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FISCAL YEAR 1998 YEAR-END REPORT

for the November 1997 to October 1998 Period

WASTE CONDITIONING FOR TANK HEEL TRANSFER

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NOMENCLATURE

C_1	Initial simulant concentration, (wt%)
C_2	Desired concentration, (wt%)
W_1	Weight of simulant at initial concentration, (kg)
W_2	Desired weight at desired concentration, (kg)
Ra	Radius of Outside Cylinder
Ri	Radius of Inside Cylinder
L	Length of Cylinder
H	Total sample height, (cm)
H_1	Height of clear layer, (cm)
H_2	Height of cloudy layer, (cm)
H_3	Settled layer, (cm)
H_{12}	$H_2 + H_1$, (cm)
Md	torque
A	stress factor
M	Shear Factor
$(^{du}/_{dy})$	Shear Rate

Greek Symbols

τ	shear stress
$\dot{\gamma}$	Shear Rate
Ω	Angular Velocity
γ	Deformation
φ	Torsion Angle in Radians
μ	Viscosity
τ_o	Yield stress
η	Viscosity

EXECUTIVE SUMMARY

This report summarizes the research carried out at Florida International University's Hemispheric Center for Environmental Technology (FIU-HCET) for the fiscal year 1998 (FY98) under the Tank Focus Area (TFA) project "Waste Conditioning for Tank Slurry Transfer." The objective of this project is to determine the effect of chemical and physical properties on the waste conditioning process and transfer. The focus of this research consisted in building a waste conditioning experimental facility to test different slurry simulants under different conditions, and analyzing their chemical and physical properties. This investigation would provide experimental data and analysis results that can make the tank waste conditioning process more efficient, improve the transfer system, and influence future modifications to the waste conditioning and transfer system.

A waste conditioning experimental facility was built in order to test slurry simulants. The facility consists of a slurry vessel with several accessories for parameter control and sampling. The vessel also has a lid system with a shaft-mounted propeller connected to an air motor. In addition, a circulation system is connected to the slurry vessel for simulant cooling and heating.

Experimental data collection and analysis of the chemical and physical properties of the tank slurry simulants has been emphasized. For this, one waste slurry simulant (Fernald) was developed, and another two simulants (SRS and Hanford) obtained from DOE sites were used. These simulants, composed of water, soluble metal salts, and insoluble solid particles, were used to represent the actual radioactive waste slurries from different DOE sites. The simulants' chemical and physical properties analyzed include density, viscosity, pH, settling rate, and solubility. These analyses were done to samples obtained from different experiments performed at room temperature but different mixing time and strength.

The experimental results indicate that the viscosity of the slurries follow the Bingham plastic model, especially when the solids concentration is increased. At low concentrations slurries may behave as Newtonian fluids.

The three simulants follow a similar settling rate behavior. This behavior can be explained as a combination of one or more decreasing exponential curves. This means that the particle settling rate of the simulants decreases exponentially as time increases.

The pH range for the three simulants was from 8 to 13 at all concentrations. The SRS simulant showed the highest pH, around 12; the other two simulants, Hanford and Fernald, had about the same pH range, from 8 to 9.

When comparing solubility of the three simulants at the same concentration (5 wt%), SRS simulant showed higher solubility, followed by the Hanford simulant and the Fernald simulant, in that order.

Further work is scheduled for next year (FY99) in this project, when other parameters like simulants' particle size distribution, particle shape, and crystallization behavior will be studied. The same tests performed this period also will be performed at different temperatures for data comparison.

1.0 INTRODUCTION

The first year of this project was conducted according to the Project Technical Plan (PTP) corresponding to the fiscal year 1998 (FY98). This PTP was prepared by Florida International University's Hemispheric Center for Environmental Technology (FIU-HCET) and approved by DOE contact.

1.1 PROJECT JUSTIFICATION

The U.S. Department of Energy (DOE) has established an interim retrieval performance goal in order to specify the slurry transfer requirements from the underground tanks. The interim activities include removal and treatment of radioactive, non-radioactive, hazardous, and mixed solid and liquid wastes in tanks. A significant amount of research and management work has dealt with solid waste, slurry waste, and liquid effluents. The evaluations and demonstrations of the retrieval technologies have mainly focused on verifying that a sufficient amount of waste can be removed from the tank to permit tank closure; however, the retrieval and waste conditioning technologies needed also to be evaluated for environmental and downstream waste processing impact. For this, in order to specify and design tank waste transfer equipment and pipeline, the effects of physical and chemical properties of waste on mixing, pipeline transfer, interim storage, and subsequent transfer to pretreatment facilities need to be better understood.

1.2 PROJECT DESCRIPTION

To support decisions for tank closure activities, the DOE needs information and technologies as well as methods for tank slurry conditioning and transfer.

These research efforts include

- Conditioning of waste into slurries acceptable for transport
- Techniques to determine the residual amount of waste in the tank after retrieval efforts
- Methods for sampling and analysis of tank waste that is not accessible to the current sampling technology
- Methods for monitoring contaminants in the operating areas.

Therefore, FIU-HCET concentrates its research activities on waste conditioning for tank slurry transfer. In this project, FIU-HCET conducts a fundamental study of the problems encountered in tank slurry transfer and investigates possible solutions for waste conditioning. The study involves identification and evaluation of existing waste conditioning parameters that have been used in the nuclear or industrial waste treatment and the conditions that may directly or indirectly affect this process. Since the waste conditioning will have a direct impact on the transfer of the waste, this project is done in conjunction with the waste transfer line-unplugging project.

1.3 OBJECTIVE

The overall objective of this project was to build an experimental facility to test waste surrogates in order to determine the effect of chemical and physical properties on the waste conditioning process. This information can be used for the storage and/or transfer equipment design and operation.

1.4 ACCOMPLISHMENTS

In accordance with the project PTP, the following tasks have been accomplished during FY98:

- The existing limits and requirements on waste slurry that have been published or used in the DOE nuclear or industrial waste transfer were investigated and identified in a literature review.
- Fernald tank heel simulant was developed in conjunction with the Fernald Rheology project, which was held at same time at FIU. Two other surrogates, Savannah River Site (SRS) and Hanford, were available for testing from a previous project.
- A waste conditioning experimental setup was built for simulant testing.
- Chemical and physical properties measurements were performed to samples obtained from different experiments done under different conditions.

1.5 IMPORTANCE OF WORK

This investigation of the influence of operating conditions and waste properties on waste conditioning provides experimental data and analysis results that can make the tank waste transfer process safer and more efficient. These results may influence future modifications to the waste conditioning and transfer system. Findings in this study can lead to significant cost savings for the DOE sites that face this problem.

1.6 PURPOSE OF YEAR-END REPORT

The main purpose of this report is to summarize the activities developed and progress attained in the first year of this project.

2.0 ACTIVITIES COMPLETED IN FY98

This project was divided into five main tasks that were completed throughout FY98. These tasks are described in the Project Technical Plans (PTP) for the corresponding fiscal year.

- TASK 1. Survey and evaluate existing tank waste slurry transfer specifications.
- TASK 2. Create tank heel simulants and prepare samples.
- TASK 3. Set up waste conditioning experimental facility.
- TASK 4. Perform testing on waste simulant chemical and physical properties.
- TASK 5. Determine the chemical and physical property effects on waste conditioning and transfer.

2.1 WASTE CONDITIONING METHODS AND TECHNOLOGIES

Several papers and articles were reviewed with the purpose of evaluating any problems and difficulties experienced during the operation of technologies and processes in the DOE industrial and nuclear waste industry. The overall objective of this task was to use this investigation as a guideline for this project so some conclusions could be made for the experiments and analyses to be performed.

2.1.1 Review of Existing Works Done by DOE

In this section, a summary of these findings are cited:

- A letter report by R.L. McKay for Westinghouse Hanford Company on *TWRS Retrieval Technology Project Slurry Transport – Plugging Investigation.*

  The reason for this investigation was the plugging of cross-site transfer lines at the Hanford Site. Although in many cases plugs were successfully removed by high-pressure flushing, some transfer lines could not be unplugged. So, a study was necessary to describe current research and theory available to predict pipe-plugging phenomena, review current waste transfer characteristics, and make any recommendations to optimize waste transfer.

  The report states that the three main factors that contributed to line plugging are

  - Settling of solid particles during transfer
  - Crystallization of the waste
  - Gelation of the waste.

  These phenomena cause high viscosity and may contribute to the formation of immobile plugs. The report also states that temperature has the most significant influence on the flow characteristics of the slurry. Based on these statements, some conclusions and recommendations are cited below.

Conclusions

- The tendency for the waste to become gelatinous and difficult to pump/transfer is due mainly to the transfer temperature and relative amounts of phosphate, aluminate, and sodium in the waste. This phenomenon's mechanisms are extremely complex and not so easy to understand.
- If waste dilution is inadequate, it may cause formation of gelatinous material or may lead to crystallization of some chemical species. If this happens, there exists a high probability of cross-site lines plugging.
- If needle-like crystals are formed due to the temperature and relative amounts of specific waste components, this will cause extremely high viscosities and may result in a plug due to sedimentation of solids.
- Since different waste compositions respond differently to the amount of water added, it may not be efficient to set standard dilution rates. An example of this behavior is the phosphate and aluminate species, whose solubilities are directly related to the amount of Na+ in the waste. If water is added to decrease aluminate and phosphate concentrations, it will also decrease the amount of sodium. Thus, solubility will stay about the same.
- In order to minimize solids settling, a minimum velocity of 6 ft/s is required to ensure turbulent flow. This is true as long as the temperature remains high during transfer. Furthermore, the adequate viscosity range is in the order of 1 to 30 cP.
- Based on particle size distribution data obtained, stratification of the waste stream is predicted not to occur.

Recommendations

- Since the expected chemical behavior of the tank waste is extremely complicated and difficult to accurately predict, further work is needed to establish the waste component and to set valid dilution rates.
- In order to determine proper dilution rates, a sufficient laboratory analysis must be completed prior to any cross-site transfer.
- Unexpected reactions could occur between different wastes if dilution with supernate from other tanks is made. Therefore, this practice is not recommended unless a laboratory trial is conducted.
- When proper dilution amount is experimentally determined, the safest way of adding dilution water is directly into the pump suction. High water temperature should be used to increase slurry temperature at the point of origin.
- Further work is needed to determine minimum operating temperature. Viscosity and solubility of the components of the waste are critical here, since they are extremely sensitive to temperature.
- Alternatives to heat the transfer lines over the entire line length should be explored. Heat-traced lines have been used in the past, but this process has become exorbitantly expensive.

- Installation of rigid jumpers rather than flexible ones in the diversion boxes should be considered. This is based on the fact that plugs have usually occurred in the flexible jumpers in the past.
- Backup systems must be provided in the event of a pump failure.
- Operating procedure for cross-site transfers must include continuous monitoring of the transfer line flow rate. In the event that the flow rate decreases below that which is required for turbulent flow, immediate transfer re-start or entire line flushing is necessary to avoid line plugging.
- To ensure proper routing of waste, electric valve actuators with position indicators should be considered. Misrouting could lead to a mixture of two or more wastes, which could cause severe transfer problems.

- *Technical Data Summary for In-tank Sludge Processing*. This report prepared by T. Motyka in 1984 explains how radioactive waste sludge must undergo several preprocessing steps to reduce its volume and ensure its compatibility with the environment where it will eventually be placed for long-term storage. This sludge preprocessing operation consisted of
  - Alumina dissolution to reduce the aluminum in the sludge.
    - As part of the in-tank process, aluminum is dissolved from the sludge into the supernate. Decantation or water washing subsequently removes aluminum species. This process is needed because if aluminum is left in the sludge solution, it will adversely affect the viscosity of the solution and add to the overall waste volume.
    - The dissolving was done by adding 50 wt% NaOH to the processing tank. In this form, the dissolution reaction was the following, assuming gibbsite (alumina trihydrate) was present in the sludge.

$$Al_2O_3 \cdot 3H_2O_{(s)} + 2NaOH_{(l)} \longrightarrow 2NaAlO_{2(l)} + 4H_2O$$

    - Dissolving temperatures were from 80°C to 90°C, and the dissolving time was three days.
  - Washing to remove soluble salts.
    - This process was needed to meet vitrification criteria, which require minimum weight concentrations in a dry basis of less than 3%, 5%, and 10% for sulfates, sodium ion, and nitrates, respectively.
    - Washing also served to reduce the volume of glass produced and remove caustic and aluminum salts.
  - Compaction to increase solids concentration.
    - Gravity settling plays a key role at this point. This is required to concentrate the sludge before the next process operation.

- The main factors affecting the settling of the sludge are the type of sludge material and its initial solids concentration.

This "in-tank" sludge process was actually performed in a full-scale plant demonstration with excellent results. Over 75% of the aluminum was removed from the sludge, and the total salt content of the sludge was reduced to about 2 wt% in a dry basis.

- *Effect of the Rheological Properties of Fines Fraction on Slurry Hydraulics* by Ramesh L. Gandhi, Bechtel Inc., San Francisco.

The objective of this paper was to examine the effect of the rheology of the fines vehicle on slurry hydraulics. Since fine particles in a slurry form a vehicle that provides support to the coarse particles, the hydraulic behavior of this mixture depends upon the rheological properties of the vehicle. Some conclusions are stated, based on past slurry transport studies.

- With flocculated suspensions, the vehicle exhibits Bingham plastic properties with a yield stress.
- In the absence of flocculation, the fines component normally gives rise to Newtonian flow behavior.
- The settling velocity of coarse solids is significantly reduced due to the presence of yield stress.
- At very high concentrations, coarse solids can be supported under a laminar flow condition in the presence of yield stress.
- The increase in apparent yield stress and plastic viscosity of such slurries can be explained by a flow model in which coarse solids are assumed to form a central unshared plug that is surrounded by a layer of fines vehicle.

- *Preliminary Investigation of Suspended Solids Monitors and Supernate/Sludge Interface Level Monitors for DOE Radioactive Slurries.* Authors: F.R. Ruppel and J.S. Hicks, Instrumentation and Control Division, Oak Ridge National Laboratory, September 1992.

The investigation approach used in this work was similar to that of this literature review, to survey existing scientific and manufacturer's literature for references to technologies that looked feasible for the target application, in this case, suspended solids monitors and supernate/sludge interface level monitors for radioactive slurries.

Several technologies are listed in this investigation. These technologies depend on what parameter of the slurry is analyzed. Following is a brief description of some of these technologies and methods mentioned:

- *Density-related Methods:* The principle behind this kind of measurement is that the density of the carrier liquid (usually water) is known and density of the solid is as well known, so by finding the mixture density, the suspended solids can be deducted. However, if any of the densities change, there will not be a good result.
- *Nuclear Radiation Methods:* These methods have the capability of measuring the highest solids fraction. There are two techniques in this category:
  - *Gamma absorption:* This technique is based on the principle that transmission of gamma rays through a medium is related to the density of the medium. A problem

with this method is that if the material is radioactive, it will by itself emit gamma rays and consequently would affect any readings obtained.

- *Neutron backscatter:* The principle here is that neutrons are moderated by collision with the hydrogen present in the water content of the slurry. The number of slow neutrons diffusing back from the water in the pipe is detected by a count-rate meter to give a volumetric concentration of the water in the slurry. From this, the volumetric percent solids can be calculated. However, if the slurry contains forms of Pu, U, or Am, and it is bombarded with a neutron source, a fission reaction could occur.

– *Electrical Methods:* Electrical properties of a slurry can be used to detect presence of solids in limited cases. Conductivity and capacitance are two examples of those properties.

- The electric conductivity of a solid-liquid mixture can be indicative of the solids fraction of the mixture, especially when the carrier liquid's conductivity is not great. A complication for using conductivity to determine the solids fraction is that the conductivity of the pure supernate must also be measured. Also, any changes in chemical composition change the conductivity of the mixture.
- Capacitance can be used as a means of determining percent solids of slurries. The principle is that the dielectric constant of a mixture is related to the amount of solids present. Previous Oak Ridge National Laboratory (ORNL) experience indicates that an impedance probe can be used to determine void fractions of two-phase (liquid-vapor) fluids. The same model could be used for solid-liquid mixtures.

– *Ultrasonic Methods:* This technique is divided into ultrasonic attenuation and backscatter methods.

- *Ultrasonic attenuation:* In this case, solid particles in a solid-liquid mixture will absorb energy from an ultrasonic beam. If an ultrasonic signal is transmitted at one side of a pipeline, reflected on the other side, and received back, this received signal would be maximum for a pure liquid. However, when solids are present, the signal level decreases as a function of the amount of solids present because of absorption and scattering effects.
- *Ultrasonic backscatter:* Solid particles in a solid-liquid mixture will deflect energy from an ultrasonic source. So, to detect suspended solids in a mixture, one can look for backscattered ultrasonic energy. This method cannot read as high a concentration of solids as ultrasonic attenuation because solids absorb much of the energy. Also, care should be taken that bubbles are not present, as they will also scatter the ultrasonic beam, thus causing errors in the instrument's output.

– *Optical Methods:* These techniques are typically restricted to measuring dilute concentrations of suspended solids as compared to other methods. Optical methods are commonly used for turbidity measurements. However, some optically based instruments may work for suspended solids detection.

- *Optical backscatter:* In this method a fiber-optic bundle delivers light to the sample using the bundle's interior fiber. The fibers surrounding the interior bundle are used to receive near-scattered light from the source and compensate the reading based on

the source intensity. The outside of the bundle contains fibers that receive far-backscattered light and transmit it back to a receiver for solids fraction calculation.

- *Optical attenuation:* This technique uses laboratory-grade optical attenuation suspended solid monitors. Usually, they have a very limited concentration range and are not meant to be field mounted. For this reason, they are used mostly as particle counters.
- *Image analysis:* This new innovative technology has been used for online particle size distribution analysis. One problem is the flow that has to be limited to speed of most commercial video systems. Any faster flow would not be caught on the video freeze frame. Furthermore, when the volume fraction exceeds 5-10%, masking occurs.

After description of the different methods and techniques for determining suspended solids concentration, it appeared that for the ORNL case, the ultrasonic attenuation-based instruments were the most viable.

2.1.2 Conclusions from Review of Existing Work

As stated before, the purpose of the literature review on tank waste slurry conditioning and transport was to be used as a tool to determine parameters to be studied and properties to be measured in this project. Therefore, some factors were found to be of vital importance in a waste conditioning project.

These factors include

- Particle size distribution
- Particle shape
- Solid particles morphology
- Particle settling velocity
- Slurry viscosity at various concentrations
- Solubility of the waste
- pH of the waste
- Density of the waste
- Corrosion behavior.

If waste transport is to be studied, the following factors are of prime importance:

- A slurry pipe loop.
- Large L/D pipe flow facility with horizontal and vertical lengths.
- Flow visualization and optical measurements.
- Loop should be equipped to measure:
  - slurry flow rates
  - pressure drops

- temperature changes
- local concentrations
- pipeline erosion.

2.2 TANK SLURRY SIMULANT DEVELOPMENT

Task 2, as described in the project technical plans (PTP), consisted in developing representative tank heel simulants based on requirements from DOE sites to conduct physical and chemical property analyses. In addition, the task provided that if DOE sites or facilities had waste conditioning needs, they would be inquired for obtaining their tank heel simulant for experimental testing. Because FIU-HCET had performed similar projects in the past, two simulants from two different DOE sites, SRS and Hanford, were available at the beginning of the project. In addition, a third simulant (Fernald) was developed in conjunction with the Fernald Rheology project. These three simulants were used for experimental testing and physical and chemical property analyses.

2.2.1 Fernald Surrogate

Though Fernald surrogate was developed to simulate the rheological and hydraulic properties of the K-65 materials used in the Fernald Rheology project, the main objective in this project was to test this surrogate and compare the results with those of the SRS and Hanford surrogates.

Two surrogate formulations have been developed, based on the particle size distribution and chemical composition information provided by Fluor Daniel Fernald (FDF) DOE site. Table 2.2.1.1 shows the composition of each surrogate. The sand used was fine construction sand. The soil is topsoil manufactured by VitaGreen Inc. The soil was composed of sand, peat, and suspended materials. The identified results and other information are shown in Table 2.2.1.2. The sand and the soil have been grounded and sieved into particles with the size distribution shown in Table 2.2.1.3.

Table 2.2.1.1
Formula of surrogates #1 and #2 (wt% dry)

Materials	Surrogate #1 (wt%)	Surrogate #2 (wt%)
Sand	40	44.5
Soil	40	44.5
Diatomaceous Earth	11	5
Al_2O_3	3	3
Fe_2O_3	3	3
$CaCO_3$	1.5	0
$MgCO_3$	1.5	0

Table 2.2.1.2
Soil information

Brand	VitaGreen		
Manufacturer	VitaGreen Inc., Florida		
Composition	Sand	Peat	Suspension
Weight (gram)	151.5	29.44	19
Wt %	75.7	14.7	9.6

Table 2.2.1.3
Particle size data of sand and soil in the surrogate

Particle Size	Sand (wt%)	Soil (wt%)
1 mm	10	10
Mesh # 60	18	18
Mesh # 80	27	27
Mesh # > 80	45	45

Comparison of physical and chemical properties such as pH, density, settling rate, and viscosity of the surrogates with those of the K-65 material indicated that surrogate #2 had similar properties under the testing range, and it could be recommended as a good substitute for the K-65 material.

2.2.2 SRS and Hanford Simulants

In addition to the Fernald simulant developed at FIU, two other simulants were tested in this project: SRS and Hanford. These simulants were used in a similar project two years ago. The Westinghouse Savannah River Technology Center (SRTC) supplied both simulants. Tables 2.2.2.1 and 2.2.2.2 show the composition of the SRS and Hanford simulants, respectively.

Table 2.2.2.1
SRS simulant composition (wt%)

Al	6.7
Ca	2.7
Cr	0.2
Fe	26.8
Mg	1.3
K	0.15
Mn	2.8
Na	10.2
Ni	0.24
Pb	0.1
Si	0.81
Zn	0.17
SO_4	0.33
PO_4	0.84
C_2O_4	0.2
CO_3	1.94
NO_3	1.96
NO_2	5.86
OH	2.95
TOC	<50 ppm
Total Solids	26.3

Table 2.2.2.2
Hanford simulant composition (wt%)

AL	6.3
Ca	0.448
Cr	0.006
Fe	27.3
Mg	0.193
K	0.003
Mn	2.22
Na	1.38
Ni	2.44
Pb	<0.004
Si	0.238
Zn	0.017
Ammonium	<100 mg/L
Fluoride	0.84 mg/L
Formate	0.2 mg/L
Chloride	1.94 mg/L
Nitrite	1.96 mg/L
Nitrate	0.00215 mg/L
Sulfate	359 mg/L
TOC	510 ppm
Total Inorganic Carbon	189 ppm

2.3 WASTE CONDITIONING EXPERIMENTAL FACILITY

An experimental facility was necessary for waste conditioning testing. The facility needed to be designed so that chemical and physical parameters like pH, concentration, and temperature of the surrogate could be controlled and measured.

Therefore, a workbench was constructed to house a slurry vessel and its accessories, a cooling system, and any other pertinent equipment and/or device necessary. The simulant could then be tested in the slurry vessel at the desired conditions.

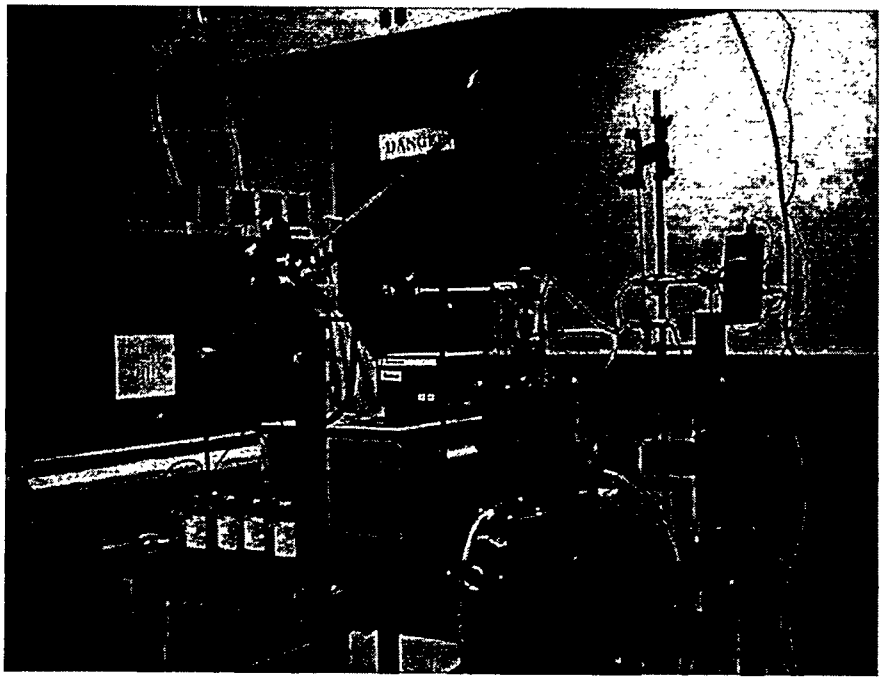


Figure 2.3.1 Waste conditioning experimental facility.

2.3.1 The Slurry Vessel

As can be observed in the following schematic, the slurry vessel consists of a conditioned container with a circulation system in the lower portion and a lid system in the upper portion. While the circulation system is connected to a Fisher Scientific Model 9001 chiller, the lid system contains several inlets/outlets as well as an air motor connected to a shaft-type mixer.

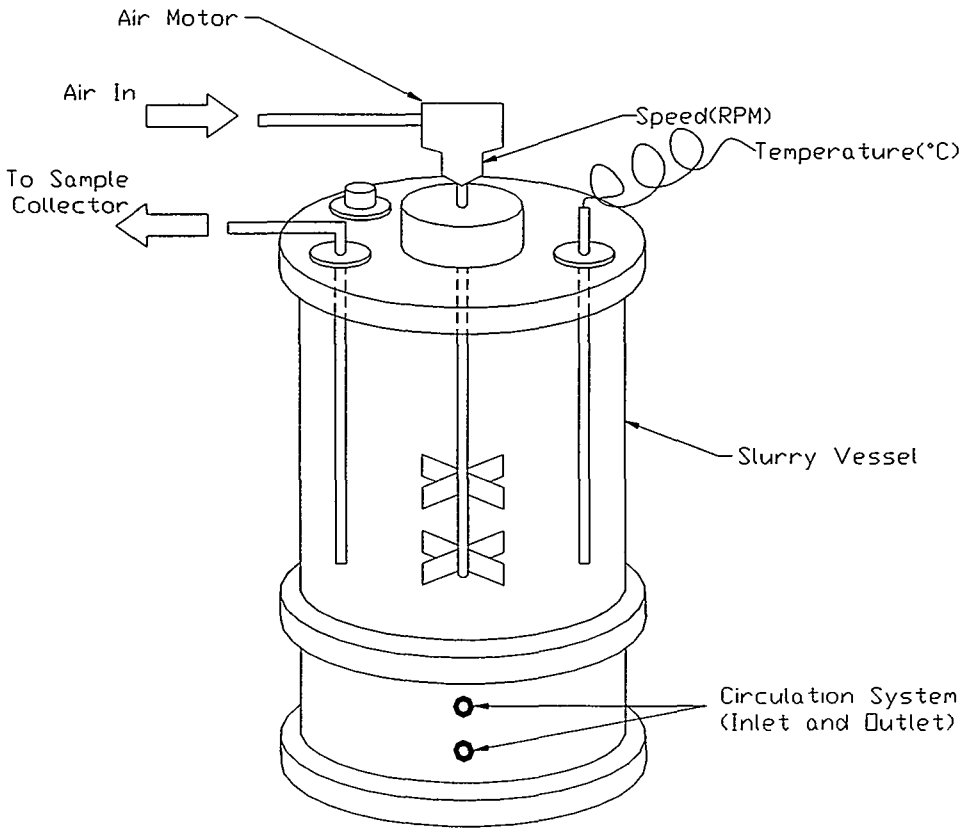


Figure 2.3.1.1 Slurry vessel for waste conditioning.

