.064	22.7	172
0.3	77.2	77100.0	49.086	7.128-04	0.064	22.7	173
0.3	77.2	77100.0	49.086	7.128-04	0.064	22.7	174
0.3	77.3	77200.0	49.150	7.138-04	0.064	22.7	175
0.3	77.3	77200.0	49.150	7.138-04	0.064	22.7	176
0.3	77.3	77200.0	49.150	7.138-04	0.064	22.7	177
0.3	77.3	77200.0	49.150	7.138-04	0.064	22.7	178
0.3	77.3	77200.0	49.150	7.138-04	0.064	22.7	179
0.3	77.3	77200.0	49.150	7.138-04	0.064	22.7	180
0.3	77.4	77300.0	49.214	7.148-04	0.064	22.7	181

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 Date: 06/02/93 Model: LV
 Time: 08:21 Sprinkle: LV2
 File: SPULIT10 Sample: Agnew's Simulant

Speed RPM	Torque %	Viscosity cP	Shear Stress D/Co2 ps:	Shear Rate 1/Sec	Temperature °C	Time Sec.
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	1
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	2
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	3
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	4
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	5
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	6
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	7
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	8
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	9
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	10
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	11
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	12
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	13
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	14
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	15
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	16
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	17
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	18
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	19
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	20
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	21
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	22
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	23
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	24
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	25
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	26
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	27
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	28
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	29
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	30
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	31
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	32
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	33
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	34
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	35
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	36
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	37
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	38
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	39
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	40
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	41
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	42
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	43
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	44
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	45
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	46
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	47
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	48
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	49
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	50
0.0	4.8	0.0	0.00 0.00E+00	0.000	21.6	51

0.3	56.0	56790.0	36.12	5.248-04	0.064	21.6	52
0.3	56.1	58090.0	36.95	5.368-04	0.064	21.6	53
0.3	56.2	59190.0	37.39	5.428-04	0.064	21.6	54
0.3	56.3	59790.0	37.52	5.448-04	0.064	21.6	55
0.3	56.4	59990.0	37.64	5.468-04	0.064	21.6	56
0.3	56.5	59990.0	37.64	5.468-04	0.064	21.6	57
0.3	56.6	59990.0	37.64	5.468-04	0.064	21.6	58
0.3	56.7	59990.0	37.64	5.468-04	0.064	21.6	59
0.3	56.8	59990.0	38.15	5.538-04	0.064	21.6	60
0.3	56.9	60190.0	38.28	5.558-04	0.064	21.6	61
0.3	57.0	60290.0	38.41	5.578-04	0.064	21.6	62
0.3	57.1	60390.0	38.41	5.578-04	0.064	21.6	63
0.3	57.2	60390.0	38.41	5.578-04	0.064	21.6	64
0.3	57.3	60390.0	38.41	5.578-04	0.064	21.6	65
0.3	57.4	60390.0	39.04	5.668-04	0.064	21.6	66
0.3	57.5	61690.0	39.23	5.698-04	0.064	21.6	67
0.3	57.6	61690.0	39.43	5.728-04	0.064	21.6	68
0.3	57.7	61990.0	39.43	5.728-04	0.064	21.6	69
0.3	57.8	61990.0	39.43	5.728-04	0.064	21.6	70
0.3	57.9	61990.0	39.43	5.728-04	0.064	21.6	71
0.3	58.0	63190.0	40.19	5.838-04	0.064	21.6	72
0.3	58.1	63290.0	40.25	5.848-04	0.064	21.6	73
0.3	58.2	63590.0	40.44	5.868-04	0.064	21.6	74
0.3	58.3	63590.0	40.44	5.868-04	0.064	21.6	75
0.3	58.4	63590.0	40.44	5.868-04	0.064	21.6	76
0.3	58.5	63590.0	40.44	5.868-04	0.064	21.6	77
0.3	58.6	64290.0	40.35	5.948-04	0.064	21.6	78
0.3	58.7	64490.0	41.02	5.958-04	0.064	21.6	79
0.3	58.8	64690.0	41.14	5.978-04	0.064	21.6	80
0.3	58.9	64790.0	41.27	5.998-04	0.064	21.6	81
0.3	59.0	64890.0	41.27	5.998-04	0.064	21.6	82
0.3	59.1	64890.0	41.27	5.998-04	0.064	21.6	83
0.3	59.2	65690.0	41.79	6.068-04	0.064	21.6	84
0.3	59.3	65790.0	41.84	6.078-04	0.064	21.6	85
0.3	59.4	65790.0	41.84	6.078-04	0.064	21.6	86
0.3	59.5	65790.0	41.84	6.078-04	0.064	21.6	87
0.3	59.6	65790.0	41.84	6.078-04	0.064	21.6	88
0.3	59.7	66190.0	42.10	6.108-04	0.064	21.6	89
0.3	59.8	66490.0	42.29	6.138-04	0.064	21.6	90
0.3	59.9	66790.0	42.48	6.168-04	0.064	21.6	91
0.3	60.0	66790.0	42.48	6.168-04	0.064	21.6	92
0.3	60.1	66790.0	42.48	6.168-04	0.064	21.6	93
0.3	60.2	66790.0	42.48	6.168-04	0.064	21.6	94
0.3	60.3	66790.0	42.48	6.168-04	0.064	21.6	95
0.3	60.4	67590.0	42.95	6.218-04	0.064	21.6	96
0.3	60.5	67590.0	42.99	6.238-04	0.064	21.6	97
0.3	60.6	67690.0	43.05	6.248-04	0.064	21.6	98
0.3	60.7	67690.0	43.05	6.248-04	0.064	21.6	99
0.3	60.8	67690.0	43.05	6.248-04	0.064	21.6	100
0.3	60.9	67690.0	43.05	6.248-04	0.064	21.6	101
0.3	61.0	68290.0	43.42	6.308-04	0.064	21.6	102
0.3	61.1	68290.0	43.42	6.308-04	0.064	21.6	103
0.3	61.2	68390.0	43.50	6.318-04	0.064	21.6	104
0.3	61.3	68490.0	43.56	6.328-04	0.064	21.6	105
0.3	61.4	68490.0	43.56	6.328-04	0.064	21.6	106
0.3	61.5	68490.0	43.56	6.328-04	0.064	21.6	107
0.3	61.6	68590.0	43.62	6.338-04	0.064	21.6	108
0.3	61.7	68590.0	43.62	6.338-04	0.064	21.6	109

