SRNL-STI-2009-00697
Revision 0

Keywords: *Melter Feed
Rheology Modifiers
Rheology*

Retention: *Permanent*

Summary of 2009 Rheology Modifier Program

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December 2009

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Prepared for the U.S. Department of Energy under
contract number DE-AC09-08SR22470.

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U.S. Department of Energy

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EXECUTIVE SUMMARY

The overall objective of the EM-31 Rheological Modifiers and Wetting Agents program is to utilize commercially available rheology modifiers to increase the solids fraction of radioactive sludge based waste streams, resulting in an increase in throughput and decreasing the overall processing time. The program first investigates the impact of rheology modifiers on slurry simulants and then utilizes the most effective rheology modifiers on radioactive slurries. The work presented in this document covers the initial investigation of rheology modifier testing with simulants. This task is supported by both the Savannah River National Laboratory (SRNL) and Pacific Northwest National Laboratory (PNNL).

The SRNL EM-31 task, for this year, was to investigate the use of rheology modifiers on simulant Defense Waste Processing Facility (DWPF) melter feeds. The task is to determine, based on the impact of the rheology modifier, if there are rheology modifiers that could reduce the water content of the slurry going to the DWPF melter, hence increasing the melt rate by decreasing the water loading. The rheology modifier in essence would allow a higher solids content slurry to have the same type of rheology or pumpability of a lower solids slurry. The modifiers selected in this report were determined based on previous modifiers used in high level waste melter feed simulants, on-going testing performed by counterparts at PNNL, and experiences gain through use of modifiers in other Department of Energy (DOE) processes such as grout processing. There were 12 rheology modifiers selected for testing, covering both organic and inorganic types and they were tested at four different concentrations for a given melter feed. Five different DWPF melter feeds were available and there was adequate material in one of the melter feeds to increase the solids concentration, resulting in a total of six simulants for testing. The mass of melter feed available in each simulant was not adequate for testing each rheology modifier, hence based on the changes in rheology for a given rheology modifier, rheology modifiers were either dropped or added between simulants. Three rheology modifiers were used on all simulants.

The results from this testing indicate that citric acid or polycarboxylate based rheology modifiers are the most effective in reducing the yield stress, by as much as 70% at the higher rheology modifier additions and were effective on most of the tested simulants. These rheology modifiers are organic, hence the can also be used as reductants in melter operations. The most effective non-organic rheology modifiers, sodium metasilicate reduced the yield stress by 10%.

It is recommended that both citric acid and commercially available polycarboxylate rheology modifiers be further investigated. Different molecular weight polycarboxylates and different types of polycarboxylates used in other industries must be considered. These polycarboxylates are extensively utilized in the cement, ceramic, and water treatment processes, hence readily available. Future work on DWPF melter feeds involving rheology modifiers should include, assuming the present method of processing sludge through DPWF does not change, is:

1. Investigate the use of polycarboxylate in various processes and procure polycarboxylates for testing. Limit rheology modifier selection and future testing between four and eight different types.
2. Test rheology modifiers on at least two different chemical types or bounding DWPF SME product simulants. Test to include the impact of boiling and the effectiveness in reducing water content via rheology versus weight percent curves.
3. Based on selected modifiers, perform testing on actual radioactive melter feed based on results from simulant testing.

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LIST OF ABBREVIATIONS

BPV	Bingham Plastic Viscosity
BPYS	Bingham Plastic Yield Stress
CPC	Chemical Processing Cell
DOE	Department of Energy
DWPF	Defense Waste Processing Facility
EM	Environmental Management
FY	Fiscal Year
GFC	Glass Former Chemicals
PNNL	Pacific Northwest National Laboratory
PUREX	Plutonium Uranium Extraction Process
RPP	River Protection Project-
SME	Slurry Mix Evaporator Tank
SMS	Sodium Meta-Silicate
SRAT	Sludge Receipt and Adjustment Tank
SRNL	Savannah River National Laboratory
SRS	Savannah River Site
SSS	Soluble Solids in the Supernate
THOREX	Thorium Extraction Process
TS	Total Solids
UDS	Undissolved Solids
Wt%	Weight Percent
WTP	Waste Treatment Plant

1.0 Introduction

The objective of the Department of Energy (DOE) Environmental Management (EM)-31 Support Program is to assist EM-30 in meeting its objectives or reducing risk of technical uncertainty in the DOE-EM cleanup missions. The work performed in this report supports the fiscal year (FY) 08 and FY09 objectives described in EM-30 project SR081201, "Rheology Modifiers and Wetting Agents".[1] One of the objectives was to determine what effect commercially available rheology modifiers have on the rheology of the simulant waste slurry feeds. At the Savannah River National Laboratory (SRNL), simulant melter feed used to support Defense Waste Processing Facility (DWPF) operations were selected, since the impact of the modifiers would potentially have the least downstream effects, if implemented at DWPF. The downstream impacts were not investigated in this report. It is expected that rheology modifiers will benefit DWPF by reducing the water content in the melter feed, hence increasing the overall solids and undissolved solids concentration going to the melter, increasing throughput, since less energy would be required to evaporate the available water. The pumpability and flowability of melter feed in the melter feed loop and natural spreading of melter feed in the melter is typically dominated by the yield stress of the fluid. For example, Figure 1-1 shows the benefit rheology modifiers could have on the rheology of a fluid where the process limit has a 20 Pascal yield stress. The addition of the rheology modifier increases the total solids concentration from 48.8 weight percent (wt%) to 52.1 wt%, hence delivering more solids for the same pressure drop (in feet of liquid) if the plastic viscosity is inconsequential. The rheology modifiers would be more beneficial if both the yield stress and plastic viscosity for a Bingham Plastic fluid are reduced.

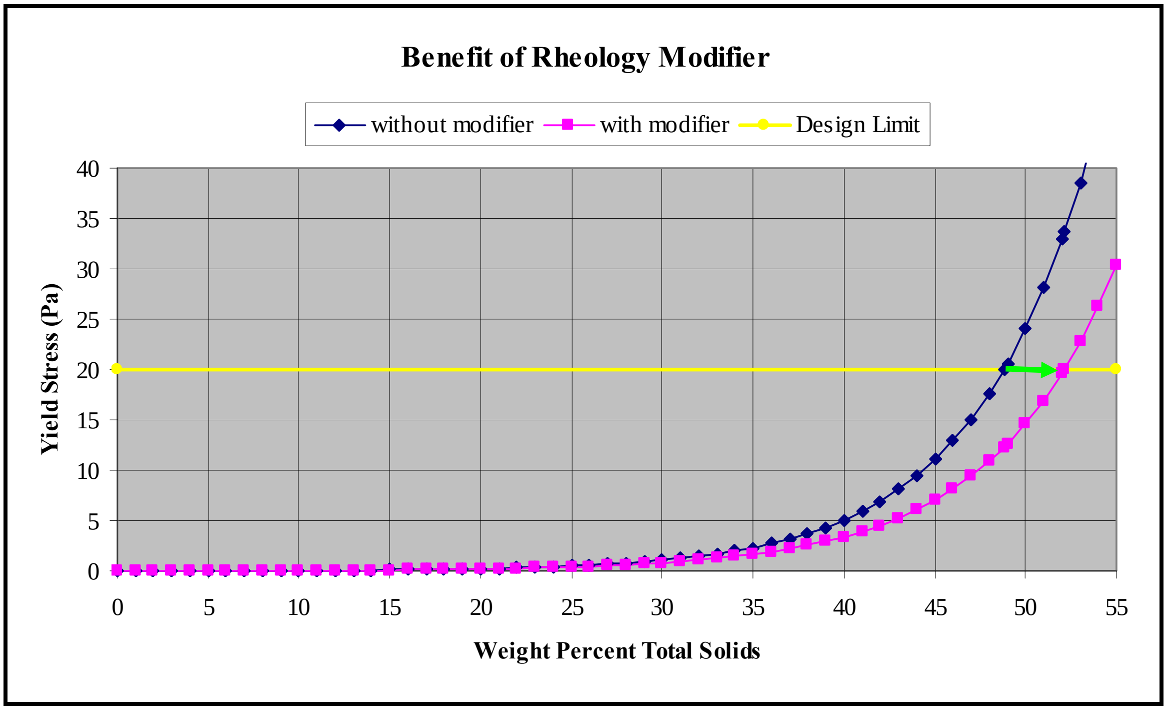


Figure 1-1 Beneficial Effect of Rheology Modifier on the Bingham Plastic Yield Stress

In this report, simulant DWPF melter feeds were obtained from testing used to support both the Chemical Processing Cell (CPC) and melt rate programs in the DWPF flow sheet. Multiple melter feed simulants from various sludge batch streams were tested at a single wt% solids concentration, due to the quantity of material available. Only one melter feed was tested at two different wt% solids, via decanting. The chemical compositions of the simulants are those reported to support the CPC/melt rate programs. The rheology, density, pH and complete solids analysis were performed on the baseline simulants prior to modifier addition. After modifier addition, only the rheology and pH were measured, due to sample quantity. The modifiers selected for testing were based on previous HLW modifier studies, experiences with other high undissolved solids (UDS) processes such as grout/ceramic, or from ongoing rheology modifier testing performed by PNNL. The underlying basis for why these modifiers are effective will not be described in this report. A test plan supporting this task performed at both SRNL and PNNL has been written.[2]

A brief history of rheology modifier utilized on either actual or simulant high level waste streams at the various DOE sites will also be discussed in this report. The previous work provided recommended modifiers that were studied in this task.

2.0 Previous Rheology Modifier Testing

The production of plutonium and tritium during the Cold War and specific radioisotopes for use in other government programs have generated radioactive waste slurries that are currently stored in waste tanks or have been immobilized in a borosilicate glass matrix using joule heated glass melters at various Department of Energy complexes. The West Valley Demonstration Project at West Valley, New York has completed its mission to safely immobilize the high level activity waste (HLW) stored in high level waste tanks by 2002.[3] This facility is now in the process of decontamination and decommissioning. At the Savannah River Site (SRS), four HLW sludge batches have been processed at the DWPF and a fifth sludge batch is being processed. Twelve additional HLW sludge batches are planned[4] for the complete removal of HLW from the SRS tank farms, by 2030. Vitrification facilities are planned as part of the Hanford River Protection Project-Waste Treatment Plant,(RPP-WTP) vitrifying both HLW and low activity waste streams. The vitrification plants are expected to start full operations in October 2018 and to complete processing the HLW by 2049.[5]

2.1 West Valley Experience

The HLW was the result from reprocessing spent nuclear fuel utilizing the plutonium uranium extraction (PUREX)[6] process. This HLW was blended with waste generated from the thorium extraction (THOREX) process, resulting in a HLW/THOREX waste.[7] The HLW/THOREX waste was concentrated via evaporation and glass forming chemicals (GFC) were added and the resulting slurry vitrified.[8]

Simulant testing was performed to determine if a deflocculant[a] could be added to reduce the water content and increase throughput.[9] The HLW/THOREX simulant consisted of oxides, predominately iron hydroxide and silicon dioxide and was basic in nature due to the addition of sodium hydroxide. Deflocculants such as sodium meta-silicate (SMS) and polyglycols (Rohm & Hass products, Duramax-3005 and CER-3019) were used to reduce the apparent viscosity at a shear rate of 256 sec^{-1} by at least 85% at a concentration level of 1000ppm of the deflocculant.

[a] Deflocculant is the dispersion of agglomerates to form a colloidally stable suspension or emulsion. It is a chemical agent used for thinning suspensions or slurries. Deflocculants reduce rheology or prevents flocculation.

Concentrated nitric acid was also tested and was even more effective than the deflocculants, but was not selected due to reaction with sugar, generating NO_x via the addition of sugar as a glass forming chemical. SMS was selected and utilized in the actual waste stream at West Valley, since SMS was inorganic and contained chemicals already present in the waste stream. The effectiveness SMS had on the rheology of the actual waste streams was never quantified.

2.2 Savannah River Site Experience

At SRS, nuclear materials for national defense, research, medical, and space programs were produced. The separation of fissionable nuclear material from irradiated targets and fuels generated large quantities of radioactive waste that are currently stored onsite in large underground waste storage tanks. Radioactive waste generation started in 1954. Most of the tank waste inventory is a complex mixture of chemical and radioactive waste generated during the acid-side separation of special nuclear materials and enriched uranium from irradiated targets and spent fuel using the PUREX process in F-Canyon and the modified PUREX process in H-Canyon (HM process). Waste generated from the recovery of Pu-238 for the production of heat sources for space missions is also included. The HLW sludge can be further processed to remove excess aluminum via the aluminum dissolution process in the tank farm.[10] Prior to sending the HLW sludge to DWPF, with or without aluminum dissolution, it is washed to reduce the concentration of soluble salts to acceptable processing levels. The HLW sludge is then transferred to DWPF and can be further concentrated via evaporation in the receipt vessel. The sludge is then transferred to the Sludge Receipt and Adjustment Tank (SRAT), where nitric acid and formic acid are added to the sludge to react with carbonates and hydroxides in the sludge to adjust its rheology and to reduce Hg ions in the sludge. This sludge is then transferred to the Slurry Mix Evaporator (SME) tank, where frit/water[b] is added and the excess water is evaporated to make melter feed. This melter feed is then pumped to the melter feed tank and then fed to the melter, resulting in a vitrified product ready for long term disposal. Mechanical agitators, boiling (or temperature control), and centrifugal pumps (including jet pumps) are used to process the HLW sludge in/from the waste storage tanks to and through the DWPF processes. Transfer pumps are limited by the pump curve or by the design limit of the transfer piping in the tank farm. For DWPF, the design basis for the various unit operations, consisting of mixing and pumping, is provided in Table 2-1[11] based on the Bingham Plastic rheological model.

Table 2-1 Bingham Plastic Design Limits for the Various DWPF Unit Operations

Unit Operations	Yield Stress (Pascal)		Plastic Viscosity (centipoise)	
	Min	Max	Min	Max
Slurry Receipt Adjustment Tank	1.5	5	5	12
Slurry Mix Evaporator	2.5	15	10	40
Melter Feed	2.5	15	10	40

A weekly highlight by Fowler[12] in May 1981 showed ongoing work was being performed by the Savannah River Laboratory to determine the impact of acids on simulant frit-sludge slurry. In this brief memo, the effect of formic and nitric acid on simulant frit-sludge slurry was

[b] FRIT is a glassy material that is chemically selected when blended with the HLW waste stream, produces a stable glass form and waste loading ranging between 30 to 50 % of the combined stream.

summarized. Formic acid was more effective in reducing the yield stress than nitric acid, noting that simple reduction of pH was not necessarily the controlling factor, partial dissolution maybe important as well.

A subsequent memo issued by Fowler[13] in 1981 compared acidic and basic SME simulants as well as the impact of frit size on SME rheology. The SME simulant was basic in nature and was made acidic using formic acid, which reduced mercury to its metal state allowing for its removal and reduced foaming in melter operations. The results showed that the acidic waste stream was more fluid than the basic waste stream and the smaller the frit size the greater impact it had on increasing the yield stress for both acidic and basic waste streams (see Figure 2-1).

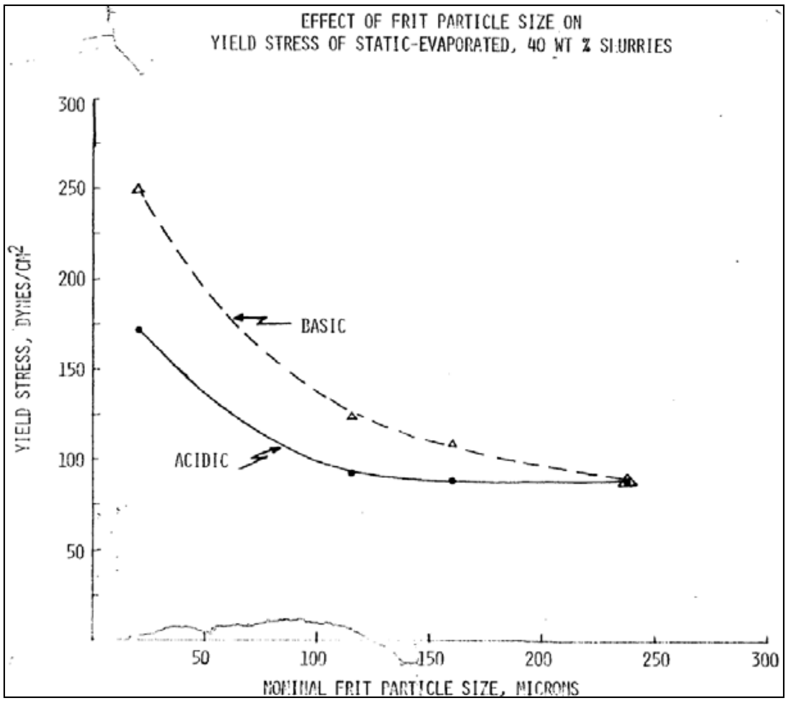


Figure 2-1 Beneficial Effect of Rheology Modifier on the Bingham Plastic Yield Stress[13]

In 2003, Kay[14] investigated the impact of antifoams 747 and B52, and Duramax D-3005 (previously investigated by WV) had on the rheology of a simulant DWPF melter feed. The simulant DPWF melter feed contained 41 wt% UDS, 47 wt% TS, and the pH ranged between 6 and 7, slightly acidic. The modifiers were added at one concentration, 1000ppm, and in all cases, the yield stress increased as compared to the baseline. The B52 had the worst performance, increasing the yield stress by almost 300%.

The first extensive study of rheology modifier impact on simulant DWPF SRAT and SME products was performed by Stone.[15] The SME product was based on a SRAT product made for the FY02 melt rate program, with Frit addition. This was a sludge batch 2, iron rich simulant, which was precipitated and other metal oxides added.[16] The rheology modifier, chemical type, manufacturer, active agent concentration, range of ppm tested, and % change in the yield stress as compared to the baseline condition are provided in Table 2-2. From this testing, only two of the modifiers, Dolapix CE64 and Disperse Ayd W28 were effective in reducing the yield stress by at least 10% and were recommended for future testing. Both of these modifiers are liquid base. In this report, the impact of water dilution to the SME product was characterized and reported in

Table 2-2 and shown in Figure 2-2. Interpolation of this data would be required to determine the effect of low water addition, 1000 to 10000ppm, would have on rheology and its overall contribution in the reduction of the yield stress when modifiers are added as a water based liquid. This report also provides the impact these modifiers had on the simulant SRAT product.

Table 2-2 Rheology Modifier Results on DWPF SME, Stone [2004][15]

Rheology Modifier	Chemical Type	Manufacture	Active Agent Concentration	PPM Tested	% Change on Yield Stress
Sodium Meta Silicate	Crystallized silicate	Various	Solid	2494 – 4975	-2.7 to 1.5
Sodium Polyphosphate	Phosphate polymer	Various	Solid	1719 – 6863	16.5 to 23.1
Darvan 7.	Polymethylacrylate, anionic	Vanderbilt Co. Inc	Liquid 25 wt%	623 – 1244	12.3 to 12.9
Duramax 3005	Ammonium Polyacrylate	Rohm and Haas	Liquid 30 wt%	873 – 1741	10.3 to 12.6
Dolapix CE64	Proprietary Ethylene Glycol	Zschimmer and Schwartz	Liquid 65 wt%	649 – 3234	-21.6 to 4.1
Disperse-Ayd W28	Proprietary Polyacrylate	Elementis Specialties	Liquid 46 wt%	460 – 2289	-42.1 to 3.1
Disperse-Ayd W30	Proprietary Polyacrylate	Elementis Specialties	Liquid 33.5 wt%	335 – 1667	1.4 to 6.3
Disperse-Ayd W39	Proprietary Polyacrylate	Elementis Specialties	Liquid 44 wt%	440 – 2189	-7.5 to 0.3
Alcosperse 149	Sodium Polyacrylate	Alco Chemical	Liquid 40 wt%	400 – 1990	18.6 to 24.7
Alcosperse 240	Proprietary Polyacrylate	Alco Chemical	Liquid 44 wt%	440 – 2189	25.3 to 74.8
Alcosperse 408	Proprietary Polyacrylate	Alco Chemical	Liquid 41 wt%	410 – 2040	13.6 to 52.4
Alcosperse 725	Proprietary Polyacrylate	Alco Chemical	Liquid 35 wt%	350 – 1741	9.8 to 23.5
EDA Plan 470	Proprietary Polyacrylate	Ultra Additives	Liquid 50 wt%	500 – 2488	8.8 to 19.7
EDA Plan 472	Proprietary Polyacrylate	Ultra Additives	Liquid 50 wt%	500 – 2488	9.7 to 14.9
Pomosperse AL36	Proprietary Polyacrylate	Piedmont Chemical Co.	Liquid 42 wt%	420 – 2090	12.5 to 72.3
Cyanamer P-35	Proprietary Polyacrylate	Cytec	Liquid 50 wt%	500 – 2488	24.5 to 269.4
Cyanamer P-70	Proprietary Polyacrylate	Cytec	Liquid 49.8 wt%	498 – 2478	5.4 to 10.3
Water	H_2O	-	Liquid 100 wt%	90909 – 285714	-43.1 to 82.6

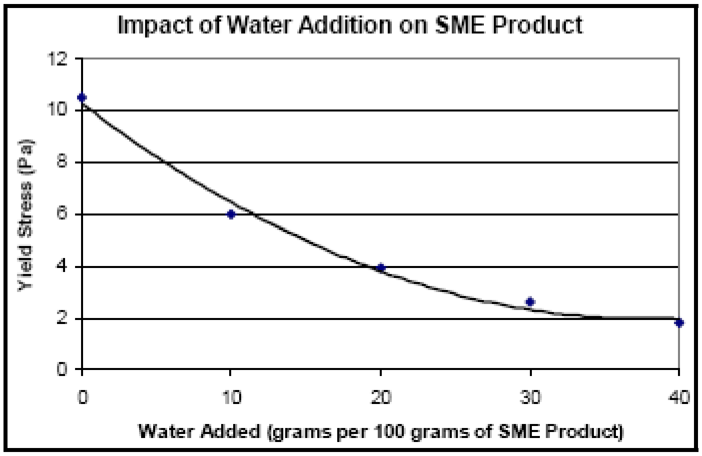


Figure 2-2 Effect of Water Dilution on the Yield Stress, DWPF SME, Stone [2004][15]

A follow on study, based on the previous results with Dolapix CE64, was performed by Marinik.[17] The effect of boiling and replacing the frit with spherical glass particles was studied to investigate rheological as well as foaming issues. The Dolapix CE64 was added at 4000 ppm to a 44 wt% SME product simulant, no reference or detail of the SME product composition was provided. Inspection of the flow curves in this document show that any combination of Dolapix CE64 or spherical glass beads decreased both the yield stress and plastic viscosity. The reduction in the yield stress was based on linearly interpolating the data in this report back to the axis to determine the yield stress. The Dolapix CE64 reduced the yield stress of the Frit containing SME product was 23.1%. The replacement of Frit with spherical glass beads reduced the yield stress by 15.4%. The addition of Dolapix CE64 and use of spherical glass beads reduced the yield stress by 50%. These results show that a combination of a modifier and change in morphology is synergetic.