2.3.2 Equipment Calibration

After completion of an experimental facility for waste conditioning, control experiments were performed. The purpose of running such experiments was to determine the parameters at which the facility could safely be operated and to check the proper functioning of the different equipment and accessories. The two main parameters tested were temperature and motor speed, since plans were to test surrogates at different temperatures and different mixing speeds. Results of these control experiments are detailed next.

- Testing of chiller to cool down or heat up the system.
  - Plans were to test surrogates at three different temperatures, 4°C, room temperature, and 40°C. Therefore, this control test was performed to check proper equipment functioning at those temperatures.
  - Tap water was used inside the slurry vessel for control experiments.
  - A Fisher Scientific Model 9001 chiller was connected to the slurry vessel through a circulation system.

- The chiller can be set to either cool down or heat up the system. The temperature range is from about –10 to 100°C, so it was within the temperatures desired. The circulating coolant temperature was directly read on the chiller panel.
- The temperature inside the slurry vessel was read on an Omega Model CL23 calibrator/thermometer instrument, which is connected to a type T thermocouple that is actually located in the vessel, in direct contact with solution in the vessel.
- The chiller was first set to cool down the system to 4°C. Even though the chiller reading was 4°C after one hour of operation, the vessel system was at 10°C. This situation changed with the passing of time, so that after another hour, both the chiller and the system had similar readings.
- The same situation occurred when heating up the system to 40°C. But in this case, the time frame was much less to reach the desired temperature.
- Other tests were performed setting the chiller temperatures lower than 4°C and higher than 40°C to check if the desired temperature could be reached faster. This was actually true, but the problem was that because of the heat transfer between the coolant and the system, it kept either cooling or heating even after the desired temperature was reached.
- So, the conclusion was that at the beginning (first 10-15 minutes), the chiller could be set to a lower or higher temperature than 4 or 40°C and then be set to 4 or 40°C. In this form, the initial cooling or heating will be faster and then it will gradually come to equilibrium to the desired value.
- It is also good to note that the room temperature in the water system was about 22°C when no heating or cooling was going on.

- Testing of mixer speed (RPM).
  - The mixer is assembled to an air motor. The mixer speed (RPM) was read on a panel/ bench top tachometer, which is connected to an optical sensor.
  - Since an air motor was used, it was important to have a constant airflow at the air inlet. This cannot be guaranteed when using a lab's air source. So, to keep the airflow constant, a pressure regulator was installed between the air supply and the motor air inlet.
  - In this form, a constant airflow pressure of 50 psi was set on the regulator. The mixer speed was controlled with a valve located between the regulator and the air motor.
  - After testing different speeds and airflow, the following was determined for the different mixer speeds in RPM:

Minimum	Middle	Maximum
100	500	1000

  - These numbers indicated that with water in the system, the mixer worked well at a minimum speed of 100 RPM. Below 100 RPM, the mixer may have stopped or did not work consistently, and above 1000 RPM the whole system became unstable because of vibration.

2.4 SIMULANTS TESTING

The purpose of Task 4 in the PTP was to perform testing on the different simulants focusing special attention on the physical and chemical properties of the surrogates. In this form, their potential influence on the waste conditioning and transfer could be determined and studied.

Therefore, an experimental plan table was created. This table was designed based on past experiences and according to the conclusions in the literature review. As can be observed in Table 2.4.1, the main idea was to test the three simulants at different concentrations, temperatures, and mixing speeds. The physical and chemical properties analyzed in this project were density, viscosity, pH, solubility, and settling rate.

Table 2.4.1
Waste conditioning experimental plan table

Concentration wt%	Temperature °C	Mixing Speed RPM	Mixing Time h	pH Adjustment
5	4	MIN, MID, MAX	1, 6, 24	LO, N, HI
	RT	MIN, MID, MAX	1, 6, 24	LO, N, HI
	40	MIN, MID, MAX	1, 6, 24	LO, N, HI
25	4	MIN, MID, MAX	1, 6, 24	LO, N, HI
	RT	MIN, MID, MAX	1, 6, 24	LO, N, HI
	40	MIN, MID, MAX	1, 6, 24	LO, N, HI
40	4	MIN, MID, MAX	1, 6, 24	LO, N, HI
	RT	MIN, MID, MAX	1, 6, 24	LO, N, HI
	40	MIN, MID, MAX	1, 6, 24	LO, N, HI

MIN, MID, MAX = Minimum, Middle, Maximum
LO, N, HI = Low, Neutral (solution original pH), High
RT = Room Temperature

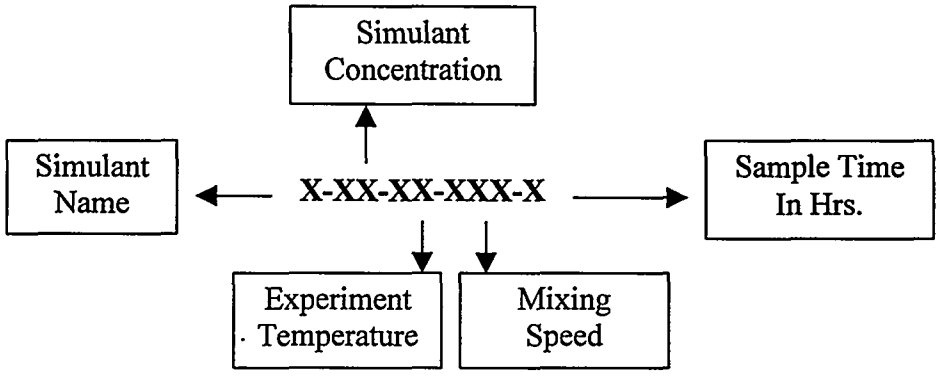
3.0 EXPERIMENTAL METHODS AND SYSTEMS

Even though not all planned experiments were performed because of surrogate availability, several room temperature experiments were performed using the parameters described in the project experimental plan table. Each experiment was performed in the waste conditioning experimental facility and following a standard procedure according to its specifications.

3.1 TEST PROCEDURE

The following test procedure was used in all waste conditioning experiments performed at FIU-HCET.

1. Naming the experiment to be performed is the first step. This is done according to the following naming model.



   Example:

   F-5-RT-400-6 means sample taken at 6 hrs. from 5% Fernald simulant experiment performed at room temperature, with mixing speed of 400 RPM.

2. Since each simulant is available at different concentrations, it is necessary to determine their concentrations before starting any experiment. This is done according to the Solids Concentration Determination procedure, described later in this section.
3. Once the concentration of the simulant to be used is known, calculations are done to determine the amount of water needed to reach the desired experiment concentration. This is done on a weight-to-weight basis using the following equation.

$$C_1 \times W_1 = C_2 \times W_2$$

where

C_1 = initial simulant concentration, wt%

C_2 = desired concentration, wt%

W_1 = weight of simulant at initial concentration, kg

W_2 = desired weight at desired concentration, kg

Example:

If 3 kgs. of 5% simulant is to be prepared from a 40% available simulant, the following calculation must be used to determine the amount of water to be added.

$$W_1 \times 0.4 = 3 \text{ kgs.} \times 0.05$$

$$\text{So, } W_1 = (3)(0.05)/0.4 = 0.375 \text{ kgs.} = \text{weight of surrogate needed}$$

$$\text{And weight of water} = 3.0 - 0.375 = 2.625 \text{ kgs.}$$

4. After the calculations, the raw surrogate is shaken for a short period of time so it becomes homogeneous.
5. The simulant and the water are then weighed based on the calculations performed before.
6. The simulant first and then the water are poured into the slurry vessel. Empty containers are weighed again to ensure that the proper weight was delivered.
7. The mixer is turned ON only for homogeneity of the solution in the vessel. Mixer is turned OFF.
8. At this point, a sample (time zero) is taken from the slurry vessel. All samples are about 400 mL in volume.
9. The time at which each sample is taken as well as the temperature and mixing speed are recorded in a lab form provided.
10. The mixer is turned ON and the mixer speed is adjusted according to the experiment's requirements.
11. Samples are taken after 1, 6, and 24 hours of mixing at the same mixing strength.
12. The following analyses are then performed to each sample:
    - Density
    - pH
    - Viscosity
    - Particle settling rate
    - Solubility.

3.2 PROPERTIES MEASUREMENT

Density

Two methods were used for determining the density of the surrogate samples. The first method consisted in weighing each sample and calculating the density dividing by the known sample volume. The second method was to use a set of hydrometers provided by Fisher Scientific for determining the densities of samples with low solids concentration and slow solids settling that

would not affect the measurements. Results indicated that both methods worked fine for the samples available. Density results and data correlation analysis are listed in the next section.

pH

A Corning pH-meter (electrode type) was used for sample pH analysis. The procedure for using this pH-meter is straightforward. The electrode is introduced directly into the sample; the pH and temperature can be read on the instrument panel. In addition, before each measurement, the pH-meter was calibrated to a pH range from 4 to 10. This calibration is done by using the buffer solutions provided by the vendor. pH results of the different simulants tested are listed in the next section.

Viscosity

Because of the different viscoelastic behaviors that a fluid may experience, viscosity is one of the main properties that needs to be analyzed when waste slurry conditioning and transfer are studied.

In this project, a RS75 HAAKE's Rheometer was utilized for determining the viscosity of the simulants. This rheometer model was chosen because of its flexibility to measure several parameters that are related to the substance viscosity. In addition, the Windows version of the software (RheoWin) needed to operate the system is straightforward to use and provides a broad range of data correlation options.

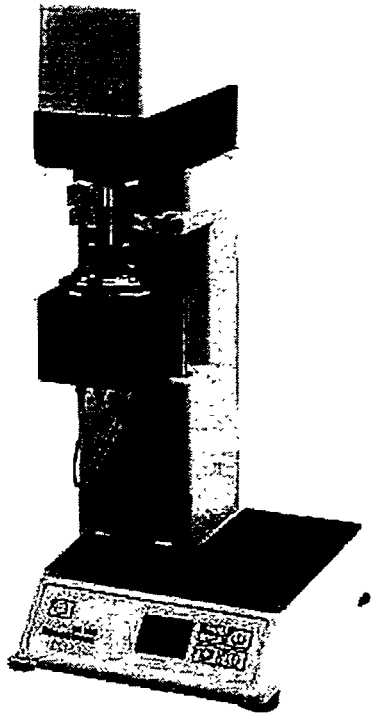


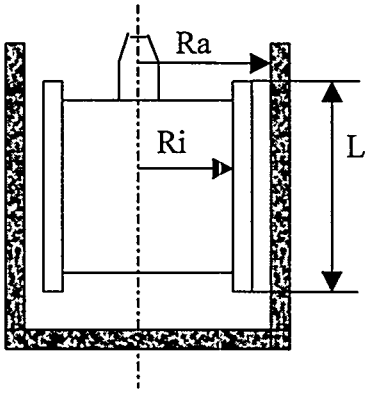
Figure 3.2.1 RS75 HAAKE's Rheometer.

With this equipment, the viscoelastic behavior of a fluid or a soft solid can be characterized in two ways:

- The fluid is deformed by a speed (angular velocity) which in the sensor system filled with a sample causes a shear rate. The torque required for achieving and maintaining the desired shear rate is the viscosity-proportional parameter. This is called the Controlled Rate method (CR).
- A shear stress is applied and the resulting movement (deformation) of the fluid is monitored. This is called the Controlled Stress method (CS).

In this project, the CR method was used in order to check the simulants viscosity variation at a determined shear rate range. For this, the following procedure was developed:

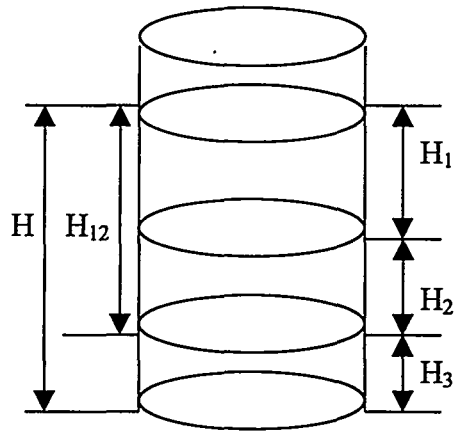
- A cylinder sensor system was selected to determine all viscosities. This sensor system is preferred for medium viscous fluids. These sensors have an extremely small front surface influence and are therefore intended for exact measurements. So, a Z38 sensor system was selected according to DIN 53018 along with its corresponding Z43 measuring cup. Following is the geometry description of this sensor system.



- Once the rheometer is turned ON and the program file opened, the measuring cup and the corresponding sensor are installed in the provided space.
- Then in the device section of the job manager, the accessories previously installed (measuring cup and sensor) are selected according to their description.
- Open an existing operating file created, which includes automatic lift control, select CR mode and check that the shear rate is in the proper range for the corresponding sensor. In this case range is from 0 to 495 1/s.
- Select automatic control and start the run.
- The results are saved in a data file. They can be seen in the next section and in the Appendix.

Particle Settling Velocity

The particle settling phenomenon has been observed and measured in settling bottles. The settling velocity was determined by examining the movement of the settled interface along with the settling time. The following diagram defines the settling portions and distances in the settling bottle, and the equation was used to calculate the settling velocity:



Where:

H = Total sample height
H_1 = Height of clear layer
H_2 = Height of cloudy layer
H_3 = Settled layer
$H_{12} = H_1 + H_2$

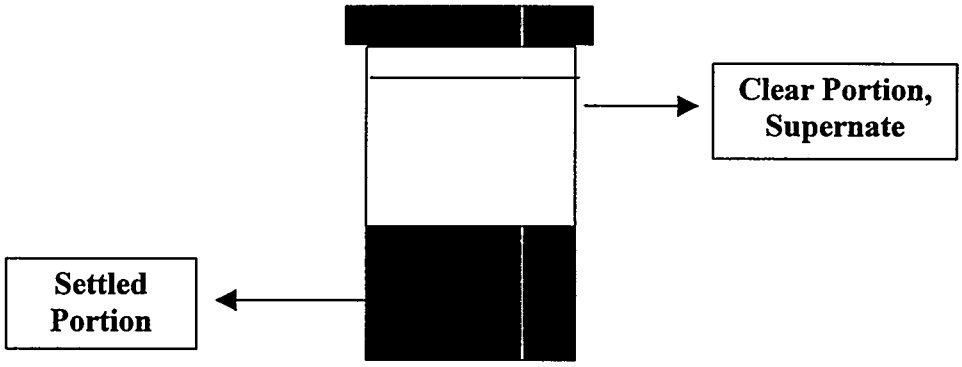
And:

Settling Velocity = H_{12} / Settling Time

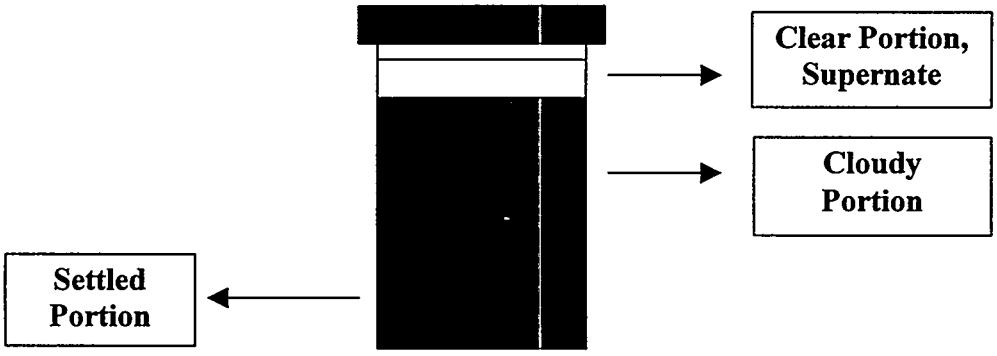
Based on this principle, the following procedure was used to measure the simulants' settling velocity:

- Pour sample into settling bottles.
- Record sample height (use this as a reference point to determine the settled height).
- Determine zero time (zero time is determined by shaking the sample so that the solution is homogeneous).
- After every hour measure the supernate height.

- Case 1.When only two phases are observed (clear and settled), measure the supernate distance.



- Case 2. When three phases are observed (clear, cloudy, settled portion). Measure each portion.



Settling velocities for all samples can be found in the next section.

Solubility

The three surrogates (Fernald, SRS, and Hanford) were subjected to various mixing conditions with respect to mixing speed and time. It was desired to evaluate several properties of these formulations as a function of these parameters. Among the properties of interest the degree of solubility of these formulations needed to be estimated to evaluate waste conditioning of these mixtures to improve their transfer properties. Accordingly, the levels of soluble components in several samples subjected to various mixing and storage conditions were estimated.

Therefore, samples of the simulants subjected to varied mixing conditions were submitted to the Analytical Laboratory for solubility analysis.

Procedure

In some cases the samples exhibited an obvious interface between settled solid and clear supernatant liquid. In other cases the supernatant liquid remained somewhat turbid. For those

cases where a clear supernate was present, an aliquot of the supernate was taken for analysis. In the cases where complete settling was not observed, the supernate was filtered through an appropriate sized filter paper and the resulting clear filtrate was analyzed for dissolved solids.

Typically a 10 mL aliquot of the clear supernatant liquid was pipetted into a previously tared aluminum weighing dish. The solution was allowed to evaporate at ambient conditions until no further liquid was present (typically >16 hours). The aluminum dish was then placed in an oven at 105°C for approximately 30 minutes. The dish was removed from the oven and allowed to cool in a desiccator. The dish and residue were reweighed, and from the difference between the weight of the dish with residue and that empty dish the weight of the residue was calculated. The concentration of the soluble material was then calculated by dividing the weight of the residue by the volume of sample taken. For those samples that required filtration it was often necessary to take smaller aliquots because of loss of liquid due to the filtration process. In those cases 2 to 5 ml aliquots were taken. In some cases complete clarification of the sample was not attained despite filtration of the supernatant liquid. Certain samples were analyzed using a glass Petri dish rather than an aluminum one because they exhibited a high pH resulting in attack of the aluminum.

Dissolved solids varied from a high of approximately 54 mg/mL to a low of 0.05 mg/mL. Results of these solubility analyses are shown in the next section.

4.0 EXPERIMENTAL RESULTS AND DATA CORRELATION

As stated before, although a plan table for experiments containing all pertinent parameters was created, the available simulants were not enough to complete all of the planned experiments. Therefore, the following experiments were performed with the available material.

Table 4.1
Waste conditioning experiments performed

EXPERIMENT ID	CONCENTRATION, WT%	TEMPERATURE, ^{o}C	RPM
*F-40-RT-400	40	Room Temperature	400
F-25-RT-400	25	Room Temperature	400
F-5-RT-400	5	Room Temperature	400
**H-5-RT-400	5	Room Temperature	400
***S-5-RT-400	5	Room Temperature	400
S-25-RT-400	25	Room Temperature	400
F-5-RT-750	5	Room Temperature	750
F-40-RT-750	40	Room Temperature	750
F-25-RT-750	25	Room Temperature	750
H-5-RT-750	5	Room Temperature	750
S-5-RT-750	5	Room Temperature	750

*F = Fernald simulant
**H = Hanford simulant
***S = SRS simulant

As can be observed in the table, all experiments were performed at room temperature and at two mixing speeds: 400 and 750 RPM. Furthermore, samples from each experiment were taken for physical and chemical analysis at 0, 1, 6, and 24 hours.

Samples were first taken from the slurry vessel into an Erlenmeyer through a vacuum pump and then delivered into a 400 mL sample bottle for analyses.

4.1 PHYSICAL AND CHEMICAL PROPERTY DATA

The samples' pH, density, and solids solubility are presented in Tables 4.1.1 to 4.1.11. The viscosities are presented in rheograms. The settling velocities are presented in a different table because each sample was individually tested at different times.

4.1.1 pH, Density, and Solubility

Table 4.1.1
F-40-RT-400 experiment

SAMPLE NAME	TEMPERATURE, ^{o}C	PH	DENSITY, G/CM^3	SOLUBILITY, MG/ML
F-40-RT-400-0	21.2	8.39	1.14	2.97
F-40-RT-400-1	21.8	8.57	1.14	2.73
F-40-RT-400-6	22.5	8.83	1.14	2.68
F-40-RT-400-24	21.2	9.18	1.13	2.60

Table 4.1.2
F-25-RT-400 experiment

SAMPLE NAME	TEMPERATURE, ^{o}C	PH	DENSITY, G/CM^3	SOLUBILITY, MG/ML
F-25-RT-400-0	23.2	8.45	1.11	1.83
F-25-RT-400-1	22.9	8.78	1.13	1.75
F-25-RT-400-6	23.0	8.92	1.10	1.83
F-25-RT-400-24	21.2	9.09	1.11	1.71

Table 4.1.3
F-05-RT-400 experiment

SAMPLE NAME	TEMPERATURE, ^{o}C	PH	DENSITY, G/CM^3	SOLUBILITY, MG/ML
F-05-RT-400-0	25.2	9.16	1.05	0.66
F-05-RT-400-1	23.6	9.25	1.08	0.57
F-05-RT-400-6	21.5	9.08	1.07	0.54
F-05-RT-400-24	21.3	9.05	1.06	0.59

Table 4.1.4
H-05-RT-400 experiment

SAMPLE NAME	TEMPERATURE,°C	PH	DENSITY, G/CM^3	SOLUBILITY, MG/ML
H-05-RT-400-0	20.6	8.19	1.05	8.27
H-05-RT-400-1	20.6	8.20	1.05	7.92
H-05-RT-400-6	21.6	8.15	1.04	8.21
H-05-RT-400-24	20.8	8.11	1.04	5.26

Table 4.1.5
S-05-RT-400 experiment

SAMPLE NAME	TEMPERATURE,°C	PH	DENSITY, G/CM^3	SOLUBILITY, MG/ML
S-05-RT-400-0	22.8	11.85	1.05	16.46
S-05-RT-400-1	22.1	11.85	1.04	16.27
S-05-RT-400-6	21.4	11.81	1.05	16.20
S-05-RT-400-24	20.7	11.67	1.06	16.04

Table 4.1.6
S-25-RT-400 experiment

SAMPLE NAME	TEMPERATURE,°C	PH	DENSITY, G/CM^3	SOLUBILITY, MG/ML
S-25-RT-400-0	21.2	13.09	1.03	28.46
S-25-RT-400-1	21.1	13.16	1.10	29.50
S-25-RT-400-6	21.3	13.15	1.06	29.90
S-25-RT-400-24	21.0	13.11	1.01	29.66

Table 4.1.7
F-05-RT-750 experiment

SAMPLE NAME	TEMPERATURE,°C	PH	DENSITY, G/CM^3	SOLUBILITY, MG/ML
F-05-RT-750-0	21.5	8.93	1.02	0.55
F-05-RT-750-1	22.2	9.07	1.02	0.50
F-05-RT-750-6	23.8	9.11	1.01	0.53
F-05-RT-750-24	22.5	9.01	1.01	0.40

Table 4.1.8
F-40-RT-750 experiment

SAMPLE NAME	TEMPERATURE, °C	PH	DENSITY, G/CM^3	SOLUBILITY, MG/ML
F-40-RT-750-0	20.8	8.36	1.212	2.86
F-40-RT-750-1	21.8	8.52	1.221	2.80
F-40-RT-750-6	23.1	8.98	1.217	2.55
F-40-RT-750-24	21.3	9.32	1.193	3.24

Table 4.1.9
F-25-RT-750 experiment

SAMPLE NAME	TEMPERATURE, °C	PH	DENSITY, G/CM^3	SOLUBILITY, MG/ML
F-25-RT-750-0	20.4	8.50	1.11	1.54
F-25-RT-750-1	20.8	8.72	1.10	1.67
F-25-RT-750-6	21.1	9.01	1.09	1.74
F-25-RT-750-24	22.1	9.11	1.10	1.58

Table 4.1.10
H-05-RT-750 experiment

SAMPLE NAME	TEMPERATURE, °C	PH	DENSITY, G/CM^3	SOLUBILITY, MG/ML
H-05-RT-750-0	21.1	8.06	1.02	5.66
H-05-RT-750-1	21.2	8.15	1.04	5.50
H-05-RT-750-6	21.9	8.01	1.05	5.66
H-05-RT-750-24	21.6	7.91	1.04	5.80

Table 4.1.11
S-05-RT-750 experiment

SAMPLE NAME	TEMPERATURE, °C	PH	DENSITY, G/CM^3	SOLUBILITY, MG/ML
S-05-RT-750-0	21.4	11.80	1.04	16.08
S-05-RT-750-1	22.3	11.77	1.04	15.92
S-05-RT-750-6	24.0	11.56	1.04	15.72
S-05-RT-750-24	21.1	11.12	1.04	15.78

Table 4.1.12
Simulants' settling velocities

Sample Name	Time, h	H1, cm	H2,cm	H3,cm	H, cm	Settling Velocity, cm/h
F-5-RT-400-0	0	0	0	0	8.5	0
	1	0	4.3	4.2	8.5	4.3
	2	0.1	5.2	3.2	8.5	2.65
	3	0.2	5.4	2.9	8.5	1.87
	4	0.2	5.6	2.7	8.5	1.45
	5	0.4	5.5	2.6	8.5	1.18
	6	0.4	5.7	2.4	8.5	1.02
	7	0.4	5.9	2.2	8.5	0.90
	8	0.6	5.8	2.1	8.5	0.80
	16	0.8	6	1.7	8.5	0.43
	24	1	5.9	1.6	8.5	0.29
	48	1.2	5.8	1.5	8.5	0.15
F-5-RT-400-1	0	0	0	0	8.5	0.00
	1	0	4.4	4.1	8.5	4.40
	2	0.1	5.3	3.1	8.5	2.70
	3	0.2	5.5	2.8	8.5	1.90
	4	0.2	5.6	2.7	8.5	1.45
	5	0.4	5.5	2.6	8.5	1.18
	6	0.4	5.6	2.5	8.5	1.00
	7	0.4	5.7	2.4	8.5	0.87
	8	0.5	5.8	2.2	8.5	0.79
	16	0.7	6.1	1.7	8.5	0.43
	24	0.8	6.1	1.6	8.5	0.29
	48	1	6	1.5	8.5	0.15
F-5-RT-400-6	0	0	0	0	8.5	0.00
	1	0	3.9	4.6	8.5	3.90
	2	0.1	5.4	3	8.5	2.75
	3	0.2	5.4	2.9	8.5	1.87
	4	0.3	5.4	2.8	8.5	1.43
	5	0.3	5.6	2.6	8.5	1.18