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0.3	71.9	71000.0	45.72	6.638-00	0.064	21.6	160
0.3	71.9	71000.0	45.72	6.638-00	0.064	21.6	160
0.3	71.9	71000.0	45.72	6.638-00	0.064	21.7	170
0.3	71.9	71000.0	45.72	6.638-00	0.064	21.7	171
0.3	71.9	71000.0	45.72	6.638-00	0.064	21.7	172
0.3	72.1	72000.0	45.00	6.658-00	0.064	21.6	173
0.3	72.1	72000.0	45.00	6.658-00	0.064	21.6	174
0.3	72.2	72000.0	45.91	6.608-00	0.064	21.7	175
0.3	72.3	72000.0	45.97	6.678-00	0.064	21.7	176
0.3	72.3	72000.0	45.97	6.678-00	0.064	21.7	177
0.3	72.3	72000.0	45.97	6.678-00	0.064	21.7	178
0.3	72.3	72000.0	45.97	6.678-00	0.064	21.7	179
0.3	72.3	72000.0	45.97	6.678-00	0.064	21.7	180
0.3	72.3	72000.0	45.97	6.678-00	0.064	21.7	181
0.3	72.3	72000.0	45.97	6.678-00	0.064	21.7	182
0.3	72.3	72000.0	45.97	6.678-00	0.064	21.7	183
0.3	72.3	72000.0	45.97	6.678-00	0.064	21.7	184
0.3	72.3	72000.0	45.97	6.678-00	0.064	21.7	185
0.3	72.3	72000.0	45.97	6.678-00	0.064	21.7	186
0.3	72.3	72000.0	45.97	6.678-00	0.064	21.7	187
0.3	72.3	72000.0	45.97	6.678-00	0.064	21.7	188
0.3	72.3	72000.0	45.97	6.678-00	0.064	21.7	189
0.3	72.3	72000.0	45.97	6.678-00	0.064	21.7	190
0.3	72.3	72000.0	45.97	6.678-00	0.064	21.7	191
0.3	72.3	72000.0	45.97	6.678-00	0.064	21.7	192
0.3	72.3	72000.0	45.97	6.678-00	0.064	21.7	193
0.3	72.3	72000.0	45.97	6.678-00	0.064	21.7	194
0.3	72.3	72000.0	45.97	6.678-00	0.064	21.7	195
0.3	72.3	72000.0	45.97	6.678-00	0.064	21.7	196
0.3	72.3	72000.0	45.97	6.678-00	0.064	21.7	197
0.3	72.3	72000.0	45.97	6.678-00	0.064	21.7	198
0.3	72.3	72000.0	45.97	6.678-00	0.064	21.7	199
0.3	72.3	72000.0	45.97	6.678-00	0.064	21.7	200

Combined Data For LV2, CP41, and SC4-34 Spindles

**Data contained in the following spreadsheets were used to construct
Figures 5.33, 5.34, and 5.35**

Data: 8/19/93 data Copyright 1992 Brookfield Engineering Labs
 Date: 8/19/93 Model: LV
 Time: 08:25 Spindle: LV2
 File: SPL2LV7/SPL21723 Sample: Agnew's Stainant

Speed RPM	Torque g	Viscosity cP	Shear Stress PSI	Shear Rate 1/Sec	Temp. °C	Uncertainty	Variation
0.2	42.7	4250.0	3.94E-04	0.064	22.4	2.34%	1.02%
0.2	43.2	4310.0	3.98E-04	0.064	22.4	2.33%	-0.15%
0.2	43.5	4340.0	4.01E-04	0.064	22.4	2.30%	-0.84%
				0.094			
				0.094			
				0.094			
0.6	55.2	2790.0	5.09E-04	0.127	22.5	1.81%	3.26%
0.6	58.3	2910.0	5.37E-04	0.127	22.5	1.72%	-2.23%
0.6	61.5	2970.0	5.50E-04	0.127	22.5	1.74%	-0.37%
				0.168			
				0.168			
				0.168			
1.0	70.4	2120.0	6.44E-04	0.212	22.6	1.42%	-0.03%
1.0	70.8	2120.0	6.53E-04	0.212	22.6	1.41%	-0.66%
1.0	69.3	2090.0	6.45E-04	0.212	22.6	1.42%	0.76%
				0.250			
				0.250			
				0.250			
1.2	81.1	1840.0	9.29E-04	0.414	22.7	1.12%	0.84%
1.2	80.7	1850.0	9.23E-04	0.414	22.6	1.12%	0.77%
1.2	81.3	1870.0	9.47E-04	0.414	22.6	1.09%	-1.57%

Model: LV/ND

Spindle: LV2/CP41

Sample: Agnew's Simulacrat

[illegible]

DV Gather+ V1.0 data Copyright 1992, Brookfield Engineering Labs
 Date: 05/19/93 Model: LV
 Time: 12:59 Spindle: SC4-34
 File: SPL21LVU/SPL21SSA Sample: Agnew's Simulant