Though not a chemical rheological modifier, the replacement of Frit with spherical glass bead is a rheological change, specifically with respect to the morphology. Additional work was performed to characterize the impact of spherical glass beads to help modify the rheology of SME products.[18] In this study, simulant sludge batch 2 and sludge batch 2/3 blend, used to support melt rate studies were utilized to make the SME products. The spherical beads reduced both the yield stress and plastic viscosity of the SME products as compared with frit as shown in Table 2-3. The large differences in the reduction of Bingham Plastic properties for the two different SME products was not explained, such as waste loading or fraction of beads in each stream.

Table 2-3 Spherical Bead Results on DWPF SB2 & SB2/3 SME Products, Stone [2004][18]

SME Product	% Reduction	
	Yield Stress	Plastic Viscosity
SB2	21.4	6.1
SB2/SB3	41.5	19.7

Further testing of spherical beads was performed.[19] In this work, two different SME products were tested. A sludge batch 3 SRAT/SME product is described in the report and is a precipitated sludge with trim metals added. With this SB3 SRAT product, different size spherical beads were added to make SME products. The results are shown in Table 2-4, the spherical beads for any size class is more fluid slurry than the frit SME product. This data shows little change in yield stress, but the plastic viscosity drops as the size increases. The preparation of the other SB3 SRAT product used in this report is described in reference 20 and is also a precipitated and trim metals added. In this case, two different wt% total solids were studied, 45 and 52 wt%. The results showed that the spherical beads were again more effective in reducing the rheologically properties as the solids increased.

Table 2-4 Sized Spherical Bead Results on DWPF SB3 SME Products, Smith [2005][19]

Spherical Bead Size	% Reduction with respect to Frit	
	Yield Stress	Plastic Viscosity
Less than 140 Mesh	23	28
Less than 100 greater than 140 Mesh	30	34
Less than 70 greater than 100 Mesh	25	59

2.3 Hanford Experience

The vitrification of HLW at Hanford has yet to begin. Unlike SRS, various separation processes were used to extract the plutonium, uranium, and fission products. These include the PUREX, REDOX, Bismuth Phosphate, Uranium Recovery (tri-butyl phosphate), and Cesium and Strontium encapsulation processes. [21] Waste products were generated from these various processes until the 1990s and feed to the tank farm storage tanks. The waste from the tank farm will be pumped to the RPP-WTP pretreatment facility. The RPP-WTP pretreatment facility will be designed to:[5]

- Receive and store waste feed from the tank farm double-shell tank (DST) System;
- Concentrate waste feed, recycle streams, and treated low activity waste (LAW) product to facilitate RPP-WTP processing;
- Mix appropriate amounts of HLW feed with LAW feed for use as feed to the ultra filter process (UFP) system;
- Use the UFP system to concentrate solids, caustic and oxidative leach solids, and water wash solids;
- Store pretreated HLW solids for HLW vitrification feed;
- After removal of solids, strontium, transuranic (TRU), and cesium, transfer the remaining process stream to the LAW Vitrification Facility and/or the East Supplemental Treatment Plant (East STP); and
- Blend pretreated HLW feed with the separated cesium, strontium, and TRU material and then transfer it to the HLW Vitrification Facility.

After the HLW feed is transferred to the HLW vitrification facility, it is characterized, processed, and then blended with mineral oxides and sugar (dry material typically called glass former chemicals),[22] and vitrified. There is a LAW vitrification plant similar to that of the HLW vitrification plant that is not considered in this review that can process some of the LAW feed prepared in the pretreatment facility. In the RPP-WTP facilities; pulse jet mixers, centrifugal pumps, mechanical agitators, pneumatic pumps, and heating/cooling (presently only in the pretreatment facility) are used for processing the fluids. This author could find no HLW design limits for the pretreatment facility, but for the HLW vitrification facility, the rheological limits for the pretreated HLW sludge and melter feed are the same;[23] yield stress 0 to 30 Pascal and plastic viscosity 0.4 to 30 centipoise.

The processing of sludge, starting from the tank farm to its final destination, melter feed for vitrification, requires many processing steps, at both SRS and Hanford. In each of the processing steps, mechanical or pneumatic systems are required to mix or transport these slurries and the equipment used in these processes are limited by the physical properties of the sludge, which can easily change during/after each processing step. For instance, sludges in the tank farm at SRS during washing, where excess salts are removed, can change both rheologically and in settling behavior, after each washing step. During this washing sequence, there may be need to reduce both rheological properties and settling times, between and after each wash. Decreasing the settling time would reduce the time required so an adequate quantity of supernate can be decanted. Reducing the rheological properties would permit a large quantity of insoluble solids to be transferred upon completion of washing/decanting. Another example is when the glass former chemicals or glass frit are added to the pretreated HLW sludge. The use of rheology modifiers may permit further dewatering of the HLW sludge or melter feed prior to actual vitrification, hence reducing energy required to evaporate the water. Increasing the solids content of the melter feed would decrease the energy required to evaporate the water in the slurry, and would, therefore, increase the overall production (melt) rate of the immobilization process.

There are no documents investigating the impact of rheology modifiers on RPP-WTP HLW melter feeds. Work performed by Kay[14] tested modifiers on simulate RRP-WTP HLW sludge. Present work at PNNL supporting this EM-31 task is investigating the use of rheology modifiers on washed sludge.

Work on simulant RPP-WTP low activity waste was performed by Zhao.[24] In this study, polyacrylic acid (PPA) was used on low activity waste streams blended with a broad range of raw materials used to make a glass product for disposal. The study looked at different wt% (5.5 to 14.4) Na_2O waste loading in glass, total solids ranging between 55 to 75 wt% and pH values between 7 to +12. The total solids are much higher than those of HLW melter feeds. The results showed the PPA was effective on some of these waste streams in reducing the water content, hence increasing melt rate. It also concludes that starting pH may affect the performance of PPA.

3.0 Experimental Procedure

The first step to determine the effect the rheology modifiers have on simulant DWPF melter feeds is to first determine the physical properties and pH of the baseline condition of the simulants, prior to modifier addition. The baseline physical properties that will be measured are; weight percent total solids in the slurry and soluble solids in the supernate, density, and rheology as well as the pH. Sub samples of the baseline simulants are then prepared and varying concentrations of selected rheology modifiers added, mixed and allowed to react for at least one hour prior to any rheology or pH measurements. The experimental procedure is broken into four parts; selected melter feed simulants, selected rheology modifiers, physical properties and pH measurements, and sample preparation. Each of these will be discussed in more detail below.

3.1 Melter Feed Simulants

In this study, five different readily available melter feed simulants were used. No simulants were specifically developed to support the work completed in FY2009.

3.1.1 *RuRhHg 1-9 SME Product*

The RuRhHg SME simulants were developed to understand how combinations of ruthenium, rhodium, and mercury effect the generation of hydrogen during the acid addition/boiling phases of the SRAT and SME processes.[25] The simulant used to make the RhRhHg SME simulants contain an intermediate elemental composition between PUREX and HM sludges, a blended sludge.[26] The undissolved solids in this slurry are a combination of both precipitated solids as well as the addition of oxide solids. The calcined elemental composition of this SRAT product is provided in Table 3-1. The targeted acid concentration for this sludge was 197% of stoichometry. The average wt% TS was approximately 26.1.

Table 3-1 Calcined Elemental Composition of Baseline RuRhHg SRAT Product

Element	Wt%	Element	Wt%	Element	Wt%	Element	Wt%
Al	16.1	Cu	0.143	Mn	4.05	Si	1.72
Ba	0.221	Fe	21.8	Na	12.2	Ti	0.018
Ca	2.55	K	0.276	Ni	0.998	Zn	0.213
Cr	0.163	Mg	1.76	Pb	0.055	Zr	0.628

The SRAT product was blended with frit and the resulting SME product calcined elemental composition is provided in Table 3-2. The averaged SME product anion data and solids data for this baseline case are provided in Table 3-3 and Table 3-4 respectively.

Table 3-2 Calcined Elemental Composition of Baseline RuRhHg SME Product

Element	Wt%	Element	Wt%	Element	Wt%	Element	Wt%
Al	5.83	Cu	0.035	Mn	1.06	Ti	0.043
B	1.45	Fe	8.22	Na	8.85	Zn	0.073
Ba	0.075	K	0.153	Ni	0.265	Zr	0.242
Ca	0.835	Li	2.33	Pb	0.023		
Cr	0.156	Mg	0.560	Si	24.0		

Table 3-3 Baseline RuRhHg SME Product Anion Data

Compound	mg/kg
Nitrate	19,300
Formate	52,850
Sulfate	2,390
Chloride	378

Table 3-4 Baseline RuRhHg SME Product Solids Data

Property	%
Wt% total solids	51.55
Wt% insoluble solids	42.0
Wt% Calcined solids	41.5

The above simulant, starting with the sludge, was spiked with different concentrations of noble medals and processed through the CPC. Fourteen different combinations of noble metals were used and only run 1, 4, 5 and 9 were available, resulting in the RuRhHg1-9 SME product. The concentrations of noble metals added to the starting sludge simulant are provided in reference 25.

RuRhHg-1, -4, -5, and -9 simulant runs were available for blending, yielding the final RhRhHg1-9 simulant. The primary difference between these simulants is the concentrations of Ru, Rh, and Hg added to the baseline RuRhHg sludge and these concentrations are shown in Table 3-5. These concentrations are based on the weight percent total solids of the starting sludge. Each of the runs provided approximately a quarter of the material for testing in this task, resulting in a mass that was adequate for testing at two different solids concentration.

Table 3-5 Concentration of Noble Metals in RuRhHg Simulants

Run	Rh, wt %	Ru, wt%	Hg, wt%
1	0.00263	0.01012	0.506
4	0.01314	0.05054	0.505
5	0.00257	0.00990	2.457
9	0.00780	0.03000	1.500

The concentrated RuRhHg 1-9 SME simulant was obtained by decanting the supernate of the baseline simulant after it was allowed too settled for a minimum of 30 days. The concentrated simulant was never centrifuged.

3.1.2 *08-SB5-12-13 SME Product*

This SME simulant was developed to support processing of sludge batch (SB) 5, the fifth macro batch at SRS. This SB had a significant fraction of aluminum removed through Al-dissolution, and is high in mercury and noble metals. Tests were conducted using the expected SB5 composition to determine the impact of varying the acid stoichometry during the SRAT and SME processes.[27] The undissolved solids were produced via co-precipitation and no oxides were added. This baseline sludge was defined as SB5-C in reference 27. SB5-C runs 12 and 13 SME products were available for this task and the primary difference between the two were the targeted acid stoichometry, which were 130% and 145% respectively. The different acid stoichometry resulted in different pH endpoints, the higher the percent acid the more acidic the final waste stream. Approximately one liter of each SME product was available for blending. The calcined elemental composition, anions, and solids data of the 08-SB5-12-13 SME blend are provided in Table 3-6, Table 3-7, and Table 3-8.

Table 3-6 Calcined Elemental Composition of 08-SB5-12-13 SME Product

Element	Wt%	Element	Wt%	Element	Wt%
Al	4.64	Fe	7.42	Na	10.2
B	1.29	K	0.111	Ni	0.885
Ba	0.011	Li	2.20	Si	24.1
Ca	0.620	Mg	0.369	Ti	0.019
Cr	0.016	Mn	1.71	Zr	0.017

Table 3-7 08-SB5-12-13 SME Product Anion Data

Compound	mg/kg
Nitrate	20,425
Formate	52,325
Sulfate	73
Chloride	280

Table 3-8 08-SB5-12-13 SME Product Solids Data

Property	%
Wt% total solids	44.7
Wt% insoluble solids	34.4
Wt% Calcined solids	36.3

3.1.3 *09-SB5-23 SME Product and 09-SB5-24 SME Product*

These SME products were based on the SB5-C baseline sludge as described in section 3.1.2. These runs were performed to determine the impact of longer processing times that were occurring in the CPC process at DWPF and their impact on pH profile, anion destruction, and acid stoichometry.[28] Two different acid stoichometry 130% (SB5-23) and 160% (SB5-24) runs were performed. In this case, the two different runs yielded adequate sample for testing individually and were used to provide some insight into what effect different acid stoichometry endpoints could have on the rheology modifiers, given the undissolved solids are very similar. The calcined elemental composition, anions, and solids/pH data of the 09-SB5-23 and 09-SB5-24 SME products are provided in Table 3-9, Table 3-10, and Table 3-11.

Table 3-9 Calcined Elemental Composition of 09-SB5-23 and 09-SB5-24 SME Products

09-SB5-23				09-SB5-24			
Element	Wt%	Element	Wt%	Element	Wt%	Element	Wt%
Al	4.21	Mn	1.63	Al	4.22	Mn	1.76
B	1.34	Na	11.9	B	1.33	Na	11.9
Ba	0.010	Ni	0.719	Ba	0.010	Ni	0.721
Ca	0.654	P	0.033	Ca	0.648	P	0.033
Cr	0.016	S	0.052	Cr	0.017	S	0.052
Fe	7.29	Si	23.4	Fe	7.61	Si	23.7
K	0.108	Ti	0.041	K	0.150	Ti	0.041
Li	2.09	Zr	0.084	Li	2.05	Zr	0.084
Mg	0.324			Mg			

Table 3-10 09-SB5-23 and 09-SB5-24 SME Product Anion Data

Compound	mg/kg	
	09-SB5-23	09-SB5-24
Nitrate	41,400	46,000
Formate	53,350	59,150
Sulfate	<100	117
Chloride	205	297

Table 3-11 09-SB5-23 and 09-SB5-24 SME Product Solids and pH Data

Property	09-SB5-23	09-SB5-24
Wt% total solids	49.6	48.8
Wt% insoluble solids	35.1	34.5
Wt% Calcined solids	39.8	38.2
pH	8.28	5.45

3.1.4 *SB6-1,2,3,4 SME Product*

This SME simulant was developed to support initial studies in preparation of processing SB6, the sixth macro batch. A co-precipitated baseline Tank 40 blend simulant, SB6-A, was developed and tested at four different acid stoichometry, 90%, 100%, 120%, and 150% to determine the impact of varying acid stoichometry had during the SRAT and SME processes. The resulting SME products, at approximately equal volumes,[c] were blended resulting in the SB-1,2,3,4 SME product. The SB6-1 though SB6-4 chemical and physical data were averaged to obtain the SB-1,2,3,4 data and the calcined elemental composition, anions, and solids data of the simulant are provided in Table 3-12, Table 3-13, and Table 3-14. There were very little difference between the calcined and solid data between the four individual batches, but differences existed in the anions due to the acid stoichometry.

[c] Per discussion with Brad Pickenheim, 9-25-2009

Table 3-12 Calcined Elemental Composition of SB6-1,2,3,4 SME Product

Element	Wt%	Element	Wt%	Element	Wt%	Element	Wt%
Al	5.58	Cu	0.035	Mg	2.38	Zn	0.054
B	1.49	Fe	6.34	Na	9.42	Zr	0.220
Ba	0.081	K	0.087	Ni	1.38		
Ca	0.716	La	0.031	S	0.091		
Ce	0.068	Li	2.23	Si	23.4		
Cr	0.103	Mg	0.511	Ti	0.046		

Table 3-13 SB6-1,2,3,4 SME Product Anion Data

Compound	mg/kg
Nitrate	26,875
Formate	53,250
Chloride	336

Table 3-14 SB6-1,2,3,4 SME Product Solids Data

Property	%
Wt% total solids	46.9
Wt% insoluble solids	37.2
Wt% Calcined solids	37.6

3.2 Rheology Modifiers

The selection of the majority of rheological modifiers were based on rheology modifiers used in previous simulant testing at DOE facilities, present testing of rheology modifiers at PNNL, recommendation provided by a vendor whom previous rheology modifiers were used at SRNL, and experiences gained by this author via grout processing. The list of rheology modifiers used in this task, the composition, structure, wt% of active component (via solids analysis), pH, density, and notes are provided in Table 3-15. Polyacrylic acid (PAA), sodium pyrophosphate tetrabasic (SPPT), and citric acid (CA) are presently being tested by PNNL and were shown to be effective for the basic AZ-101 processed sludge stream[d]. Sodium metasilicate (SMS) has been tested with both acidic and basic simulants, but was shown to be more effective for basic streams. Dolapix CE64 (CE64) has been used in previous DWPF and WTP simulants. Dolapix A88 (A88) and PC75 (PC75) were recommended by the vendor as additional modifiers that maybe effective in acid waste stream.[e] Grace Recover® is used for the stabilization of cement hydration, delaying set. The other concrete additives are polycarboxylate-based, the ADVA Flex is a high range water reducer (requiring less water for the same type of flow performance) and the ADVA Cast 555 is a superplasticizer (high range water reducer without causing undue set retardation or entrainment of air) were selected based on experiences gained through effective mixing of grouts used to support various SRS processes, though the results were never published. Polycarboxylates are also used as scale inhibitors and dispersants in the water treatment business. Sugar was selected, since it is a reductant for glass processing. In fact, most of the modifiers in this task can also perform the function of a reductant, when making glass. Phenylboric acid was selected without any basis, other than it is an acid that contains boron. The physical and pH values provided in Table 3-15 were based on the MSDS associated with the rheology modifier.

[d] Results will be presented at Waste Management 2010.
[e] Email from Paul Curtbert, "Re: Dolapix CE64", 5-12-2009

Table 3-15 Rheology Modifiers Used in SRNL FY-2009 Testing

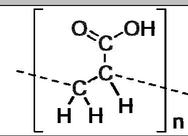
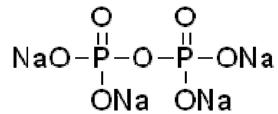
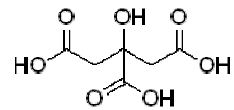
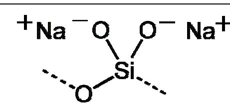
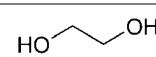
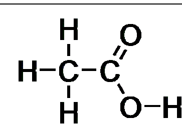
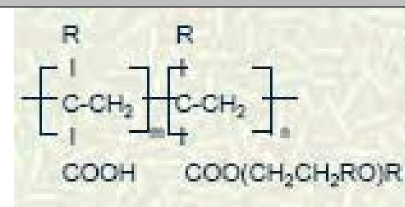
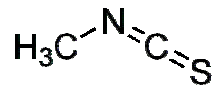
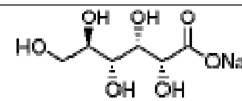
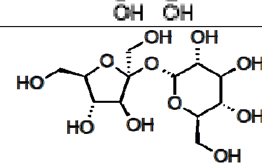
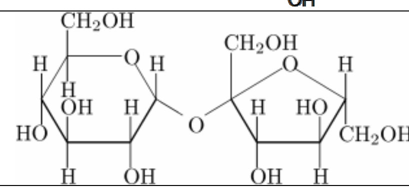
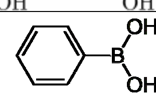
Vendor	Chemical Name	Components of Admixture	Structure	wt%	pH	Density	NOTES
Aldrich Chemical Co.	Poly (Acrylic Acid)	Polyacrylic acid, average molecular weight is 2000		100%	-	-	Solid
Sigma Aldrich	Sodium Pyrophosphate tetrabasic	$Na_4O_7P_2$		100%	-	-	Solid
NOAH Technologies	Citric Acid, anhydrous	$C_6H_8O_7$		100%	-	-	Solid
Sigma Chemicals	Sodium Metasilicate	Na_2SiO_3		100%	-	-	Solid
Zschimmer & Schwarz	Dolapix A88	1-propanol, 2-amino-2-methyl-	-	90	11	0.95	Liquid
Zschimmer & Schwarz	Dolapix CE64	Ethylene glycol, $C_2H_6O_2$		<10	7	1.2	Liquid
Zschimmer & Schwarz	Dolapix PC75	Synthetic polyelectrolyte	-	25	8.5	1.1	Liquid
W.R. Grace	ADVA Cast 555	2-propenoic acid, polymer with methyloxirane polymer with oxirane, sodium salt	-	10-25	3 - 5	1.0 - 1.1	Liquid
		Acetic Acid, $C_2H_4O_2$		<1			
		Polycarboxylate	See ADVA Flex	1 – 10			

Table 3-15 Rheology Modifiers Used in SRNL FY-2009 Testing

Vendor	Chemical Name	Components of Admixture	Structure	wt%	pH	Density	NOTES
W. R. Grace	ADVA Flex	Polycarboxylate, proprietary		10 - 25	4 - 6		Liquid
W. R. Grace	Recover®	Methy isothiocyanate, C_2H_3NS		0.004	5 - 8	1.1 - 1.2	Liquid
		Tetrahydro-3, 5-dimethyl-2H-1,3,4-thiadiazine-2-thione	-	0.04			
		Sodium Gluconate, $NaC_6H_{11}O_7$		-			
		Sucrose, $C_{12}H_{22}O_{11}$		-			
Domino	Sugar	Disaccharide		100%	-	-	Solid
Aldrich Chemicals Co.	Phenylboronic acid	$C_6H_7BO_2$		100%	-	-	Solid
Taylor	Antifoam 747	Polyether Siloxane	-	> 70%			Liquid

3.3 Physical Properties and pH Measurements

The physical properties that are directly calculated from the actual measurements are; weight percent (wt%) total solids in the sludge (TS), wt% dissolved solids in the supernate (DSS), density, and rheological properties. Weight percent undissolved solids (UDS) in the sludge is calculated from wt% TS and wt% DSS. The methods used to measure and calculate these physical properties are described below. The only chemical property that is measured is pH and is also described below.

Physical properties and pH measurements were performed on all baseline SME products. Rheology and pH measurements were performed on all SME products where rheology modifiers were used. Solids measurements were not performed on SME products, where rheology modifiers were used, due to the lack of sample volume.

3.3.1 *Solids Analysis*

Samples used for solids analysis were homogenized (via shaking of the bottle) prior to performing the analyses. The supernates were obtained by filtering a homogenized SME sample through a 0.2 micron filter.