Table 4.1.12
Simulants' settling velocities (continued)

Sample Name	Time, h	H1, cm	H2,cm	H3,cm	H, cm	Settling Velocity, cm/h
	6	0.3	5.7	2.5	8.5	1.00
	7	0.4	5.7	2.4	8.5	0.87
	8	0.5	5.7	2.3	8.5	0.78
	16	0.8	5.9	1.8	8.5	0.42
	24	0.9	6	1.6	8.5	0.29
	48	1	6.1	1.4	8.5	0.15
F-5-RT-400-24	0	0	0	0	8.6	0.00
	1	0	4	4.6	8.6	4.00
	2	0.2	5.2	3.2	8.6	2.70
	3	0.3	5.2	3.1	8.6	1.83
	4	0.3	5.4	2.9	8.6	1.43
	5	0.4	5.5	2.7	8.6	1.18
	6	0.4	5.7	2.5	8.6	1.02
	7	0.4	5.8	2.4	8.6	0.89
	8	0.5	5.7	2.4	8.6	0.78
	16	0.7	5.7	2.2	8.6	0.40
	48	1	6.1	1.5	8.6	0.15
H-5-RT-400-0	0	0	0	0	8.6	0.00
	1	1.2	0	7.4	8.6	1.20
	2	1.7	0	6.9	8.6	0.85
	3	2.2	0	6.4	8.6	0.73
	4	2.4	0	6.2	8.6	0.60
	5	2.7	0	5.9	8.6	0.54
	6	2.8	0	5.8	8.6	0.47
	7	2.9	0	5.7	8.6	0.41
	8	3.1	0	5.5	8.6	0.39
	16	4.2	0	4.4	8.6	0.26
	24	4.2	0	4.4	8.6	0.18
	48	4.2	0	4.4	8.6	0.09
H-5-RT-400-1	0	0	0	0	8.5	0.00
	1	1.3	0	7.2	8.5	1.30

Table 4.1.12
Simulants' settling velocities (continued)

Sample Name	Time, h	H1, cm	H2,cm	H3,cm	H, cm	Settling Velocity, cm/h
	2	1.9	0	6.6	8.5	0.95
	3	2.4	0	6.1	8.5	0.80
	4	2.6	0	5.9	8.5	0.65
	5	2.9	0	5.6	8.5	0.58
	6	3	0	5.5	8.5	0.50
	7	3.1	0	5.4	8.5	0.44
	8	3.4	0	5.1	8.5	0.43
	16	4.1	0	4.4	8.5	0.26
	24	4.2	0	4.3	8.5	0.18
	48	4.2	0	4.3	8.5	0.09
H-5-RT-400-6	0	0	0	0	8.3	0.00
	1	1.1	0	7.2	8.3	1.10
	2	1.6	0	6.7	8.3	0.80
	3	2	0	6.3	8.3	0.67
	4	2.15	0	6.15	8.3	0.54
	5	2.3	0	6	8.3	0.46
	6	2.6	0	5.7	8.3	0.43
	7	2.8	0	5.5	8.3	0.40
	8	2.9	0	5.4	8.3	0.36
	16	3.9	0	4.4	8.3	0.24
	24	4	0	4.3	8.3	0.17
	48	4.1	0	4.2	8.3	0.09
H-5-Rt-400-24	0	0	0	0	8.5	0.00
	1	1.1	0	7.4	8.5	1.10
	2	1.4	0	7.1	8.5	0.70
	3	1.8	0	6.7	8.5	0.60
	4	1.9	0	6.6	8.5	0.48
	5	2.5	0	6	8.5	0.50
	6	2.5	0	6	8.5	0.42
	7	2.6	0	5.9	8.5	0.37

Table 4.1.12
Simulants' settling velocities (continued)

Sample Name	Time, h	H1, cm	H2,cm	H3,cm	H, cm	Settling Velocity, cm/h
	8	2.7	0	5.8	8.5	0.34
	16	4	0	4.5	8.5	0.25
	24	4.1	0	4.4	8.5	0.17
F-25-RT-400-0	0	0	0	0	8.2	0.00
	1	0.1	0	8.1	8.2	0.10
	2	0.15	0	8.05	8.2	0.08
	3	0.2	0	8	8.2	0.07
	4	0.45	0	7.75	8.2	0.11
	5	0.5	0	7.7	8.2	0.10
	6	0.5	0	7.7	8.2	0.08
	7	0.6	0	7.6	8.2	0.09
	8	0.7	0	7.5	8.2	0.09
	16	0.8	0	7.4	8.2	0.05
	24	1.3	0	6.9	8.2	0.05
	48	1.8	0	6.4	8.2	0.04
F-25-RT-400-1	0	0	0	0	8.4	0.00
	1	0.1	0	8.3	8.4	0.10
	2	0.2	0	8.2	8.4	0.10
	3	0.3	0	8.1	8.4	0.10
	4	0.5	0	7.9	8.4	0.13
	5	0.5	0	7.9	8.4	0.10
	6	0.5	0	7.9	8.4	0.08
	7	0.6	0	7.8	8.4	0.09
	8	0.8	0	7.6	8.4	0.10
	16	1.1	0	7.3	8.4	0.07
	24	1.4	0	7	8.4	0.06
	48	2	0	6.4	8.4	0.04
F-25-RT-400-6	0	0	0	0	8.5	0.00
	1	0.1	0	8.4	8.5	0.10
	2	0.2	0	8.3	8.5	0.10
	3	0.25	0	8.25	8.5	0.08

Table 4.1.12
Simulants' settling velocities (continued)

Sample Name	Time, h	H1, cm	H2,cm	H3,cm	H, cm	Settling Velocity, cm/h
	4	0.3	0	8.2	8.5	0.08
	5	0.5	0	8	8.5	0.10
	6	0.5	0	8	8.5	0.08
	7	0.7	0	7.8	8.5	0.10
	8	0.8	0	7.7	8.5	0.10
	16	1.3	0	7.2	8.5	0.08
	24	1.4	0	7.1	8.5	0.06
	48	1.9	0	6.6	8.5	0.04
F-25-RT-400-24	0	0	0	0	8.4	0.00
	1	0.1	0	8.3	8.4	0.10
	2	0.2	0	8.2	8.4	0.10
	3	0.3	0	8.1	8.4	0.10
	4	0.4	0	8	8.4	0.10
	5	0.5	0	7.9	8.4	0.10
	6	0.5	0	7.9	8.4	0.08
	7	0.6	0	7.8	8.4	0.09
	8	0.7	0	7.7	8.4	0.09
	16	1.1	0	7.3	8.4	0.07
	24	1.2	0	7.2	8.4	0.05
S-5-RT-400-0	0	0	0	0	8.2	0.00
	1	1.9	0	6.3	8.2	1.90
	2	2.8	0	5.4	8.2	1.40
	3	3.4	0	4.8	8.2	1.13
	4	3.6	0	4.6	8.2	0.90
	5	4.4	0	3.8	8.2	0.88
	6	4.5	0	3.7	8.2	0.75
	7	4.8	0	3.4	8.2	0.69
	8	4.9	0	3.3	8.2	0.61

Table 4.1.12
Simulants' settling velocities (continued)

Sample Name	Time, h	H1, cm	H2,cm	H3,cm	H, cm	Settling Velocity, cm/h
	16	5.1	0	3.1	8.2	0.32
	24	5.3	0	2.9	8.2	0.22
	48	5.3	0	2.9	8.2	0.11
S-5-RT-400-1	0	0	0	0	8.2	0.00
	1	1.8	0	6.4	8.2	1.80
	2	2.8	0	5.4	8.2	1.40
	3	3.3	0	4.9	8.2	1.10
	4	3.7	0	4.5	8.2	0.93
	5	4.3	0	3.9	8.2	0.86
	6	4.5	0	3.7	8.2	0.75
	7	4.7	0	3.5	8.2	0.67
	8	4.9	0	3.3	8.2	0.61
	16	5.2	0	3	8.2	0.33
	24	5.2	0	3	8.2	0.22
	48	5.2	0	3	8.2	0.11
S-5-RT-400-6	0	0	0	0	8.2	0.00
	1	1.7	0	6.5	8.2	1.70
	2	3	0	5.2	8.2	1.50
	3	3.5	0	4.7	8.2	1.17
	4	3.8	0	4.4	8.2	0.95
	5	4.3	0	3.9	8.2	0.86
	6	4.5	0	3.7	8.2	0.75
	7	4.7	0	3.5	8.2	0.67
	8	4.8	0	3.4	8.2	0.60
	16	5.1	0	3.1	8.2	0.32
	24	5.3	0	2.9	8.2	0.22
	48	5.3	0	2.9	8.2	0.11
S-5-RT-400-24	0	0	0	0	8.2	0.00
	1	1.8	0	6.4	8.2	1.80
	2	3.2	0	5	8.2	1.60
	3	3.9	0	4.3	8.2	1.30

Table 4.1.12
Simulants' settling velocities (continued)

Sample Name	Time, h	H1, cm	H2,cm	H3,cm	H, cm	Settling Velocity, cm/h
	4	4.2	0	4	8.2	1.05
	5	4.7	0	3.5	8.2	0.94
	6	4.8	0	3.4	8.2	0.80
	7	4.9	0	3.3	8.2	0.70
	8	5.1	0	3.1	8.2	0.64
	16	5.4	0	2.8	8.2	0.34
	24	5.4	0	2.8	8.2	0.23
F-40-RT-400-0	0	0	0	0	7.7	0
	1	0.1	0	7.6	7.7	0.10
	2	0.1	0	7.6	7.7	0.05
	3	0.1	0	7.6	7.7	0.03
	4	0.1	0	7.6	7.7	0.03
	5	0.3	0	7.4	7.7	0.06
	6	0.3	0	7.4	7.7	0.05
	7	0.5	0	7.2	7.7	0.07
	8	0.6	0	7.1	7.7	0.08
	16	0.8	0	6.9	7.7	0.05
	24	1	0	6.7	7.7	0.04
	48	1.3	0	6.4	7.7	0.03
F-40-RT-400-1	0	0	0	7.5	7.5	0.00
	1	0.1	0	7.4	7.5	0.10
	2	0.1	0	7.4	7.5	0.05
	3	0.1	0	7.4	7.5	0.03
	4	0.2	0	7.3	7.5	0.05
	5	0.3	0	7.2	7.5	0.06
	6	0.3	0	7.2	7.5	0.05
	7	0.4	0	7.1	7.5	0.06
	8	0.5	0	7	7.5	0.06

Table 4.1.12
Simulants' settling velocities (continued)

Sample Name	Time, h	H1, cm	H2,cm	H3,cm	H, cm	Settling Velocity, cm/h
	16	0.7	0	6.8	7.5	0.04
	24	0.8	0	6.7	7.5	0.03
	48	1.2	0	6.3	7.5	0.03
F-40-RT-400-6	0	0	0	0	7.7	0
	1	0.1	0	7.6	7.7	0.10
	2	0.1	0	7.6	7.7	0.05
	3	0.1	0	7.6	7.7	0.03
	4	0.1	0	7.6	7.7	0.03
	5	0.1	0	7.6	7.7	0.02
	6	0.3	0	7.4	7.7	0.05
	7	0.4	0	7.3	7.7	0.06
	8	0.5	0	7.2	7.7	0.06
	16	0.7	0	7	7.7	0.04
	24	0.8	0	6.9	7.7	0.03
	48	1.3	0	6.4	7.7	0.03
F-40-RT-400-24	0	0	0	7.6	7.6	0
	1	0.1	0	7.5	7.6	0.10
	2	0.1	0	7.5	7.6	0.05
	3	0.1	0	7.5	7.6	0.03
	4	0.1	0	7.5	7.6	0.03
	5	0.1	0	7.5	7.6	0.02
	6	0.3	0	7.3	7.6	0.05
	7	0.4	0	7.2	7.6	0.06
	8	0.5	0	7.1	7.6	0.06
	16	0.6	0	7	7.6	0.04
	24	0.7	0	6.9	7.6	0.03
F-40-RT-750-0	0	0	0	0	7.5	0
	1	0.1	0	7.4	7.5	0.10
	2	0.1	0	7.4	7.5	0.05
	3	0.2	0	7.3	7.5	0.07

Table 4.1.12
Simulants' settling velocities (continued)

Sample Name	Time, h	H1, cm	H2,cm	H3,cm	H, cm	Settling Velocity, cm/h
	4	0.2	0	7.3	7.5	0.05
	5	0.2	0	7.3	7.5	0.04
	6	0.2	0	7.3	7.5	0.03
	7	0.3	0	7.2	7.5	0.04
	8	0.4	0	7.1	7.5	0.05
	16	0.5	0	7	7.5	0.03
	24	0.5	0	7	7.5	0.02
	48	1	0	6.5	7.5	0.02
F-40-RT-750-1	0	0	0	0	7.7	0
	1	0.1	0	7.6	7.7	0.10
	2	0.1	0	7.6	7.7	0.05
	3	0.1	0	7.6	7.7	0.03
	4	0.1	0	7.6	7.7	0.03
	5	0.2	0	7.5	7.7	0.04
	6	0.2	0	7.5	7.7	0.03
	7	0.3	0	7.4	7.7	0.04
	8	0.3	0	7.4	7.7	0.04
	16	0.4	0	7.3	7.7	0.03
	24	0.5	0	7.2	7.7	0.02
	48	1	0	6.7	7.7	0.02
F-40-RT-750-6	0	0	0	0	7.5	0
	1	0.1	0	7.4	7.5	0.10
	2	0.1	0	7.4	7.5	0.05
	3	0.1	0	7.4	7.5	0.03
	4	0.1	0	7.4	7.5	0.03
	5	0.1	0	7.4	7.5	0.02
	6	0.2	0	7.3	7.5	0.03
	7	0.3	0	7.2	7.5	0.04
	8	0.3	0	7.2	7.5	0.04

Table 4.1.12
Simulants' settling velocities (continued)

Sample Name	Time, h	H1, cm	H2,cm	H3,cm	H, cm	Settling Velocity, cm/h
	16	0.4	0	7.1	7.5	0.03
	24	0.5	0	7	7.5	0.02
	48	0.8	0	6.7	7.5	0.02
F-40-RT-750-24	0	0	0	0	7.6	0
	1	0.1	0	7.5	7.6	0.10
	2	0.1	0	7.5	7.6	0.05
	3	0.1	0	7.5	7.6	0.03
	4	0.1	0	7.5	7.6	0.03
	5	0.1	0	7.5	7.6	0.02
	6	0.2	0	7.4	7.6	0.03
	7	0.2	0	7.4	7.6	0.03
	8	0.3	0	7.3	7.6	0.04
	16	0.3	0	7.3	7.6	0.02
	24	0.3	0	7.3	7.6	0.01
F-5-RT-750-0	0	0	0	0	8	0
	1	0.2	4.8	3	8	5.0
	2	0.3	4.8	2.9	8	2.55
	3	0.3	5.2	2.5	8	1.83
	4	0.3	5.4	2.3	8	1.43
	5	0.3	5.5	2.2	8	1.16
	6	0.3	5.6	2.1	8	0.98
	7	0.3	5.9	1.8	8	0.89
	8	0.4	5.8	1.8	8	0.78
	16	0.4	6	1.6	8	0.40
	24	0.5	5.9	1.6	8	0.27
	48	0.7	5.8	1.5	8	0.14
F-5-RT-750-1	0	0	0	0	7.8	0
	1	0.2	4.3	3.3	7.8	4.50
	2	0.2	4.5	3.1	7.8	2.35
	3	0.2	4.6	3	7.8	1.60
	4	0.2	5	2.5	7.8	1.30

Table 4.1.12
Simulants' settling velocities (continued)

Sample Name	Time, h	H1, cm	H2,cm	H3,cm	H, cm	Settling Velocity, cm/h
	5	0.3	5.2	2.5	7.8	1.10
	6	0.3	5.2	2.3	7.8	0.92
	7	0.3	5.4	2.1	7.8	0.81
	8	0.4	5.4	2	7.8	0.73
	16	0.4	5.6	1.8	7.8	0.38
	24	0.5	5.5	1.8	7.8	0.25
	48	0.8	5.4	1.6	7.8	0.13
F-5-RT-750-6	0	0	0	0	8	0
	1	0.2	4.5	3.3	8	4.70
	2	0.2	4.7	3.1	8	2.45
	3	0.2	5	2.8	8	1.73
	4	0.2	5	2.5	8	1.30
	5	0.3	5.2	2.5	8	1.10
	6	0.3	5.4	2.3	8	0.95
	7	0.3	5.6	2.1	8	0.84
	8	0.4	5.6	2	8	0.75
	16	0.5	5.7	1.8	8	0.39
	24	0.5	5.8	1.7	8	0.26
	48	0.8	5.6	1.6	8	0.13
F-5-RT-750-24	0	0	0	0	7.90	0
	1	0.2	4.40	3.3	7.90	4.60
	2	0.2	4.60	3.1	7.90	2.40
	3	0.2	4.70	3	7.90	1.63
	4	0.2	4.40	2.5	7.90	0.84
	5	0.3	5.10	2.5	7.90	1.08
	6	0.3	5.30	2.3	7.90	0.93
	7	0.4	5.50	2	7.90	0.84
	8	0.4	5.30	2.2	7.90	0.71

Table 4.1.12
Simulants' settling velocities (continued)

Sample Name	Time, h	H1, cm	H2,cm	H3,cm	H, cm	Settling Velocity, cm/h
	16	0.5	5.50	1.9	7.90	0.38
	24	0.5	5.70	1.7	7.90	0.26
H-5-RT-750-0	0	0	0	0	7.7	0
	1	1	0	6.7	7.7	1.00
	2	1.3	0	6.4	7.7	0.65
	3	1.5	0	6.2	7.7	0.50
	4	1.5	0	6.2	7.7	0.38
	5	1.9	0	5.8	7.7	0.38
	6	2.2	0	5.5	7.7	0.37
	7	2.5	0	5.2	7.7	0.36
	8	2.9	0	4.8	7.7	0.36
	16	3	0	4.7	7.7	0.19
	24	3.5	0	4.2	7.7	0.15
	48	3.8	0	3.9	7.7	0.08
H-5-RT-750-1	0	0	0	0	8.1	0
	1	1	0	7.1	8.1	1.00
	2	1.3	0	6.8	8.1	0.65
	3	1.5	0	6.6	8.1	0.50
	4	1.7	0	6.4	8.1	0.43
	5	1.8	0	6.3	8.1	0.36
	6	2.2	0	5.9	8.1	0.37
	7	2.4	0	5.7	8.1	0.34
	8	2.8	0	5.3	8.1	0.35
	16	3.2	0	4.9	8.1	0.20
	24	3.6	0	4.5	8.1	0.15
	48	3.8	0	4.3	8.1	0.08
H-5-RT-750-6	0	0	0	0	7.9	0
	1	0.8	0	7.1	7.9	0.80
	2	1	0	6.9	7.9	0.50
	3	1.5	0	6.4	7.9	0.50
	4	1.8	0	6.1	7.9	0.45

Table 4.1.12
Simulants' settling velocities (continued)

Sample Name	Time, h	H1, cm	H2,cm	H3,cm	H, cm	Settling Velocity, cm/h
	5	2	0	5.9	7.9	0.40
	6	2.2	0	5.7	7.9	0.37
	7	2.4	0	5.5	7.9	0.34
	8	2.8	0	5.1	7.9	0.35
	16	3.1	0	4.8	7.9	0.19
	24	3.6	0	4.3	7.9	0.15
	48	3.7	0	4.2	7.9	0.08
H-5-RT-750-24	0	0	0	0	7.8	0
	1	0.8	0	7	7.8	0.80
	2	1	0	6.8	7.8	0.50
	3	1.5	0	6.3	7.8	0.50
	4	1.5	0	6.3	7.8	0.38
	5	1.8	0	6	7.8	0.36
	6	2	0	5.8	7.8	0.33
	7	2.3	0	5.5	7.8	0.33
	8	2.5	0	5.3	7.8	0.31
	16	3.2	0	4.6	7.8	0.20
	24	3.5	0	4.3	7.8	0.15
F-25-RT-750-0	0	0	0	0	7.9	0
	1	0.2	0	7.7	7.9	0.20
	2	0.3	0	7.6	7.9	0.15
	3	0.4	0	7.5	7.9	0.13
	4	0.5	0	7.4	7.9	0.13
	5	0.5	0	7.4	7.9	0.10
	6	0.7	0	7.2	7.9	0.12
	7	0.8	0	7.1	7.9	0.11
	8	0.9	0	7	7.9	0.11
	16	1.5	0	6.4	7.9	0.09

Table 4.1.12
Simulants' settling velocities (continued)

Sample Name	Time, h	H1, cm	H2,cm	H3,cm	H, cm	Settling Velocity, cm/h
	24	1.9	0	6	7.9	0.08
	48	2.5	0	5.4	7.9	0.05
F-25-RT-750-1	0	0	0	0	7.7	0
	1	0.3	0	7.4	7.7	0.30
	2	0.5	0	7.2	7.7	0.25
	3	0.8	0	6.9	7.7	0.27
	4	1.1	0	6.6	7.7	0.28
	5	1.1	0	6.6	7.7	0.22
	6	1.3	0	6.4	7.7	0.22
	7	1.5	0	6.2	7.7	0.21
	8	1.5	0	6.2	7.7	0.19
	16	2	0	5.7	7.7	0.13
	24	2.3	0	5.4	7.7	0.10
	48	3	0	4.7	7.7	0.06
F-25-RT-750-6	0	0	0	0	7.6	0
	1	0.2	0	7.4	7.6	0.20
	2	0.5	0	7.1	7.6	0.25
	3	1	0	6.6	7.6	0.33
	4	1	0	6.6	7.6	0.25
	5	1.2	0	6.4	7.6	0.24
	6	1.3	0	6.3	7.6	0.22
	7	1.5	0	6.1	7.6	0.21
	8	1.6	0	6	7.6	0.20
	16	1.9	0	5.7	7.6	0.12
	24	2.1	0	5.5	7.6	0.09
	48	2.6	0	5	7.6	0.05

Table 4.1.12
Simulants' settling velocities (continued)

Sample Name	Time, h	H1, cm	H2,cm	H3,cm	H, cm	Settling Velocity, cm/h
F-25-RT-750-24	0	0	0	0	7.8	0
	1	0.2	0	7.6	7.8	0.20
	2	0.3	0	7.5	7.8	0.15
	3	0.5	0	7.3	7.8	0.17
	4	0.7	0	7.1	7.8	0.18
	5	0.7	0	7.1	7.8	0.14
	6	0.8	0	7	7.8	0.13
	7	0.9	0	6.9	7.8	0.13
	8	1	0	6.8	7.8	0.13
	16	1.4	0	6.4	7.8	0.09
	24	1.6	0	6.2	7.8	0.07
	48	2.4	0	5.4	7.8	0.05

4.2 DATA CORRELATION

Based on the results obtained, several data correlations were performed to analyze the different parameters studied. The purpose of this study is to check how these properties may affect the waste conditioning process.

4.2.1 Settling Rate

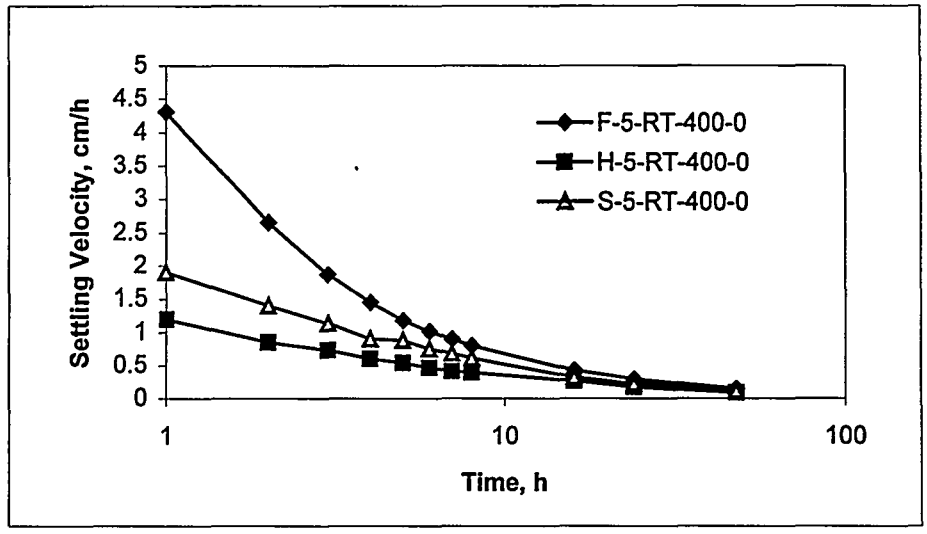


Figure 4.2.1.1 Fernald, Hanford, and SRS simulants (5 wt%) settling velocity comparison at time zero.

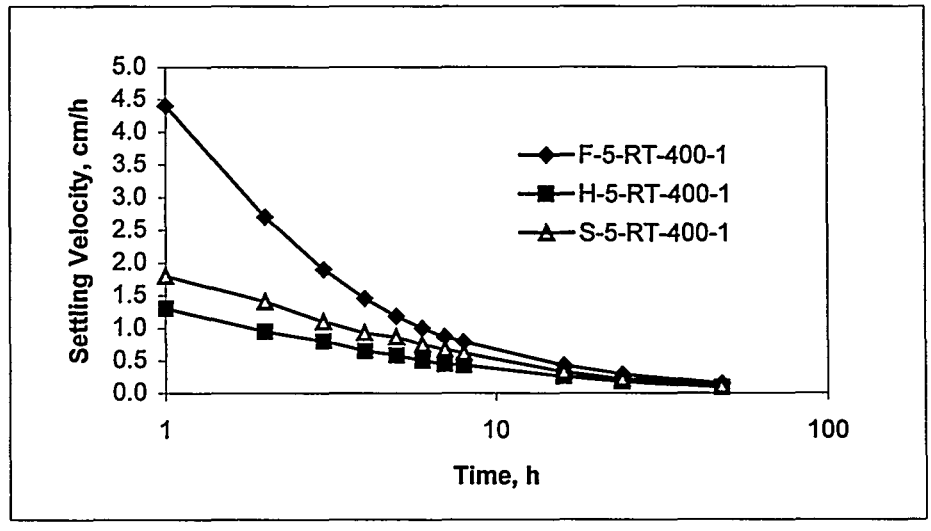


Figure 4.2.1.2 Fernald, Hanford, and SRS simulants (5 wt%) settling velocity comparison after 1 hour mixing at 400 RPM.