Speed RPM	Torque %	Viscosity cP	Shear Stress D/Cm2 psi	Shear Rate 1/Sec	Temperature °C	Uncertainty	Variation
				0.064			
				0.064			
				0.064			
0.3	22.9	45790.0	38.5 5.58E-04	0.084	22.6	4.37%	3.64%
0.3	23.6	47190.0	39.6 5.74E-04	0.084	22.6	4.24%	0.57%
0.3	24.7	49390.0	41.5 6.02E-04	0.084	22.6	4.05%	-0.31%
				0.127			
				0.127			
				0.127			
0.6	26.0	25990.0	43.7 6.34E-04	0.168	22.6	3.85%	1.41%
0.6	26.8	26790.0	45.0 6.53E-04	0.168	22.6	3.73%	-1.62%
0.6	26.3	26290.0	44.2 6.41E-04	0.168	22.6	3.80%	0.25%
				0.212			
				0.212			
				0.212			
1.0	30.0	18090.0	50.4 7.31E-04	0.280	22.6	3.33%	-0.22%
1.0	29.7	17820.0	49.9 7.24E-04	0.280	22.6	3.37%	0.79%
1.0	30.1	18060.0	50.6 7.34E-04	0.280	22.6	3.32%	-0.55%
				0.424			
				0.424			
				0.424			
2.0	36.1	10830.0	60.6 8.79E-04	0.560	22.6	2.77%	0.65%
2.0	36.3	10890.0	61.0 8.85E-04	0.560	22.6	2.75%	0.09%
2.0	36.6	10980.0	61.5 8.92E-04	0.560	22.6	2.73%	-0.73%
4.0	45.0	6749.0	75.6 1.10E-03	1.120	22.6	2.22%	-0.07%
4.0	44.6	6689.0	74.9 1.09E-03	1.120	22.6	2.24%	0.82%
4.0	45.3	6794.0	76.1 1.10E-03	1.120	22.6	2.21%	-0.74%
10.0	61.9	3713.0	104.0 1.51E-03	2.800	22.6	1.62%	-0.22%
10.0	61.8	3707.0	103.8 1.51E-03	2.800	22.6	1.62%	-0.05%
10.0	61.6	3695.0	103.5 1.50E-03	2.800	22.6	1.62%	0.27%

Cone and Plate Spindle CP41 Data

Data contained in the following spreadsheet were used to construct Figure 5.36.

DVGather+ V1.0 data Copyright 1992, Brookfield Engineering Labs
 Date: 06/01/93 Model: HB
 Time: 12:50 Spindle: CP41
 File: SPL21TM8 Sample: UNNAMED DATA

Speed	Torque	Viscosity	Shear Stress	Shear Rate	Temperature	Time
RPM	%	cP	D/Cm2 psi	1/Sec	°C	Sec
0.0	0.4	0.0	0.0 0.00E+00	0.0	26.3	1
0.3	0.4	1310.0	7.9 1.15E-04	0.6	26.4	2
0.3	0.9	2947.0	17.7 2.57E-04	0.6	26.4	3
0.3	0.9	2947.0	17.7 2.57E-04	0.6	26.4	4
0.3	1.8	5894.0	35.4 5.13E-04	0.6	26.4	5
0.3	1.8	5894.0	35.4 5.13E-04	0.6	26.4	6
0.3	1.8	5894.0	35.4 5.13E-04	0.6	26.4	7
0.3	7.1	23250.0	139.5 2.02E-03	0.6	26.4	8
0.3	7.1	23250.0	139.5 2.02E-03	0.6	26.4	9
0.3	7.1	23250.0	139.5 2.02E-03	0.6	26.4	10
0.3	7.1	23250.0	139.5 2.02E-03	0.6	26.4	11
0.3	7.1	23250.0	139.5 2.02E-03	0.6	26.4	12
0.3	13.9	45520.0	273.1 3.96E-03	0.6	26.4	13
0.3	13.9	45520.0	273.1 3.96E-03	0.6	26.4	14
0.3	12.4	40610.0	243.6 3.53E-03	0.6	26.4	15
0.3	12.2	39950.0	239.7 3.48E-03	0.6	26.4	16
0.3	12.2	39950.0	239.7 3.48E-03	0.6	26.4	17
0.3	12.2	39950.0	239.7 3.48E-03	0.6	26.4	18
0.3	12.0	39300.0	235.8 3.42E-03	0.6	26.4	19
0.3	11.4	37330.0	224.0 3.25E-03	0.6	26.4	20
0.3	10.7	35040.0	210.2 3.05E-03	0.6	26.4	21
0.3	10.5	34380.0	206.3 2.99E-03	0.6	26.4	22
0.3	10.5	34380.0	206.3 2.99E-03	0.6	26.4	23
0.3	10.5	34380.0	206.3 2.99E-03	0.6	26.4	24