The Mettler Toledo HR83 Halogen Moisture analyzer, see Figure 3-1, was used to perform the wt% TS and wt% DSS. This moisture analyzer uses a load cell that continuously measures the mass of the sample during the measurement. Water and volatiles (105°C) are evaporated using a halogen heat lamp that is controlled by an infrared thermometer that measures the temperature of the surface of the sample. The mass of the sample pan is first measured and the weight tarred. Approximately 1.5 to 3 grams of a sub-sample is placed onto the sample pan and this mass is recorded by the analyzer. The temperature of the sample is then ramped to 105°C and maintained at 105°C throughout the measurement. The measurement stops when the weight of the sample does not change more than 1 milligram over a 20 second period and this final mass is recorded by the analyzer. The wt% TS or wt% DSS is then determined by taking the ratio of the final mass to initial mass and multiplying this value by 100% as shown in equations[1] and [2] respectively. The analyzer load cell is checked on a daily basis (when used) using a 2.0 gram weight and functionally checked using an 8.0 wt% TS NaCl solution.

$$wt\%_{TS} = \frac{M_{TS}}{M_T} \cdot 100\% \qquad [1]$$

$$wt\%_{DSS} = \frac{M_{DSS}}{M_{SUP}} \cdot 100\% \qquad [2]$$

Figure 3-1 Mettler Toledo HR83 Halogen Moisture Analyzer

The wt% UDS is calculated using the wt% TS and wt% DSS results. This analysis is based on conservation of mass. Equation [3] is the total mass of solids (M_{TS}) in a sample and is the sum of the undissolved solids (M_{UDS}) and soluble (M_{SS}) solids. Equation [4] is the total mass (M_T) of the sample which is the sum of the insoluble solids and supernate (M_{SUPT}). The mass of soluble solids in this sample can be determined by multiplying the mass of the supernate in the sample by the ratio of the mass fraction of the dissolved solids in the supernate measured above and substituting equation [4], M_{SUPT} , yields equation [5]. Substituting equation [5] into equation [3] and dividing by M_T and solving for mass ratio of M_{UDS}/M_T yields the mass fraction of UDS. Multiply each side of equation [6] by 100% and substituting equations [1] and [2], yields the final relation for wt% UDS.

$$M_{TS} = M_{UDS} + M_{SS} \quad [3]$$

$$M_T = M_{UDS} + M_{SUPT} \quad [4]$$

$$M_{SS} = M_{SUPT} \cdot \frac{M_{DSS}}{M_{SUP}} = \left(M_T - M_{UDS}\right) \cdot \frac{M_{DSS}}{M_{SUP}} \quad [5]$$

$$\frac{M_{UDS}}{M_T} = \frac{\frac{M_{TS}}{M_T} - \frac{M_{DSS}}{M_{SUP}}}{1 - \frac{M_{DSS}}{M_{SUP}}} \quad [6]$$

$$wt\%_{UDS} = \frac{wt\%_{TS} - wt\%_{DSS}}{100\% - wt\%_{DSS}} \cdot 100\% \quad [6]$$

For liquid based rheology modifiers, wt% TS measurements were performed.

3.3.2 *Density*

Densities were measured using an Anton Paar DMA 4500 Density analyzer, see Figure 3-2. A sample is pushed into the density analyzer glass u-tube and the sample temperature controlled to 25°C. A vibration is then induced on one end of the u-tube and the frequency is measured at the other end. The density of the sample is determined on the measured frequencies. The density analyzer is functionally checked on a daily basis (when used) with DI water.

Figure 3-2 Anton Paar DMA 4500 Density Analyzer

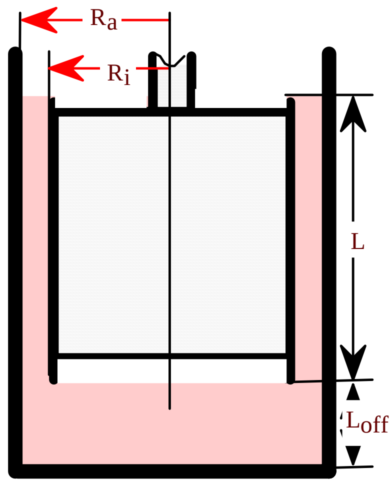
In some cases, the baseline sample could not be measured using the DMA 4500, due to the very viscous nature of the slurry. In these cases, a density cup (Cole Palmer part number EW-38000-14) was used. The density cup (volume) is verified using DI water prior to use. The density of the sample is determined by measuring the mass of sample required to fill the volume and dividing this mass by the volume of the cup.

3.3.3 *Rheology*

Flow curve measurements were obtained using the normal Z38 cylindrical rotor and Z43 cup and Haake RS600 rheometer in most cases. The Z38 serrated cylindrical rotor and Z43 serrated cup was used on various baseline sludges to determine if slip was an issue when using the normal Z38 rotor. The rotor specification for either rotor type is shown in Table 3-16. The cup and rotor are initially installed onto the rheometer. The zero reference point (point at which the rotor makes full contact with the bottom of the cup) is then determined by the rheometer. The rotor and cup are removed and the appropriate volume of sample to fill the gap between the rotor and cup is added. The cup and rotor are then reinstalled onto the rheometer. The rheometer drives the rotor into the predetermined bottom off-set position. A cooling/heating bath is used to control the temperature of the rotor/sample/cup at 25°C. The rheometer is programmed to control the rate at which the rotor spins and measures both the rotational speed and the torque (the resistance to shear). The shear stress at the wall of the rotating rotor is then calculated (internally by the Haake™ software) based on the product of the measured torque and geometry (A-factor) of the rotor. The shear rate of the rotating rotor is calculated as the product of the measured speed and geometry (M-factor) of the rotor/cup and assumes the fluid is Newtonian. The A-factor, M-factor, and flow curve (shear rate range and the linear ramp up time, hold time at maximum shear rate, and linear ramp down time) are provided in Table 3-16. The linear ramp rates (or acceleration) is $\pm$ 30 sec^{-1} per minute. The flow curve profile is consistent with the protocol used to obtain DWPF SME samples.[29]

Table 3-16 Z38 Rotor Specification and Program Ramp Rates

Design of Rotor



Z38 Rotor Specifications

Rotor	Z38
Rotor radius (mm)	R_i = 19.010
Cup Radius (mm)	R_a = 21.700
Height of rotor (mm)	L = 55
Sample Volume (cm^3)	V = 33
Bottom off-set (mm)	L_{off} = 4
A factor (Pa/(N·m))	8010
M factor (s^{-1}/rad s^{-1})	8.60
Shear rate measuring range (s^{-1})	0 – 300
Ramp up time (min)	5
Hold time (min)	1
Ramp down time (min)	5

Prior to any flow curve measurement, the rotor and cup are inspected for visual damage that could potentially impact the rheological measurement. A National Institute of Standards and Technology (NIST) traceable Newtonian oil standard is then used to verify the operability of the rheometer at a measurement temperature of 25°C. The resulting flow curves are analyzed as a Newtonian fluid and the calculated viscosity is compared to that of the NIST traceable Newtonian oil standard. The rheometer is considered operable if the calculated viscosity is within ± 10% of the NIST traceable Newtonian oil standard viscosity. The NIST traceable Newtonian oil standard is used each day that a flow curve or vane measurements was required. The measured viscosities were well within the ± 10% of the standard.

Upon completion of a flow curve measurement, the bottom of the rotor is inspected to determine if the sample completely fills the void space, and if so, noted. This void space is an air buffer, where the shear stress contribution is negligible compared to the shear stress contribution from the cylindrical section of the rotor, which is in complete contact with the fluid during the flow curve measurement. The effect of the bottom void being completely filled is an increase in stress. In all cases, the void was never completely filled. Partial filling of this void can occur when the bob is removed from the cup, due to a vacuum created in the void during the removal phase.

For all baseline samples, a minimum of two flow curve measurements were performed. For SME samples where rheology modifier was added, only one flow curve measurement was performed due to sample availability. The resulting flow curves are analyzed using the Bingham Plastic rheological model, equation [7]. Portions of the up curve are analyzed using the Bingham Plastic model, because of potential frit migration issues causing problems with down curve results. It is assumed that the frit particles are platting out on the cup, sliding down the sides, and accumulating in the gap between the bob and cup, increasing the stress on the rotating bob. This assumption has not been proven. Because these fluids are not true Bingham Plastic fluids, the shear rate range in which the data is fitted will also be provided, such that a linear region of the up curve is fitted.

$$\tau = \tau_{BP} + \eta_{BP} \cdot \dot{\gamma} \qquad [7]$$

Where: τ_{BP} = Bingham Plastic yield stress (Pa)
η_{BP} = Bingham Plastic Viscosity (or consistency) (reported as cP)

One of the issues related to slurries is slippage, which typically occurs when a layer of fluid, depleted of most of the UDS, is coating the spinning rotor, resulting in a lower measured shear stress. This results in reporting a fluid with less viscous properties and can occur with very viscous slurries. DWPF SRAT and SME slurries typically are not considered to have this issue, since they are not considered highly viscous fluids. To determine if slip is an issue, various measurements were performed, such as using a serrated rotor/cup geometry or vane geometry. The baseline RuRhHg 1-9 prior to decanting was analyzed for slippage and details are provided in Appendix A, indicating slippage is not an issue. Additionally, the serrated Z-38 geometry was used on the decanted RhRhHg 1-9 sample, due to the very viscous state of this simulant.

The flow curves for each of the simulants, including baseline and with rheology modifiers are provided in the appendices as shown in Table 3-17. These appendices also contained the Bingham Plastic fit to each flow curve, the coefficient of determination (R^2), and the range in which the data was fitted. The flow curves were analyzed using EXCEL™ to determine the Bingham Plastic parameters and the coefficient of determination.

Table 3-17 Appendices For Each of the SME Simulants

Appendix	SME Simulant
B	RuRhHg 1-9
C	RuRhHg 1-9 Decanted
D	SB5 12-13
E	SB6-1,2,3,4
F	09-SB5-23-2630
G	09-SB5-24-2640

3.3.4 *pH Measurements*

The pHs was measured using an IQ Scientific Instruments 1Q150NP pH meter (Figure 3-3) and PH-77 stainless steel pH probe. All measurements are obtained at ambient conditions (18 to 22°C). The pH meter and probe is calibrated prior to performing measurements using three different pH buffers of pH 4, 7, and 10. These buffers are from Fisher Scientific and are certified to within ± 0.02 pH units. The pH measurements of samples containing a rheology modifier were obtained upon completion of the rheological measurement.

Figure 3-3 IQ Scientific pH Instrument

3.4 Sample Preparation, Batching, and Processing

Prior to any physical property measurement, samples are homogeneously mixed, by vigorously shaking the bottle. For density or rheology measurements, the bottle (or rheology cup after transfer) is tapped prior to performing the measurement to assist in the removal of entrained air. The pH measurements were obtained after the rheological measurement is complete.

Samples prepared for rheology modifier addition were sized to permit at most only one flow curve measurement, due to availability and too maximize the number of modifiers for testing. Under nominal conditions, at least two rheology measurements are performed using virgin sample. Sample reuse is typically not recommended for slurry samples.

A majority of the powder rheology modifiers were added at concentration levels of 1000, 3500, 7000, and 10000 parts per million (ppm). A few of the powder rheology modifiers were added at 3000 and 6000ppm rather than at 3500 and 7000ppm, due to batching errors that occurred when transitioning between liquid and dry solid basis rheology modifier. Solution rheology modifiers were added at concentrations levels of 1000, 6000, 10000, and 16000ppm. The concentration of rheology modifier added was based on the mass of the batched sample. After the addition of the rheology modifier to the sample, the resulting material was mixed rapidly by shaking the sample bottle for at least one minute. The sample was allowed to equilibrate for at least 1 hour prior to rheology measurements, at which point the bottle was shaken prior to measurement.

The following is a sequence in which the various SME products were processed and rheology modifiers used in these SME products. As testing progressed, additional rheology modifiers were identified and decisions were made to determine which of the existing rheology modifiers would be dropped to test the new rheology modifiers, based on previous rheology modifier performance, specifically their impact on the Bingham Plastic yield stress. The scope of this work was to incorporate as many rheology modifiers for testing. Table 3-18 provides the sequence of testing SME products and what modifiers were utilized. For instance, RuRhHg 1-9 was the first simulant tested, then 08-SB-5-12-13, and so forth.

Table 3-18 Rheology Modifier Utilization and Sequence of Testing

Rheology Modifier	Sequence of Testing					
	RuRhHg 1-9	08-SB5-12-13	SB6-1,2,3,4	09-SB5-23	09-SB5-24	RuRhHg 1-9 Decanted
Recover®	X	X	X	X	X	X
Polyacrylic Acid	X	X	X	X	X	X
Citric Acid	X	X	X	X	X	X
Sodium Pyrophosphate Tetrabasic	X	X	X	-	-	-
Dolapix A88	X	X	X	-	-	-
Dolapix CE64	X	X	X	-	-	X
Dolapix PC75	X	X	X	-	-	-
ADVA Flex	X	-	-	X	X	X
ADVA Cast 555	-	X	-	X	X	X
Taylor Antifoam	-	-	X	-	-	-
Sugar	-	-	-	-	-	X
Sodium Metasilicate	-	-	-	-	-	X
Phenylboric Acid	-	-	-	-	-	X

X = Yes, - = No

3.5 Additional Calculations

The following calculations were performed in this task;

- percent change in yield stress, plastic viscosity, and pH,
- actual ppm based on the sludge and UDS masses,

The % change in the yield stress, plastic viscosity, and pH were calculated using equation [8].

$$\%change = \frac{x_{\text{mod}ifer} - x_{baseline}}{x_{baseline}} \cdot 100\% \qquad [8]$$

Where: $x_{\text{mod}ifer}$ = measured property with rheology modifier

$x_{baseline}$ = measured property of baseline condition

The ppm in the slurry was calculated using equation [9] and the ppm in the UDS was calculated using equation [10].

$$m_{ppm,sample} = \frac{m_{rheo\log y\_\text{mod}ifier}}{m_{sample}} \cdot 10^6 \ ppm \qquad [9]$$

$$m_{ppm,UDS} = \frac{m_{rheo\log y\_\text{mod}ifier} \cdot 100\%}{m_{sample} \cdot wt\%_{UDS}} \cdot 10^6 \ ppm \qquad [10]$$

4.0 Results and Discussion

The baseline physical properties and pH of the tested melter feeds are provided in Table 4-1. All the melter feeds tested are either neutral or acidic in nature and both RuRhHg 1-9 decanted and 09-SB5-23 exceeded the rheological design basis of DWPF SME/melter feed processes. Table 4-1 also includes the standard deviation and % standard deviation of both the plastic viscosity (PV) and Bingham Plastic yield stress (BPYS). The percent standard deviations for the BPYS are within 3.5%, indicating that the measurements are consistent. Rheology modifiers concentrations that reduce the yield stress and plastic viscosity by at least 10% will be identified.

Table 4-1 Physical and pH Properties of Baseline Melter Feeds

Property	Melter Feed					
	RuRhHg 1-9	RuRhHg 1-9 Decanted	08-SB5-12/13	09-SB5-23	09-SB5-24	SB6-1,2,3,4
pH	4.70	4.59	6.27	7.37	5.14	6.02
Density (g/ml)	1.374	1.652	1.386	1.501	1.481	1.119
wt% TS	51.48	59.79	46.78	50.24	49.02	45.72
wt%DSS	17.08	16.80	16.24	20.37	20.52	16.36
wt% UDS	41.49	51.67	36.46	37.51	35.86	35.10
Plastic Viscosity (cP)	38.7	92.9	31.7	66.6	32.8	21.1
PV standard deviation (cP)	2.9	2.1	0.4	1.3	1.7	0.5
PV % standard deviation	7.5	2.3	1.2	1.9	5.2	2.4
Bingham Plastic YS (Pa)	13.38	72.5	6.58	24.4	5.22	2.217
BPYS standard deviation (cP)	0.11	1.0	0.22	0.3	0.10	0.06
BPYS % standard deviation	0.8	1.4	3.4	1.4	1.9	2.6

Appendix A contains the yield stress measurements using flow curves from various geometries and the displacement vane method for RuRhHg 1-9 SME simulant. The results indicate that the basic Z38/Z41 geometry does not result in measurable slip. The slip issue was also addressed with the very viscous RuRhHg 1-9 decanted SME simulant, where the serrated Z38/Z41 geometry and basic Z38/Z41 geometry yielded essentially the same results as shown in Table C - 1. This supports that slip is not expected to be an issue with SME products and the utilization of the Z38/Z41 geometry.

The physical properties of the fluid rheology modifiers are provided in Table 4-2. The MSDS for Dolapix A88 states that boiling point is 100°C, hence the 0 wt% TS. If it is assumed that the other organic materials in the other fluid rheology modifiers are not volatile at 105°C, then the active ingredients in the rheology modifier is blended with the water so that it can be produced, transported and applied at the end users facility. The active components in these fluid rheology modifiers, assuming the boiling process at DWPF does not impact their performance, is also provided in Table 4-2 by multiplying the added ppm by the wt% solids in the rheology modifier to obtain the active ppm. The active ppm of all the fluid rheology modifiers are lower than those of the powder rheology modifiers, assuming that the four concentration levels are equivalent between the powder and fluid rheology modifiers, e.g. 10000ppm is equivalent to 16000ppm. A method to compare these two general types of modifiers is to add the fluid rheology modifiers at an equivalent ppm based on the active component, evaporate off the excess water and then compare the rheology properties.

Table 4-2 Density and Total Solids of Liquid Type Rheology Modifiers

Property	Rheology Modifier					
	Recover®	ADVA Flex	ADVA Cast 555	Dolapix A88	Dolapix C64	Dolapix PC75
Density (g/ml)	1.110	1.076	1.030	0.949	1.093	1.209
Wt% Total Solids	21.81	30.16	17.14	0.00	22.41	47.18
PPM active at 1000 PPM addition	218	302	171	0	224	472
PPM active at 6000 PPM addition	1309	1810	1028	0	1345	2831
PPM active at 10000 PPM addition	2181	3016	1714	0	2241	4718
PPM active at 16000 PPM addition	3490	4826	2742	0	3586	7549

The effect the various rheology modifiers have on pH, rheological properties and the percent changes are provided in Table 4-3, Table 4-4, Table 4-5, Table 4-6, Table 4-7, and Table 4-8 for RuRhHg 1-9, RuRhHg 1-9 decanted, 08-SB5-12-13, 09-SB5-23, 09-SB5-24, and SB6-1,2,3,4 respectively. The baseline pH and rheological values are also provided in these tables, as a reference. Highlighted light blue cells indicate that the percent changes are greater than ten percent. For pH, the change can be positive or negative. For the rheological properties, only changes which are negative are highlighted, since positive changes are not considered as effective changes. From these tables, a general observation on the pH indicates that citric acid and polyacrylic acid tend to decrease the pH and Dolapix A88 and sodium metasilicate increased the pH. The other rheology modifiers had little impact on pH. This may not be the case if the applied concentrations exceed those tested.

There was only one visual observation worth noting. When PAA was applied to the RuRhHg 1-9 SME simulants, the resulting slurry seemed to be much more cohesive as compared to the baseline and other rheology modifiers, at the higher concentrations. This observation was based on two parameters, visually on how well the simulant clung to the slides of the mixing bottles and during the mixing (shaking) activity, the noise made by fluid was uniquely different (more quite) as compare to the other RuRhHg 1-9 simulants. This typically required more vigorous mixing prior to the rheology measurement, so that the fluid would pour out of the bottle. This can also be observed in Figure B - 3,and Figure C - 3 at the higher concentrations, which show an overshoot on the measured shear stress at the beginning of the up flow curve.

Table 4-3 Modifier Effect on pH, Yield Stress, and Plastic Viscosity for RuRhHg 1-9 SME

Admixture	PPM		pH		Yield Stress		Plastic Viscosity	
	Sludge	UDS	Meas.	%change	Pa	% Change	cP	% Change
Baseline	-	-	4.7	0.0	13.4	0.0	38.7	0.0
Recover®	1007	2185	4.33	-7.9	12.0	-10.2	43.2	11.7
	6006	13030	4.31	-8.3	10.4	-22.0	42.3	9.2
	10918	23685	4.32	-8.1	9.4	-30.0	38.9	0.5
	16121	34973	4.32	-8.1	9.0	-32.7	40.9	5.5
Polyacrylic Acid	937	2033	4.32	-8.1	8.4	-37.2	32.1	-17.1
	3466	7520	4.19	-10.9	6.8	-49.0	23.9	-38.3
	6930	15034	4.08	-13.2	6.9	-48.5	24.2	-37.6
	9954	21594	4.01	-14.7	8.1	-39.8	23.8	-38.6
Citric Acid	1001	2172	4.28	-8.9	10.3	-23.1	40.6	4.9
	3518	7632	4.08	-13.2	10.1	-24.6	39.5	2.1
	7006	15198	3.94	-16.2	10.4	-22.2	41.2	6.4
	9996	21685	3.86	-17.9	11.4	-14.5	40.4	4.3
Sodium Pyrophosphate Tetrabasic	1031	2236	4.34	-7.7	12.2	-8.6	38.3	-1.0
	3488	7568	4.43	-5.7	14.8	10.6	32.6	-15.7
	7002	15190	4.50	-4.3	19.7	47.2	25.8	-33.4
	9983	21658	4.58	-2.6	23.9	79.0	34.3	-11.5
Dolapix A88	847	1837	4.64	-1.3	12.9	-3.9	43.8	13.1
	2902	6295	4.82	2.6	12.0	-10.4	44.9	16.1
	5889	12776	5.17	10.0	11.9	-11.0	40.8	5.4
	9838	21342	6.11	30.0	16.4	22.6	28.1	-27.6
Dolapix CE64	946	2053	4.55	-3.2	12.5	-6.7	40.8	5.3
	5962	12934	4.55	-3.2	10.2	-23.7	28.2	-27.2
	10928	23707	4.56	-3.0	8.5	-36.2	26.1	-32.6
	15974	34654	4.56	-3.0	7.6	-43.0	23.0	-40.6
Dolapix PC75	984	2135	4.49	-4.5	11.1	-16.9	41.3	6.7
	5987	12988	4.50	-4.3	10.0	-25.1	42.0	8.5
	11001	23866	4.50	-4.3	9.2	-31.5	40.4	4.4
	15990	34690	4.50	-4.3	9.1	-31.8	40.1	3.6
ADVA Flex	1115	2419	4.38	-6.8	11.1	-16.7	39.4	1.8
	6023	13067	4.38	-6.8	8.0	-40.2	35.5	-8.4
	11069	24013	4.33	-7.9	5.8	-57.0	32.5	-16.0
	16080	34886	4.31	-8.3	4.1	-69.2	28.8	-25.5

Table 4-4 Modifier Effect on pH, Yield Stress, and Plastic Viscosity for RuRhHg 1-9 Decanted SME