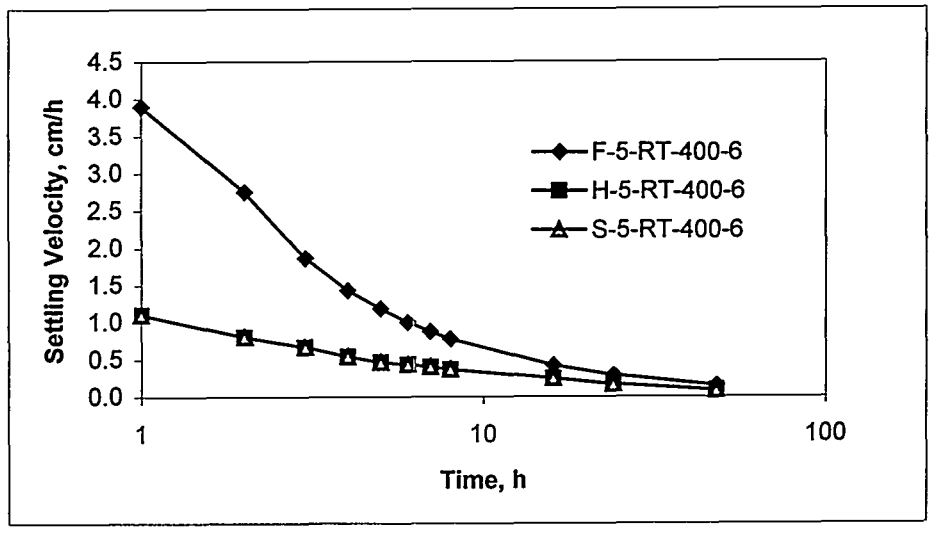


Figure 4.2.1.3 Fernald, Hanford and SRS simulants (5 wt%) settling velocity comparison after 6 hours mixing at 400 RPM.

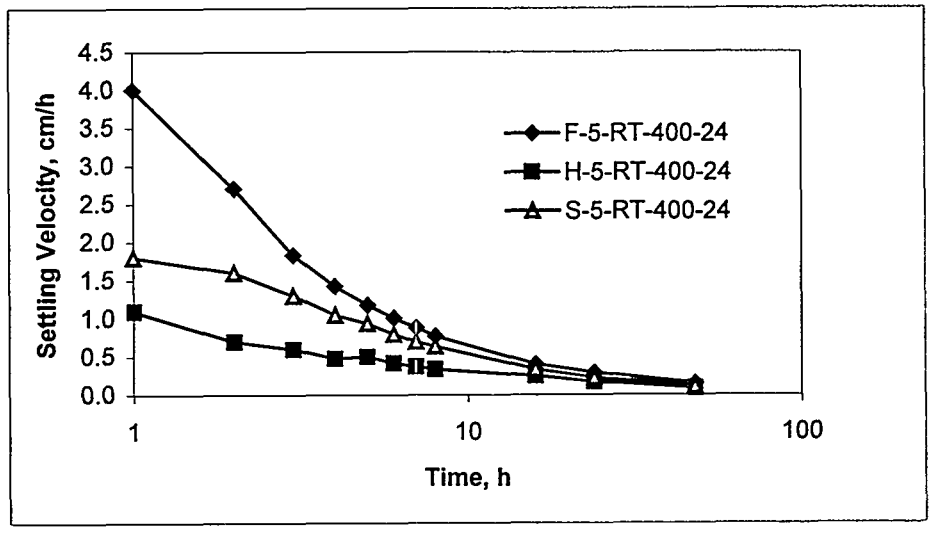


Figure 4.2.1.4 Fernald, Hanford, and SRS simulants (5 wt%) settling velocity comparison after 24 hours mixing at 400 RPM.

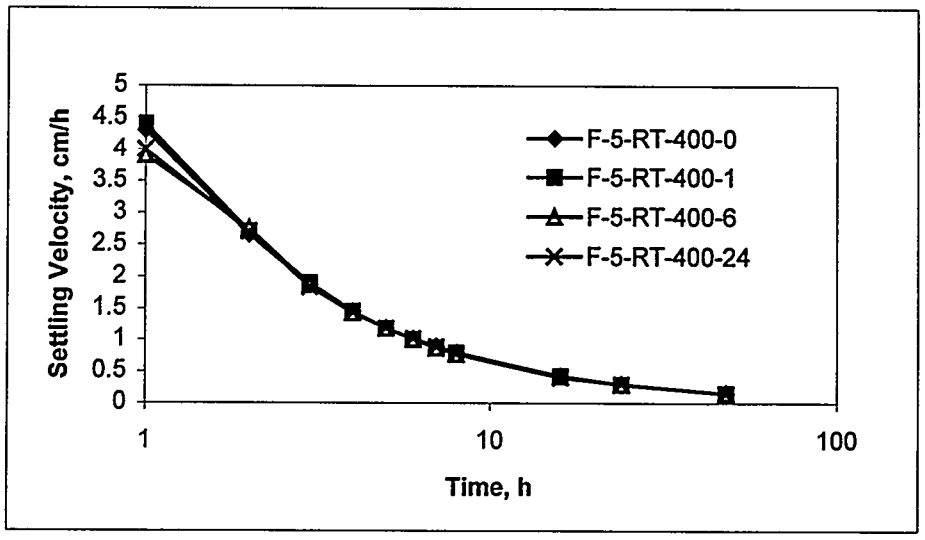


Figure 4.2.1.5 Fernald simulant (5 wt%) settling velocity comparison after 0, 1, 6, and 24 hours mixing at 400 RPM.

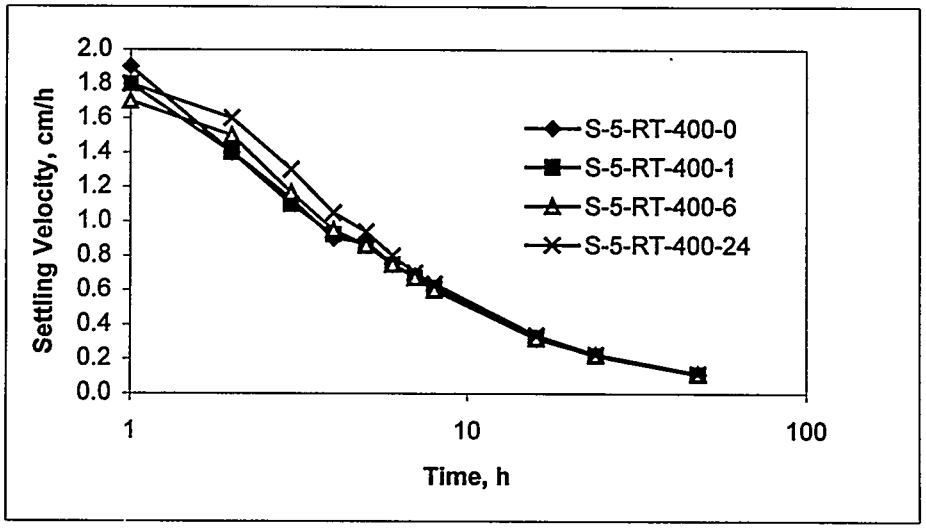


Figure 4.2.1.6 SRS simulant (5 wt%) settling velocity comparison after 0, 1, 6, and 24 hours mixing at 400 RPM.

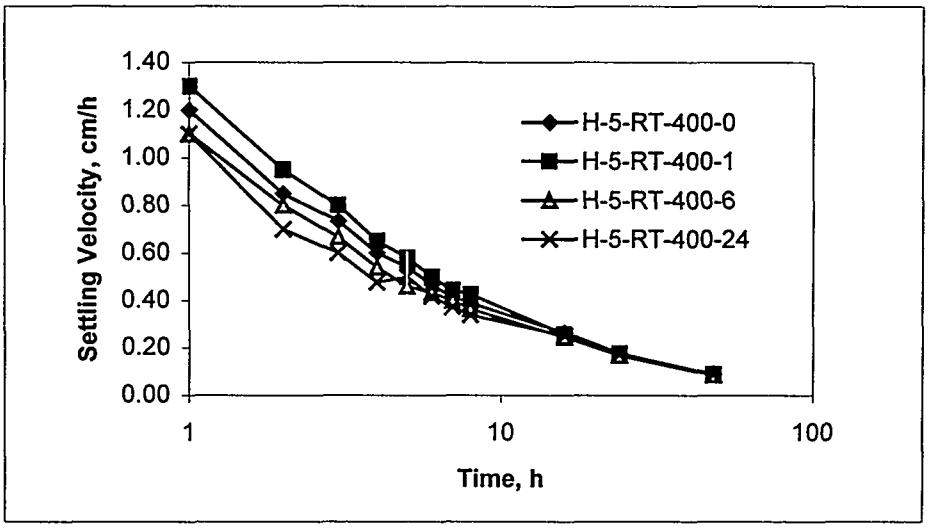


Figure 4.2.1.7 Hanford simulant (5 wt%) settling velocity comparison after 0, 1, 6, and 24 hours mixing at 400 RPM.

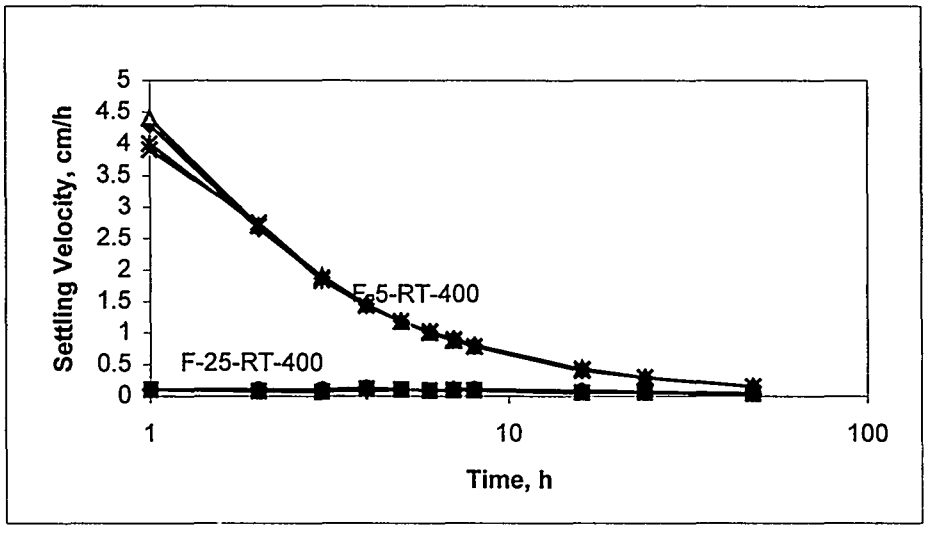


Figure 4.2.1.8 Fernald simulant settling velocity comparison for 5 wt% and 25 wt% concentrations.

4.2.2 Density

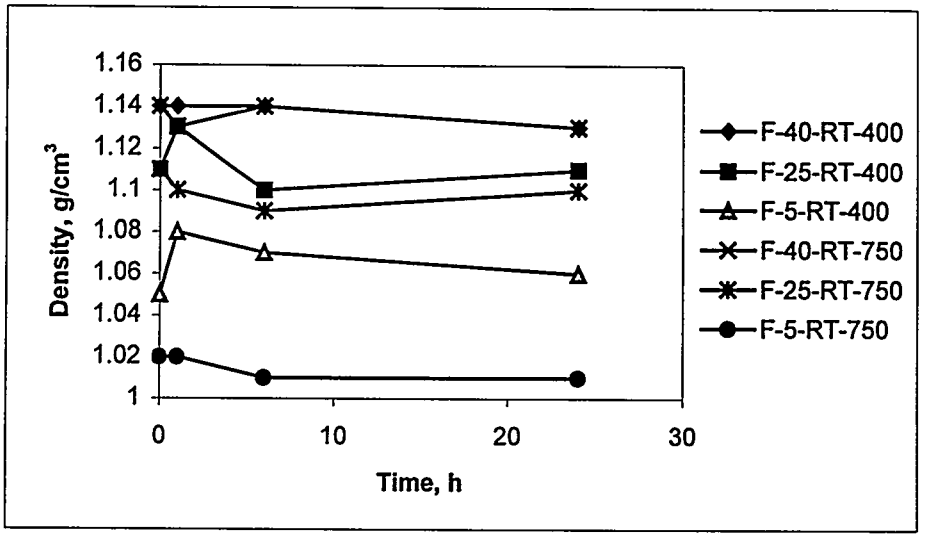


Figure 4.2.2.1 Fernald simulant density comparison at different concentrations (5,25, and 40 wt%) and different mixing speeds (400 and 750 RPM).

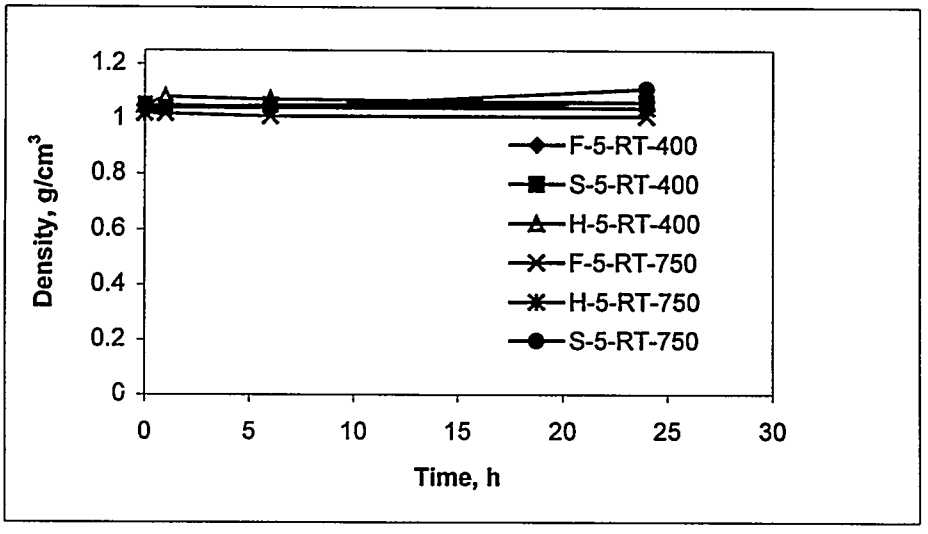


Figure 4.2.2.2 Fernald, SRS, and Hanford simulants density comparison at 5 wt% concentration and different mixing speeds (400 and 750 RPM).

4.2.3 pH

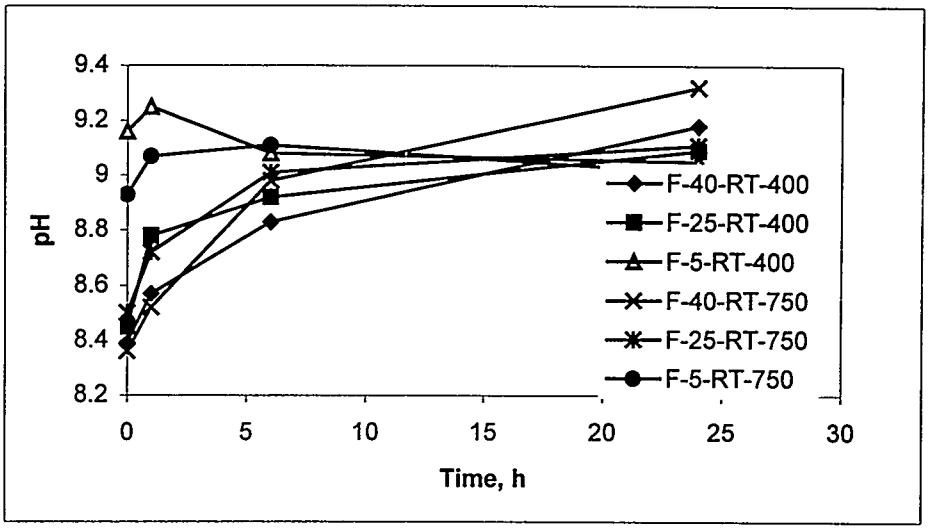


Figure 4.2.3.1 Fernald simulant pH comparison at different concentrations (5, 25, and 40 wt%) and different mixing speeds (400 and 750 RPM).

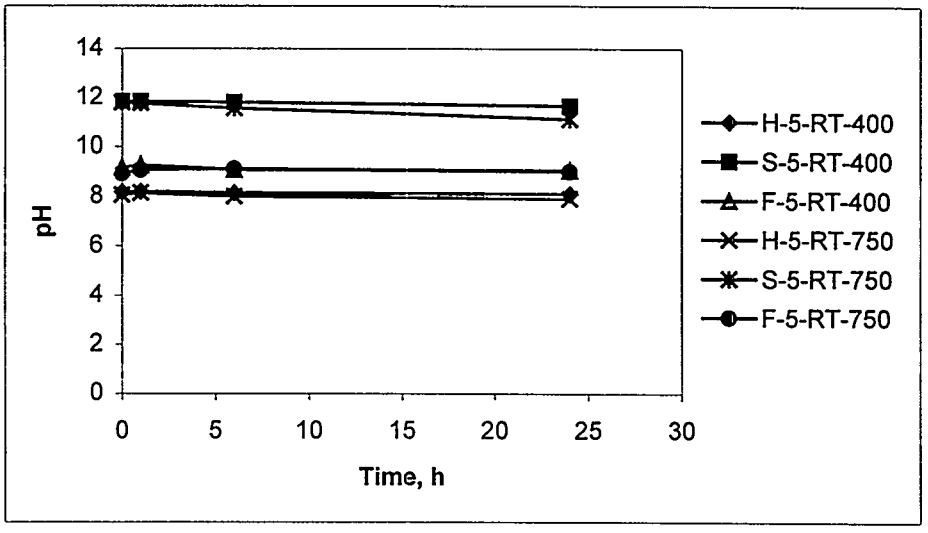


Figure 4.2.3.2 Fernald, SRS, and Hanford simulants pH comparison at 5 wt% concentration and different mixing speeds (400 and 750 RPM).

4.2.4 Solubility

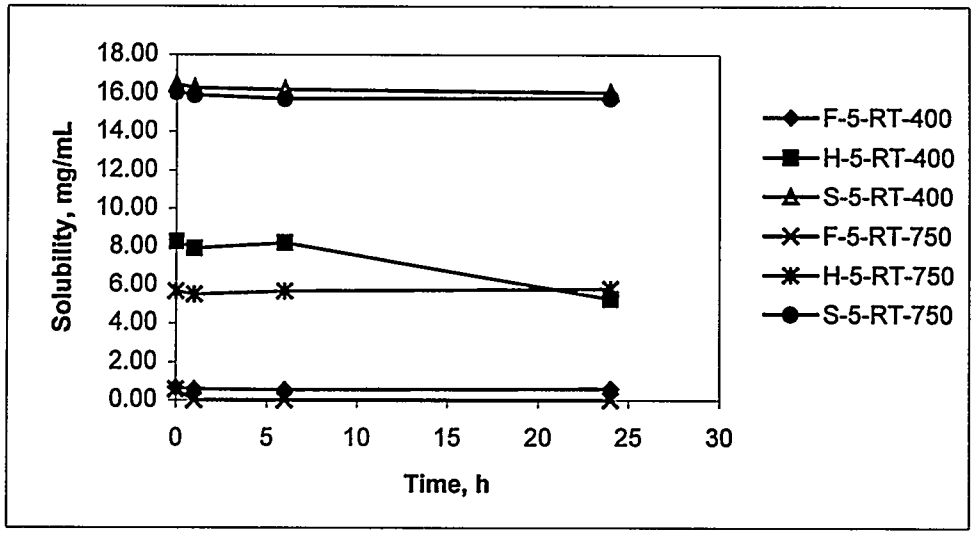


Figure 4.2.4.1 Fernald, SRS, and Hanford simulants solubility comparison at 5 wt% concentration and different mixing speeds (400 and 750 RPM).

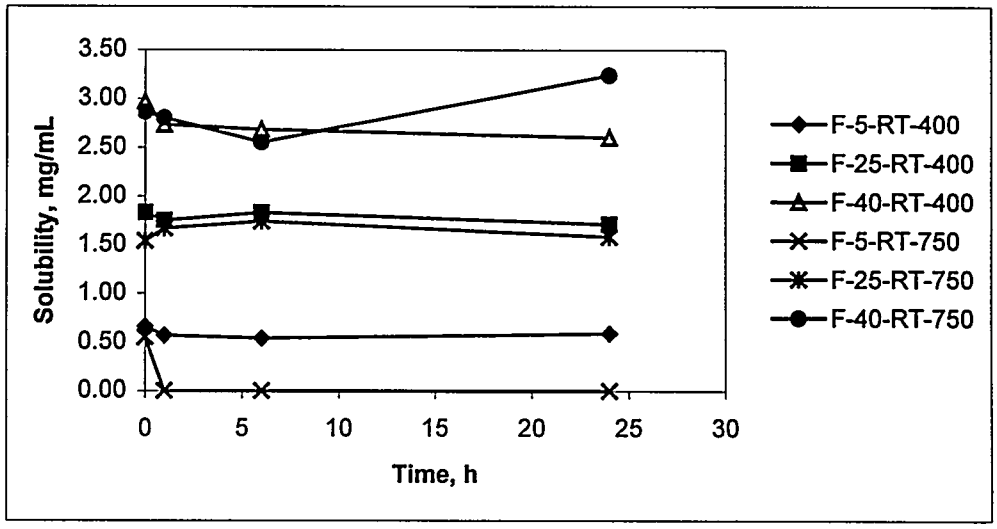


Figure 4.2.4.2 Fernald simulant solubility comparison at different concentrations (5, 25, and 40 wt%) and different mixing speeds (400 and 750 RPM).

4.2.5 Viscosity

Calculation Equations

Shear Stress τ

The shear stress is proportional to the torque Md and to a geometric factor, i.e., stress factor A.

$$\tau = \mathrm{Md} \,.\, \mathrm{A}$$

The factor A can be calculated as described by the following equation:

$$A = \frac{1}{2\pi Ri^2 L}$$

It has the unit of an inverse volume.

Shear Rate γ

The shear rate is proportionally linked to the angular velocity or speed and the shear factor M.

$$\gamma = \mathrm{M} \,.\, \Omega$$

The angular velocity Ω is calculated according to **$2\pi/60$. n** from the speed n. The factor M is calculated as follows:

$$M = \frac{2Ra^2}{Ra^2 Ri^2}$$

Deformation γ

The deformation is linearly linked to the angular deflection and the geometry of a sensor system. φ = torsion angle in radians.

$$\gamma = \mathrm{M} \,.\, \varphi$$

All of these calculations are performed by the software and they can be presented in rheograms, where the stress, shear rate, viscosity variation, as well as any other parameter involved and/or regression model can be plotted.

Rheograms

Following are the rheograms for simulants tested. These results correspond to the corresponding simulant at time zero (no mixing) and for the Fernald simulant at three different concentrations. All rheograms along with their table and information sheet can be found in Appendix A at the end of this report.

Interpretation

These rheograms need to be well interpreted; otherwise, it may lead to confusion. Consequently, the principle of operation of the equipment as well as the different viscosity models of a fluid need to be understood. When working with waste slurries, two viscosity models are commonly found: the Newtonian model and the Bingham model.

Newtonian Fluids

By definition, the viscosity of Newtonian fluids is given by the following equation:

$$\mu = \frac{\tau}{(du/dy)}$$

This equation simply states that if a plot is made of shear stress versus shear rate for a Newtonian fluid in laminar flow, a straight line passing through the origin will be obtained, the slope of the line being equal to the viscosity. Therefore, this slope will be constant. This situation can be observed in Figures 4.2.5.3 and 4.2.5.4, where the corresponding simulants follow a Newtonian model and an average viscosity is calculated. This may be due to the low concentration of those simulants (5%).

Bingham Plastic Model

Not all fluids follow the Newtonian model since their shear diagrams are not linear through the origin. These fluids are known as non-Newtonian fluids. This phenomenon is common in polymer solutions and in solutions with a high concentration of solids suspended in liquids. A Bingham plastic fluid is characterized by a flow curve that is a straight line having an intercept τ_0 on the shear stress axis. This yield stress τ_0 is a measure of the stress, which must be exceeded for flow to commence. The flow behavior is then described by the following equation:

$$\tau - \tau_o = \eta \frac{du}{dy}$$

This behavior was observed in simulants with more than 5 wt% concentration, as can be seen in Figures 4.2.5.1, and 4.2.5.2, which correspond to 40wt% and 25wt% concentrations, respectively. The model in the software calculates τ_0 and η as observed in the information sheets in the Appendix.

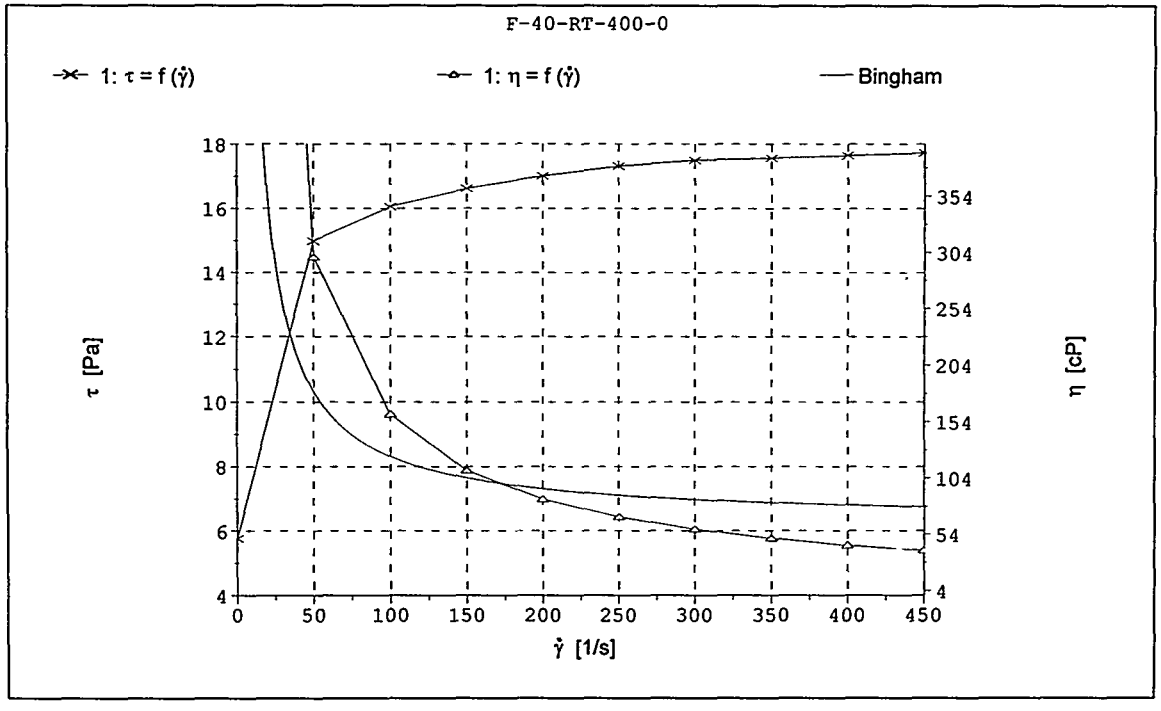


Figure 4.2.5.1 Viscosity Rheogram for 40 wt%. Fernald Simulant. Equation for the Bingham Model: $\tau = \tau o + \eta(du/dy) = 5744 + 65.67(du/dy)$.