0.3	10.5	34380.0	206.3 2.99E-03	0.6	26.4	25
0.3	10.5	34380.0	206.3 2.99E-03	0.6	26.4	26
0.3	10.5	34380.0	206.3 2.99E-03	0.6	26.4	27
0.3	10.5	34380.0	206.3 2.99E-03	0.6	26.4	28
0.3	10.5	34380.0	206.3 2.99E-03	0.6	26.4	29
0.3	9.4	30780.0	184.7 2.68E-03	0.6	26.3	30
0.3	9.4	30780.0	184.7 2.68E-03	0.6	26.3	31
0.3	9.4	30780.0	184.7 2.68E-03	0.6	26.3	32
0.3	9.4	30780.0	184.7 2.68E-03	0.6	26.3	33
0.3	9.2	30130.0	180.8 2.62E-03	0.6	26.4	34
0.3	9.2	30130.0	180.8 2.62E-03	0.6	26.4	35
0.3	9.2	30130.0	180.8 2.62E-03	0.6	26.4	36
0.3	9.2	30130.0	180.8 2.62E-03	0.6	26.4	37
0.3	9.2	30130.0	180.8 2.62E-03	0.6	26.4	38
0.3	9.1	29800.0	178.8 2.59E-03	0.6	26.4	39
0.3	8.6	28160.0	169.0 2.45E-03	0.6	26.4	40
0.3	8.5	27830.0	167.0 2.42E-03	0.6	26.4	41
0.3	8.5	27830.0	167.0 2.42E-03	0.6	26.4	42
0.3	8.5	27830.0	167.0 2.42E-03	0.6	26.4	43
0.3	8.5	27830.0	167.0 2.42E-03	0.6	26.4	44
0.3	8.2	26850.0	161.1 2.34E-03	0.6	26.4	45
0.3	8.2	26850.0	161.1 2.34E-03	0.6	26.4	46
0.3	8.2	26850.0	161.1 2.34E-03	0.6	26.4	47
0.3	8.2	26850.0	161.1 2.34E-03	0.6	26.4	48
0.3	8.1	26520.0	159.1 2.31E-03	0.6	26.4	49
0.3	9.0	29470.0	176.8 2.56E-03	0.6	26.4	50
0.3	9.4	30780.0	184.7 2.68E-03	0.6	26.4	51
0.3	10.4	34060.0	204.3 2.96E-03	0.6	26.4	52
0.3	13.1	42900.0	257.4 3.73E-03	0.6	26.4	53
0.3	13.7	44860.0	269.2 3.90E-03	0.6	26.4	54
0.3	10.6	34710.0	208.3 3.02E-03	0.6	26.4	55
0.3	9.5	31110.0	186.7 2.71E-03	0.6	26.4	56
0.3	9.5	31110.0	186.7 2.71E-03	0.6	26.4	57
0.3	7.5	24560.0	147.4 2.14E-03	0.6	26.4	58
0.3	7.4	24230.0	145.4 2.11E-03	0.6	26.4	59
0.3	7.3	23910.0	143.4 2.08E-03	0.6	26.4	60
0.3	7.3	23910.0	143.4 2.08E-03	0.6	26.4	61
0.3	7.3	23910.0	143.4 2.08E-03	0.6	26.4	62
0.3	7.3	23910.0	143.4 2.08E-03	0.6	26.4	63
0.3	7.3	23910.0	143.4 2.08E-03	0.6	26.4	64
0.3	7.5	24560.0	147.4 2.14E-03	0.6	26.4	65
0.3	7.5	24560.0	147.4 2.14E-03	0.6	26.4	66
0.3	7.4	24230.0	145.4 2.11E-03	0.6	26.4	67
0.3	7.4	24230.0	145.4 2.11E-03	0.6	26.4	68
0.3	7.3	23910.0	143.4 2.08E-03	0.6	26.4	69
0.3	7.3	23910.0	143.4 2.08E-03	0.6	26.4	70
0.3	7.3	23910.0	143.4 2.08E-03	0.6	26.4	71
0.3	7.3	23910.0	143.4 2.08E-03	0.6	26.4	72
0.3	7.3	23910.0	143.4 2.08E-03	0.6	26.4	73
0.3	7.3	23910.0	143.4 2.08E-03	0.6	26.4	74
0.3	7.2	23580.0	141.5 2.05E-03	0.6	26.4	75
0.3	7.2	23580.0	141.5 2.05E-03	0.6	26.4	76
0.3	7.2	23580.0	141.5 2.05E-03	0.6	26.4	77
0.3	7.2	23580.0	141.5 2.05E-03	0.6	26.4	78
0.3	7.3	23910.0	143.4 2.08E-03	0.6	26.4	79
0.3	7.3	23910.0	143.4 2.08E-03	0.6	26.4	80
0.3	7.3	23910.0	143.4 2.08E-03	0.6	26.4	81
0.3	7.2	23580.0	141.5 2.05E-03	0.6	26.4	82