Admixture	PPM		pH		Yield Stress		Plastic Viscosity	
	Sludge	UDS	Meas.	%change	Pa	% Change	cP	% Change
Baseline	-	-	4.59	0.0	72.5	0.0	92.9	0.0
Recover®	1064	2059	4.45	-3.1	69.7	-3.9	98.1	5.6
	6041	11693	4.48	-2.4	59.0	-18.7	88.5	-4.7
	11026	21340	4.46	-2.8	56.3	-22.4	85.5	-7.9
	16006	30979	4.49	-2.2	50.4	-30.5	84.6	-9.0
Polyacrylic Acid	992	1920	4.44	-3.3	39.5	-45.5	73.5	-20.8
	3491	6757	4.24	-7.6	25.2	-65.3	49.4	-46.9
	7009	13565	4.09	-10.9	23.1	-68.1	65.7	-29.2
	10003	19359	3.98	-13.3	26.7	-63.2	58.1	-37.4
Citric Acid	1054	2040	4.29	-6.5	59.1	-18.6	98.9	6.5
	3506	6785	4.16	-9.4	52.8	-27.2	94.9	2.2
	7020	13586	4.13	-10.0	59.6	-17.8	96.1	3.5
	10000	19355	3.85	-16.1	58.7	-19.0	96.7	4.1
Dolapix CE64	1095	2120	4.40	-4.1	65.4	-9.9	79.4	-14.5
	6015	11641	4.34	-5.4	50.5	-30.3	68.0	-26.8
	11001	21292	4.34	-5.4	42.2	-41.8	49.1	-47.1
	16051	31066	4.38	-4.6	37.2	-48.6	30.4	-67.3
ADVA FLEX	1062	2056	4.44	-3.3	61.3	-15.5	102.1	9.9
	5994	11602	4.46	-2.8	42.9	-40.8	88.8	-4.4
	11005	21300	4.44	-3.3	31.0	-57.2	79.7	-14.2
	16011	30988	4.45	-3.1	21.7	-70.1	77.0	-17.1
ADVA Cast 555	1023	1979	4.64	1.1	65.9	-9.2	89.7	-3.5
	6073	11755	4.61	0.4	45.8	-36.9	94.3	1.5
	11042	21371	4.60	0.2	32.4	-55.3	86.5	-6.9
	16040	31044	4.58	-0.2	25.4	-65.0	74.7	-19.6
Sugar	1012	1959	4.64	1.1	69.0	-4.9	97.1	4.5
	3511	6796	4.56	-0.7	70.9	-2.3	89.3	-3.9
	7031	13608	4.59	0.0	63.8	-12.1	97.3	4.8
	10012	19378	4.57	-0.4	59.9	-17.4	98.3	5.8
Sodium Metasilicate	1019	1972	4.72	2.8	70.1	-3.3	92.7	-0.2
	3523	6819	4.81	4.8	61.8	-14.8	95.0	2.3
	7044	13634	5.04	9.8	58.9	-18.8	87.8	-5.5
	10002	19358	5.20	13.3	65.2	-10.1	79.5	-14.4
Phenylboric Acid	1045	2022	4.83	5.2	66.8	-7.9	102.0	9.8
	3506	6785	4.68	2.0	66.3	-8.6	102.0	9.7
	7033	13612	4.65	1.3	68.4	-5.7	90.2	-2.9
	10018	19389	4.65	1.3	66.1	-8.9	107.0	15.2

Table 4-5 Modifier Effect on pH, Yield Stress, and Plastic Viscosity for 08-SB5-12/13 SME

Admixture	PPM		pH		Yield Stress		Plastic Viscosity	
	Sludge	UDS	Meas.	%change	Pa	% Change	cP	% Change
Baseline	-	-	6.27	0.0	6.6	0.0	31.7	0.0
Recover®	990	2715	6.30	0.5	6.3	-3.6	32.8	3.3
	6174	16935	6.28	0.2	5.3	-19.4	35.5	11.8
	10897	29888	6.22	-0.8	4.7	-28.9	32.0	0.9
	16041	43997	6.18	-1.4	4.2	-36.2	29.7	-6.5
Polyacrylic Acid	976	2677	5.98	-4.6	7.6	14.8	34.4	8.3
	3575	9805	5.31	-15.3	8.7	32.9	28.6	-10.1
	7166	19656	4.89	-22.0	6.5	-1.2	25.7	-18.9
	10509	28823	4.63	-26.2	3.3	-49.1	23.7	-25.4
Citric Acid	1029	2823	5.89	-6.1	5.5	-16.0	32.5	2.4
	3590	9847	5.19	-17.2	4.3	-35.3	29.8	-6.3
	7064	19375	4.70	-25.0	3.9	-40.6	26.5	-16.6
	10005	27442	4.51	-28.1	3.2	-50.8	28.7	-9.7
Sodium Pyrophosphate Tetrabasic	1125	3085	6.35	1.3	7.3	10.8	35.3	11.2
	3551	9739	6.36	1.4	7.7	17.1	34.5	8.7
	7078	19413	6.44	2.7	8.2	24.8	37.2	17.2
	10075	27633	6.35	1.3	8.4	27.5	41.3	30.2
Dolapix A88	1057	2900	6.76	7.8	8.7	31.8	36.5	15.0
	3103	8510	7.03	12.1	10.4	57.8	36.2	14.0
	6132	16819	7.52	19.9	13.9	111.3	31.7	-0.2
	10009	27453	7.92	26.3	17.0	158.1	32.0	0.9
Dolapix CE64	1058	2901	6.37	1.6	7.2	8.9	34.2	7.8
	6074	16659	6.27	0.0	9.0	36.0	33.5	5.4
	11009	30196	6.32	0.8	9.5	44.4	32.2	1.5
	16057	44040	6.28	0.2	8.5	29.4	29.3	-7.8
Dolapix PC75	1034	2836	6.23	-0.6	6.4	-3.2	35.5	12.0
	6096	16721	6.21	-1.0	5.9	-10.8	33.4	5.3
	11083	30397	6.20	-1.1	6.3	-4.6	31.8	0.3
	16055	44037	6.19	-1.3	6.6	0.3	34.2	7.7
ADVA CAST 555	1121	3076	6.33	1.0	6.65	1.0	32.2	1.4
	3446	9451	6.35	1.3	5.26	-20.1	34.0	7.0
	7099	19472	6.37	1.6	3.53	-46.3	31.6	-0.4
	11189	30688	6.27	0.0	2.32	-64.8	32.9	3.5

Table 4-6 Modifier Effect on pH, Yield Stress, and Plastic Viscosity for 09-SB5-23 SME

Admixture	PPM		pH		Yield Stress		Plastic Viscosity	
	Sludge	UDS	Meas.	%change	Pa	% Change	cP	% Change
Baseline	-	-	7.37	0.0	24.4	0.0	66.6	0.0
Recover®	1044	2784	7.02	-4.7	23.7	-2.9	61.3	-8.0
	6104	16273	7.13	-3.3	19.5	-20.2	56.7	-14.9
	11221	29915	7.21	-2.2	16.5	-32.3	59.6	-10.6
	16108	42943	7.15	-3.0	15.1	-38.3	57.7	-13.5
Polyacrylic Acid	988	2634	6.92	-6.1	24.8	1.5	57.9	-13.1
	3548	9458	6.54	-11.3	20.6	-15.8	42.3	-36.5
	6986	18624	5.96	-19.1	12.5	-49.0	28.4	-57.4
	10010	26685	5.43	-26.3	5.7	-76.7	27.7	-58.4
Citric Acid	1055	2813	7.15	-3.0	19.4	-20.4	57.8	-13.3
	3512	9363	6.81	-7.6	17.7	-27.7	59.0	-11.4
	7065	18834	6.20	-15.9	11.6	-52.5	54.0	-19.0
	10055	26805	5.62	-23.7	8.5	-65.3	42.5	-36.2
ADVA FLEX	1068	2847	7.40	0.4	21.6	-11.5	57.7	-13.5
	6142	16373	7.50	1.8	15.2	-37.9	50.2	-24.6
	11007	29343	7.52	2.0	12.1	-50.4	40.7	-39.0
	16120	42975	7.47	1.4	9.4	-61.7	40.2	-39.7
ADVA CAST 555	1077	2872	7.22	-2.0	22.4	-8.4	65.8	-1.3
	6068	16178	7.30	-0.9	18.2	-25.3	58.8	-11.7
	11082	29542	7.47	1.4	15.4	-36.8	56.0	-15.9
	16130	43000	7.47	1.4	13.3	-45.5	55.2	-17.2

Table 4-7 Modifier Effect on pH, Yield Stress, and Plastic Viscosity for 09-SB5-24 SME

Admixture	PPM		pH		Yield Stress		Plastic Viscosity	
	Sludge	UDS	Meas.	%change	Pa	% Change	cP	% Change
Baseline	-	-	5.14	0.0	5.22	0.0	32.8	0.0
Recover®	1115	3109	5.60	8.9	4.98	-4.6	32.7	-0.2
	6010	16760	5.69	10.7	4.06	-22.4	31.9	-2.7
	11156	31112	5.64	9.7	3.64	-30.3	31.5	-3.9
	16000	44619	5.61	9.1	3.28	-37.2	30.8	-6.0
Polyacrylic Acid	1020	2844	5.20	1.2	6.45	23.5	30.5	-7.1
	3528	9839	4.75	-7.6	6.08	16.3	28.3	-13.6
	7096	19789	4.41	-14.2	4.12	-21.2	28.2	-14.1
	10158	28329	4.19	-18.5	2.67	-48.9	25.4	-22.5
Citric Acid	1049	2926	5.22	1.6	3.96	-24.1	31.1	-5.2
	3536	9860	4.64	-9.7	3.70	-29.1	29.1	-11.2
	7018	19573	4.26	-17.1	4.24	-18.9	28.2	-13.9
	10054	28040	4.01	-22.0	4.65	-11.0	28.7	-12.3
ADVA FLEX	1035	2886	5.30	3.1	4.99	-4.5	31.8	-3.1
	6201	17292	5.12	-0.4	4.04	-22.6	29.3	-10.8
	11100	30956	4.99	-2.9	4.29	-17.8	29.3	-10.8
	16154	45049	4.92	-4.3	4.78	-8.6	32.0	-2.5
ADVA CAST 555	1008	2811	5.37	4.5	4.78	-8.5	31.6	-3.6
	6070	16927	5.36	4.3	3.94	-24.5	32.4	-1.3
	11189	31204	5.33	3.7	3.42	-34.6	33.6	2.4
	16397	45726	5.27	2.5	4.25	-18.7	32.2	-1.7

Table 4-8 Modifier Effect on pH, Yield Stress, and Plastic Viscosity for SB6-1,2,3,4 SME

Admixture	PPM		pH		Yield Stress		Plastic Viscosity	
	Sludge	UDS	Meas.	%change	Pa	% Change	cP	% Change
Baseline	-	-	6.02	0.0	2.2	0.0	21.1	0.0
Recover®	1093	3114	6.21	3.2%	2.43	11.6%	17.5	-17.0%
	6103	17388	6.17	2.5%	1.91	-12.3%	19.4	-7.9%
	11107	31643	6.10	1.3%	1.62	-25.5%	18.7	-11.4%
	16145	45996	5.85	-2.8%	1.41	-35.2%	18.7	-11.5%
Polyacrylic Acid	1025	2920	5.89	-2.2%	3.25	49.4%	18.6	-11.9%
	3589	10226	5.32	-11.6%	2.96	36.2%	16.4	-22.1%
	7010	19972	4.77	-20.8%	2.38	9.6%	15.3	-27.4%
	9996	28479	4.50	-25.2%	1.61	-26.1%	15.6	-26.1%
Citric Acid	1050	2992	5.10	-15.3%	2.26	3.9%	20.2	-4.2%
	3523	10036	4.49	-25.4%	2.16	-0.5%	17.6	-16.6%
	7029	20026	3.97	-34.1%	2.21	1.5%	19.8	-6.1%
	10035	28588	3.70	-38.5%	2.33	7.4%	20.0	-5.4%
Sodium Pyrophosphate Tetrabasic	1007	2869	6.17	2.5%	2.44	12.1%	19.5	-7.8%
	3513	10008	6.26	4.0%	-	-	-	-
	7104	20238	6.27	4.2%	2.46	13.0%	21.8	3.5%
	10036	28593	6.28	4.3%	2.43	11.7%	22.5	6.6%
Dolapix A88	1080	3076	6.06	0.7%	3.11	42.9%	21.0	-0.5%
	3058	8712	6.13	1.8%	3.24	49.2%	21.9	3.9%
	6149	17518	6.42	6.6%	4.25	95.5%	21.3	1.1%
	10055	28646	6.77	12.5%	5.12	135.6%	20.6	-2.4%
Dolapix CE64	1044	2975	6.09	1.2%	2.91	33.9%	20.3	-3.8%
	6138	17486	6.13	1.8%	3.36	54.8%	21.8	3.4%
	11126	31698	6.12	1.7%	3.23	48.8%	22.0	4.1%
	16049	45723	6.10	1.3%	2.65	22.1%	21.8	3.5%
Dolapix PC75	1083	3085	6.03	0.2%	2.12	-2.4%	18.3	-13.1%
	6084	17334	6.01	-0.2%	1.78	-17.9%	20.9	-0.7%
	10998	31333	6.01	-0.2%	1.84	-15.4%	20.4	-3.4%
	16519	47062	6.03	0.2%	1.88	-13.7%	19.9	-5.5%
Taylor Antifoam 747	1013	2886	6.01	-0.2%	2.57	18.4%	20.9	-0.7%
	6009	17120	6.10	1.3%	2.51	15.4%	21.8	3.5%
	11143	31747	6.08	1.0%	2.48	13.9%	22.1	4.8%
	16027	45660	6.08	1.0%	2.47	13.7%	23.6	11.9%

The results from Table 4-3 through Table 4-8 are summarized in Table 4-9 and Table 4-10, showing only the effective rheology modifiers (greater than 10% reduction) on the yield stress and the combination of both the yield stress and plastic viscosity respectively. Modifiers which reduced the yield stress by as much as 50 percent were polyacrylic acid, citric acid, ADVA Flex, and ADVA Cast 555 and typically occur at the higher concentrations. Sodium pyrophosphate terabasic, phenylboric acid, and Taylor Antifoam were found to be ineffective rheology modifiers. The effect of starting pH can be observed in 09-SB5-23 and 09-SB5-24, where the rheology modifier was not as effective in the more acidic stream, 09-SB5-24.

Table 4-9 Rheology Modifier That Reduced Yield Stress by at Least 10%

Modifier	Sequence of Testing (if YES, then percent change is provided)						
	Nominal ppm sludge basis	RuRhHg 1-9	08-SB5-12/13	SB6-1,2,3,4	09-SB5-23	09-SB5-24	RuRhHg 1-9 Decanted
Recover®	1000	YES,-10.2	No	No	No	No	No
	6000	YES, -22.0	YES, -19.4	YES, -12.3	YES, -20.2	YES, -22.4	YES, -18.7
	11000	YES, -30.0	YES, -28.9	YES, -25.5	YES, -32.3	YES, -30.3	YES, -22.4
	16000	YES, -32.7	YES, -36.2	YES, -35.2	YES, -38.3	YES, -37.2	YES, -30.5
Polyacrylic Acid	1000	YES, -37.2	No	No	No	No	YES, -45.5
	3500	YES, -49.0	No	No	YES, -15.8	No	YES, -65.3
	7000	YES, -48.5	No	No	YES, -49.0	YES, -21.2	YES, -68.1
	10000	YES, -38.9	YES, -49.1	YES, -26.1	YES, -76.7	YES, -48.9	YES, -63.2
Citric Acid	1000	YES, -23.1	YES, -16.0	No	YES, -20.4	YES, -24.1	YES, -18.6
	3500	YES, -24.6	YES, -35.3	No	YES, -27.7	YES, -29.1	YES, -27.2
	7000	YES, -22.2	YES, -40.6	No	YES, -52.5	YES, -18.9	YES, -17.8
	10000	YES, -14.5	YES, -50.8	No	YES, -65.3	YES, -11.0	YES, -19.0
Dolapix A88	3000	YES, -10.4	No	No	-	-	-
	6000	YES, -11.0	No	No	-	-	-
Dolapix CE64	6000	YES, -23.7	No	No	-	-	YES, -30.3
	11000	YES, -36.2	No	No	-	-	YES, -41.8
	16000	YES, -43.0	No	No	-	-	YES, -48.6
Dolapix PC75	1000	YES, -16.9	No	No	-	-	-
	6000	YES, -25.1	YES, -10.8	YES, -17.9	-	-	-
	11000	YES, -31.5	No	YES, -15.4	-	-	-
	16000	YES, -31.8	No	YES, 13.7	-	-	-
ADVA Flex	1000	YES, -16.7	-	-	YES, -11.5	No	YES, -15.5
	6000	YES, -40.2	-	-	YES, -37.9	YES, -22.6	YES, -40.8
	11000	YES, -57.0	-	-	YES, -50.4	YES, -17.8	YES, -57.2
	16000	YES, -69.2	-	-	YES, -61.7	No	YES, -70.1
ADVA Cast 555	6000	-	YES, -20.1	-	YES, -25.3	YES, -24.5	YES, -36.9
	11000	-	YES, -46.3	-	YES, -36.8	YES, -34.6	YES, -55.3
	16000	-	YES, -64.8	-	YES, -45.5	YES, -18.7	YES, -65.0
Sugar	7000	-	-	-	-	-	YES, -12.1
	10000	-	-	-	-	-	YES, -17.4
Sodium Metasilicate	3500	-	-	-	-	-	YES, -14.8
	7000	-	-	-	-	-	YES, -18.8
	10000	-	-	-	-	-	YES, -10.1

- = modifier was not used for this melter feed

Table 4-10 Rheology Modifier That Reduced Yield Stress and Plastic Viscosity By At Least 10%

Modifier	Sequence of Testing (If yes, then percent change in yield stress and plastic viscosity provided)						
	Nominal ppm sludge basis	RuRhHg 1-9	08-SB5-12/13	SB6-1,2,3,4	09-SB5-23	09-SB5-24	RuRhHg 1-9 Decanted
Recover®	6000	No	No	No	YES, -20.2, -14.9	No	No
	11000	No	No	YES, -25.5, -11.4	YES, -32.3, -10.6	No	No
	16000	No	No	YES, -35.2, -11.5	YES, -38.3, -13.5	No	No
Polyacrylic Acid	1000	YES, -37.2, -17.1	No	No	No	No	YES, -45.5, -20.8
	3500	YES, -49.0, -38.3	No	No	YES, -15.8, -36.5	No	YES, -65.3, -46.9
	7000	YES, -48.5, -37.6	No	No	YES, -49.0, -57.4	YES, -21.2, -14.1	YES, -68.1, -29.2
	10000	YES, -38.9, -38.6	YES, -49.1, -25.4	YES, -26.1, -26.1	YES, -76.7, -58.4	YES, -48.9, -22.5	YES, -63.2, -37.4
Citric Acid	1000	No	No	No	YES, -20.4, -13.3	No	No
	3500	No	No	No	YES, -27.7, -11.4	YES, -29.1, -11.2	No
	7000	No	YES, -40.6, -16.6	No	YES, -52.5, -19.0	YES, -18.9, -13.9	No
	10000	No	No	No	YES, -65.3, -36.2	YES, -11.0, -12.3	No
Dolapix CE64	6000	YES, -23.7, -27.2	No	No	-	-	YES, -30.3, -26.8
	11000	YES, -36.2, -32.6	No	No	-	-	YES, -41.8, -47.1
	16000	YES, -43.0, -40.6	No	No	-	-	YES, -48.6, -67.3
ADVA Flex	1000	No	-	-	YES, -11.5, -13.5	No	No
	6000	No	-	-	YES, -37.9, -24.6	YES, -22.6, -10.8	No
	11000	YES, -57.0, -16.0	-	-	YES, -50.4, -39.0	YES, -17.8, -10.8	YES, -57.2, -14.2
	16000	YES, -69.2, -25.5	-	-	YES, -61.7, -39.7	No	YES, -70.1, -17.1
ADVA Cast 555	6000	-	No	-	YES, -25.3, -11.7	No	No
	11000	-	No	-	YES, -36.8, -15.9	No	No
	16000	-	No	-	YES, -45.5, -17.2	No	YES, -65.0, -19.6
Sodium Metasilicate	10000	-	-	-	-	-	YES, -10.1, -14.4

- = modifier was not used for this melter feed

5.0 Conclusions

Five unique DWPF melter feed simulants, RuRhHg 1-9, 08-SB5 12-13, SB6-1,2,3,4, 09-SB5-23, and 09-SB5-24.were tested using both powder and liquid rheology modifiers. RuRhHg 1-9 was decanted and tested at a higher solids loading. Twelve different rheology modifiers, Recover®, polyacrylic acid, citric acid, sodium pyrophosphate tetrabasic, Dolapix A88, Dolapix CE64, Dolapix PC75, ADVA Flex, ADVA Cast 555, Taylor Antifoam, sugar, sodium metasilicate and phenylboric acid were tested on various simulants and at different concentrations. For dry rheology modifiers, the additions were 1000 to 10,000ppm and for fluid rheology modifiers the additions were 1000 to 16,000ppm. The active ingredients in the water based rheology modifiers when corrected for wt% total solids were typically much lower than that of powder rheology modifiers.

Rheology modifiers Recover®, polyacrylic acid (molecular weight ≈ 2000 grams), and citric acid were tested on all the simulants. Recover® and polyacrylic acid were effective in reducing the yield stress by at least 10% for all the simulants at some given concentration of rheology modifier. The rheology modifiers that reduced the yield stress by more than 50% were polyacrylic acid, citric acid, ADVA Flex, and ADVA Cast 555 at this occurred at the higher modifier concentrations. ADVA Flex and ADVA Cast 555 are polycarboxylate, which are copolymers of acrylic acid and maleic acid, hence this could be the reason for the similar performance between the ADVA's and polyacrylic acid. The lengths of the organic chains (or molecular weight) of polyacrylic acid and polycarboxylate are a variable not studied in this task and are proprietary to the manufacturer for the two ADVA's tested. The ADVA series uses water to carrier the rheology modifiers while the citric acid and polyacrylic acid are solids and dissolve in the SME products. These rheology modifiers also reduced the both the yield stress and plastic viscosity by greater than 10% for many of the tested SME simulants. These rheology modifiers are also organic, hence can be used as a reductant for melter operations.

The Dolapix A88, CE64 and PC75 were not as effective as the previously mentioned rheology modifiers in the SME simulants they were tested in. For some of the melter feeds, the Dolapix series of modifiers reduced the yield stress by more than 10% and in some cases it also reduced the plastic viscosity by greater than 10%, but not to higher percentages as seen with the polycarboxylate rheology modifiers. Sugar was used on the most concentrated melter feed, RuRhHg 1-9 decanted, and was shown to slightly reduce the yield stress by 10% at the higher concentrations. These modifiers are also organic, hence can be used as a reductant for melter operations. The only inorganic rheology modifier that reduced the yield stress by 10% was sodium metasilicate and at is highest concentration. Sodium pyrophosphate tetrabasic, phenylboric acid, and Taylor Antifoam were found to be ineffective rheology modifiers.