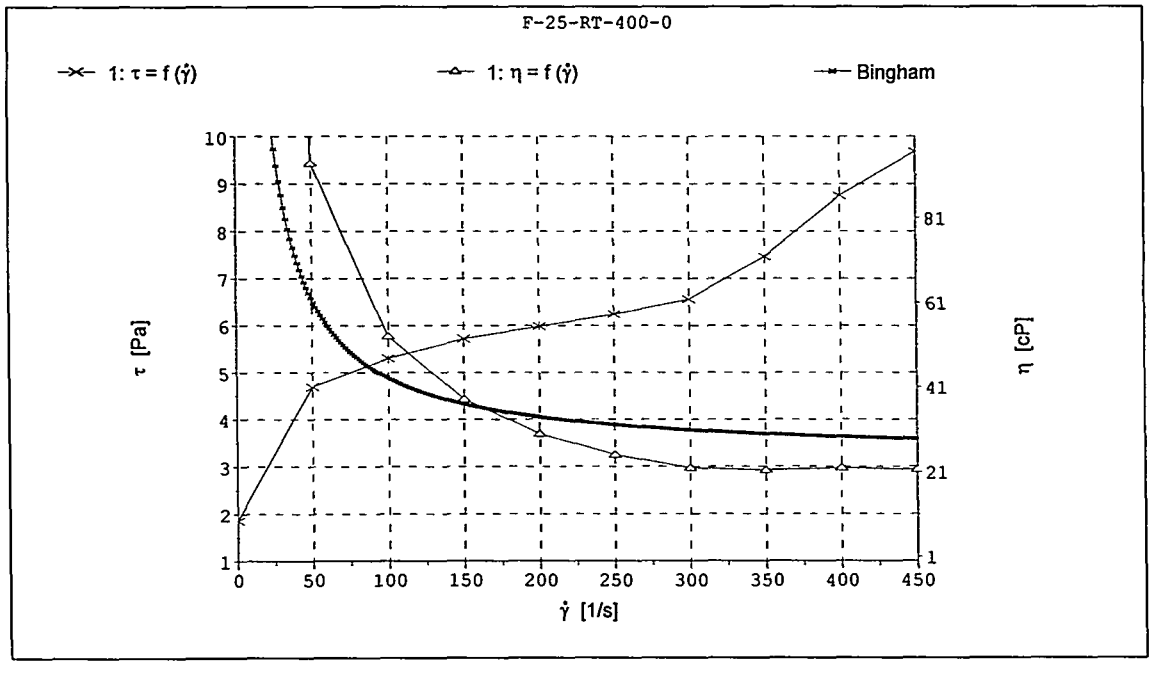


Figure 4.2.5.2 Viscosity Rheogram for 25 wt%. Fernald Simulant. Equation for the Bingham Model: $\tau = \tau o + \eta(du/dy) = 1853 + 24.58(du/dy)$.

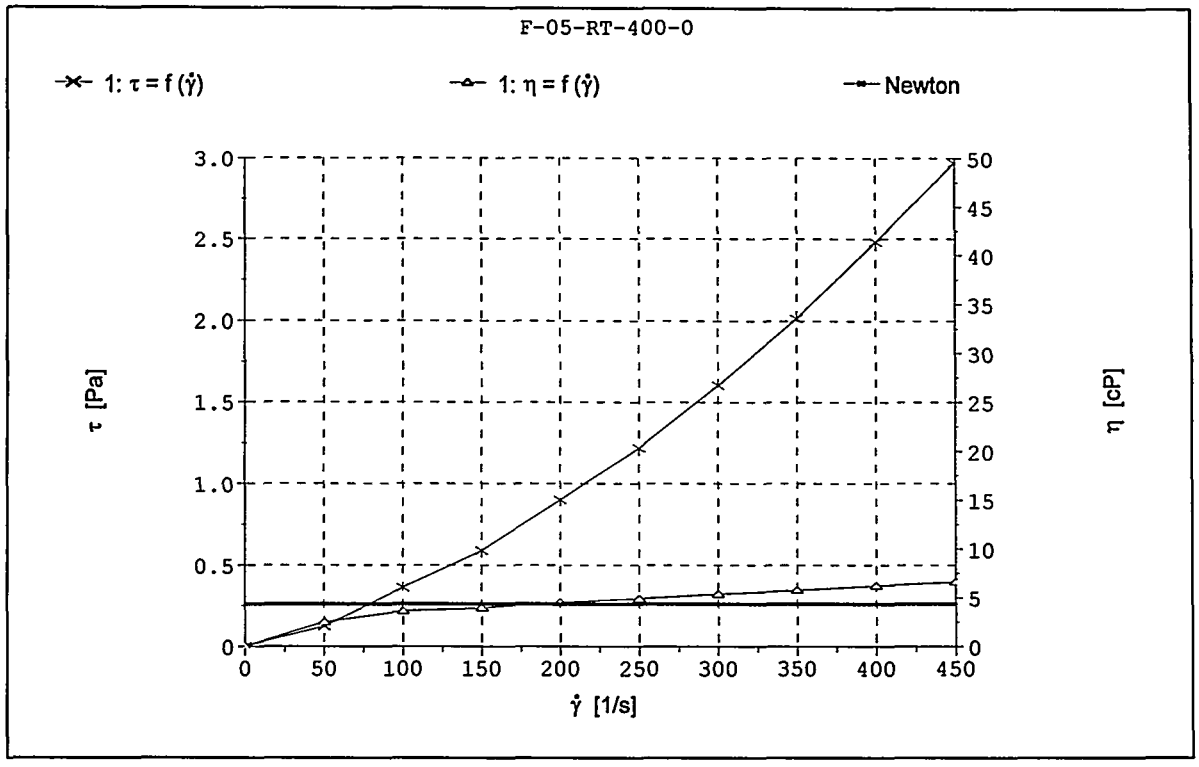


Figure 4.2.5.3 Viscosity Rheogram for 5 wt%. Fernald Simulant. Equation for the Newtonian Model: $\tau = \eta(du/dy) = 4.322(du/dy)$.

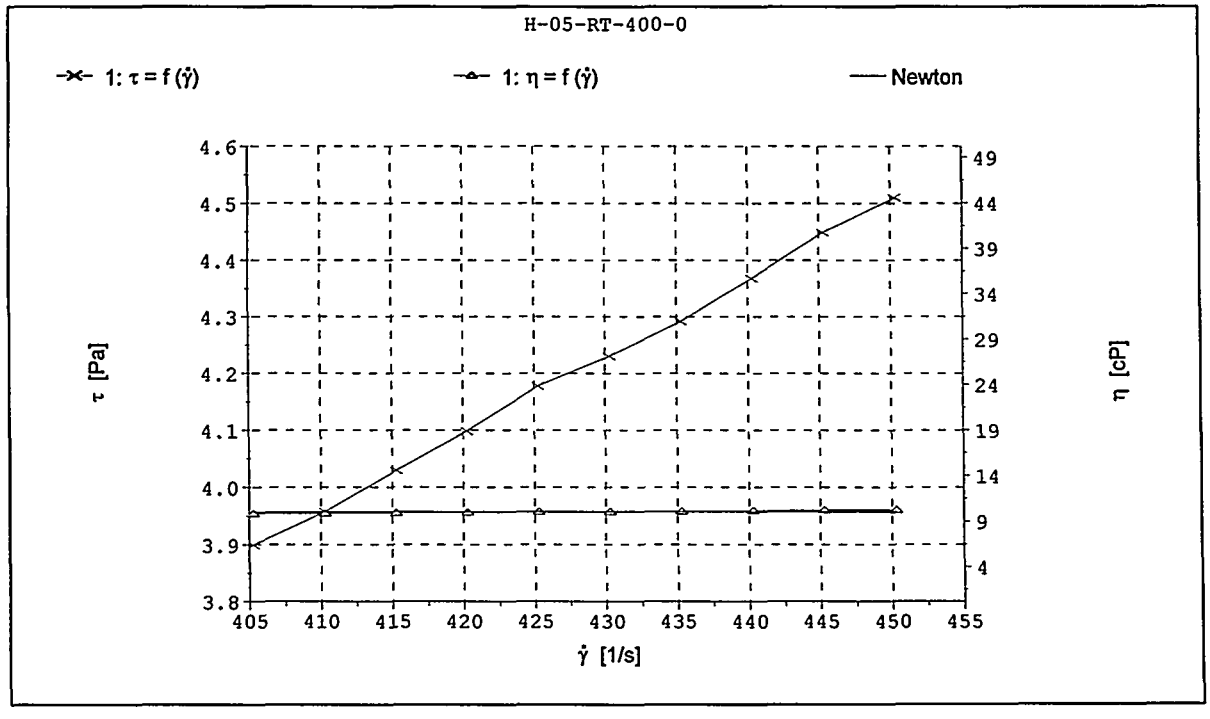


Figure 4.2.5.4 Viscosity Rheogram for 5 wt%. Hanford Simulant. Equation for the Newtonian Model: $\tau = \eta(du/dy) = 9.815(du/dy)$.

4.3 PRELIMINARY CONCLUSIONS

Some preliminary conclusions can be drawn based on the experimental data and model predictions of the different tests performed to the three different simulants.

- Waste slurry simulant viscosities follow the Bingham plastic model. This means that in order for these fluids to commence a yield stress τ_o is required. This behavior is especially evident as the solids concentration increases in a solution. At lower concentrations slurries may behave as Newtonian fluids.
- At the same concentration (5%), the Fernald simulant showed a higher settling velocity at the beginning of the test, followed by the SRS simulant. This behavior changed as time passed and as the settling rate in the three of them approached zero. This may be because of the bigger particles present in the Fernald simulant, which tend to settle faster.
- The higher the concentration, the lower the particle settling velocities observed. This behavior was observed when testing the Fernald simulant at three different concentrations (5%, 25%, and 40%).
- The three simulants follow a similar settling rate behavior. This behavior can be explained as a combination of one or more decreasing exponential curves. This means that the particle settling rate of the simulants decreases exponentially as time increases.
- As expected, no major variations occurred on the simulants' density when mixing tests were performed for a period of time. At 5 wt% concentration the density range is from 1.00 to 1.10 g/cm^3 in all simulants. For the Fernald simulant, which was also tested at 25 wt% and 40 wt% concentrations, the density range at those concentrations was from 1.10 to 1.15 g/cm^3 and from 1.15 to 1.20 g/cm^3, respectively.
- The pH range for the three simulants was from 8 to 13 at all concentrations. The SRS simulant showed the highest pH, around 12; the other two simulants, Hanford and Fernald, had about the same pH range, from 8 to 9.
- The pH behavior as the mixing time and/or mixing strength increased was linear for the three surrogates at 5 wt% concentration. This means that no major changes occurred to the simulants' pH after mixing them for a certain period of time at a certain mixing strength. However, when testing the Fernald simulant at 25 wt% and 40 wt% concentrations, a slight increase in pH was observed as mixing time increased. This phenomenon was similar at two different mixing speeds (400 RPM and 750 RPM). Figure 4.2.3.1 shows this trend.
- No significant variations were observed on the simulants' solubility at all concentrations, as mixing time and/or mixing strength increased. When comparing solubility of the three simulants at the same concentration (5 wt%), SRS simulant showed higher solubility, followed by the Hanford simulant and the Fernald simulant, in that order (Figure 4.2.4.1).

5.0 ACTIVITIES PLANNED FOR FY99

A project technical plan (PTP) for FY99 was created. Its main purpose is to serve as a guide for further work to be performed at FIU-HCET in fiscal year 1999. Although the overall objectives described in the PTP are similar to the ones explained in this report, the following specific tasks were added to complete and complement the work performed this year:

- Measure simulants particle size distributions in different layers at various pH.
- Determine simulants particle shapes at different mixing strengths.
- Characterize solid particle solubility and crystallization behaviors at different pH and temperatures.
- Measure surrogates particle settling velocity at various pH.
- Measure slurry viscosity at various pH and temperatures.

A detailed plan for each task is included in the PTP for FY99.

6.0 REFERENCES

Mao, F., Desir, F.K., and Ebadian, M.A., 1997, "Pressure Drop Measurement and Correlation for Three-Phase Flow of Simulated Nuclear Waste in a Horizontal Pipe," *International Journal of Multiphase Flow*, Vol. 23, No. 2, pp.397-402.

Landon, L.F., 1994, *Task Assignment Rheology Control-DWPF Melter Feed Preparation Processes*, WSRC-RP-92-1421, Rev. 1, Westinghouse Savannah River Technology Center, Aiken, SC.

Mao, F. and Ebadian, M.A., 1997, *Rheology Properties of Defense Waste Processing Facility (DWPF) Melter Feeds, FY96 Year-End Report*, Hemispheric Center for Environmental Technology, Miami.

Marek, J.C., 1995, "*Rheological Properties of Simulated SRS Vitrification Feeds*," Presented at the I&EC Special Symposium, American Chemical Society, Atlanta, GA, September 17-20.

McKay, R.L., Call, C.J., and Daymo, E.A., May 1994, "*Letter Report for Westinghouse Hanford Company on TWRS Retrieval Technology Project Slurry Transport-Plugging Investigation,*" Pacific Northwest Laboratory, Richland, Washington.

Motyka, T., April 1984, "*Technical Data Summary for In-tank Sludge Processing.*" DOE Defense Waste Processing and Naval Fuels.

Gandhi, Ramesh L., "*Effect of the Rheological Properties of Fines Fraction on Slurry Hydraulics,*" Bechtel Inc., San Francisco, CA.

Ruppel, F.R., and Hicks, J.S., September 1992, "*Preliminary Investigation of Suspended Solids Monitors and Supernate/Sludge Interference Level Monitors for DOE Radioactive Slurries,*" Instrumentation and Control Division, Oak Ridge National Laboratory.

APPENDIX

RHEOGRAMS FOR SLURRY SIMULANTS SAMPLES

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Figure 19. Viscosity Rheogram for 40 wt%. Fernald Simulant. Equation for the Bingham Model: $\tau = \tau_o + \eta(du/dy) = 1725 + 30.89(du/dy)$. .....Appendix 12

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Figure 24. Viscosity Rheogram for 5 wt%. Fernald Simulant. Equation for the Newtonian Model: $\tau = \eta(du/dy) = 4.312(du/dy)$. .....Appendix 14

Figure 25. Viscosity Rheogram for 5 wt%. SRS Simulant. Equation for the Bingham Model: $\tau = \tau_o + \eta(du/dy) = 42.93 + 6.188(du/dy)$. .....Appendix 15

Figure 26. Viscosity Rheogram for 5 wt%. SRS Simulant. Equation for the Bingham Model: $\tau = \tau_o + \eta(du/dy) = 46.89 + 6.335(du/dy)$. .....Appendix 15

Figure 27. Viscosity Rheogram for 5 wt%. SRS Simulant. Equation for the Bingham Model: $\tau = \tau_o + \eta(du/dy) = 31.46 + 6.181(du/dy)$. .....Appendix 16

Figure 28. Viscosity Rheogram for 5 wt%. SRS Simulant. Equation for the Bingham Model: $\tau = \tau_o + \eta(du/dy) = 26.97 + 6.321(du/dy)$. .....Appendix 16

Figure 29. Viscosity Rheogram for 5 wt%. Hanford Simulant. Equation for the Bingham Model: $\tau = \tau_o + \eta(du/dy) = 220.9 + 7.199(du/dy)$. .....Appendix 17

Figure 30. Viscosity Rheogram for 5 wt%. Hanford Simulant. Equation for the Bingham Model: $\tau = \tau_o + \eta(du/dy) = 76.83 + 7.796(du/dy)$. .....Appendix 17

Figure 31. Viscosity Rheogram for 5 wt%. Hanford Simulant. Equation for the Bingham Model: $\tau = \tau_o + \eta(du/dy) = 91.26 + 7.544(du/dy)$. .....Appendix 18

Figure 32. Viscosity Rheogram for 5 wt%. Hanford Simulant. Equation for the Bingham Model: $\tau = \tau_o + \eta(du/dy) = 85.68 + 7.694(du/dy)$. .....Appendix 18

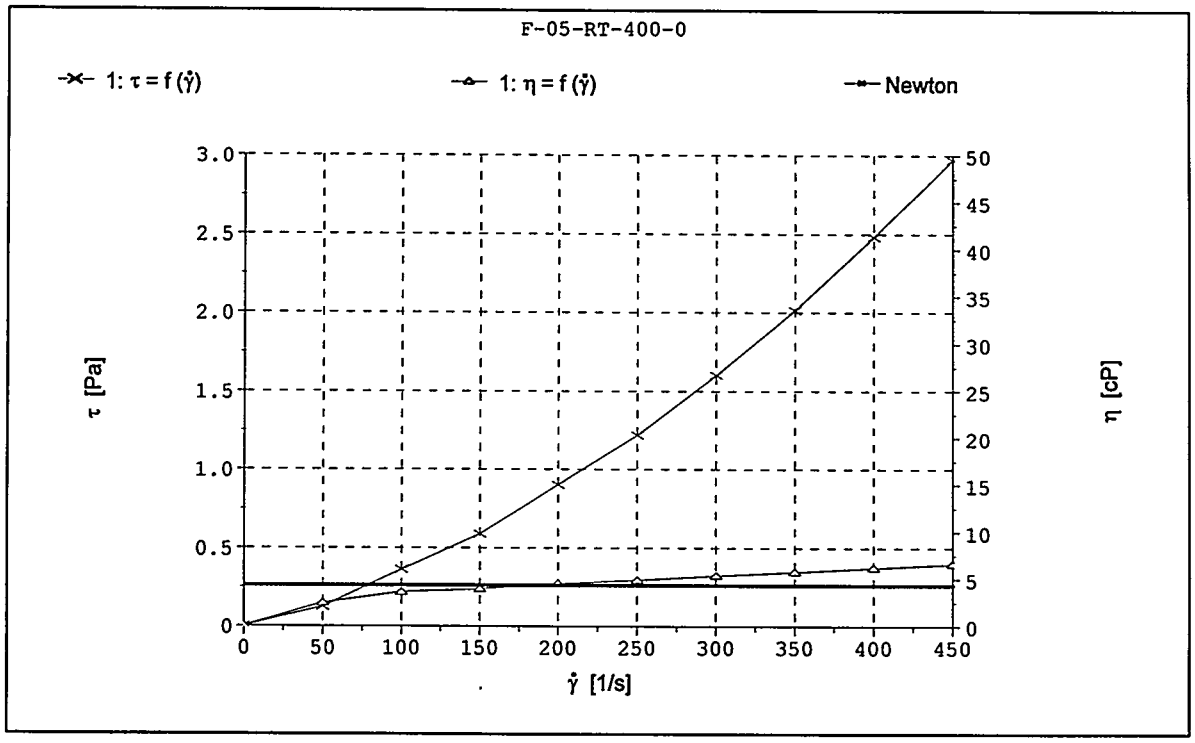


Figure 1. Viscosity Rheogram for 5 wt%. Fernald Simulant. Equation for the Newtonian Model: $\tau = \eta(du/dy) = 4.322(du/dy)$.

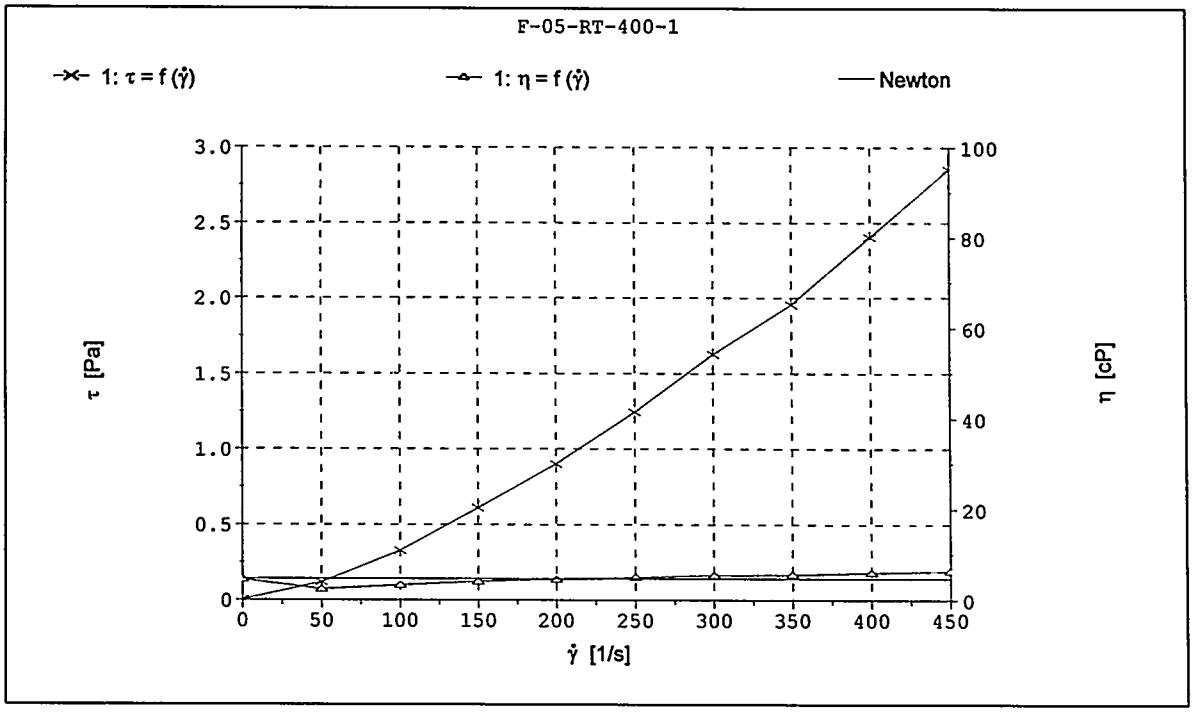


Figure 2. Viscosity Rheogram for 5 wt%. Fernald Simulant. Equation for the Newtonian Model: $\tau = \eta(du/dy) = 4.694(du/dy)$.

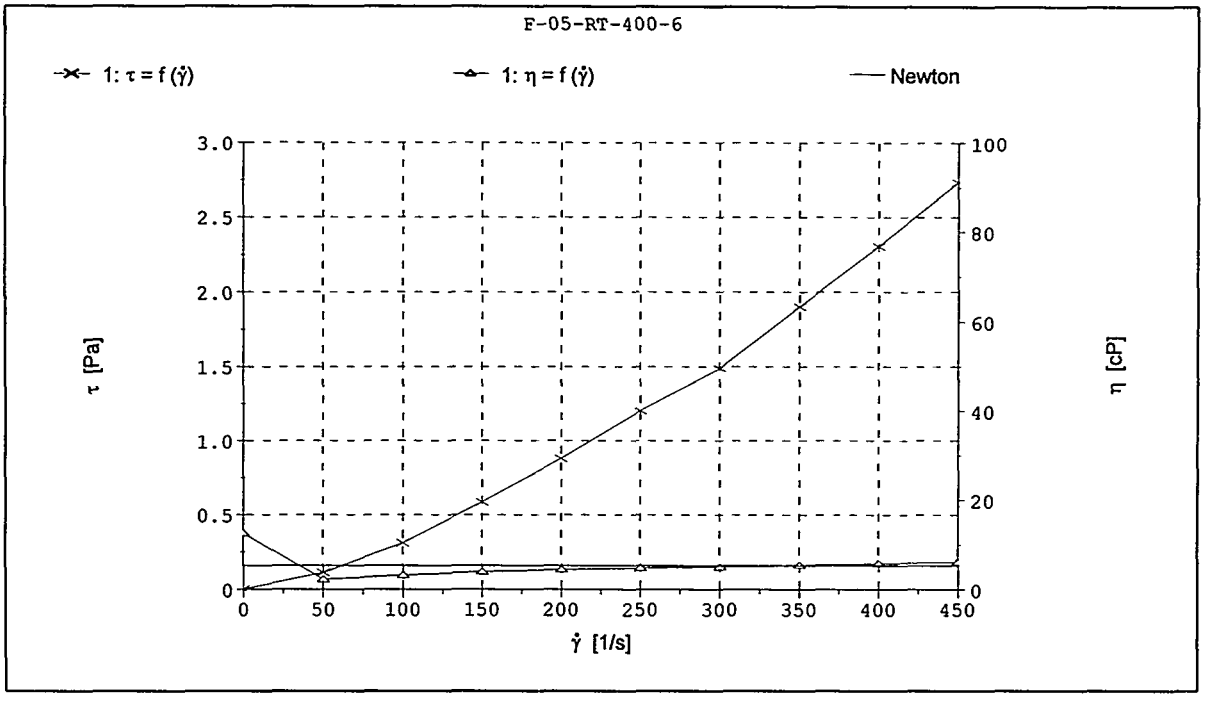


Figure 3. Viscosity Rheogram for 5 wt%. Fernald Simulant. Equation for the Newtonian Model: $\tau = \eta(du/dy) = 5.311(du/dy)$.

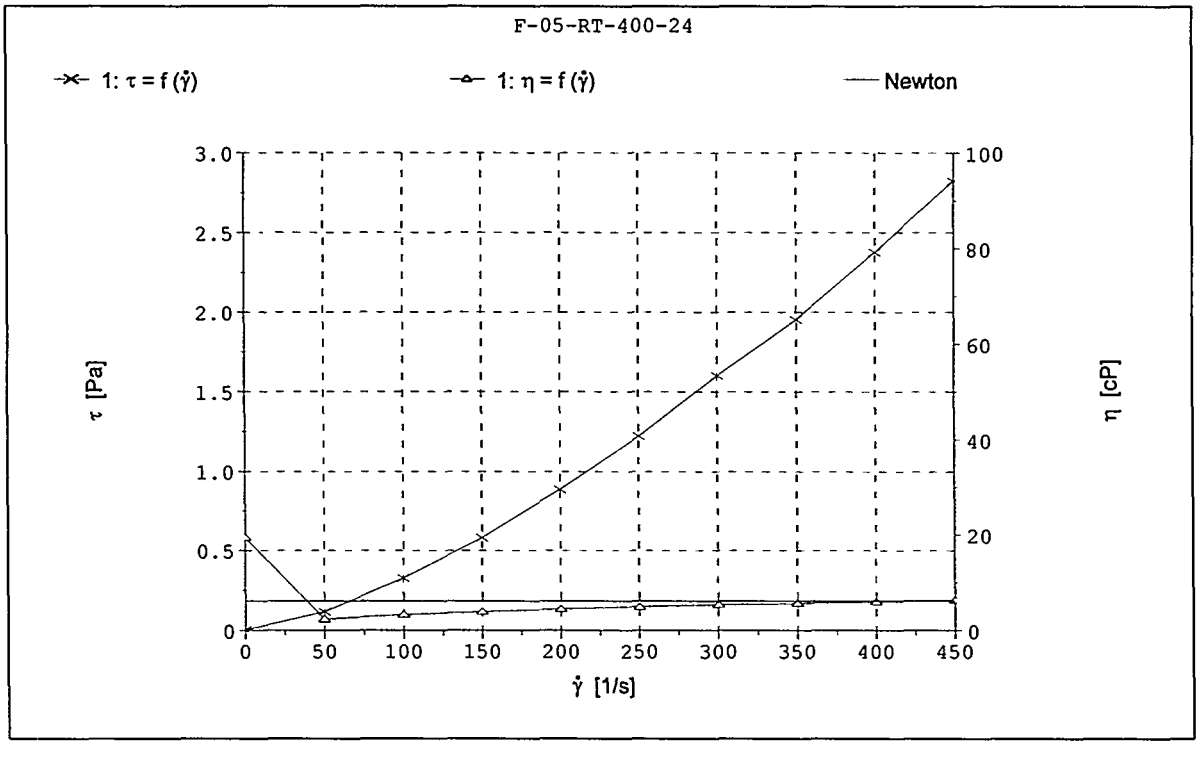


Figure 4. Viscosity Rheogram for 5 wt%. Fernald Simulant. Equation for the Newtonian Model: $\tau = \eta(du/dy) = 6.122(du/dy)$.