0.3	7.2	23580.0	141.5	2.05E-03	0.6	26.4	83
0.3	7.3	23910.0	143.4	2.08E-03	0.6	26.4	84
0.3	7.0	22920.0	137.5	1.99E-03	0.6	26.4	85
0.3	7.1	23250.0	139.5	2.02E-03	0.6	26.4	86
0.3	7.1	23250.0	139.5	2.02E-03	0.6	26.4	87
0.3	7.1	23250.0	139.5	2.02E-03	0.6	26.4	88
0.3	7.1	23250.0	139.5	2.02E-03	0.6	26.4	89
0.3	7.1	23250.0	139.5	2.02E-03	0.6	26.4	90
0.3	7.1	23250.0	139.5	2.02E-03	0.6	26.4	91
0.3	7.2	23580.0	141.5	2.05E-03	0.6	26.4	92
0.3	7.7	25210.0	151.3	2.19E-03	0.6	26.4	93
0.3	8.1	26520.0	159.1	2.31E-03	0.6	26.4	94
0.3	8.1	26520.0	159.1	2.31E-03	0.6	26.4	95
0.3	8.1	26520.0	159.1	2.31E-03	0.6	26.4	96
0.3	8.8	28820.0	172.9	2.51E-03	0.6	26.4	97
0.3	10.7	35040.0	210.2	3.05E-03	0.6	26.4	98
0.3	13.8	45190.0	271.1	3.93E-03	0.6	26.4	99
0.3	17.0	55670.0	334.0	4.84E-03	0.6	26.4	100
0.3	18.0	58940.0	353.7	5.13E-03	0.6	26.4	101
0.3	18.0	58940.0	353.7	5.13E-03	0.6	26.4	102
0.3	18.0	58940.0	353.7	5.13E-03	0.6	26.4	103
0.3	20.0	65490.0	393.0	5.70E-03	0.6	26.4	104
0.3	20.0	65490.0	393.0	5.70E-03	0.6	26.4	105
0.3	7.2	23580.0	141.5	2.05E-03	0.6	26.4	106
0.3	6.6	21610.0	129.7	1.88E-03	0.6	26.4	107
0.3	6.3	20630.0	123.8	1.80E-03	0.6	26.4	108
0.3	6.3	20630.0	123.8	1.80E-03	0.6	26.4	109
0.3	6.3	20630.0	123.8	1.80E-03	0.6	26.4	110
0.3	6.3	20630.0	123.8	1.80E-03	0.6	26.4	111
0.3	6.4	20960.0	125.7	1.82E-03	0.6	26.4	112
0.3	6.4	20960.0	125.7	1.82E-03	0.6	26.4	113
0.3	6.4	20960.0	125.7	1.82E-03	0.6	26.4	114
0.3	6.6	21610.0	129.7	1.88E-03	0.6	26.4	115
0.3	7.3	23910.0	143.4	2.08E-03	0.6	26.4	116
0.3	7.4	24230.0	145.4	2.11E-03	0.6	26.4	117
0.3	7.8	25540.0	153.3	2.22E-03	0.6	26.4	118
0.3	8.0	26200.0	157.2	2.28E-03	0.6	26.4	119
0.3	8.0	26200.0	157.2	2.28E-03	0.6	26.4	120
0.3	8.0	26200.0	157.2	2.28E-03	0.6	26.4	121
0.3	8.0	26200.0	157.2	2.28E-03	0.6	26.4	122
0.3	15.6	51080.0	306.5	4.44E-03	0.6	26.4	123
0.3	16.7	54690.0	328.1	4.76E-03	0.6	26.4	124
0.3	21.0	68770.0	412.6	5.98E-03	0.6	26.4	125
0.3	23.2	75970.0	455.8	6.61E-03	0.6	26.4	126
0.3	24.3	79570.0	477.4	6.92E-03	0.6	26.4	127
0.3	26.4	86450.0	518.7	7.52E-03	0.6	26.4	128
0.3	30.7	100500.0	603.2	8.75E-03	0.6	26.4	129
0.3	32.9	107700.0	646.4	9.37E-03	0.6	26.4	130
0.3	34.0	111300.0	668.0	9.69E-03	0.6	26.4	131
0.3	38.3	125400.0	752.5	1.09E-02	0.6	26.4	132
0.3	39.4	129000.0	774.1	1.12E-02	0.6	26.4	133
0.3	42.6	139500.0	837.0	1.21E-02	0.6	26.4	134
0.3	42.6	139500.0	837.0	1.21E-02	0.6	26.4	135
0.3	43.7	143100.0	858.6	1.24E-02	0.6	26.4	136
0.3	43.7	143100.0	858.6	1.24E-02	0.6	26.4	137
0.3	43.7	143100.0	858.6	1.24E-02	0.6	26.4	138
0.3	43.7	143100.0	858.6	1.24E-02	0.6	26.4	139
0.3	22.5	73680.0	442.1	6.41E-03	0.6	26.4	140

0.3	23.6	77280.0	463.7 6.72E-03	0.6	26.4	141
0.3	25.7	84160.0	505.0 7.32E-03	0.6	26.4	142
0.3	27.8	91040.0	546.2 7.92E-03	0.6	26.4	143
0.3	29.8	97590.0	585.5 8.49E-03	0.6	26.3	144
0.3	26.9	88090.0	528.5 7.66E-03	0.6	26.4	145
0.3	27.4	89730.0	538.4 7.81E-03	0.6	26.3	146
0.3	27.4	89730.0	538.4 7.81E-03	0.6	26.3	147
0.3	27.4	89730.0	538.4 7.81E-03	0.6	26.3	148
0.3	29.2	95620.0	573.7 8.32E-03	0.6	26.4	149
0.3	36.8	120500.0	723.0 1.05E-02	0.6	26.4	150
0.3	36.8	120500.0	723.0 1.05E-02	0.6	26.4	151
0.3	43.2	141800.0	850.9 1.23E-02	0.6	26.4	152
0.3	45.4	148700.0	892.0 1.29E-02	0.6	26.4	153
0.3	46.6	152600.0	915.6 1.33E-02	0.6	26.4	154
0.3	46.6	152600.0	915.6 1.33E-02	0.6	26.4	155
0.3	46.6	152600.0	915.6 1.33E-02	0.6	26.4	156
0.3	47.6	155900.0	935.2 1.36E-02	0.6	26.4	157
0.3	56.3	184400.0	1106.0 1.60E-02	0.6	26.4	158
0.3	56.3	184400.0	1106.0 1.60E-02	0.6	26.4	159
0.3	58.4	191200.0	1147.0 1.66E-02	0.6	26.4	160
0.3	58.4	191200.0	1147.0 1.66E-02	0.6	26.4	161
0.3	63.7	208600.0	1252.0 1.82E-02	0.6	26.4	162
0.3	63.7	208600.0	1252.0 1.82E-02	0.6	26.4	163
0.3	66.5	217800.0	1307.0 1.90E-02	0.6	26.4	164
0.3	72.6	237700.0	1426.0 2.07E-02	0.6	26.4	165
0.3	73.7	241300.0	1448.0 2.10E-02	0.6	26.4	166
0.3	73.7	241300.0	1448.0 2.10E-02	0.6	26.4	167
0.3	73.7	241300.0	1448.0 2.10E-02	0.6	26.4	168
0.3	62.8	205600.0	1234.0 1.79E-02	0.6	26.4	169
0.3	50.6	165700.0	994.2 1.44E-02	0.6	26.4	170
0.3	50.6	165700.0	994.2 1.44E-02	0.6	26.4	171
0.3	50.6	165700.0	994.2 1.44E-02	0.6	26.4	172
0.3	50.6	165700.0	994.2 1.44E-02	0.6	26.4	173
0.3	50.6	165700.0	994.2 1.44E-02	0.6	26.4	174
0.3	45.4	148700.0	892.0 1.29E-02	0.6	26.4	175
0.3	46.5	152300.0	913.6 1.32E-02	0.6	26.4	176
0.3	48.2	157800.0	947.0 1.37E-02	0.6	26.4	177
0.3	48.2	157800.0	947.0 1.37E-02	0.6	26.4	178
0.3	53.9	176500.0	1059.0 1.54E-02	0.6	26.4	179
0.3	51.7	169300.0	1016.0 1.47E-02	0.6	26.4	180