The starting pH may have an effect on the effectiveness of the rheology modifier. This was observed in the 09-SB5-23 and 09-SB5-24 SME products, where the rheology modifiers were not as effective in the more acidic stream, which was 09-SB5-24 SME.

Though there was not adequate data to determine the actual gain in solids throughput for a single SME product, due to the lack of wt% solids and rheological data points, it can be observed in the RuRhHg 1-9 simulant that the effective rheology modifiers are a definite benefit. The differences in wt% TS and wt% UDS in RuRhHg1 1-9 and RuRhHg 1-9 decanted are 8.3 and 10.2 wt%. The yield for the RuRhHg 1-9 baseline simulant is 13.4 Pa and for the RuRhHg 1-9 decanted, 16000ppm (2742ppm active) ADVA Cast 555 is 21.7 Pa. This reduction in yield stress clearly shows that there is an intermediate wt% solids condition, much greater than 51.5 wt% TS but less than 59.8 wt% than can be processed at nearly the same hydraulic conditions as the RuRhHg 1-9 SME baseline condition.

The results clearly indicate that the effective rheology modifiers can reduce the rheological properties, hence drastically increasing the wt% that could eventually be processed through the melter. The overall benefit of such modifiers must also take into consideration of process conditions, which were not investigated in this task. Such process conditions include boiling to evaporate the water, acid chemistry, and melt rate and this list may not be inclusive.

6.0 Future Work/Path Forward

It is recommended that both citric acid and commercially available polycarboxylate rheology modifiers be further investigated. Different molecular weight polycarboxylates and different types of polycarboxylates used in other industries must be considered. These polycarboxylates are extensively utilized in the cement, ceramic, and water treatment processes, hence readily available. Future work on DWPF melter feeds involving rheology modifiers should include, assuming the present method of processing sludge through DPWF does not change, is:

1. Investigate the use of polycarboxylate in various processes and procure polycarboxylates for testing. Limit rheology modifier selection and future testing between four and eight different types.
2. Test rheology modifiers on at least two different chemical types or bounding DWPF SME product simulants. Test to include the impact of boiling and the effectiveness in reducing water content via rheology versus weight percent curves.
3. Based on selected modifiers, perform testing on actual radioactive melter feed based on results from simulant testing.

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Appendix A – Yield Stress Measurements To Determine If Slip Is An Issue

An issue that can arise using the Z38 rotor/Z41 cup (or any other geometry where the surfaces are not serrated or rough) is slip. This occurs in fluids that contain high concentrations of undissolved solids, which during the measurement, migrate away from the rotating Z38 rotor due to centrifugal force, leaving a fluid at the surface of the rotor depleted of solids. This results in lowered measured shear stress. It is not expected that DWPF melter feeds, which has a fairly low design basis values for yield stress (see Table 2-1) will have slip issues. To determine if slip is occurring, the yield stress was measured using various techniques for the baseline RuRhHg 1-9 SME as described below:

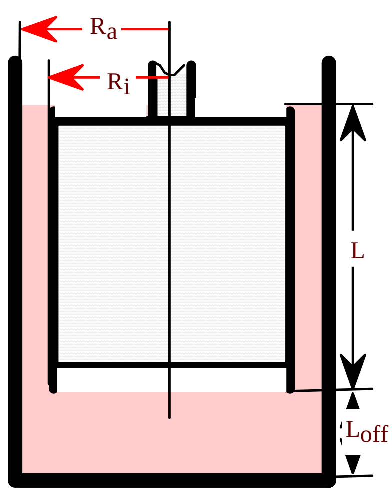
1. Flow Curves, data interpreted as a Bingham Plastic
    a. Flow curve using Z38 rotor and Z41 cup. See Table 3-16.
    b. Serrated Z38 rotor and serrated Z41 cup. Same flow curve as in Table 3-16.
    c. Modified flow curve, multiple measurements at lower shear rate
    d. Z31 rotor and Z41 cup with large gap between rotor and cup. Same flow curve program. See Table A - 2.
    e. FL22 vane rotor. Multiple flow curve program.
2. Vane Measurements – Specifically to measure yield stress
    a. FL22 vane rotor at different rotational speeds.

Table A - 1 Other Up Ramp Flow Curves

Letter	Rotor	Cup	Program
c	Z38	Z41	Shear rate: 0 – 1 sec^{-1}, Ramp Time 200 seconds Shear rate: 1 – 300 sec^{-1}, Ramp Time 100 seconds
e	FL22	Serrated Z41	(1) Shear rate: 0 – 60 sec^{-1}, Ramp Time 300 seconds (2) Shear rate: 0 – 100 sec^{-1}, Ramp Time 300 seconds

Table A - 2 Z31 Rotor Specification and Program Ramp Rates

Design of Rotor



Z31 Rotor Specifications

Rotor	Specification
Rotor radius (mm)	R_i = 15.72
Cup Radius (mm)	R_a = 21.70
Height of rotor (mm)	L = 55
Sample Volume (cm^3)	V = 52
Bottom off-set (mm)	L_{off} = 4
A factor (Pa/(N·m))	11710
M factor (s^{-1}/rad s^{-1})	4.21
Shear rate measuring range (s^{-1})	0 – 300
Ramp up time (min)	5
Hold time (min)	1
Ramp down time (min)	5

Vanes have been used to measure the yield stress of non-Newtonian fluids as shown in Figure A - 1.[a,b,c,d,e,f,g] The vane is inserted into the fluid and rotated at a very slow speed, unlike in flow curve measurement. The surface area used to determine the shear stress is the surface area produced by the vane, which is cylindrical. It has been shown that this is a good assumption for determining the yield stress of the fluid as the vane rotates through it.[f,g] Equation [A-1] assumes the stress is constant on all surfaces. The shearing due to the immersed section of the vane shaft, stress contribution of the immersed section of the shaft, and the wall effects are negligible when meeting the criteria as shown in Figure A - 1. The length of immersed shaft will need to be considered if its length starts to impact the measured stress, which was no the case in these measurements. The exclusion of the shear stress contribution of the immersed shaft length over-estimates the shear stress. For the samples measured in this task, the shaft was immerged up to the point where the shaft was turned in, which satisfies the measurement requirements.[a,b,c]

$$\tau = \frac{\Gamma}{\frac{\pi \cdot D^3}{2}\left(\frac{H}{D}+\frac{1}{3}\right)} = A \cdot \Gamma,\ A = \frac{2}{\pi \cdot D^3\left(\frac{H}{D}+\frac{1}{3}\right)}\left(\frac{1}{m^3}\ or\ \frac{Pa}{N \cdot m}\right) \qquad \text{[A-1]}$$

Where Γ = measured torque (N·m)
D = diameter of vane (m)
H = height of vane (m)
A = geometric constant (1/m^3 or Pa/(N·m))

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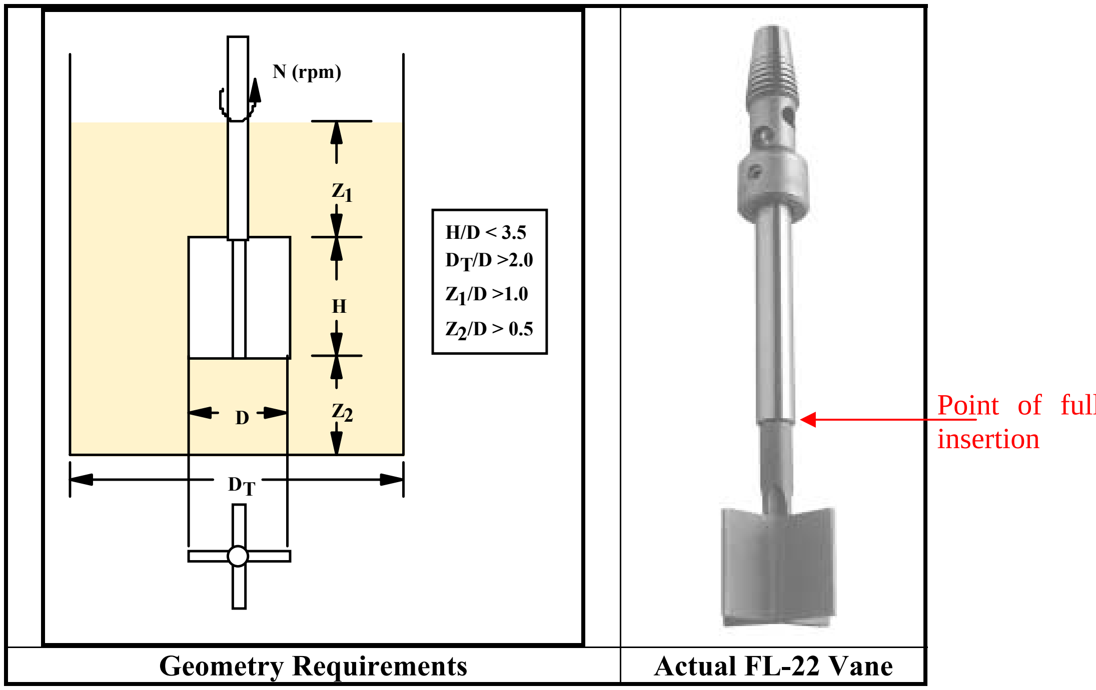


Figure A - 1 Vane Requirements and Actual Vane

A typical stress versus time (or displacement) curve is shown in Figure A - 2. The initial vane response for a non-Newtonian fluid having a yield stress is typically linear with a slope that is called the Hookean elastic modulus (G). The point of departure from this linear region, called the static yield stress,[a] occurs when the fluid starts to transition from a fully elastic to viscoelastic behavior. At the maximum stress, the behavior of the material transitions between viscoelastic and fully viscous and is called the yield stress (also known as the dynamic yield stress). This yield stress is the recorded value.

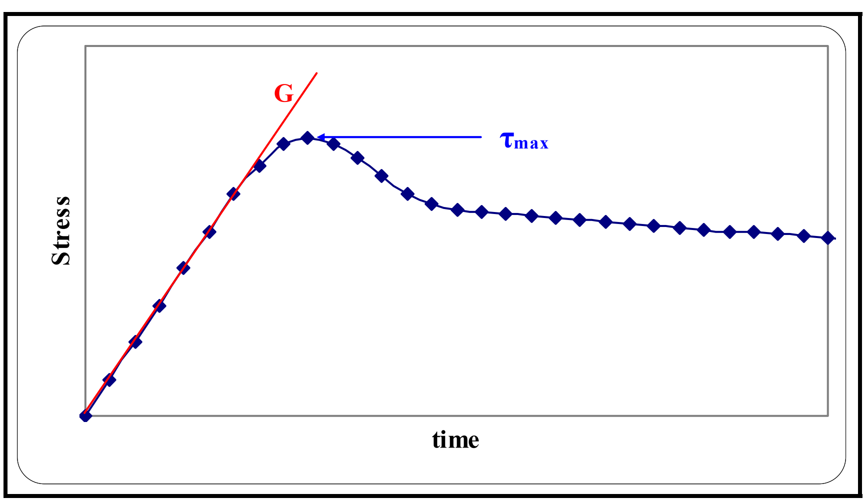


Figure A - 2 Typical Vane Torque Versus Time/Displacement Curve

The FL-22 vane dimensions are D = H = 16 mm. The A factor for this vane is shown in equation A-2.

$$A = \frac{A}{N \cdot m} = \frac{2}{\pi \cdot (0.016m)^3 \cdot \left(\left(\frac{16}{16} \right) + \frac{1}{3} \right)} \cdot \frac{N \cdot m}{N \cdot m} \cdot \frac{Pa}{\frac{N}{m^2}} = 116{,}568 \frac{Pa}{N \cdot m} \qquad \text{[A-2]}$$

The shear rate for a vane cannot be explicitly determined, due to the geometry of the vane and the method of measurement. Hence an M factor of 1.0 $sec^{-1}/(rad \cdot s^{-1})$ was selected for convenience. Rotational speeds of 0.03, 0.1, 0.3, and 1 RPM were used. The rotational speed of 0.3 RPM was obtained from literature[a,b] and from previous experience.[h] The shear rate at 0.3 RPM is determined using equation [A-3].

$$\dot{\gamma} = \frac{2\pi}{60} \cdot n = \frac{2\pi}{60} \cdot 0.3 = 0.031 \frac{1}{\sec} \qquad \text{[A-3]}$$

For the flow curve measurements using the vane as stated in Table A - 1, the maximum rotational speeds for shear rates of 60 s^{-1} and 100 s^{-1} are 573 and 955 rpm respectively. The primary advantage of using a vane is that slip does not occur.

The Bingham Plastic yield stress and plastic viscosity as well as the vane yield stress results are provided in Table A - 3. The flow curves and displacement curves are provided in Figure A - 3 through Figure A - 13 and they are listed in Table A - 3 for the corresponding results. The results indicate that slip is not an issue with the standard Z38/Z41 geometry.

The results show that the use of the standard Z38/Z41 geometry is not impacted by slip, which was expected. Items of interest include the following:

- The Z38 serrated data is almost the same as that of the standard Z38 geometry. The Z38 serrated geometry mitigates slip issues.
- Flow curves using concentric geometry (Z38 or Z31) had down flow curves above that of the up flow curves. It is assumed that the frit particles are platting out on the cup, sliding down the sides, and accumulating in the gap between the bob and cup, increasing the stress on the rotating bob. This assumption has not been proven. This increase in shear stress could potentially be mitigated if the gap at the bottom is increased to allow for the solids to settle out, but will require a large quantity of material for testing.
- The flow curves using the vane (FL22) did not have the same down flow curve issue as the concentric geometries. The up and down flow curves are almost on top of each other, even in the case where non-laminar flow was occurring at the higher shear rates as shown in Figure A - 9. The yield stress was slightly lower than that of the concentric geometries and could be due to the A and M factors used in the flow curves may not be appropriate for flow curve measurements. Definitely the M factor should be larger, for this specific geometry, which would reduce the plastic viscosity by extending the shear rate range.
- The yield stresses from the vane measurements are lower than those predicted by the flow curves. This was expected, unless the SME products are true Bingham Plastic fluids, which is not the case. The first part of the Z38 flow curves show a power law behavior, prior to following a linear response, which is were the plastic viscosity is obtained. Note that the flow curve data are fitted in a selected range of shear rates using a linear function,

[h] Smith, G.L., and Prindiville, K., "Guidelines for Performing Chemical, Physical, and Rheological Properties Measurements", 24590-WTP-GPG-RTD-001, Rev. 0, May 20,2002.

which impacts the yield stress comparison, favoring a higher reported yield stress from the flow curve measurements.

- The Z38 serrated geometry will be utilized in the case where the SME may be very thick.

Table A - 3 Yield Stress Measurements To Support Slip Issue

Name	Figure	Rotor	Plastic Viscosity (cP)	Yield Stress (Pa)	R^2	Shear Rate Range (sec^{-1})
Baseline 4-30-2009, R1	Figure A - 3	Z38	36.9	13.32	0.9983	30-300
Z31 5-5-2009	Figure A - 4	Z31	46.8	14.43	0.9971	30-300
Z38 5-5-2009, R2	Figure A - 5	Z38	39.1	13.28	0.9947	30-300
Z38 Serrated 5-5-2009	Figure A - 6	Z38	42.7	13.38	0.9972	30-300
Z38 Step 5-5-2009	Figure A - 7	Z38	36.2	13.54	0.9948	30-300
Vane Curve #1 5-5-2009	Figure A - 8	FL22	116.3	12.66	0.9045	10-60
Vane Curve #2 5-5-2009	Figure A - 9	FL22	117.1	11.93	0.9514	10-60
Vane 0.03 RPM 5-5-2009	Figure A - 10	FL22	-	8.55	-	-
Vane 0.1 RPM 5-5-2009	Figure A - 11	FL22	-	8.65	-	-
Vane 0.3 RPM 5-5-2009	Figure A - 12	FL22	-	8.70	-	-
Vane 1 RPM 5-5-20096	Figure A - 13	FL22	-	9.25	-	-