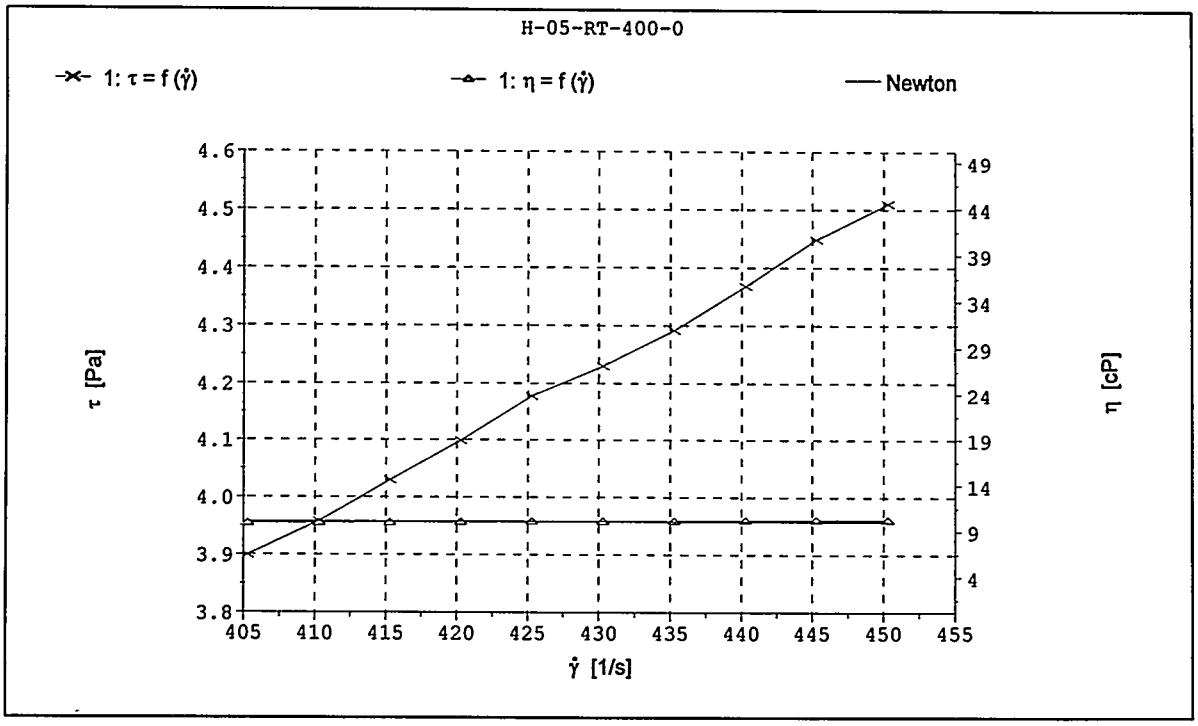


Figure 5. Viscosity Rheogram for 5 wt%. Hanford Simulant. Equation for the Newtonian Model: $\tau = \eta(du/dy) = 9.815(du/dy)$.

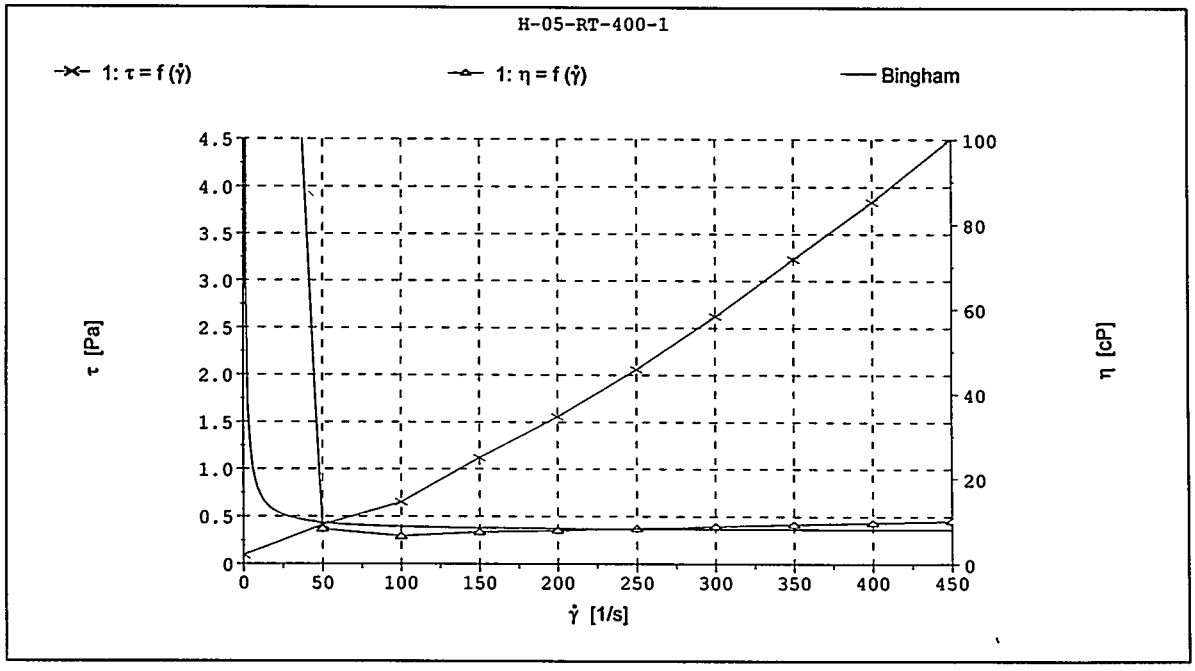


Figure 6. Viscosity Rheogram for 5 wt%. Hanford Simulant. Equation for the Bingham Model: $\tau = \tau_o + \eta(du/dy) = 90.13 + 7.836(du/dy)$.

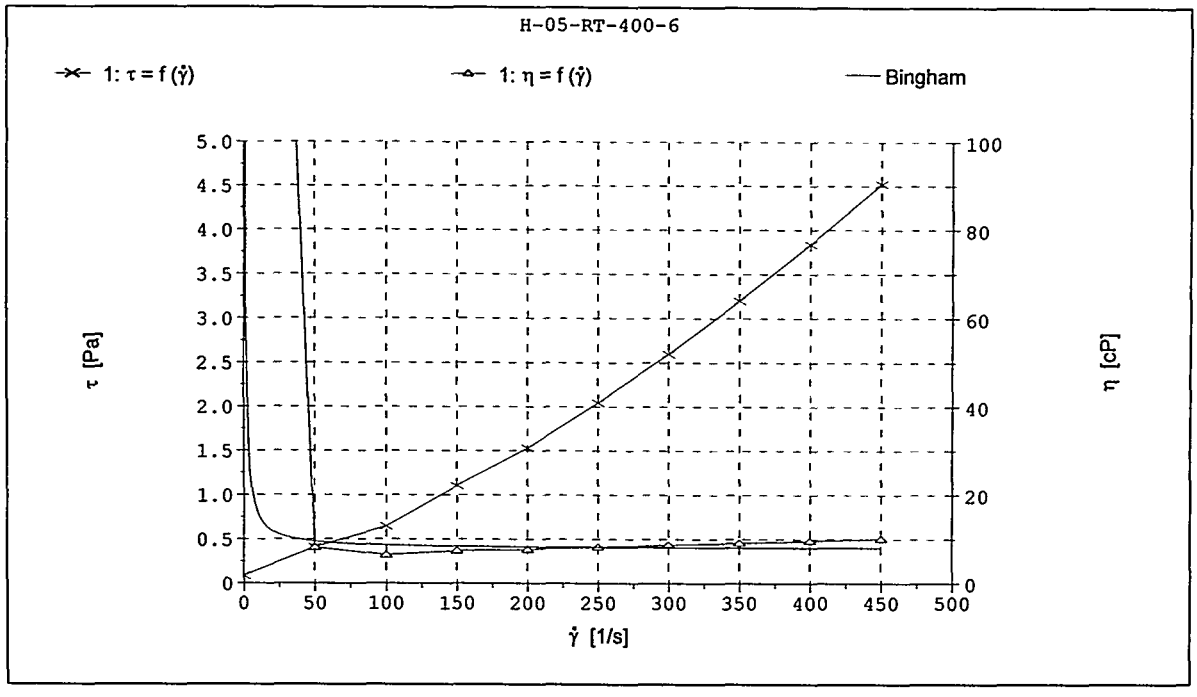


Figure 7. Viscosity Rheogram for 5 wt%. Hanford Simulant. Equation for the Bingham Model: $\tau = \tau_o + \eta(du/dy) = 80.32 + 7.836(du/dy)$.

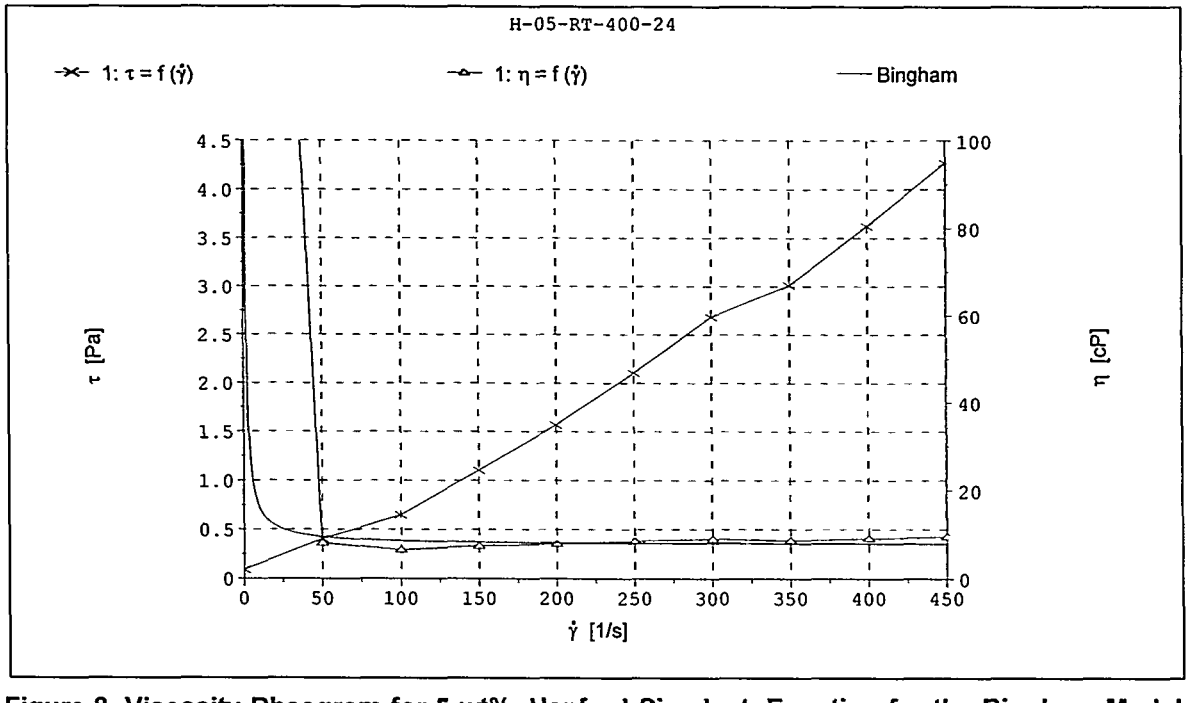


Figure 8. Viscosity Rheogram for 5 wt%. Hanford Simulant. Equation for the Bingham Model: $\tau = \tau_o + \eta(du/dy) = 85.68 + 7.694(du/dy)$.

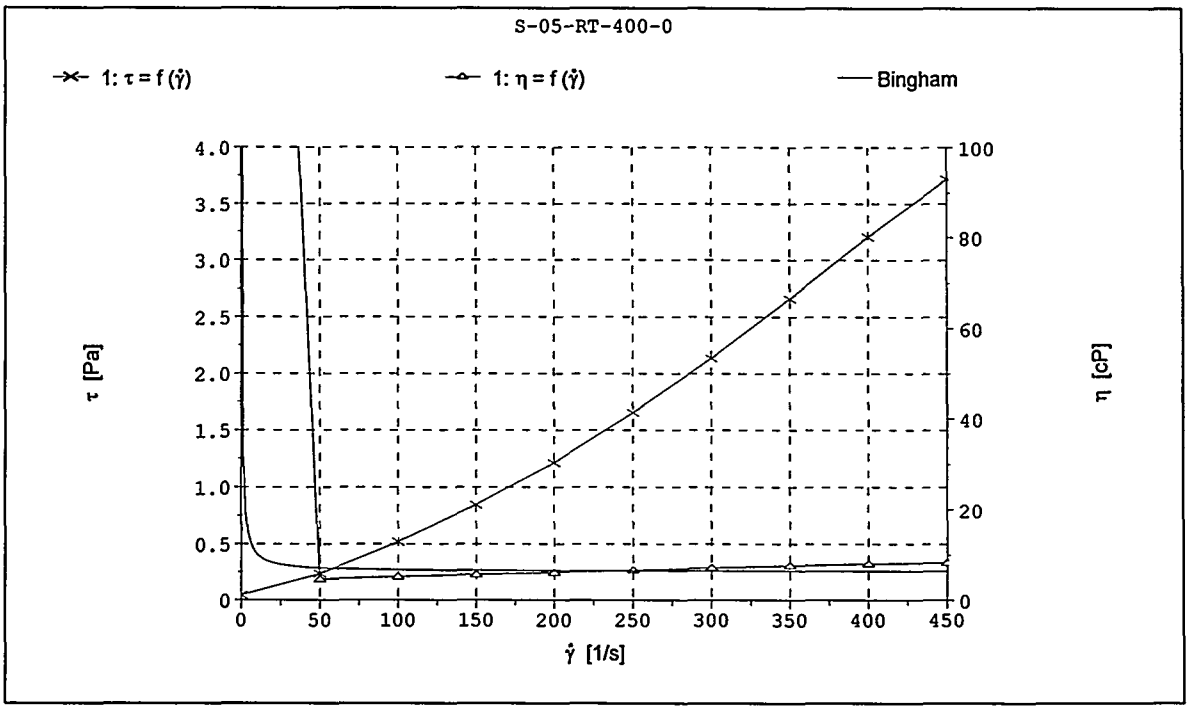


Figure 9. Viscosity Rheogram for 5 wt%. SRS Simulant. Equation for the Bingham Model: $\tau = \tau_o + \eta(du/dy) = 40 + 6.302(du/dy)$.

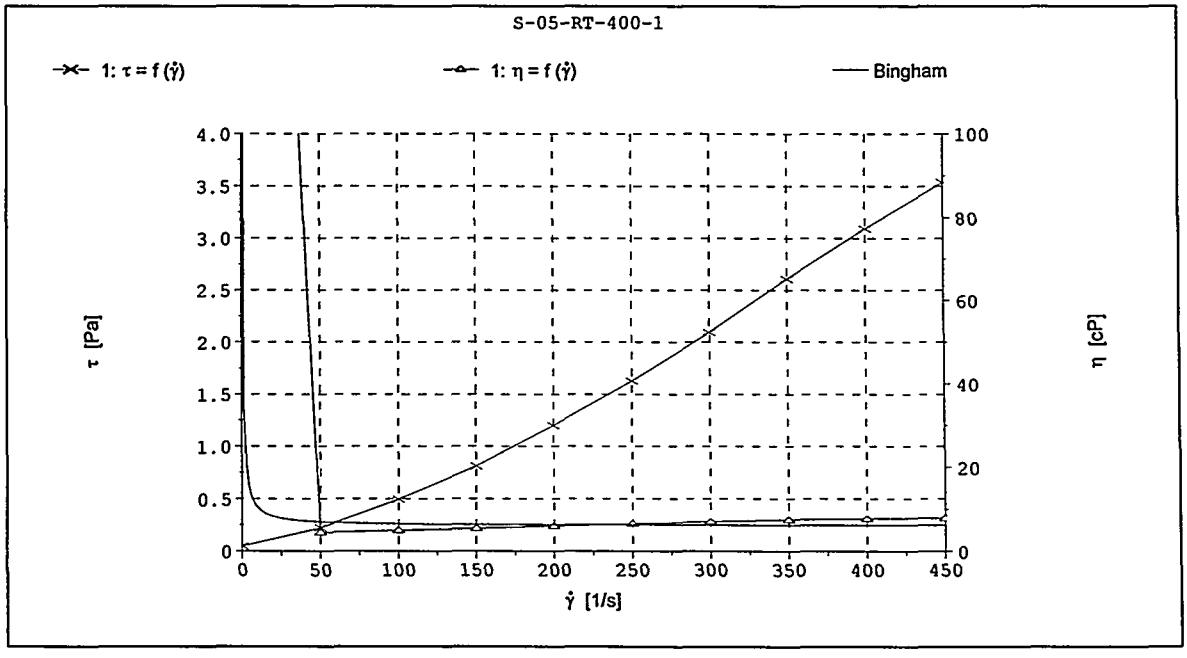


Figure 10. Viscosity Rheogram for 5 wt%. SRS Simulant. Equation for the Bingham Model: $\tau = \tau_o + \eta(du/dy) = 43.31 + 6.038(du/dy)$.

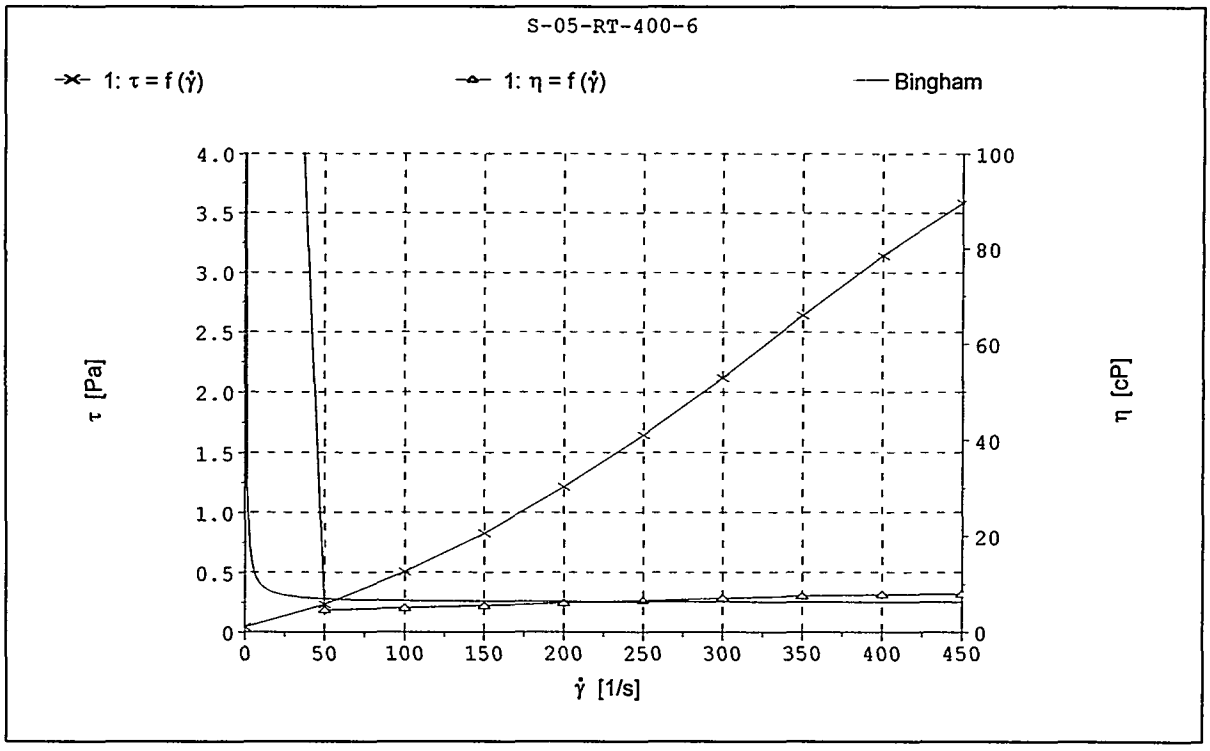


Figure 11. Viscosity Rheogram for 5 wt%. SRS Simulant. Equation for the Bingham Model: $\tau = \tau_o + \eta(du/dy) = 37.56 + 6.224(du/dy)$.

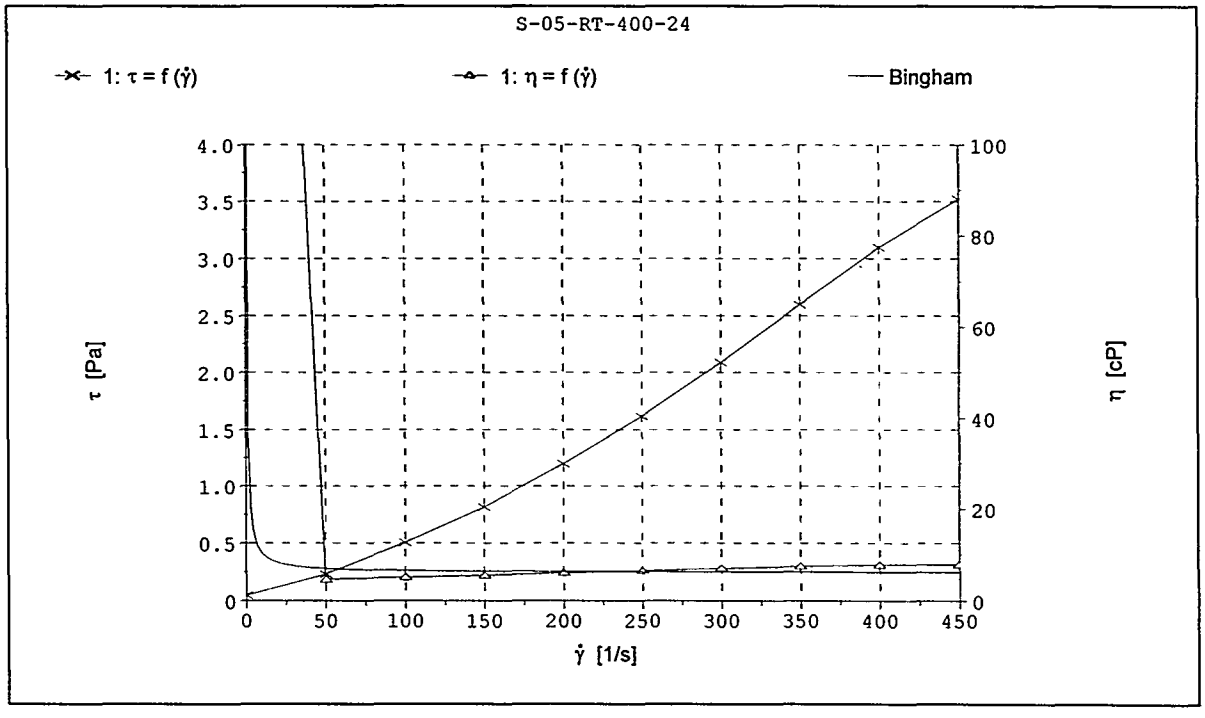


Figure 12. Viscosity Rheogram for 5 wt%. SRS Simulant. Equation for the Bingham Model: $\tau = \tau_o + \eta(du/dy) = 43.13 + 6.1(du/dy)$.

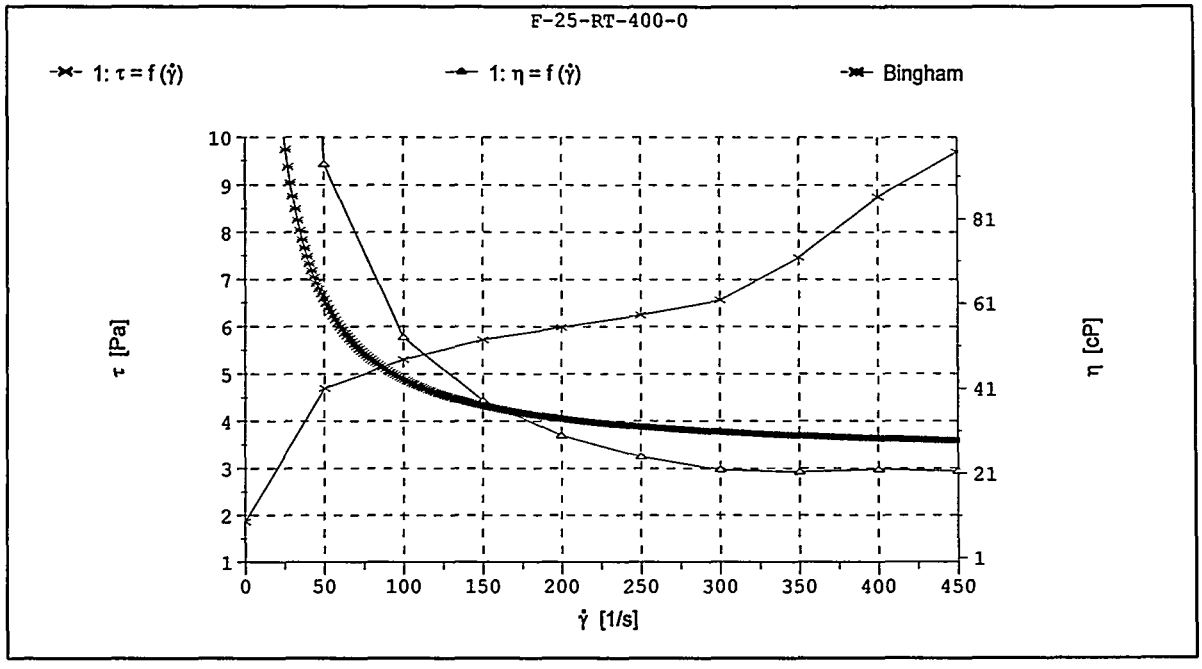


Figure 13. Viscosity Rheogram for 25 wt%. Fernald Simulant. Equation for the Bingham Model: $\tau = \tau_o + \eta(du/dy) = 1853 + 24.58(du/dy)$.