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Date: 06/02/93

Model: BB

Time: 07:25

Spindle: CPA1

File: SPL21T9

Sample: Agnew's Simulant

Speed	Torque	Viscosity	Shear Stress	Shear Rate	Temperature	Time
RPM	%	cP	D/Cn2 psi	1/Sec	°C	Sec
0.0	6.8	0.0	0.0 0.00E+00	0.0	22.4	1
0.0	6.8	0.0	0.0 0.00E+00	0.0	22.4	2
0.3	7.0	22920.0	137.5 1.99E-03	0.6	22.4	3
0.3	10.8	35370.0	212.2 3.08E-03	0.6	22.4	4
0.3	11.9	38970.0	233.8 3.39E-03	0.6	22.4	5
0.3	14.0	45850.0	275.1 3.99E-03	0.6	22.4	6
0.3	17.2	56320.0	337.9 4.90E-03	0.6	22.4	7
0.3	17.2	56320.0	337.9 4.90E-03	0.6	22.4	8
0.3	17.2	56320.0	337.9 4.90E-03	0.6	22.4	9
0.3	17.2	56320.0	337.9 4.90E-03	0.6	22.4	10
0.3	15.1	49450.0	296.7 4.30E-03	0.6	22.4	11
0.3	12.6	41260.0	247.6 3.59E-03	0.6	22.4	12
0.3	12.6	41260.0	247.6 3.59E-03	0.6	22.4	13
0.3	12.6	41260.0	247.6 3.59E-03	0.6	22.4	14
0.3	12.3	40280.0	241.7 3.50E-03	0.6	22.4	15
0.3	11.8	38640.0	231.8 3.36E-03	0.6	22.4	16
0.3	11.8	38640.0	231.8 3.36E-03	0.6	22.4	17
0.3	11.8	38640.0	231.8 3.36E-03	0.6	22.4	18
0.3	11.8	38640.0	231.8 3.36E-03	0.6	22.4	19
0.3	11.8	38640.0	231.8 3.36E-03	0.6	22.4	20
0.3	18.1	59270.0	355.6 5.16E-03	0.6	22.4	21
0.3	19.2	62870.0	377.2 5.47E-03	0.6	22.4	22
0.3	22.5	73680.0	442.1 6.41E-03	0.6	22.4	23
0.3	22.5	73680.0	442.1 6.41E-03	0.6	22.4	24
0.3	22.5	73680.0	442.1 6.41E-03	0.6	22.4	25
0.3	22.5	73680.0	442.1 6.41E-03	0.6	22.4	26
0.3	32.2	105400.0	632.7 9.17E-03	0.6	22.4	27
0.3	34.3	112300.0	673.9 9.77E-03	0.6	22.4	28
0.3	37.6	123100.0	738.8 1.07E-02	0.6	22.4	29
0.3	37.6	123100.0	738.8 1.07E-02	0.6	22.4	30
0.3	38.7	126700.0	760.4 1.10E-02	0.6	22.4	31
0.3	38.7	126700.0	760.4 1.10E-02	0.6	22.4	32
0.3	38.7	126700.0	760.4 1.10E-02	0.6	22.4	33
0.3	40.7	133300.0	799.7 1.16E-02	0.6	22.4	34
0.3	40.7	133300.0	799.7 1.16E-02	0.6	22.4	35
0.3	8.6	28160.0	169.0 2.45E-03	0.6	22.4	36
0.3	10.7	35040.0	210.2 3.05E-03	0.6	22.4	37