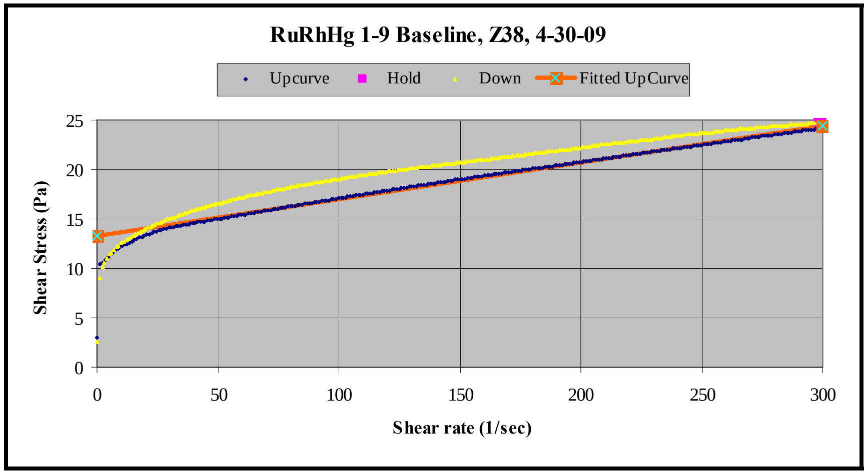


Figure A - 3 RuRhHg 1:9 Baseline: Z38_R1

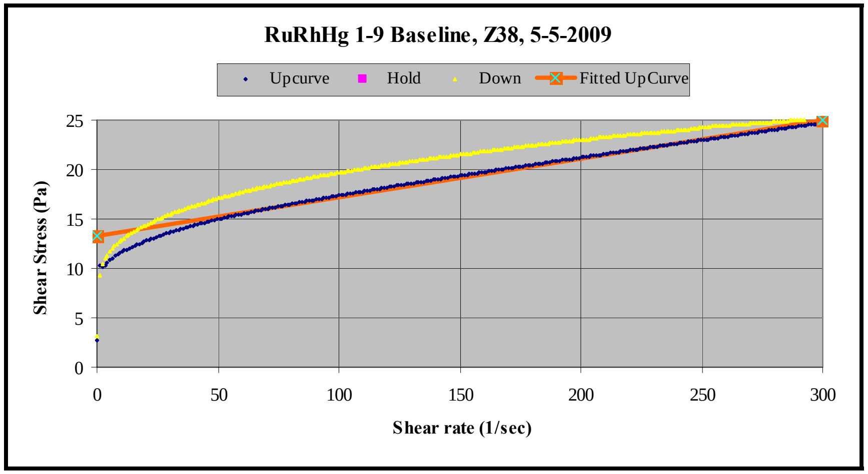


Figure A - 5 RuRhHg 1:9 Baseline: Z38_R2

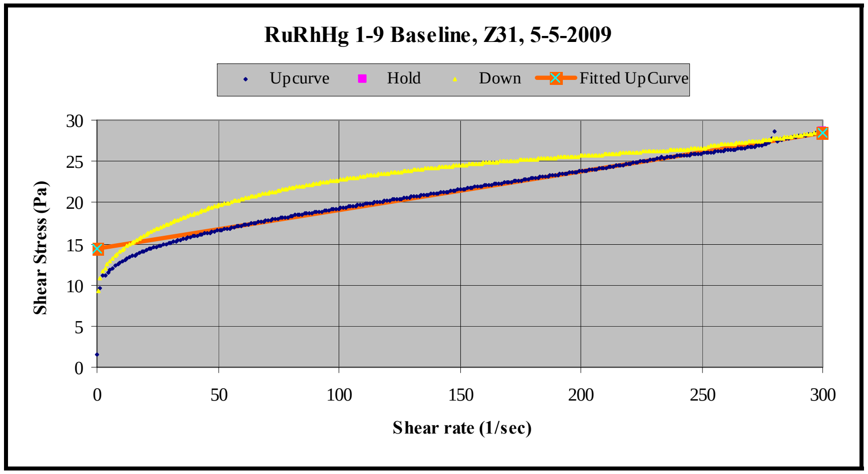


Figure A - 4 RuRhHg 1:9 Baseline, Z31

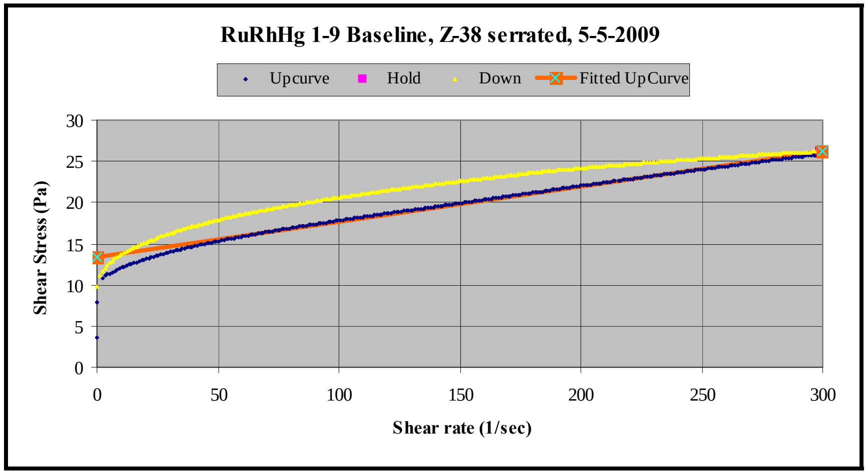


Figure A - 6 RuRhHg 1:9 Baseline: Z38 Serrated

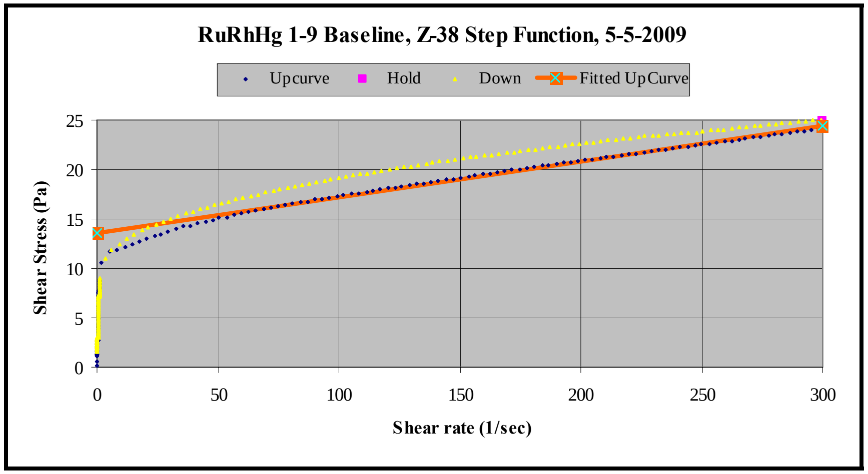


Figure A - 7 RuRhHg 1:9 Baseline, Modified Z38 Flow Profile

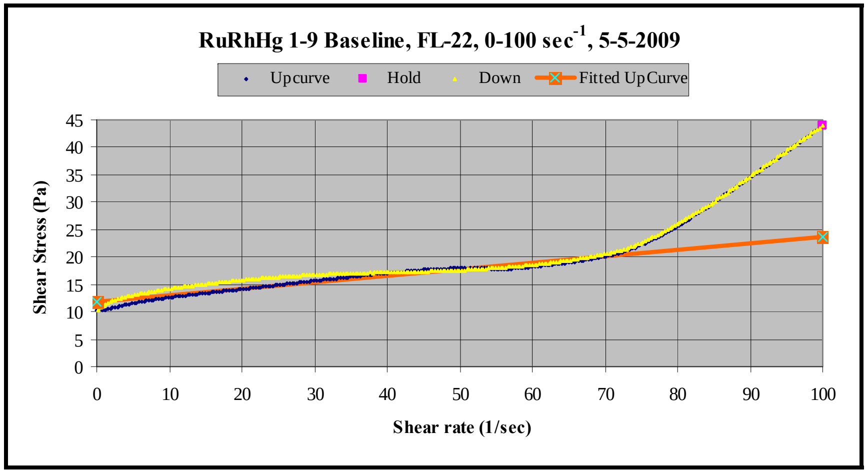


Figure A - 9 RuRhHg 1-9 Baseline, Vane 0-100 Sec^{-1}

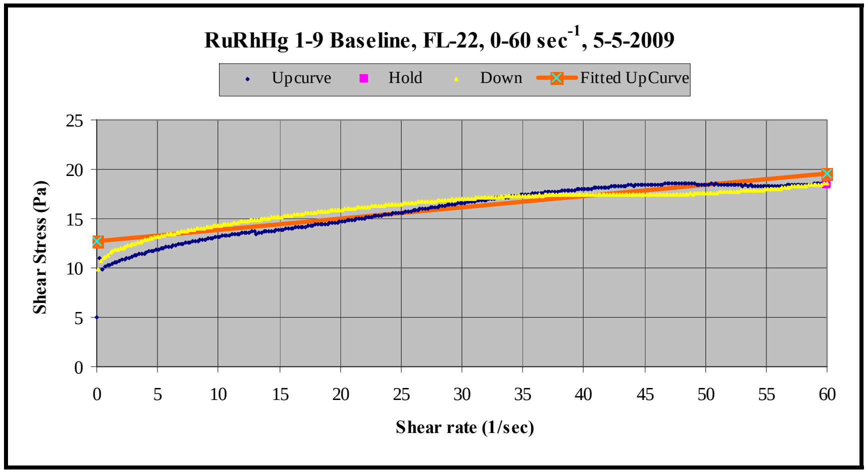


Figure A - 8 RuRhHg 1:9 Baseline, Vane 1-60 Sec^{-1}

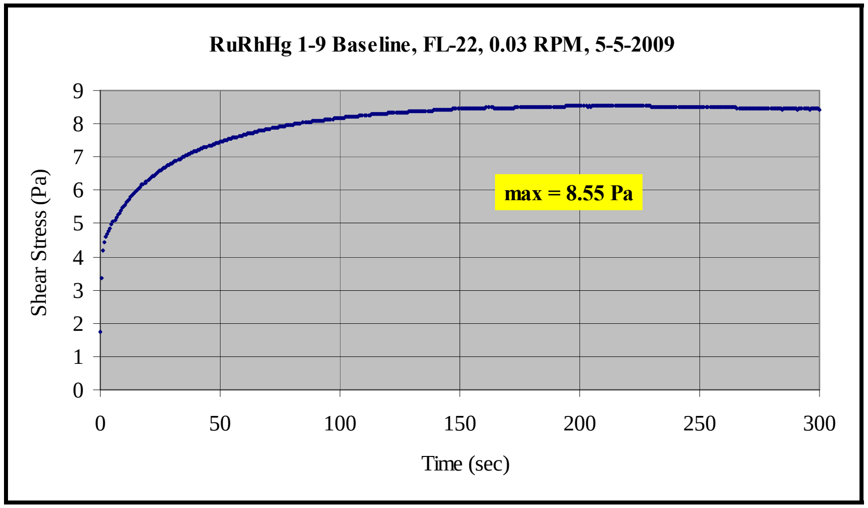


Figure A - 10 RuRhHg 1-9 Baseline, Vane 0.03 RPM

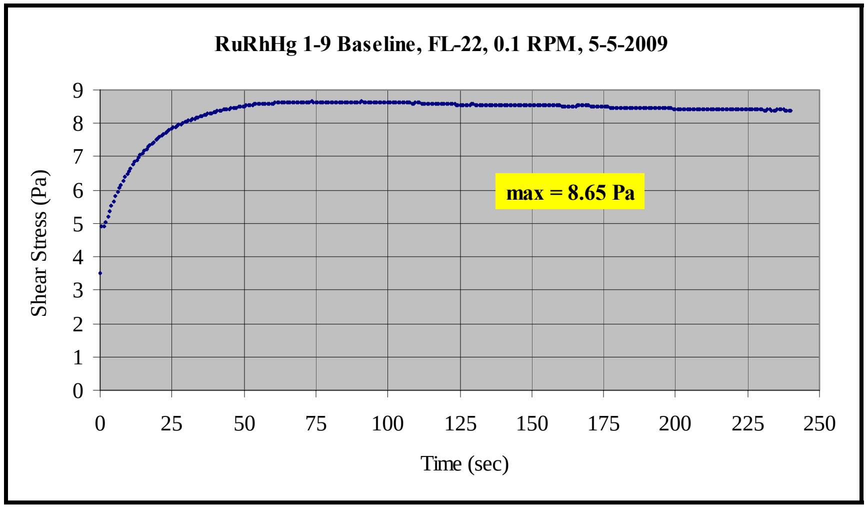


Figure A - 11 RuRhHg 1-9 Baseline, Vane 0.1 RPM

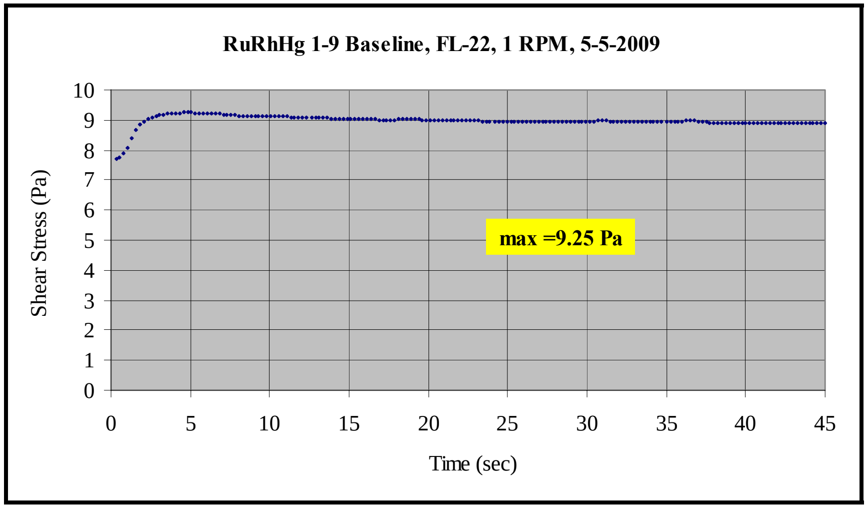


Figure A - 13 RuRhHg 1-9 Baseline, Vane 1 RPM

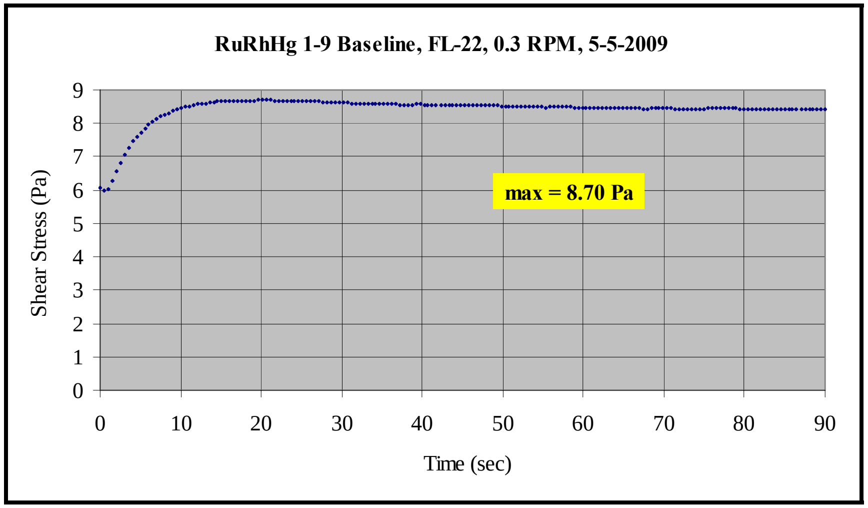


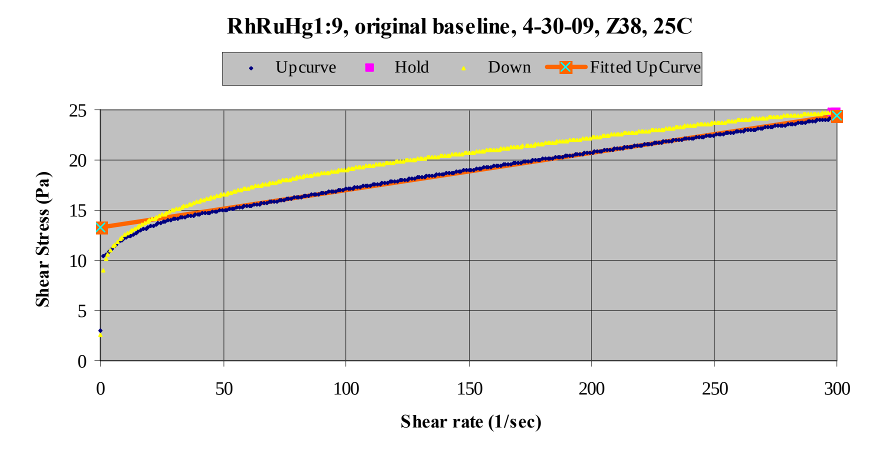
Figure A - 12 RuRhHg 1-9 Baseline, Vane 0.3 RPM

Appendix B RuRhHg 1-9 SME Flow Curves

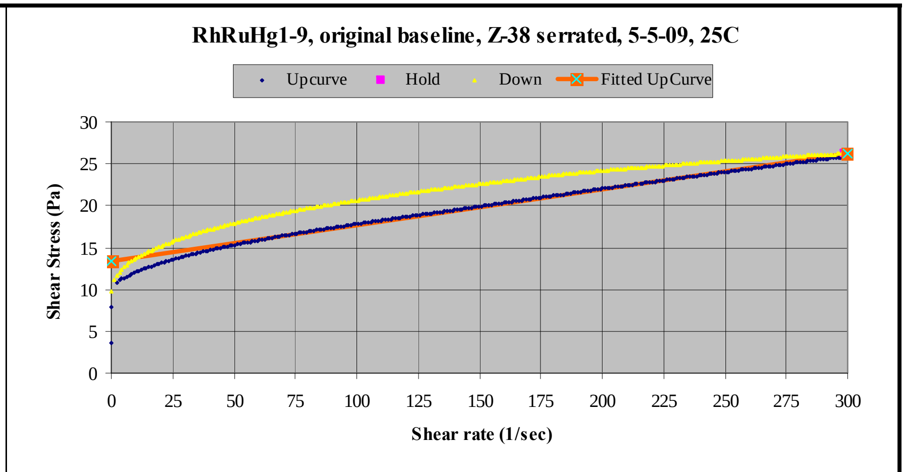
Table B - 1 RuRhHg 1:9 SME: Bingham Plastic Results

Baseline Data, Sample ID	Rotor	Plastic Viscosity (cp)	Yield Stress (Pa)	R^2	Shear Rate Range (1/sec)
Baseline 4-30-2009, R1	Z38	36.9	13.32	0.9983	30-300
Z38 5-5-2009	Z38	39.1	13.28	0.9947	30-300
Z38 Serrated 5-5-2009	Z38	42.7	13.38	0.9972	30-300
Z38 Step 5-5-2009	Z38	36.2	13.54	0.9948	30-300
	Average	**38.7**	**13.38**		
	Std. Dev.	2.9	0.11		
	% Std. Dev.	7.5	0.8		

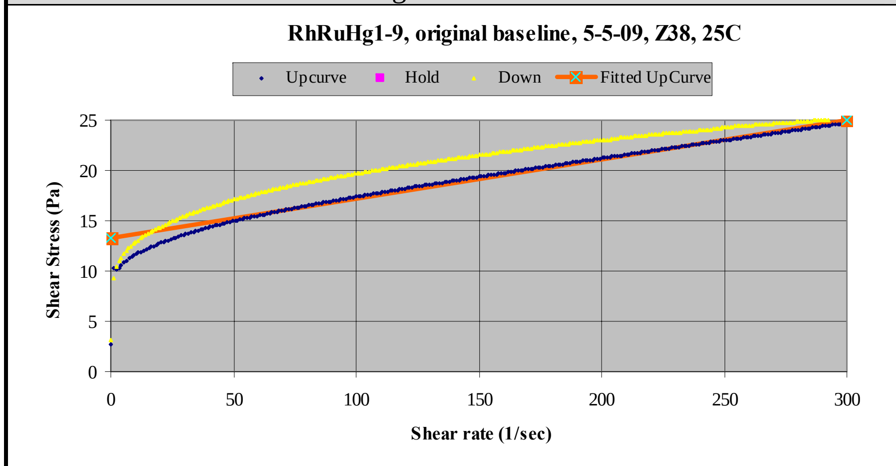
Sample Identification	Rotor	Plastic Viscosity (cp)	Yield Stress (Pa)	R^2	Shear Rate Range (1/sec)
Polyacrylic Acid - 1000 PPM	Z38	32.1	8.40	0.9955	30-250
Polyacrylic Acid - 3500 PPM	Z38	23.9	6.82	0.9885	30-175
Polyacrylic Acid - 7000 PPM	Z38	24.2	6.89	0.9959	30-175
Polyacrylic Acid - 10000 PPM	Z38	23.8	8.05	0.9931	30-175
Citric Acid - 1000 PPM	Z38	40.6	10.29	0.9982	30-300
Citric Acid - 3500 PPM	Z38	39.5	10.09	0.9978	30-300
Citric Acid - 7000 PPM	Z38	41.2	10.41	0.9989	30-300
Citric Acid - 10000 PPM	Z38	40.4	11.43	0.9979	30-300
Sodium Pyrophosphate Tetrabasic - 1000 PPM	Z38	38.3	12.23	0.9966	30-250
Sodium Pyrophosphate Tetrabasic - 3500 PPM	Z38	32.6	14.80	0.9997	30-250
Sodium Pyrophosphate Tetrabasic - 7000 PPM	Z38	25.8	19.70	0.9954	30-300
Sodium Pyrophosphate Tetrabasic - 10000 PPM	Z38	34.3	23.95	0.9978	30-300
Recover® - 1000 PPM	Z38	43.2	12.01	0.9990	30-225
Recover® - 6000 PPM	Z38	42.3	10.43	0.9984	30-225
Recover® - 11000 PPM	Z38	38.9	9.36	0.9988	30-225
Recover® - 11000 PPM	Z38	40.9	9.01	0.9979	30-225
Dolapix A88 - 1000 PPM	Z38	43.8	12.86	0.9987	30-250
Dolapix A88 - 3000 PPM	Z38	44.9	11.99	0.9990	30-250
Dolapix A88 - 6000 PPM	Z38	40.8	11.91	0.9994	30-250
Dolapix A88 - 10000 PPM	Z38	28.1	16.41	0.9867	30-250
Dolapix CE64 - 1000 PPM	Z38	40.8	12.48	0.9990	30-250
Dolapix CE64 - 6000 PPM	Z38	28.2	10.21	0.9978	30-225
Dolapix CE64 - 11000 PPM	Z38	26.1	8.54	0.9904	30-225
Dolapix CE64 - 16000 PPM	Z38	23.0	7.62	0.9917	30-200
Dolapix PC75 - 1000 PPM	Z38	41.3	11.11	0.9982	30-225
Dolapix PC75 - 6000 PPM	Z38	42.0	10.01	0.9980	30-225
Dolapix PC75 - 11000 PPM	Z38	40.4	9.17	0.9974	30-225
Dolapix PC75 - 16000 PPM	Z38	40.1	9.12	0.9971	30-225
ADVA FLEX - 1000 PPM	Z38	39.4	11.15	0.9985	30-225
ADVA FLEX - 6000 PPM	Z38	35.5	8.00	0.9970	30-175
ADVA FLEX - 11000 PPM	Z38	32.5	5.76	0.9982	30-175
ADVA FLEX- 16000 PPM	Z38	28.8	4.13	0.9984	30-175



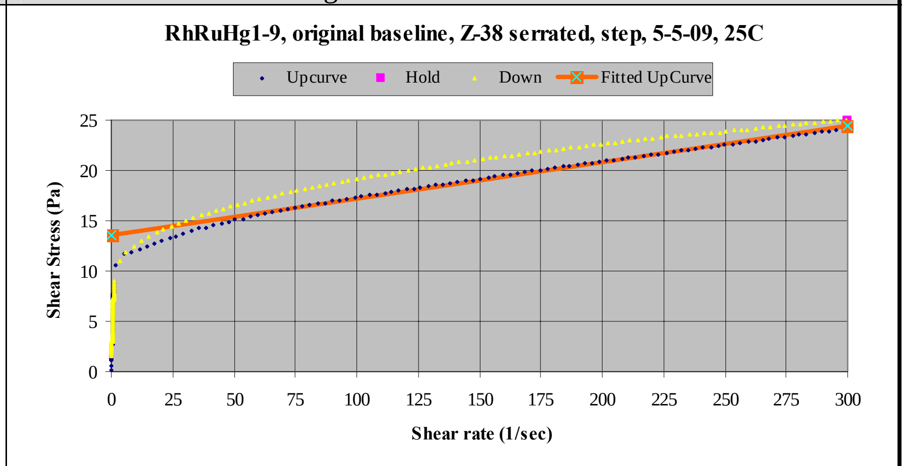
RuRhHg 1-9 Baseline R1



RuRhHg 1-9 Baseline Serrated Rotor

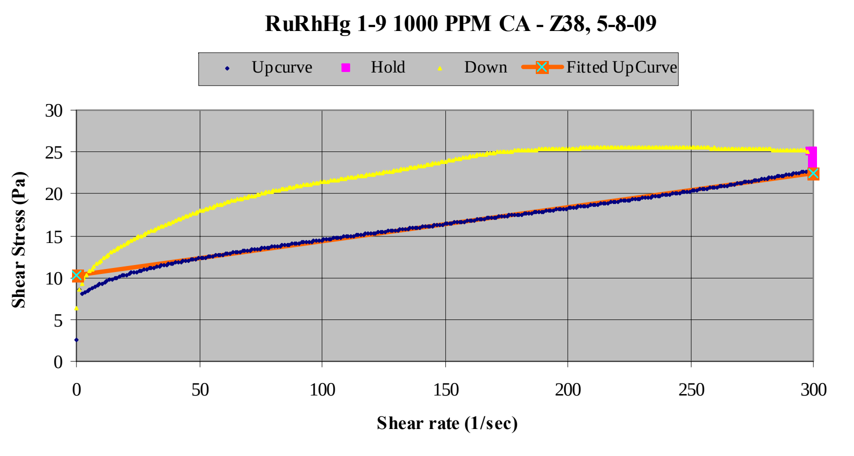


RuRhHg 1-9 Baseline R2

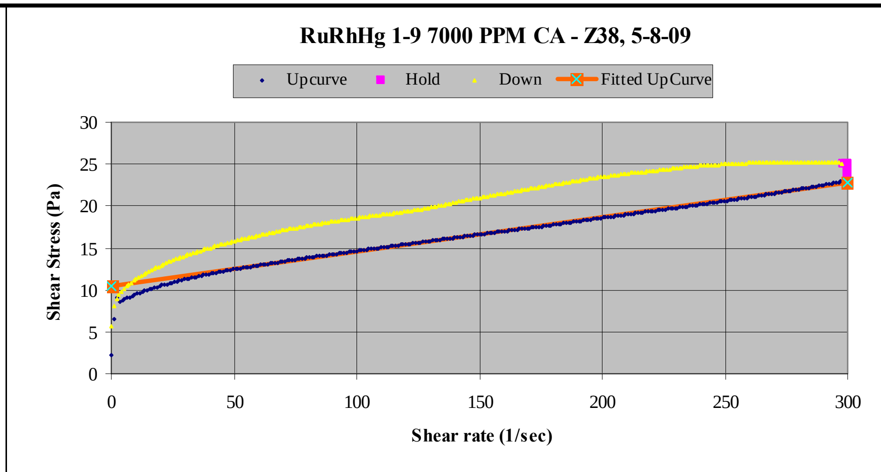


RuRhHg 1-9 Baseline Serrated Rotor Step Profile

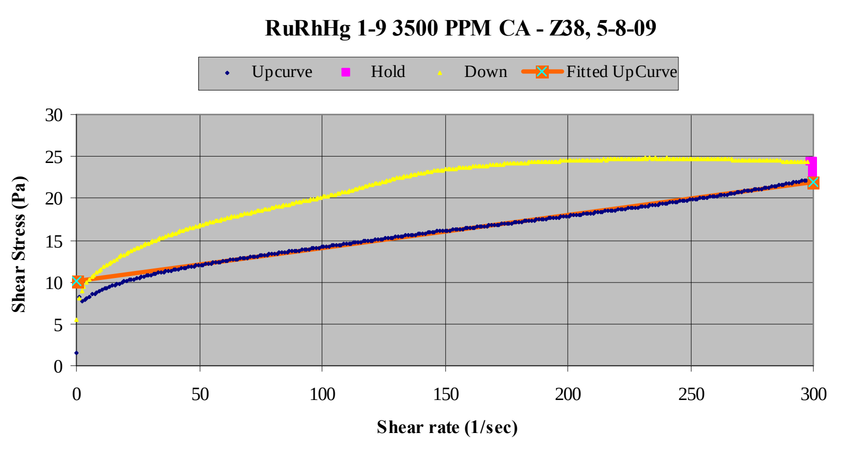
Figure B - 1 RhRhHg 1-9 SME Flow Curves: Baseline