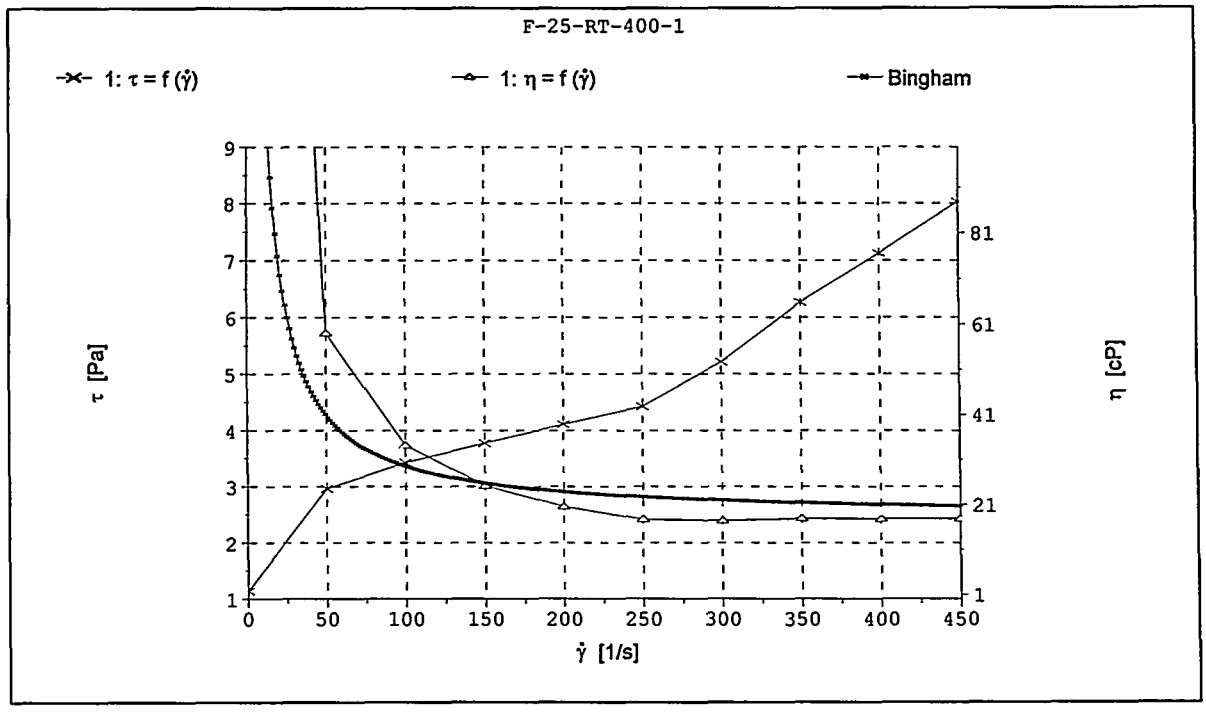


Figure 14. Viscosity Rheogram for 25 wt%. Fernald Simulant. Equation for the Bingham Model: $\tau = \tau_o + \eta(du/dy) = 1133 + 18.14(du/dy)$.

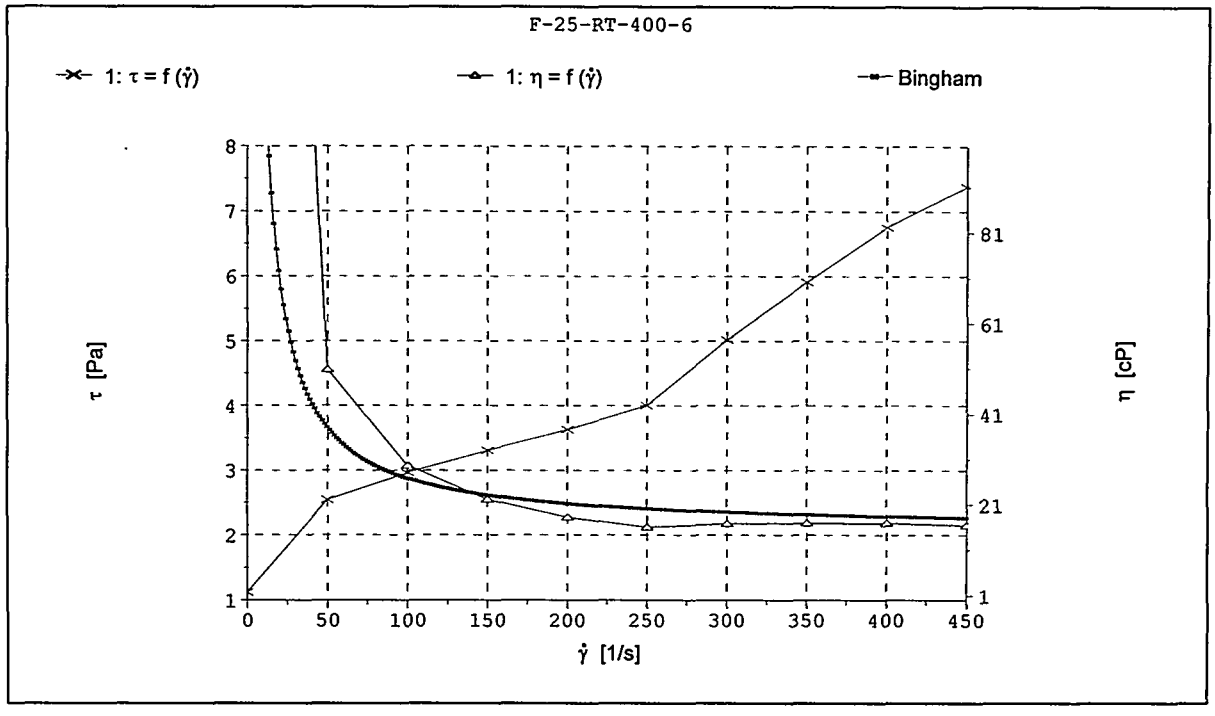


Figure 15. Viscosity Rheogram for 25 wt%. Fernald Simulant. Equation for the Bingham Model: $\tau = \tau_o + \eta(du/dy) = 1117 + 15.58(du/dy)$.

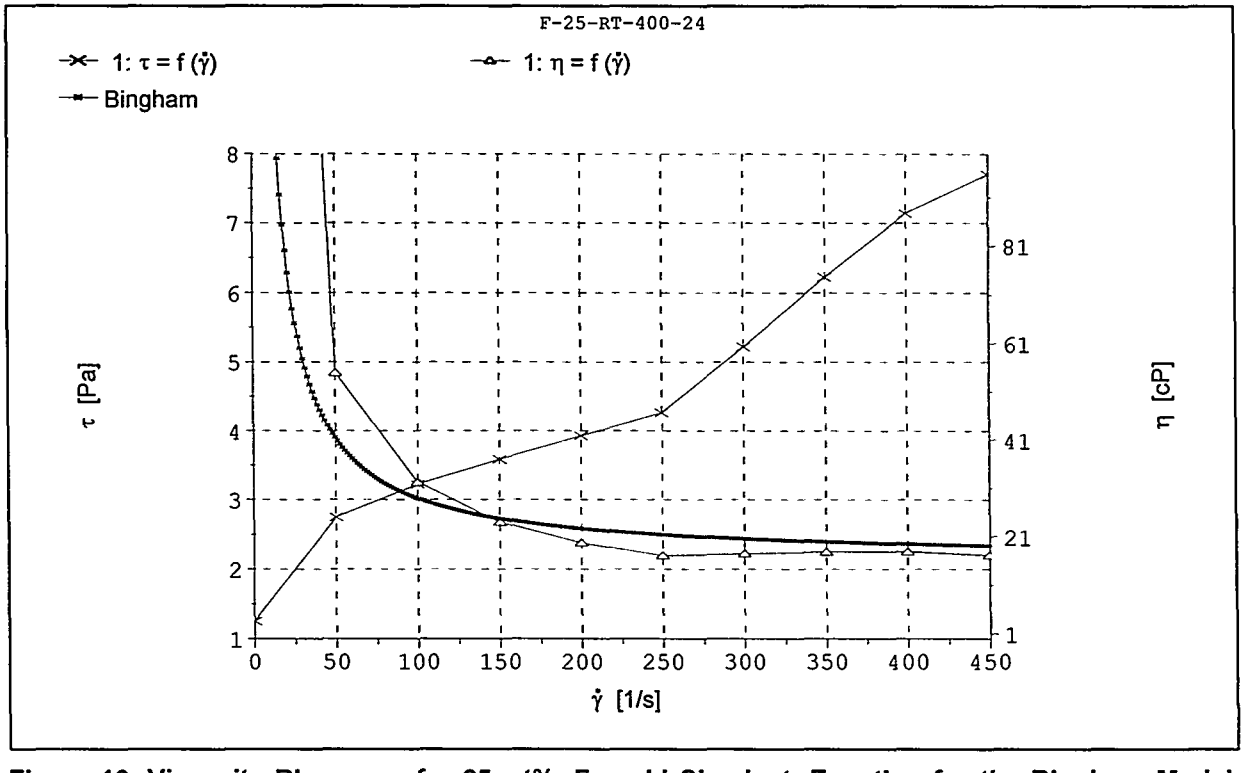


Figure 16. Viscosity Rheogram for 25 wt%. Fernald Simulant. Equation for the Bingham Model: $\tau = \tau_o + \eta(du/dy) = 1247 + 16.34(du/dy)$.

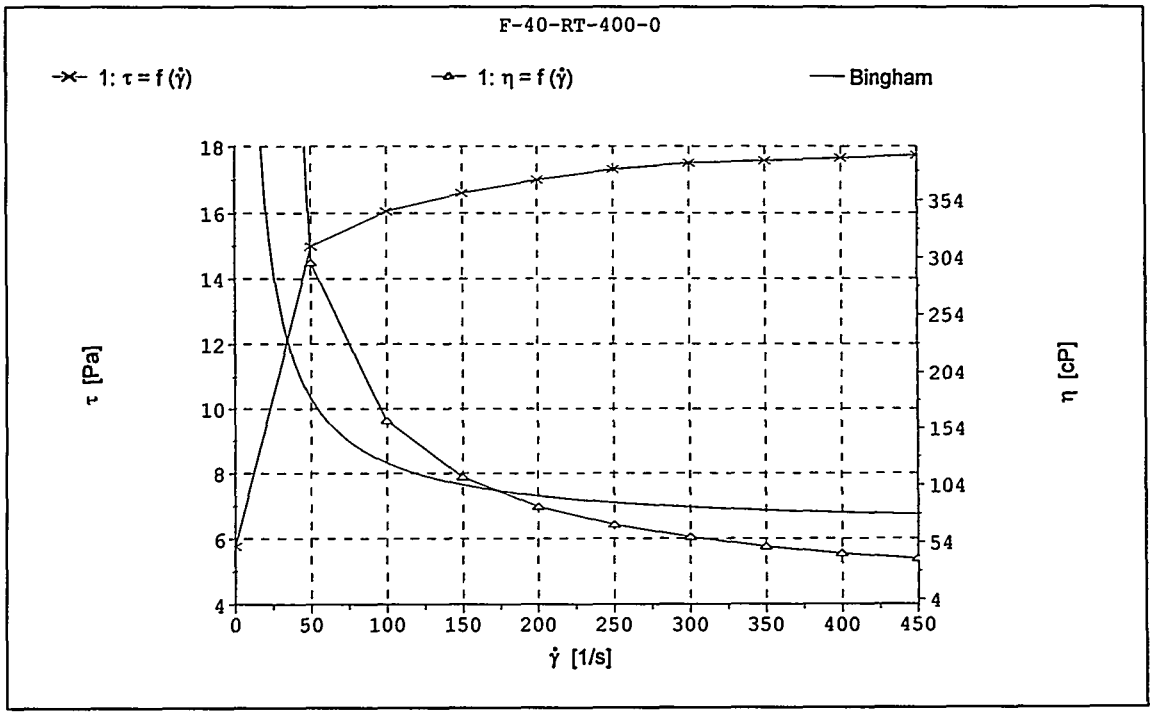


Figure 17. Viscosity Rheogram for 40 wt%. Fernald Simulant. Equation for the Bingham Model: $\tau = \tau_o + \eta(du/dy) = 5744 + 65.67(du/dy)$.

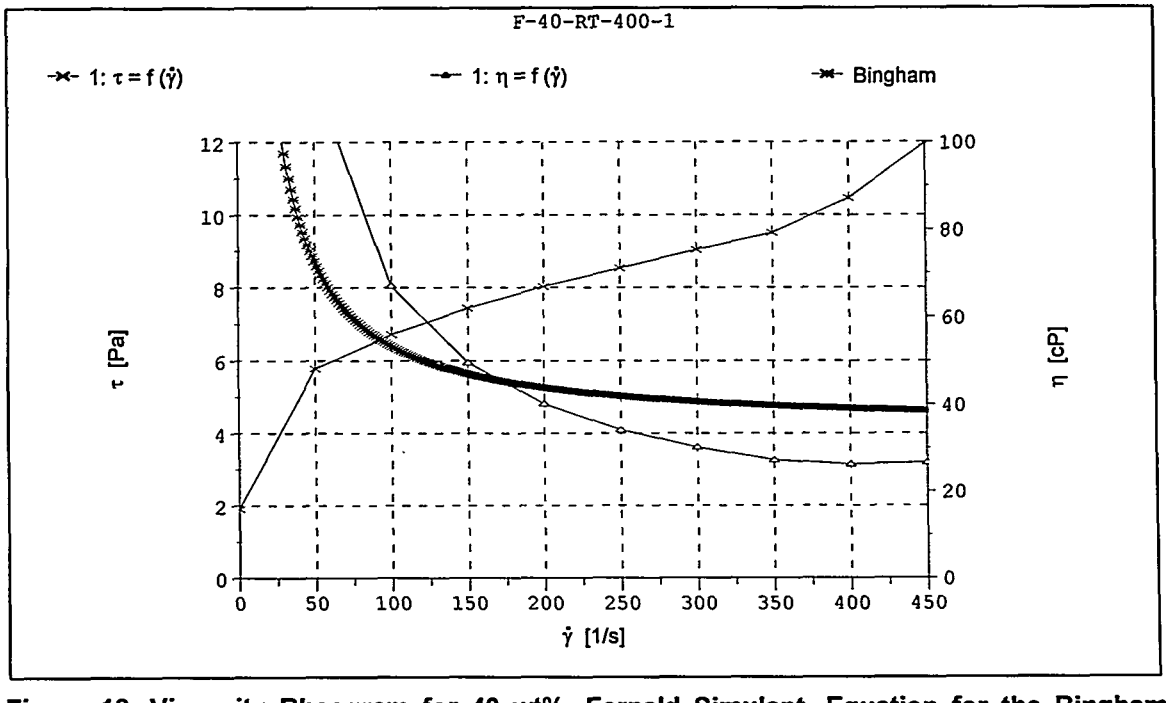


Figure 18. Viscosity Rheogram for 40 wt%. Fernald Simulant. Equation for the Bingham Model: $\tau = \tau_o + \eta(du/dy) = 1898 + 34.28(du/dy)$.

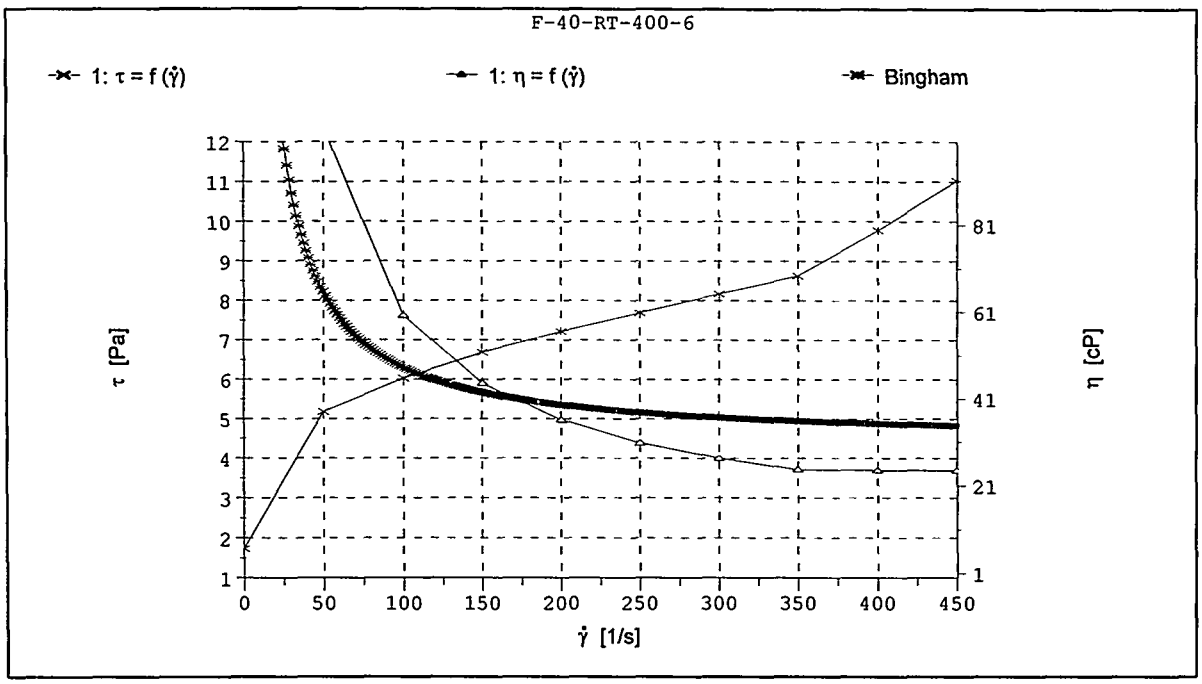


Figure 19. Viscosity Rheogram for 40 wt%. Fernald Simulant. Equation for the Bingham Model: $\tau = \tau_o + \eta(du/dy) = 1725 + 30.89(du/dy)$.

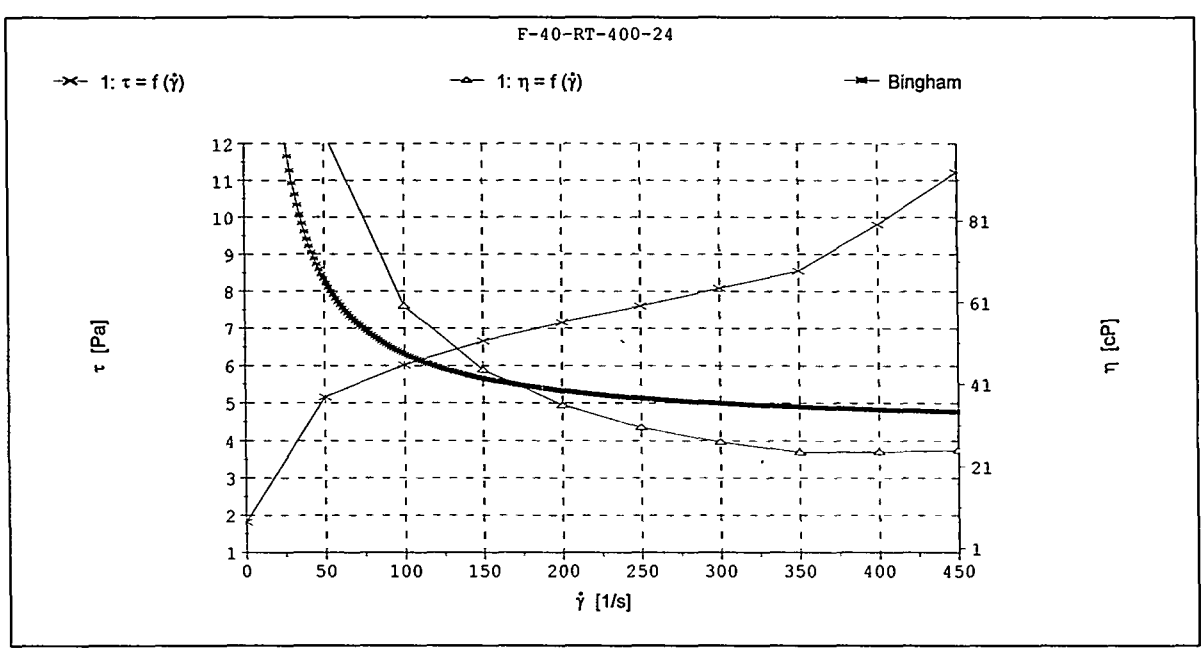


Figure 20. Viscosity Rheogram for 40 wt%. Fernald Simulant. Equation for the Bingham Model: $\tau = \tau_o + \eta(du/dy) = 1806 + 30.23(du/dy)$.

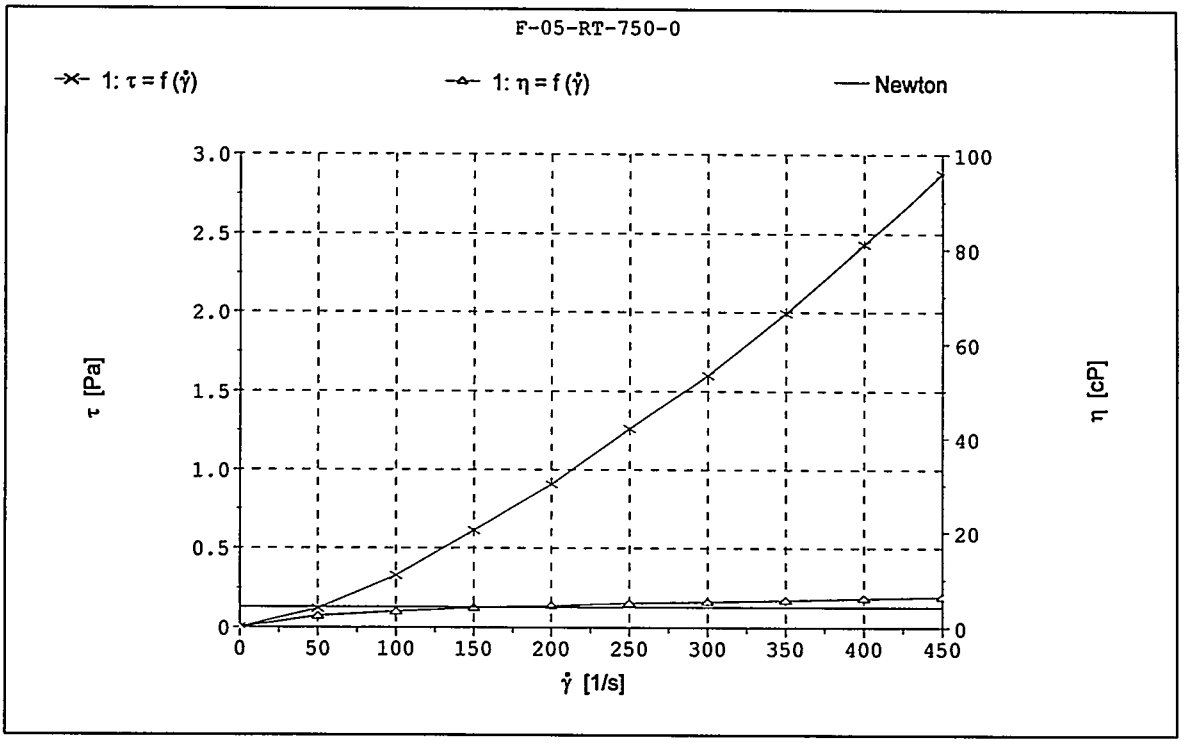


Figure 21. Viscosity Rheogram for 5 wt%. Fernald Simulant. Equation for the Newtonian Model: $\tau = \eta(du/dy) = 4.269(du/dy)$.

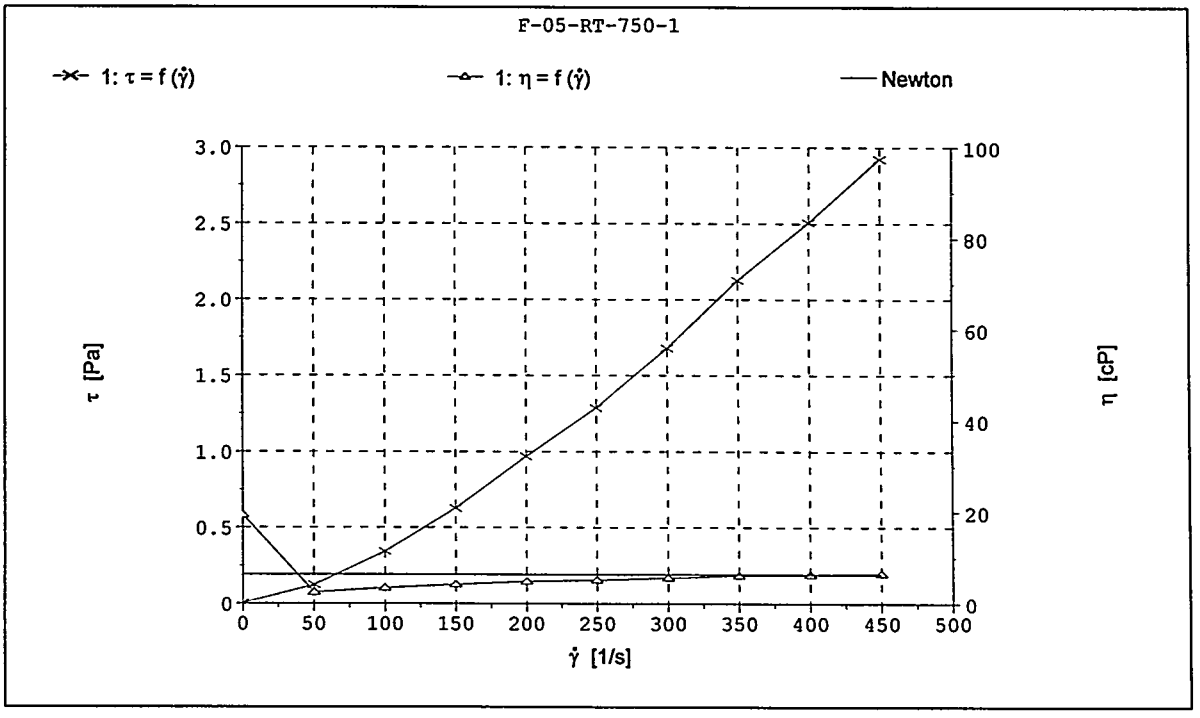


Figure 22. Viscosity Rheogram for 5 wt%. Fernald Simulant. Equation for the Newtonian Model: $\tau = \eta(du/dy) = 6.374(du/dy)$.

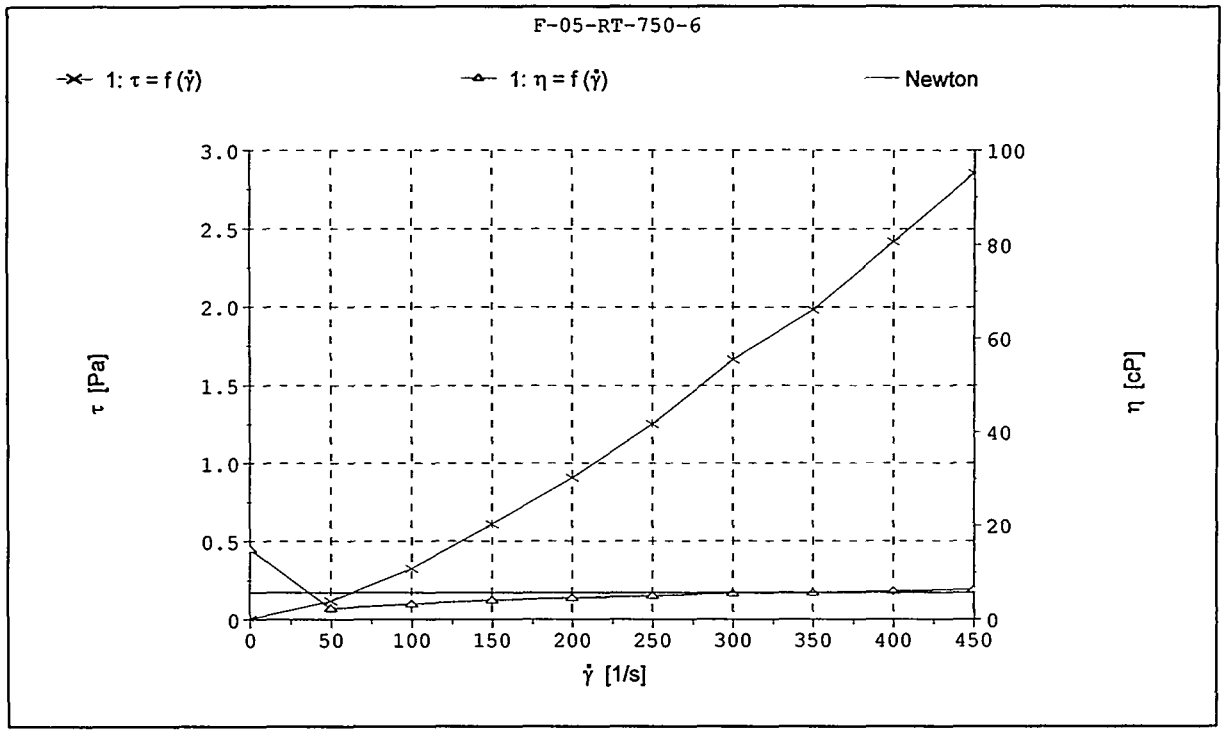


Figure 23. Viscosity Rheogram for 5 wt%. Fernald Simulant. Equation for the Newtonian Model: $\tau = \eta(du/dy) = 5.764(du/dy)$.