0.3	11.7	30310.0	229.9 3.33E-03	0.6	22.4	38
0.3	11.7	30310.0	229.9 3.33E-03	0.6	22.4	39
0.3	16.3	53300.0	320.3 4.64E-03	0.6	22.4	40
0.3	16.3	53300.0	320.3 4.64E-03	0.6	22.4	41
0.3	16.3	53300.0	320.3 4.64E-03	0.6	22.4	42
0.3	19.8	64840.0	389.0 5.64E-03	0.6	22.4	43
0.3	19.8	64840.0	389.0 5.64E-03	0.6	22.4	44
0.3	19.8	64840.0	389.0 5.64E-03	0.6	22.4	45
0.3	25.4	83100.0	499.1 7.24E-03	0.6	22.4	46
0.3	25.4	83100.0	499.1 7.24E-03	0.6	22.4	47
0.3	25.4	83100.0	499.1 7.24E-03	0.6	22.4	48
0.3	26.4	86450.0	518.7 7.52E-03	0.6	22.4	49
0.3	35.0	114600.0	687.7 9.97E-03	0.6	22.4	50
0.3	35.0	114600.0	687.7 9.97E-03	0.6	22.4	51
0.3	37.2	121800.0	730.9 1.06E-02	0.6	22.4	52
0.3	37.2	121800.0	730.9 1.06E-02	0.6	22.4	53
0.3	37.2	121800.0	730.9 1.06E-02	0.6	22.4	54
0.3	47.6	155900.0	935.2 1.36E-02	0.6	22.4	55
0.3	48.7	159500.0	956.9 1.33E-02	0.6	22.4	56
0.3	49.8	163100.0	978.5 1.42E-02	0.6	22.4	57
0.3	49.8	163100.0	978.5 1.42E-02	0.6	22.4	58
0.3	49.8	163100.0	978.5 1.42E-02	0.6	22.4	59
0.3	13.1	42900.0	257.4 3.73E-03	0.6	22.4	60
0.3	14.0	45850.0	275.1 3.99E-03	0.6	22.4	61
0.3	17.9	58620.0	351.7 5.10E-03	0.6	22.4	62
0.3	17.9	58620.0	351.7 5.10E-03	0.6	22.4	63
0.3	17.5	57310.0	343.8 4.99E-03	0.6	22.4	64
0.3	18.1	59270.0	355.6 5.16E-03	0.6	22.4	65
0.3	18.9	61890.0	371.3 5.38E-03	0.6	22.4	66
0.3	18.9	61890.0	371.3 5.38E-03	0.6	22.4	67
0.3	26.3	86120.0	516.7 7.49E-03	0.6	22.4	68
0.3	27.4	89730.0	538.4 7.81E-03	0.6	22.4	69
0.3	27.4	89730.0	538.4 7.81E-03	0.6	22.4	70
0.3	27.4	89730.0	538.4 7.81E-03	0.6	22.4	71
0.3	27.4	89730.0	538.4 7.81E-03	0.6	22.4	72
0.3	37.9	124100.0	744.7 1.08E-02	0.6	22.4	73
0.3	40.0	131000.0	785.9 1.14E-02	0.6	22.4	74
0.3	40.0	131000.0	785.9 1.14E-02	0.6	22.4	75
0.3	41.1	134600.0	807.5 1.17E-02	0.6	22.4	76
0.3	46.2	151300.0	907.7 1.32E-02	0.6	22.4	77
0.3	46.2	151300.0	907.7 1.32E-02	0.6	22.4	78
0.3	46.2	151300.0	907.7 1.32E-02	0.6	22.4	79
0.3	15.3	50100.0	300.6 4.36E-03	0.6	22.4	80
0.3	12.5	40930.0	245.6 3.56E-03	0.6	22.4	81
0.3	12.5	40930.0	245.6 3.56E-03	0.6	22.4	82
0.3	12.5	40930.0	245.6 3.56E-03	0.6	22.4	83
0.3	17.5	57310.0	343.8 4.99E-03	0.6	22.4	84
0.3	18.6	60910.0	365.5 5.30E-03	0.6	22.4	85
0.3	18.6	60910.0	365.5 5.30E-03	0.6	22.4	86
0.3	18.1	59270.0	355.6 5.16E-03	0.6	22.4	87
0.3	18.1	59270.0	355.6 5.16E-03	0.6	22.4	88
0.3	19.5	63860.0	383.1 5.55E-03	0.6	22.5	89
0.3	19.5	63860.0	383.1 5.55E-03	0.6	22.5	90
0.3	19.5	63860.0	383.1 5.55E-03	0.6	22.5	91
0.3	20.2	66150.0	396.9 5.76E-03	0.6	22.5	92
0.3	20.2	66150.0	396.9 5.76E-03	0.6	22.5	93
0.3	18.3	59930.0	359.6 5.21E-03	0.6	22.5	94
0.3	18.3	59930.0	359.6 5.21E-03	0.6	22.5	95