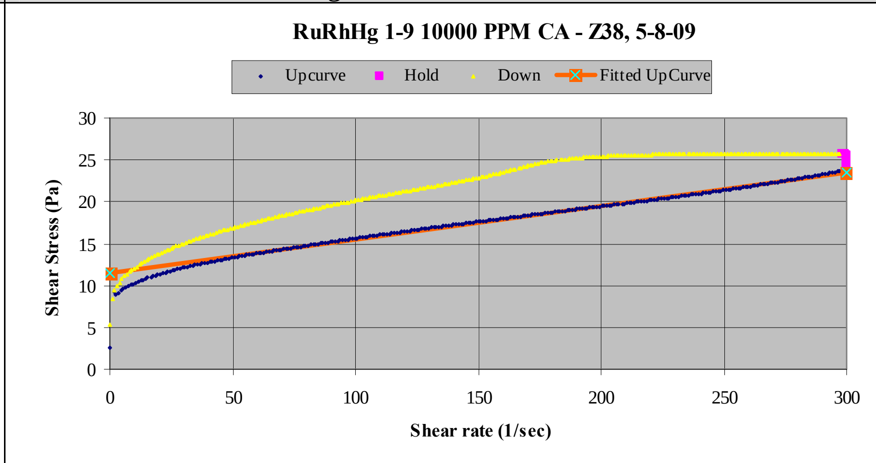
RuRhHg 1-9 1,000 PPM Citric Acid



RuRhHg 1-9 7,000 PPM Citric Acid

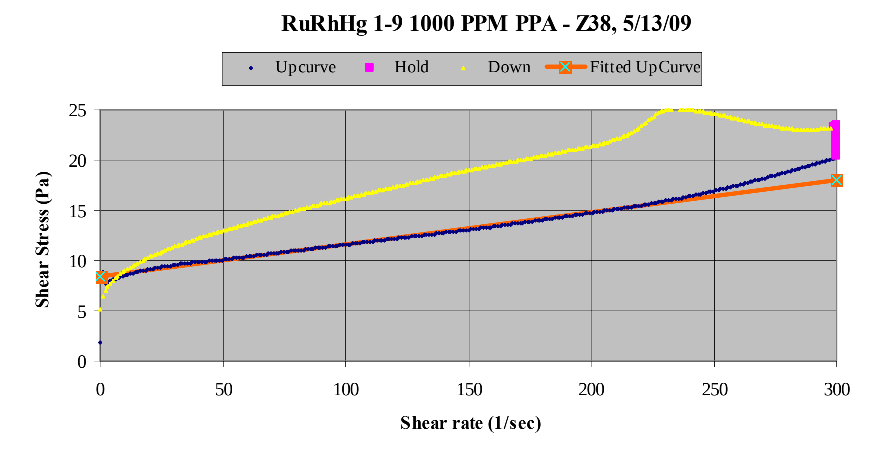


RuRhHg 1-9 3,500 PPM Citric Acid

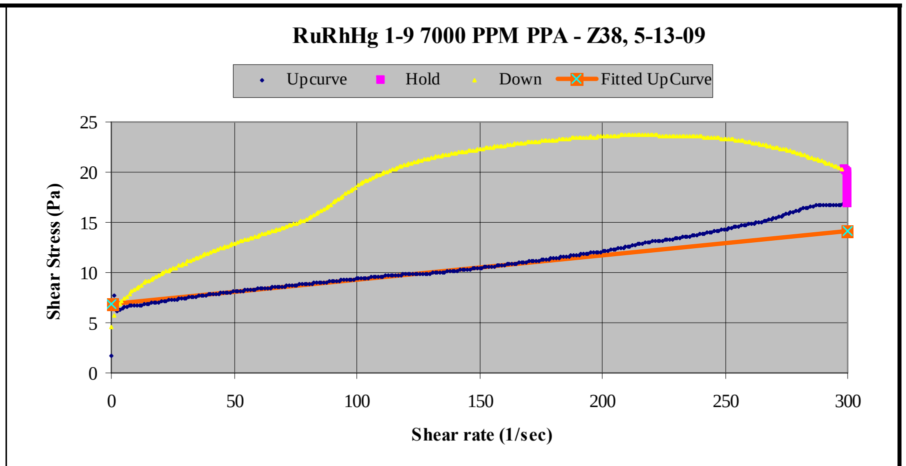


RuRhHg 1-9 10,000 PPM Citric Acid

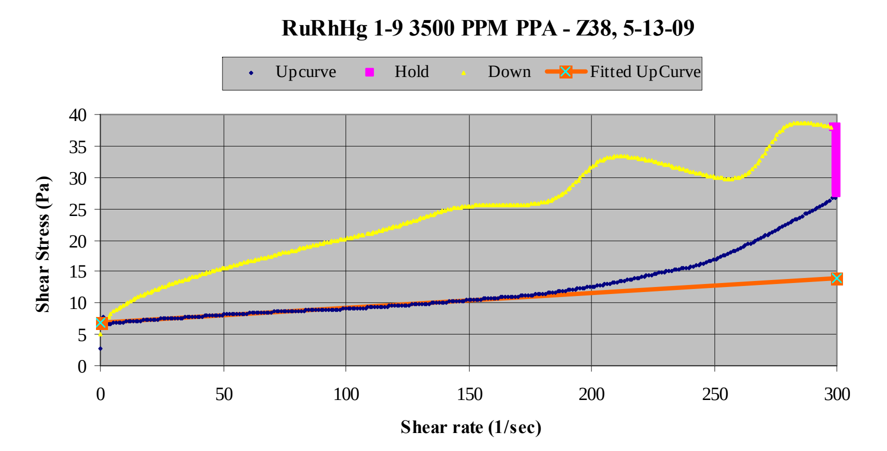
Figure B - 2 RhRhHg 1-9 SME Flow Curves : Citric Acid Addition



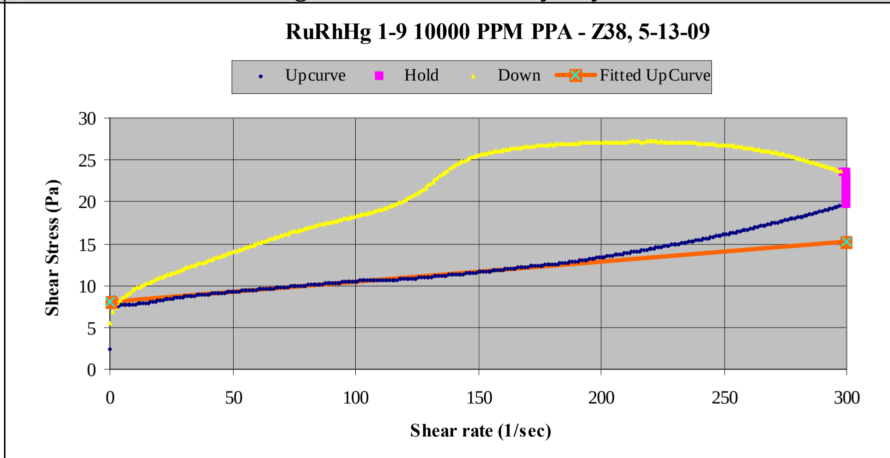
RuRhHg 1-9 1,000 PPM Polyacrylic Acid



RuRhHg 1-9 7,000 PPM Polyacrylic Acid

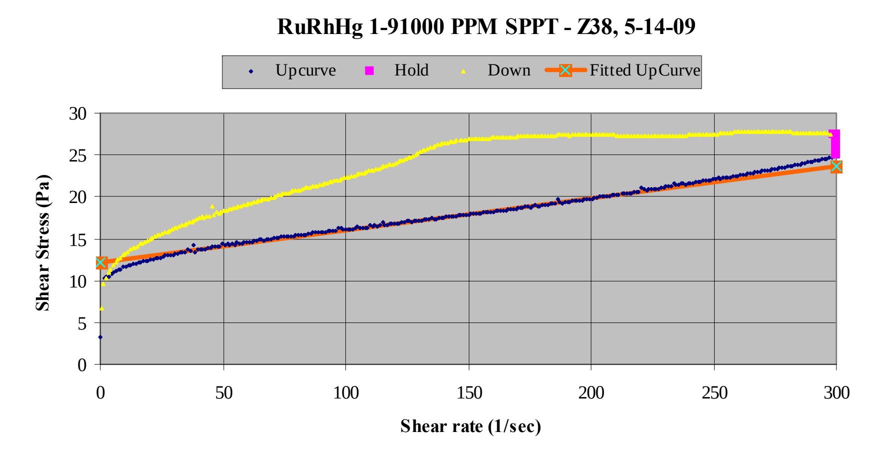


RuRhHg 1-9 3,500 PPM Polyacrylic Acid

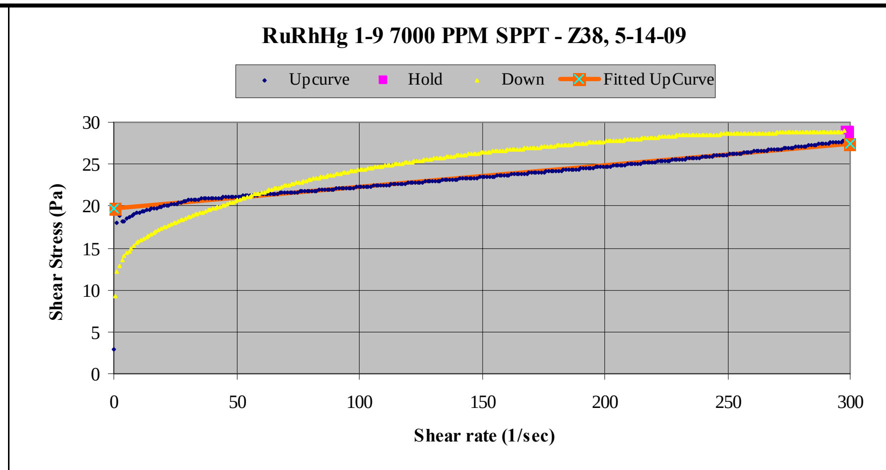


RuRhHg 1-9 10,000 PPM Polyacrylic Acid

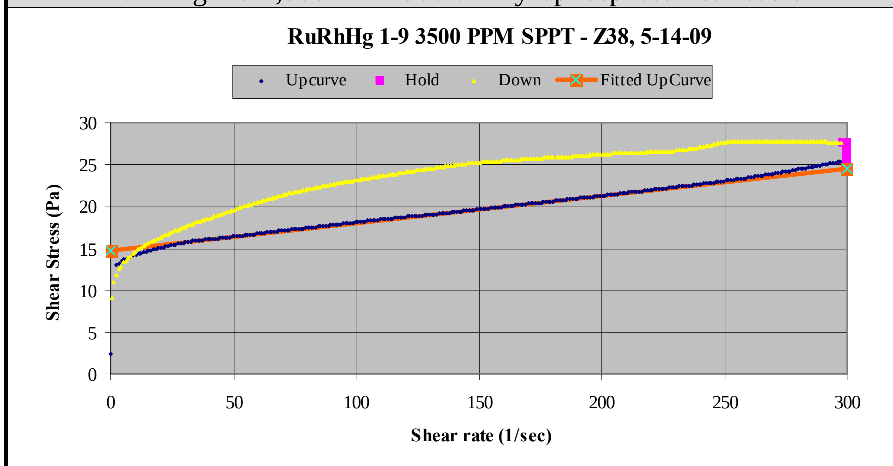
Figure B - 3 RhRhHg 1-9 SME Flow Curves: Polyacrylic Acid Addition



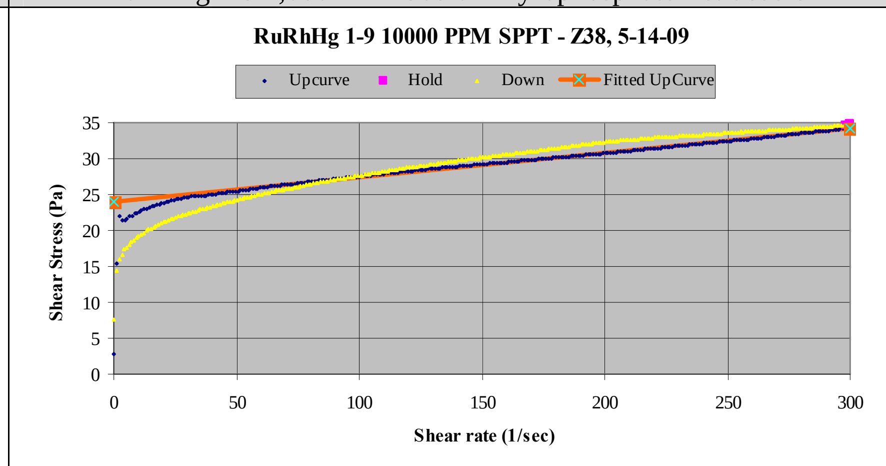
RuRhHg 1-9 1,000 PPM Sodium Pyrophosphate Tetrabasic



RuRhHg 1-9 7,000 PPM Sodium Pyrophosphate Tetrabasic

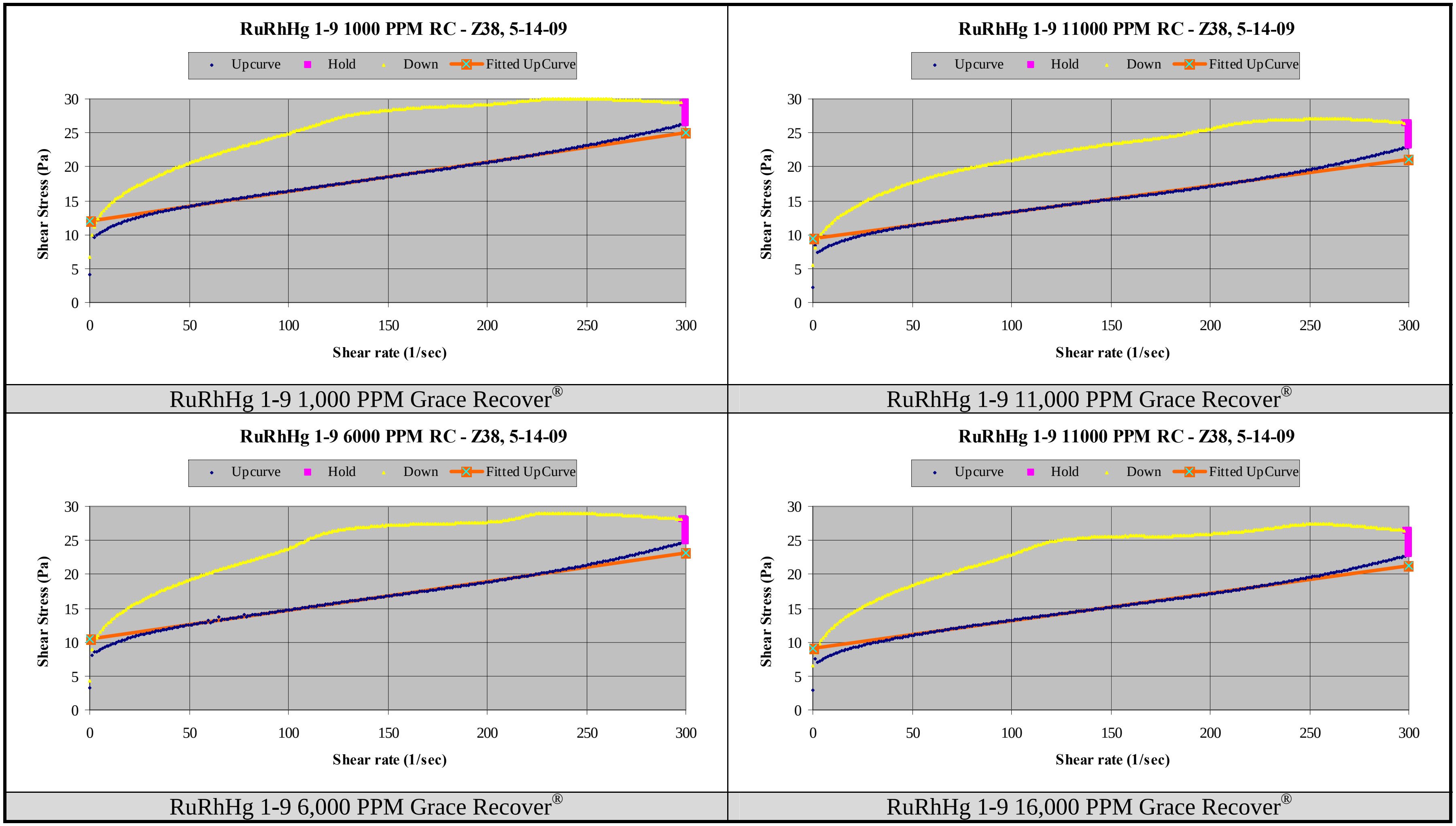


RuRhHg 1-9 3,500 PPM Sodium Pyrophosphate Tetrabasic



RuRhHg 1-9 10,000 PPM Sodium Pyrophosphate Tetrabasic

Figure B - 4 RhRhHg 1-9 SME Flow Curves: Sodium Pyrophosphate Tetrabasic Addition



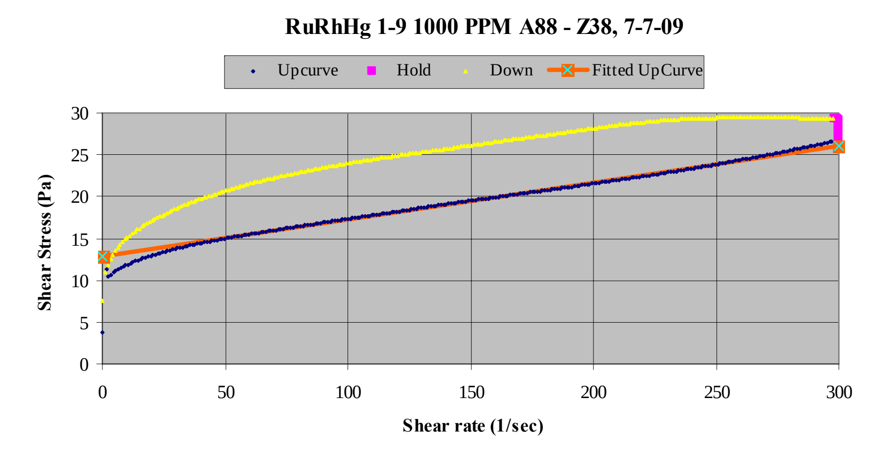
RuRhHg 1-9 1,000 PPM Grace Recover®

RuRhHg 1-9 11,000 PPM Grace Recover®

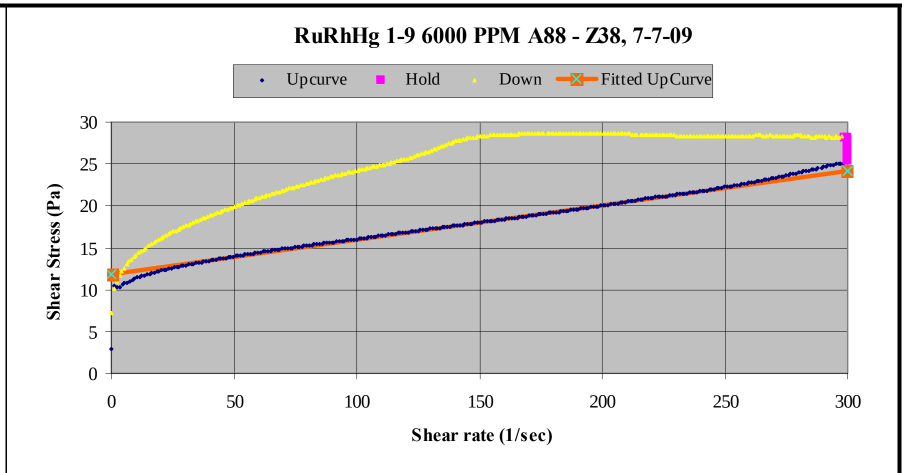
RuRhHg 1-9 6,000 PPM Grace Recover®

RuRhHg 1-9 16,000 PPM Grace Recover®

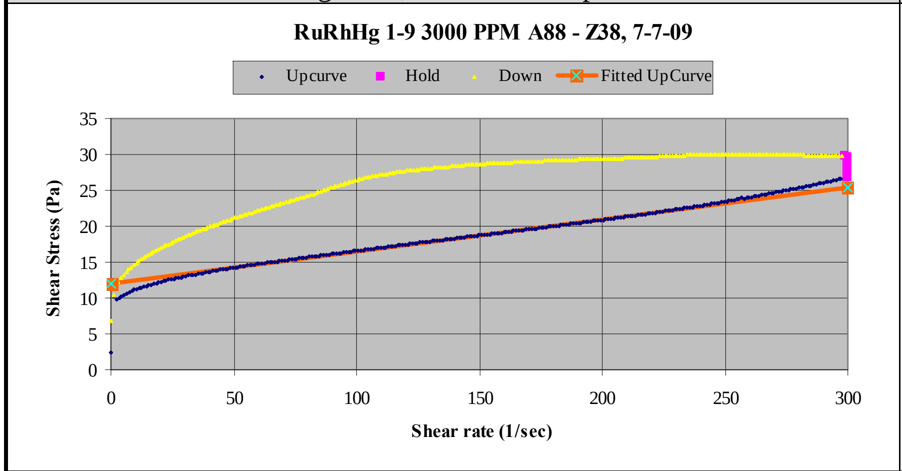
Figure B - 5 RhRhHg 1-9 SME Flow Curves: Grace Recover® Addition