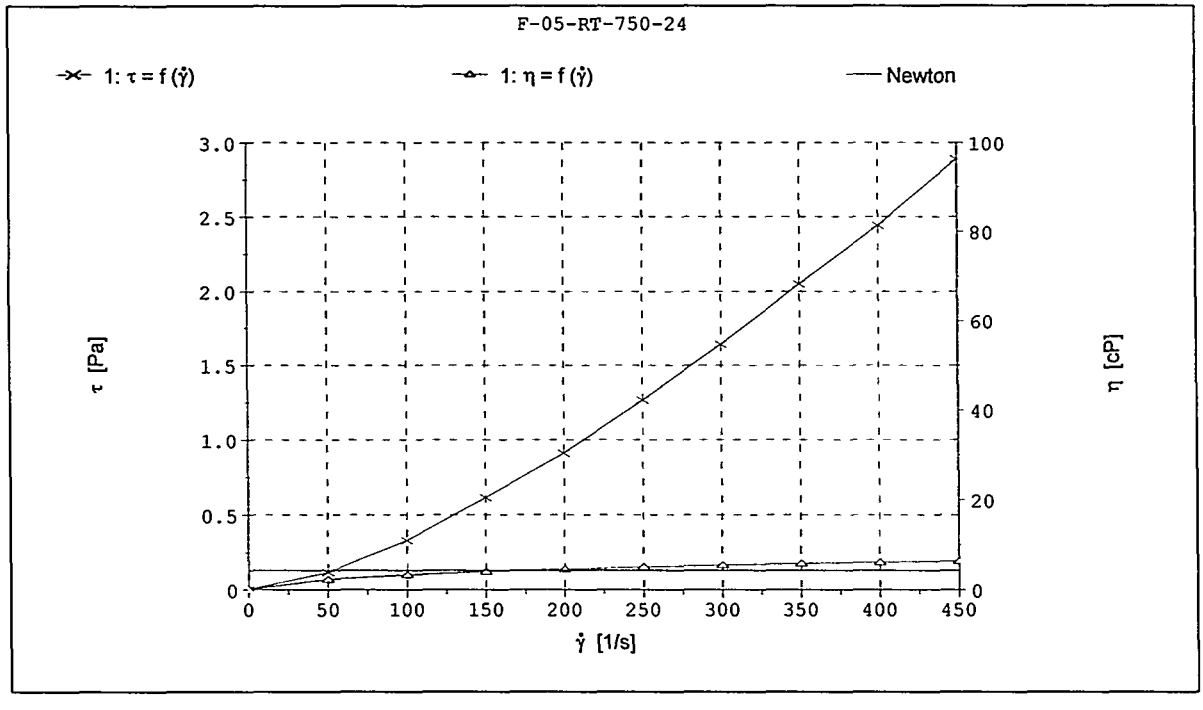
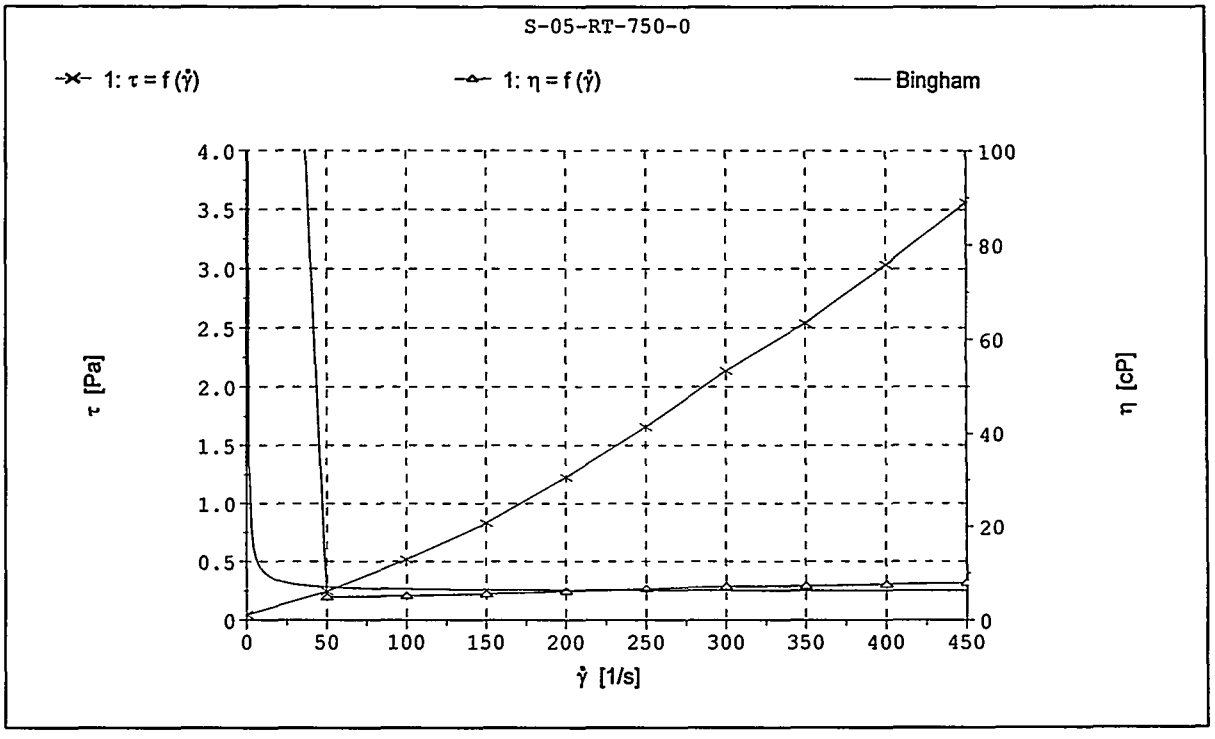


Figure 24. Viscosity Rheogram for 5 wt%. Fernald Simulant. Equation for the Newtonian Model: $\tau = \eta(du/dy) = 4.312(du/dy)$.



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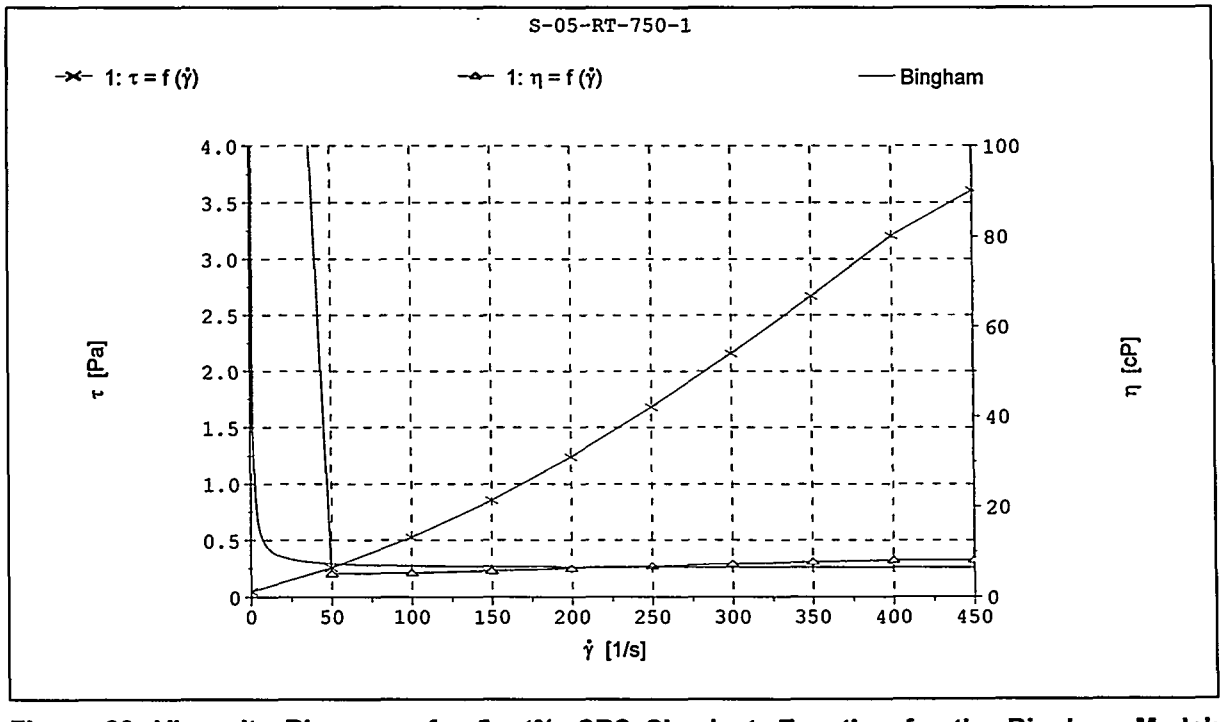

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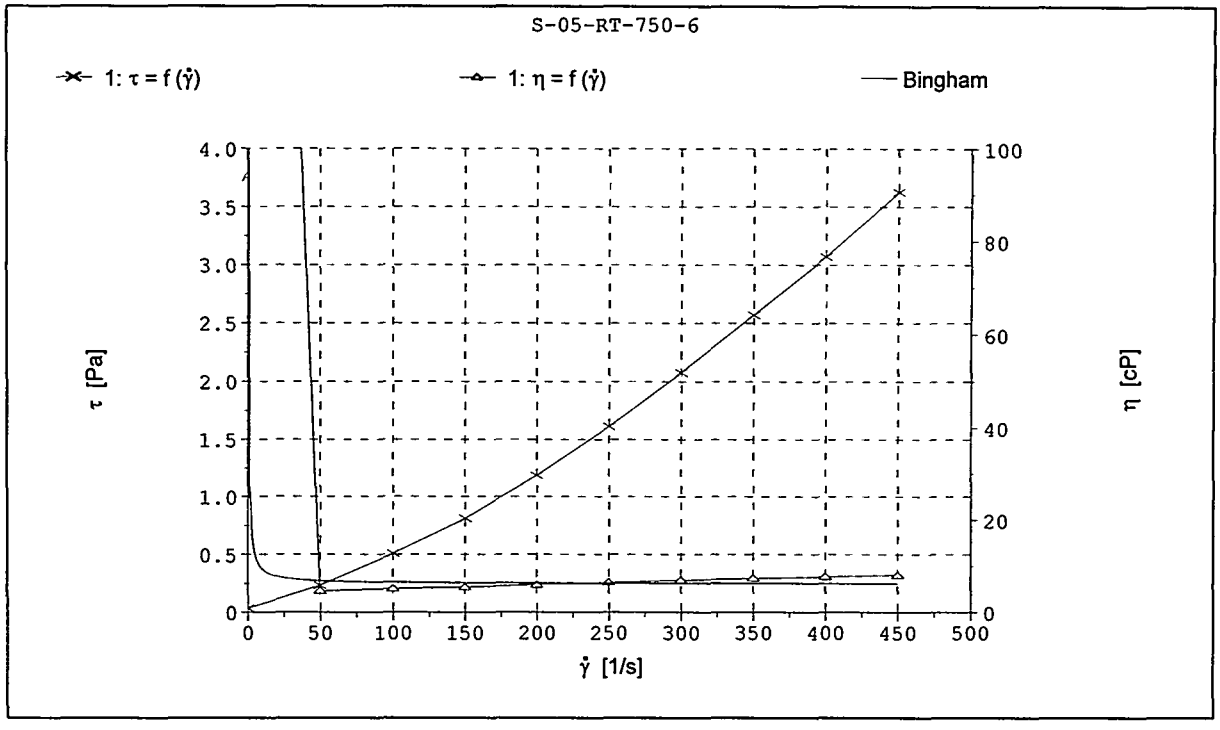

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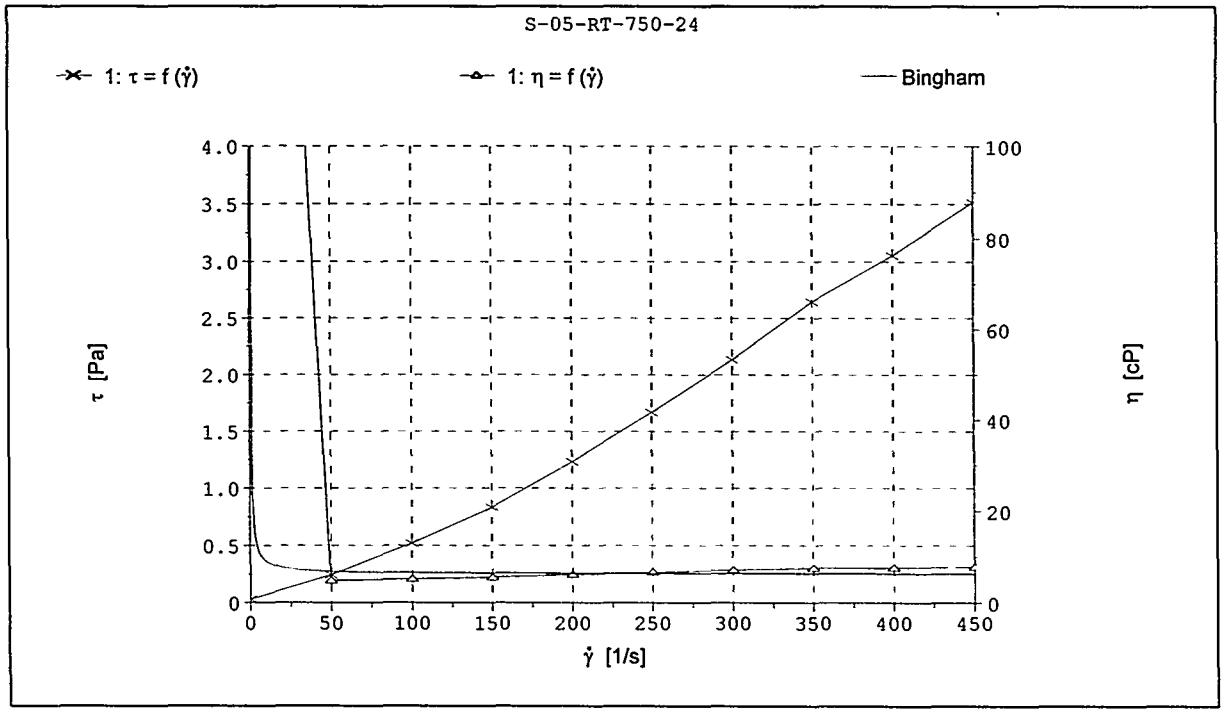

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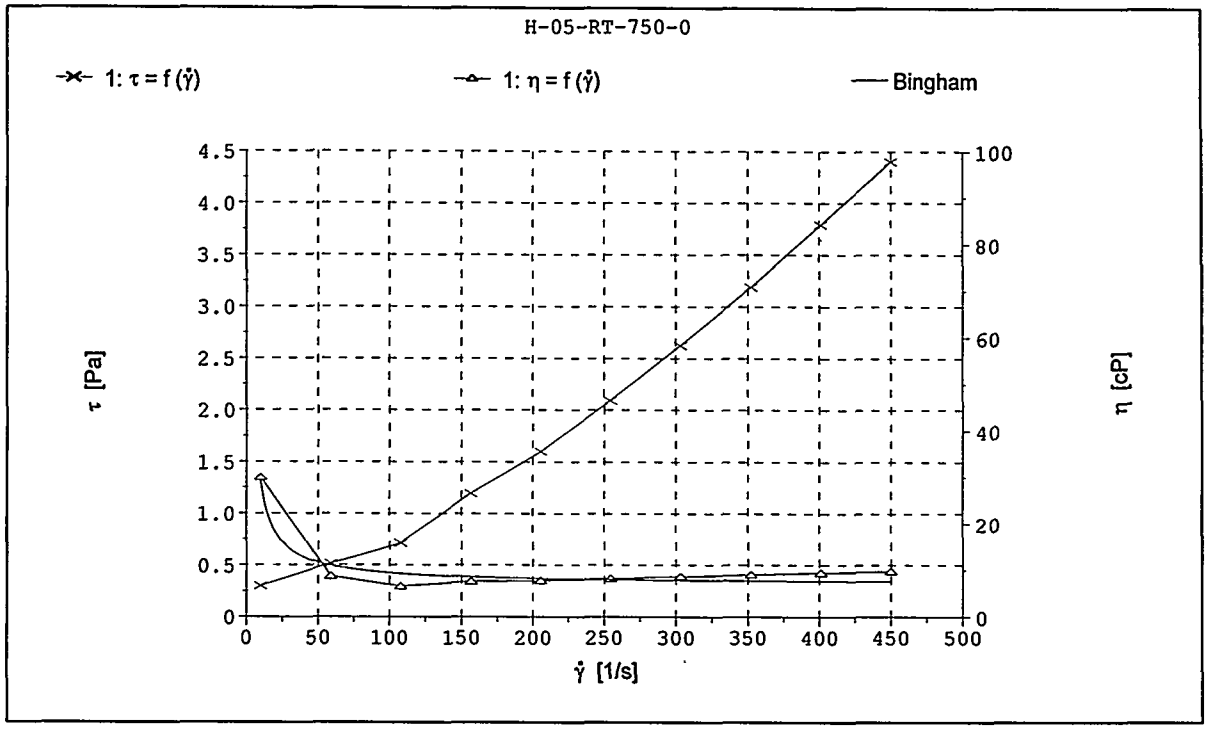
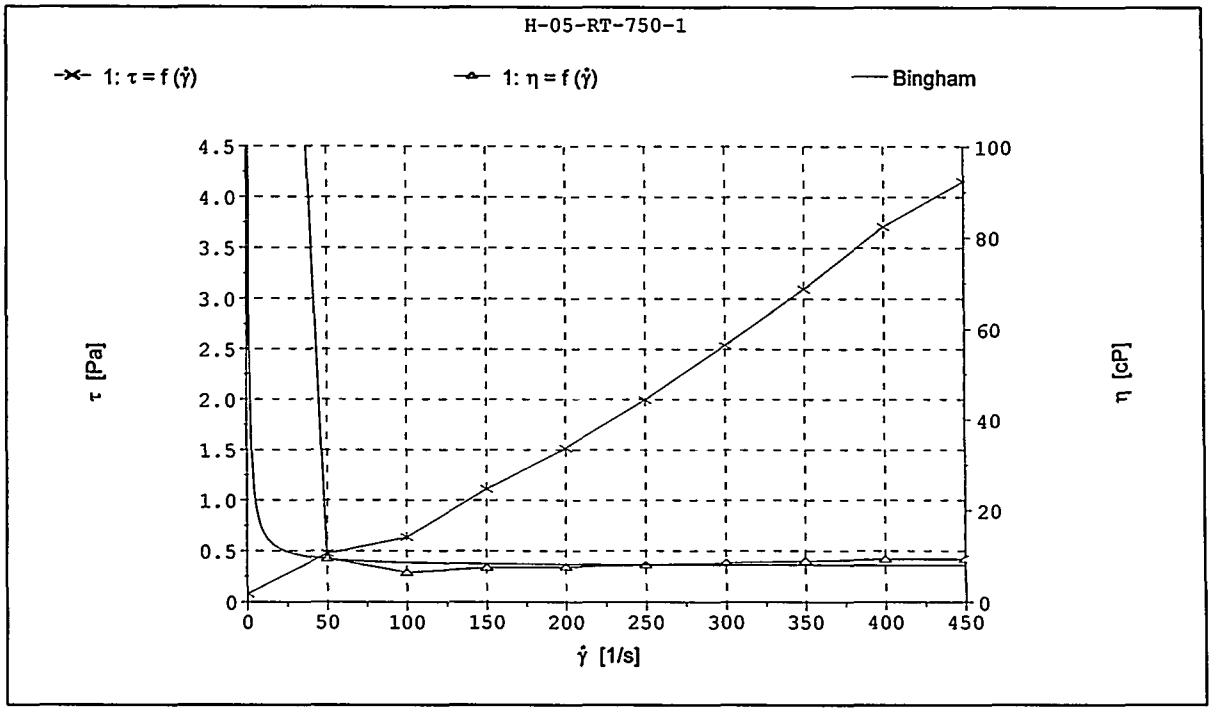


Figure 29. Viscosity Rheogram for 5 wt%. Hanford Simulant. Equation for the Bingham Model: $\tau = \tau_o + \eta(du/dy) = 220.9 + 7.199(du/dy)$.



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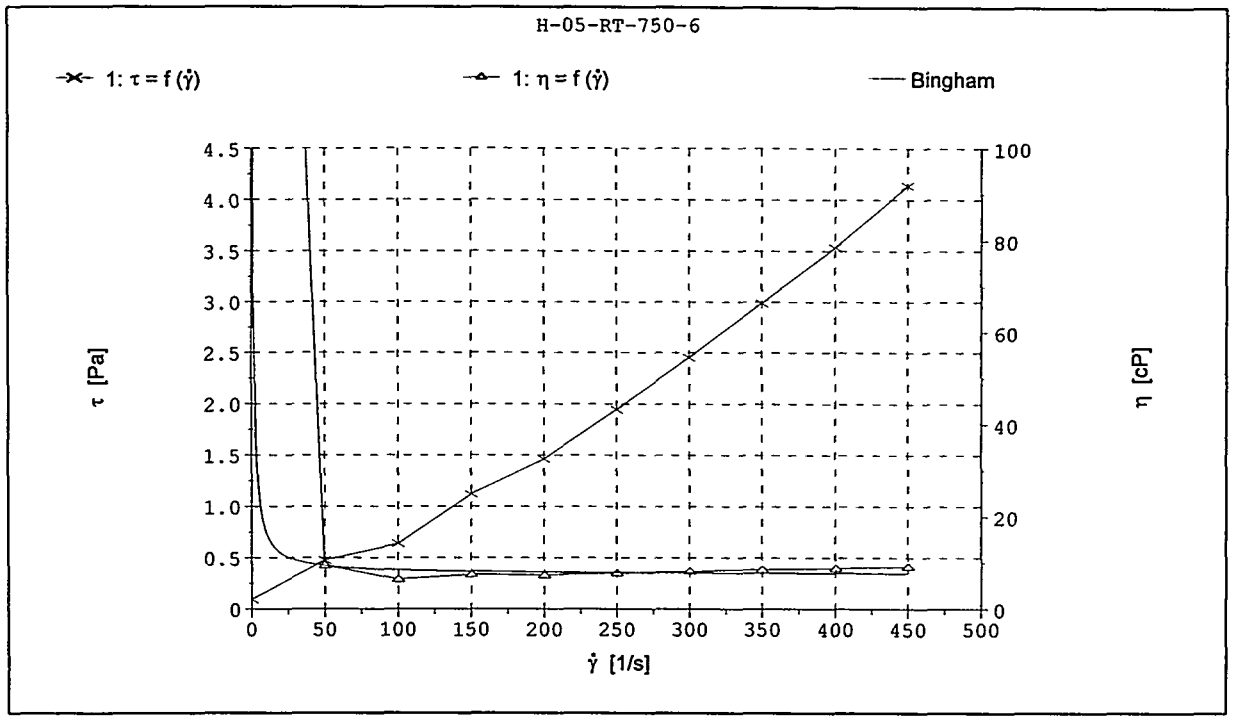

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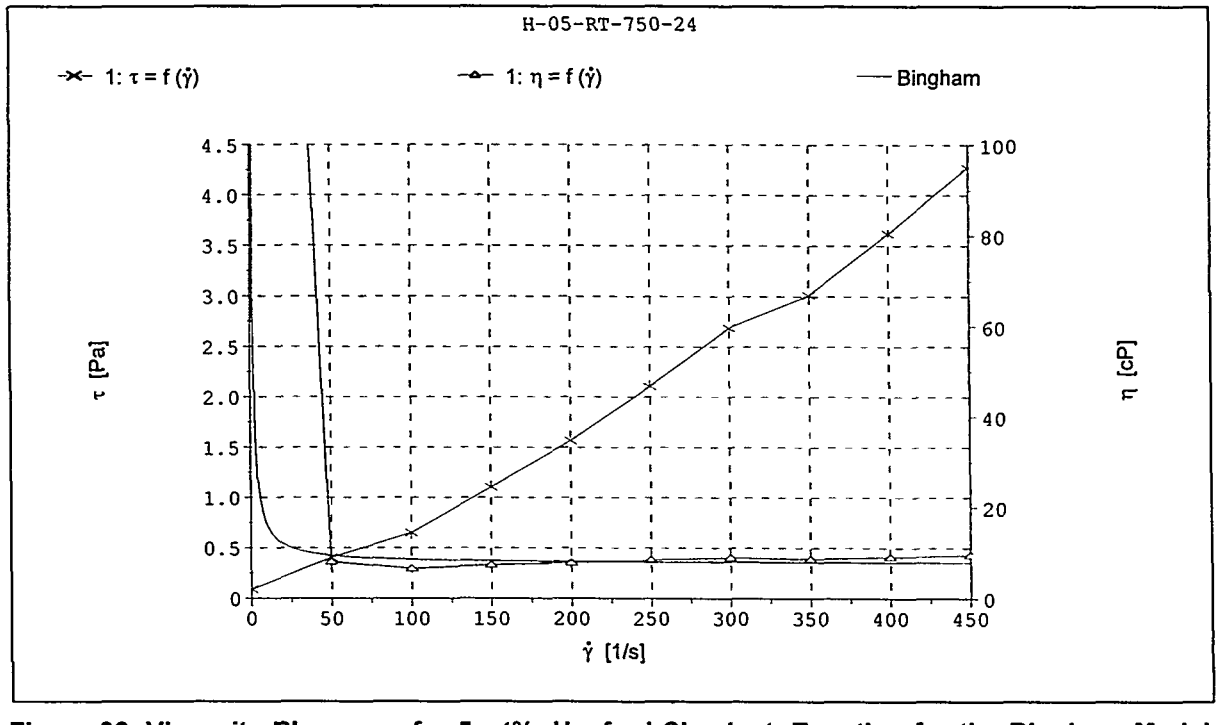

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