0.3	10.3	59930.0	359.6 5.21E-03	0.6	22.5	96
0.3	10.6	60910.0	365.5 5.30E-03	0.6	22.5	97
0.3	10.9	61910.0	365.5 5.30E-03	0.6	22.5	98
0.3	11.2	62910.0	365.5 5.30E-03	0.6	22.5	99
0.3	21.9	71720.0	430.3 6.24E-03	0.6	22.5	100
0.3	21.9	71720.0	430.3 6.24E-03	0.6	22.5	101
0.3	29.5	96600.0	579.6 8.40E-03	0.6	22.5	102
0.3	30.6	100200.0	601.2 8.72E-03	0.6	22.5	103
0.3	32.7	107100.0	642.5 9.32E-03	0.6	22.5	104
0.3	34.0	114000.0	683.8 9.92E-03	0.6	22.5	105
0.3	37.9	124100.0	744.7 1.00E-02	0.6	22.5	106
0.3	37.9	124100.0	744.7 1.00E-02	0.6	22.5	107
0.3	40.0	131000.0	785.9 1.14E-02	0.6	22.5	108
0.3	40.0	131000.0	785.9 1.14E-02	0.6	22.5	109
0.3	40.0	131000.0	785.9 1.14E-02	0.6	22.5	110
0.3	40.0	131000.0	785.9 1.14E-02	0.6	22.5	111
0.3	40.0	131000.0	785.9 1.14E-02	0.6	22.5	112
0.3	19.0	62220.0	373.3 5.41E-03	0.6	22.5	113
0.3	16.2	53050.0	318.3 4.62E-03	0.6	22.4	114
0.3	16.9	55340.0	332.1 4.82E-03	0.6	22.4	115
0.3	19.8	64840.0	389.0 5.64E-03	0.6	22.4	116
0.3	20.0	65490.0	393.0 5.70E-03	0.6	22.4	117
0.3	20.0	65490.0	393.0 5.70E-03	0.6	22.4	118
0.3	20.7	67790.0	406.7 5.90E-03	0.6	22.4	119
0.3	20.7	67790.0	406.7 5.90E-03	0.6	22.4	120
0.3	25.9	84810.0	508.9 7.38E-03	0.6	22.4	121
0.3	31.3	102500.0	615.0 8.92E-03	0.6	22.4	122
0.3	31.3	102500.0	615.0 8.92E-03	0.6	22.4	123
0.3	32.4	106100.0	636.6 9.23E-03	0.6	22.4	124
0.3	37.8	123800.0	742.7 1.00E-02	0.6	22.5	125
0.3	41.9	137200.0	823.3 1.19E-02	0.6	22.5	126
0.3	42.9	140500.0	842.9 1.22E-02	0.6	22.5	127
0.3	38.6	126400.0	758.4 1.10E-02	0.6	22.5	128
0.3	25.4	83180.0	499.1 7.24E-03	0.6	22.5	129
0.3	12.8	41920.0	251.5 3.65E-03	0.6	22.5	130
0.3	12.8	41920.0	251.5 3.65E-03	0.6	22.5	131
0.3	12.8	41920.0	251.5 3.65E-03	0.6	22.5	132
0.3	13.8	45190.0	271.1 3.93E-03	0.6	22.4	133
0.3	20.0	65490.0	393.0 5.70E-03	0.6	22.5	134
0.3	20.0	65490.0	393.0 5.70E-03	0.6	22.5	135
0.3	21.1	69100.0	414.6 6.01E-03	0.6	22.5	136
0.3	21.1	69100.0	414.6 6.01E-03	0.6	22.5	137
0.3	27.9	91360.0	548.2 7.95E-03	0.6	22.5	138
0.3	30.0	98240.0	589.4 8.55E-03	0.6	22.5	139
0.3	31.2	102200.0	613.0 8.89E-03	0.6	22.5	140
0.3	31.2	102200.0	613.0 8.89E-03	0.6	22.5	141
0.3	32.5	106400.0	638.6 9.26E-03	0.6	22.5	142
0.3	30.0	98240.0	589.4 8.55E-03	0.6	22.5	143
0.3	12.2	39950.0	239.7 3.48E-03	0.6	22.5	144
0.3	12.2	39950.0	239.7 3.48E-03	0.6	22.5	145
0.3	12.2	39950.0	239.7 3.48E-03	0.6	22.5	146
0.3	15.7	51410.0	308.5 4.47E-03	0.6	22.5	147
0.3	16.3	55340.0	332.1 4.82E-03	0.6	22.5	148
0.3	16.9	55340.0	332.1 4.82E-03	0.6	22.5	149
0.3	16.9	55340.0	332.1 4.82E-03	0.6	22.5	150
0.3	25.4	83180.0	499.1 7.24E-03	0.6	22.4	151
0.3	25.4	83180.0	499.1 7.24E-03	0.6	22.4	152
0.3	25.4	83180.0	499.1 7.24E-03	0.6	22.4	153

D.87

D.44

0.3	26.6	87110.0	522.6	7.598-03	0.6	22.4	154
0.3	33.1	108400.0	650.3	9.438-03	0.6	22.4	155
0.3	37.4	122500.0	734.8	1.078-02	0.6	22.4	156
0.3	39.5	129300.0	776.1	1.132-02	0.6	22.4	157
0.3	40.6	133000.0	795.7	1.168-02	0.6	22.4	158
0.3	40.6	133000.0	795.7	1.168-02	0.6	22.4	159
0.3	41.7	136600.0	819.3	1.198-02	0.6	22.4	160
0.3	41.7	136600.0	819.3	1.198-02	0.6	22.4	161
0.3	41.7	136600.0	819.3	1.198-02	0.6	22.4	162
0.3	54.2	177500.0	1065.0	1.548-02	0.6	22.4	163
0.3	51.6	169000.0	1014.0	1.478-02	0.6	22.4	164
0.3	51.6	169000.0	1014.0	1.478-02	0.6	22.4	165
0.3	35.2	115300.0	691.6	1.008-02	0.6	22.4	166
0.3	35.2	115300.0	691.6	1.008-02	0.6	22.4	167
0.3	35.2	115300.0	691.6	1.008-02	0.6	22.4	168
0.3	35.2	115300.0	691.6	1.008-02	0.6	22.4	169
0.3	35.2	115300.0	691.6	1.008-02	0.6	22.4	170
0.3	35.2	115300.0	691.6	1.008-02	0.6	22.4	171
0.3	35.2	115300.0	691.6	1.008-02	0.6	22.4	172
0.3	35.2	115300.0	691.6	1.008-02	0.6	22.4	173
0.3	35.2	115300.0	691.6	1.008-02	0.6	22.4	174
0.3	35.2	115300.0	691.6	1.008-02	0.6	22.4	175
0.3	32.5	106400.0	638.6	9.268-03	0.6	22.4	176
0.3	32.5	106400.0	638.6	9.268-03	0.6	22.4	177
0.3	32.5	106400.0	638.6	9.268-03	0.6	22.4	178
0.3	32.5	106400.0	638.6	9.268-03	0.6	22.4	179
0.3	40.0	131000.0	785.9	1.148-02	0.6	22.4	180
0.3	41.1	134600.0	807.5	1.178-02	0.6	22.4	181

END

DATE

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12/23/93