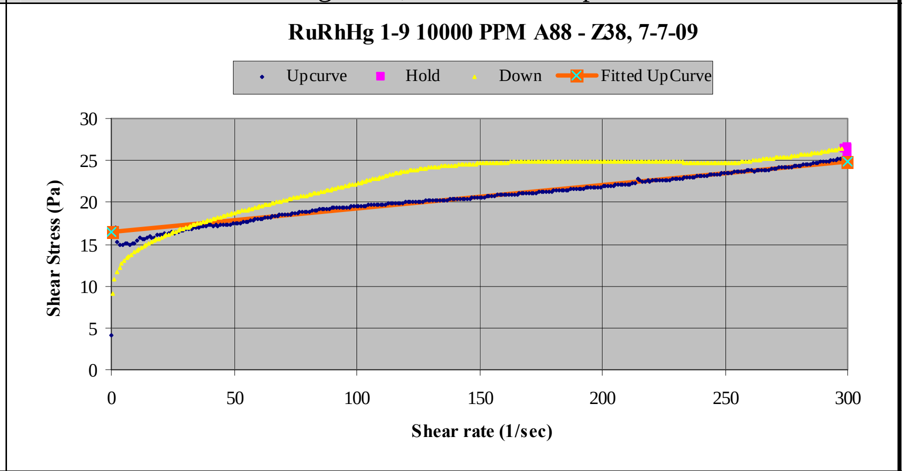
RuRhHg 1-9 1,000 PPM Dolapix A88



RuRhHg 1-9 6,000 PPM Dolapix A88

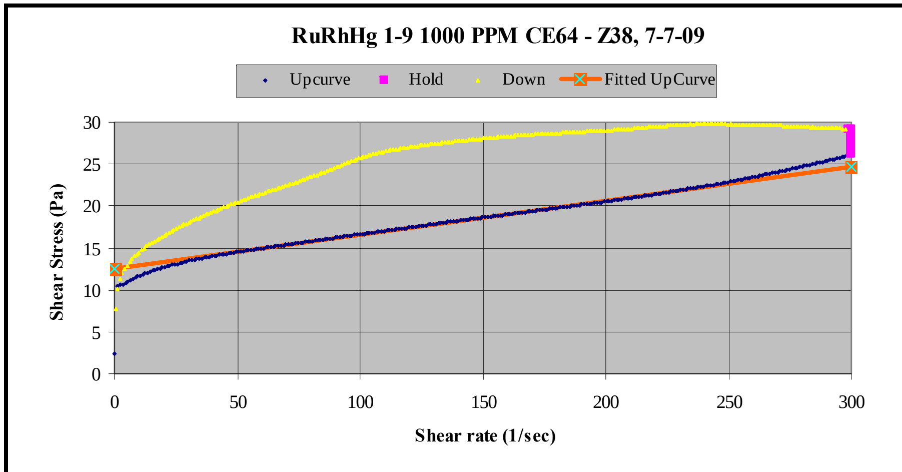


RuRhHg 1-9 3,000 PPM Dolapix A88

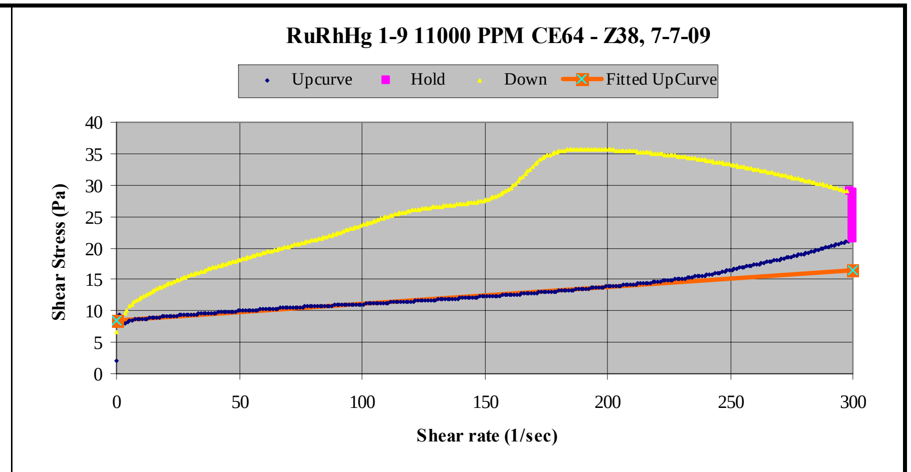


RuRhHg 1-9 10,000 PPM Dolapix A88

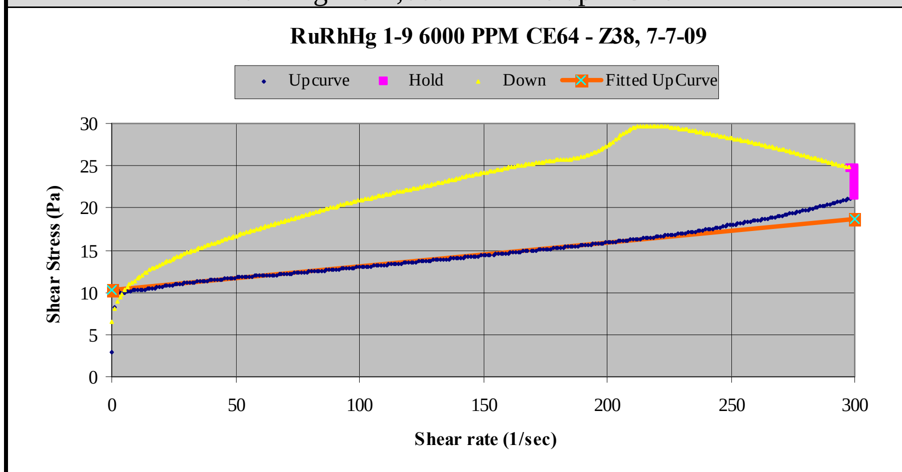
Figure B - 6 RhRhHg 1-9 SME Flow Curves: Dolapix A88 Addition



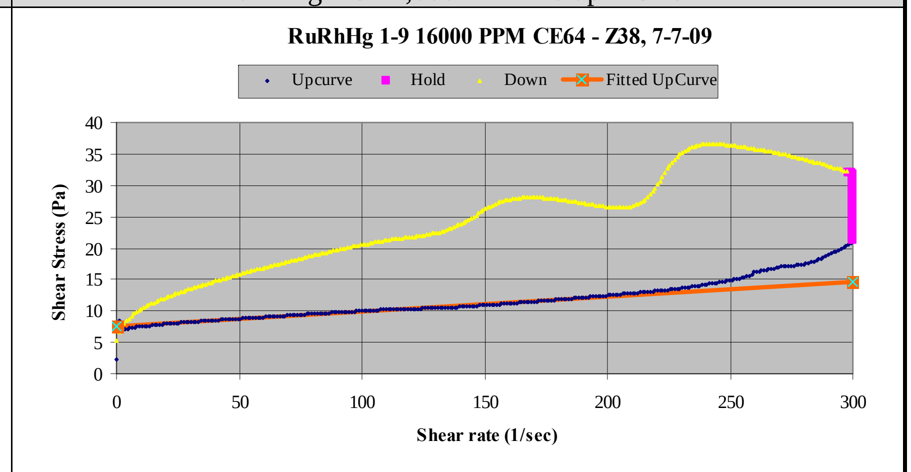
RuRhHg 1-9 1,000 PPM Dolapix CE64



RuRhHg 1-9 11,000 PPM Dolapix CE64

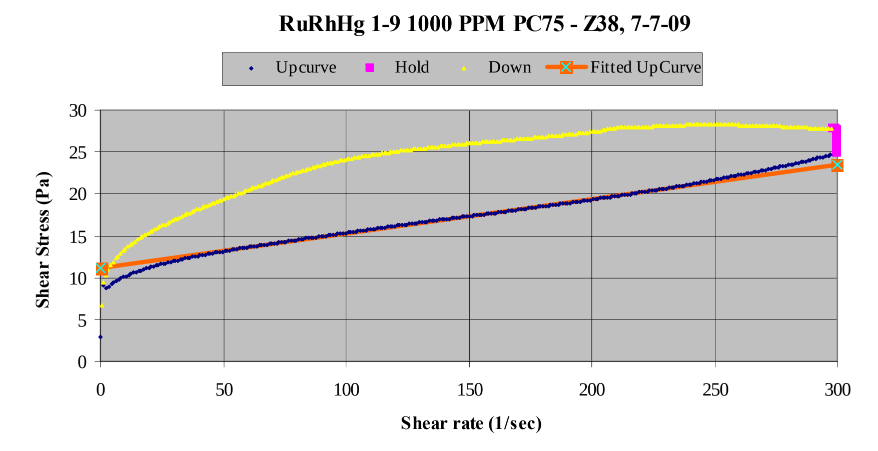


RuRhHg 1-9 6,000 PPM Dolapix CE64

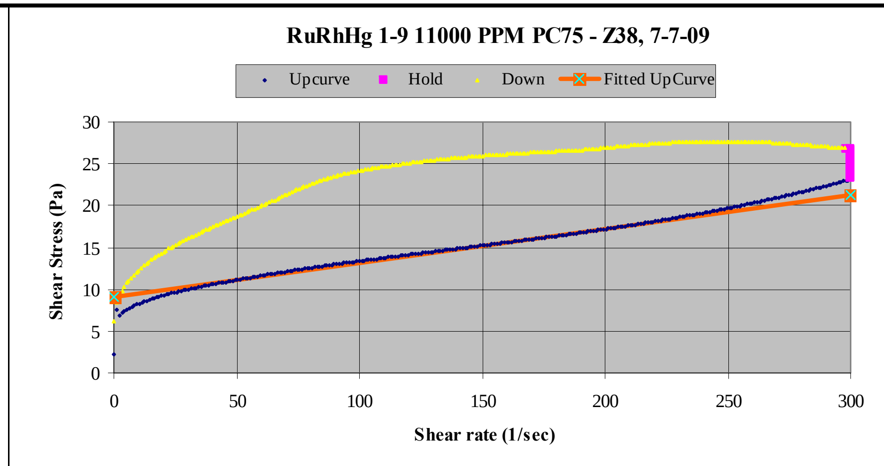


RuRhHg 1-9 16,000 PPM Dolapix CE64

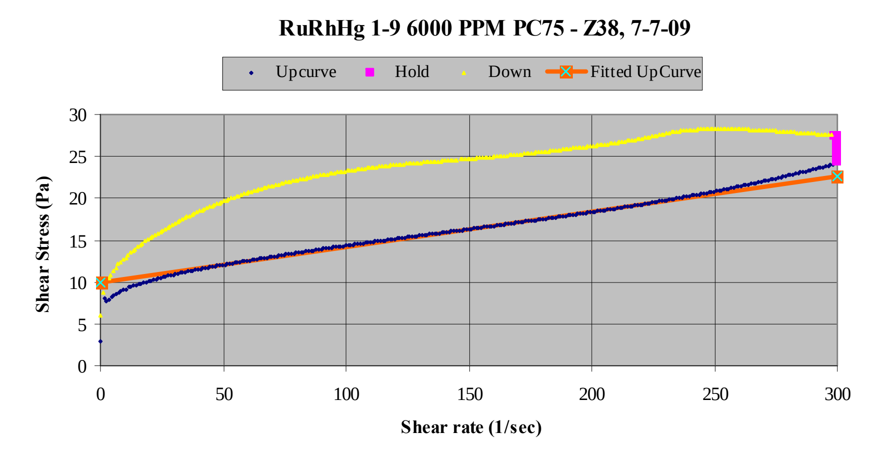
Figure B - 7 RhRhHg 1-9 SME Flow Curves: Dolapix CE64 Addition



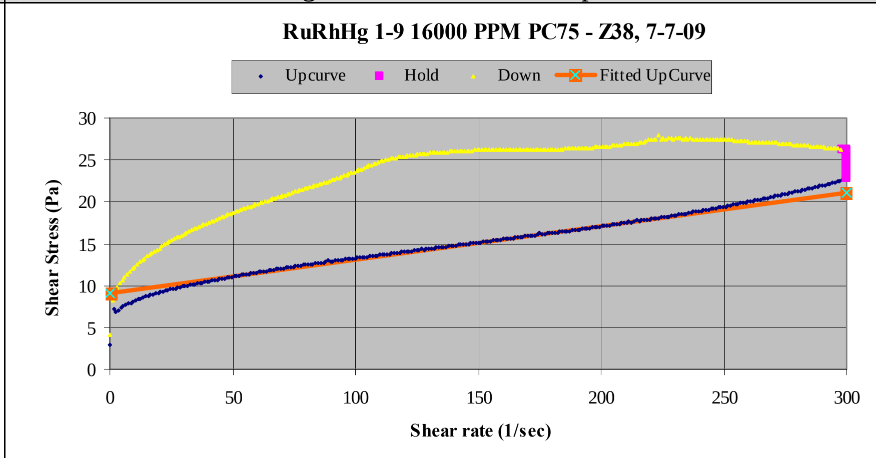
RuRhHg 1-9 1,000 PPM Dolapix PC75



RuRhHg 1-9 11,000 PPM Dolapix PC75

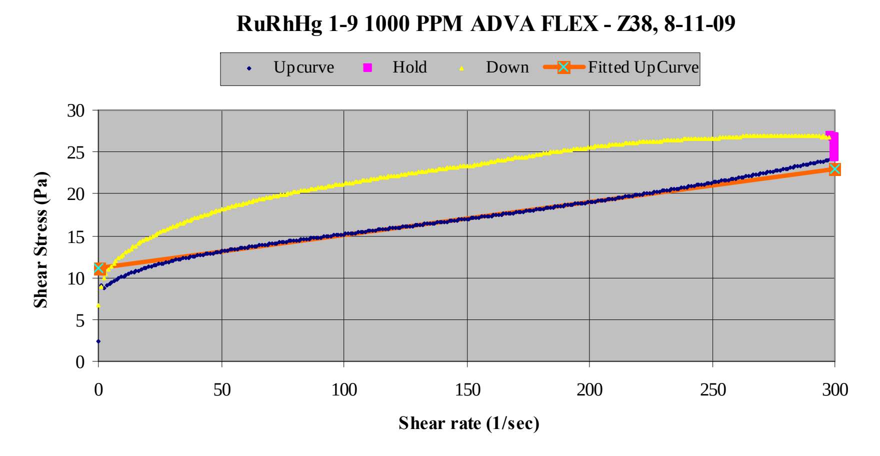


RuRhHg 1-9 6,000 PPM Dolapix PC75

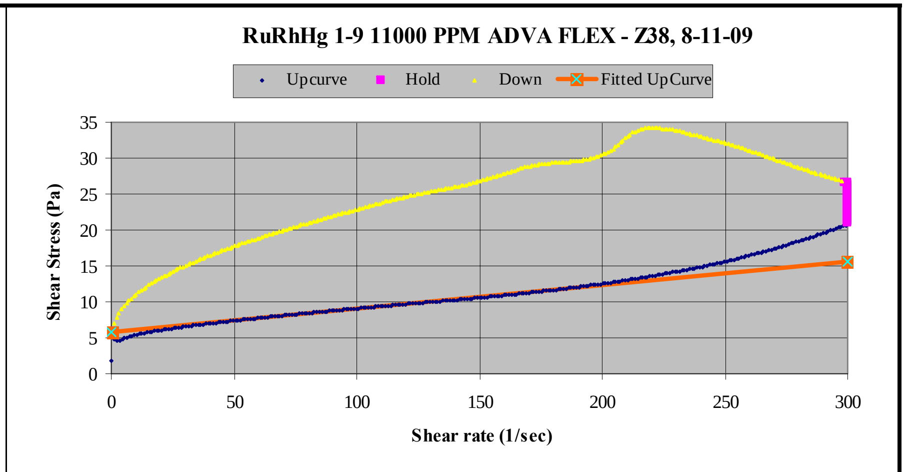


RuRhHg 1-9 16,000 PPM Dolapix PC75

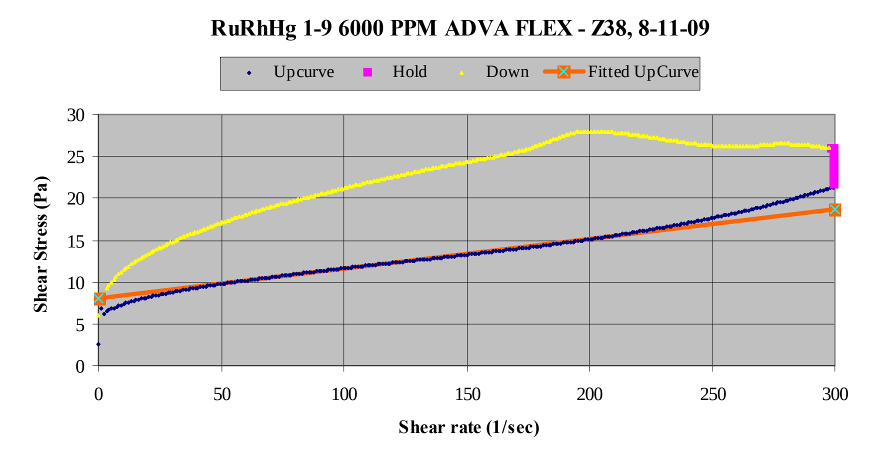
Figure B - 8 RhRhHg 1-9 SME Flow Curves: Dolapix PC75 Addition



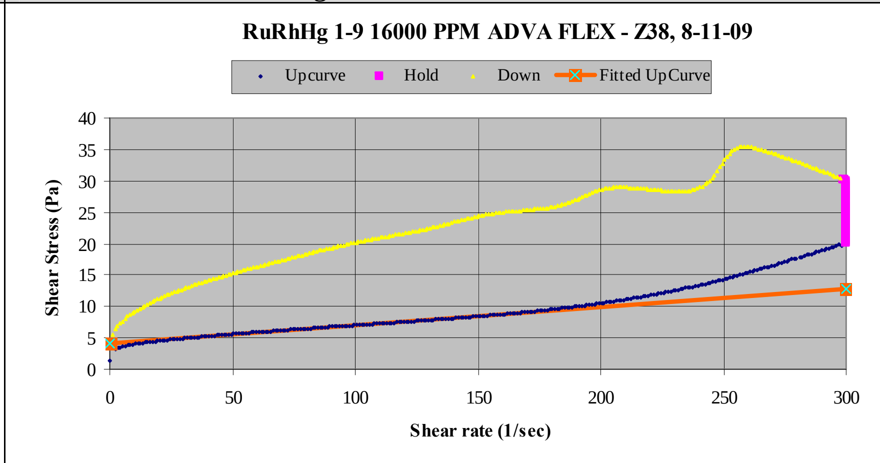
RuRhHg 1-9 1,000 PPM ADVA Flex



RuRhHg 1-9 11,000 PPM ADVA Flex



RuRhHg 1-9 6,000 PPM ADVA Flex



RuRhHg 1-9 16,000 PPM ADVA Flex

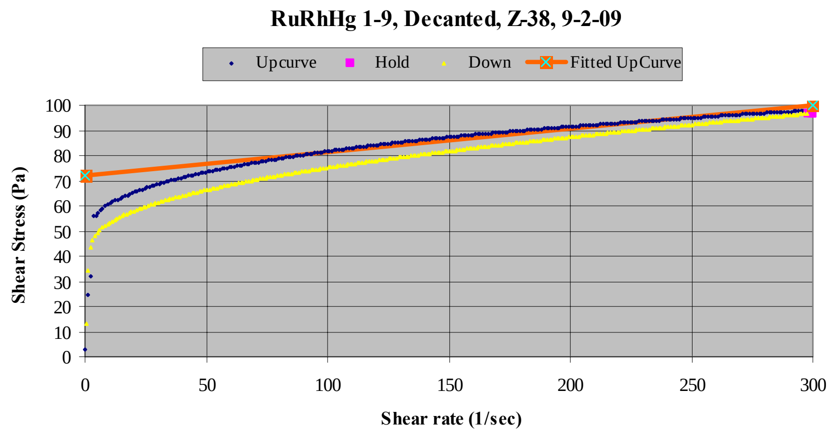
Figure B - 9 RhRhHg 1-9 SME Flow Curves: Grace ADVA Flex Addition

Appendix C RuRhHg 1-9 Decanted SME Flow Curves

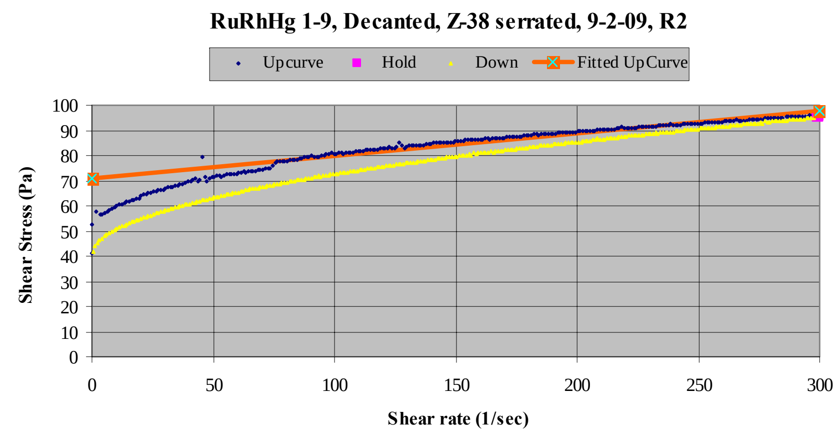
Table C - 1 RuRhHg 1-9 Decanted SME: Bingham Plastic Results

Baseline Data, Sample ID	Rotor	Plastic Viscosity (cp)	Yield Stress (Pa)	R^2	Shear Rate Range (1/sec)
Baseline 9-2-2009, R1	Z38	92.1	72.20	0.9711	50-300
Baseline Serrated, 9-2-2009_R2	Z38	89.5	70.83	0.9567	50-300
Baseline Serrated, 9-2-2009_R3	Z38	93.7	72.87	0.9825	50-300
	Average	**92.9**	**72.5**		
	Std. Dev.	2.1	1.0		
	% Std. Dev.	2.3	1.4		

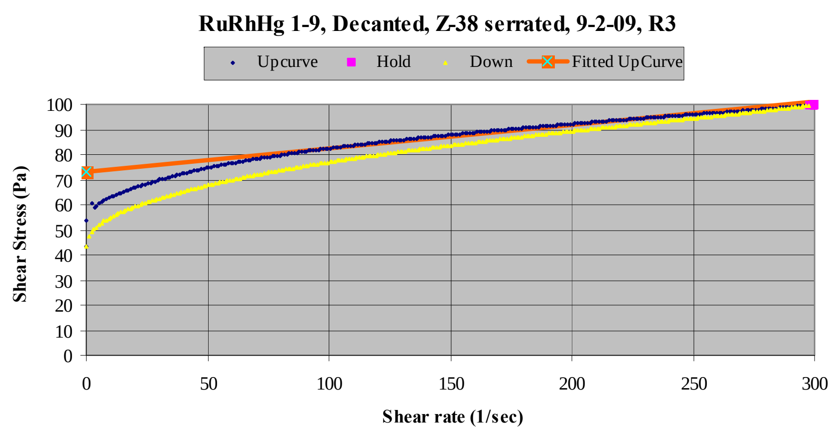
Sample Identification	Rotor	Plastic Viscosity (cp)	Yield Stress (Pa)	R^2	Shear Rate Range (1/sec)
Recover® - 1000 PPM	Z38	98.1	69.70	0.9718	50-300
Recover® - 6000 PPM	Z38	88.5	58.97	0.9704	50-300
Recover® - 11000 PPM	Z38	85.5	56.30	0.9580	50-300
Recover® - 11000 PPM	Z38	84.6	50.44	0.9692	50-300
Polyacrylic Acid - 1000 PPM	Z38	73.5	39.51	0.9952	50-300
Polyacrylic Acid - 3500 PPM	Z38	49.4	25.16	0.9862	50-300
Polyacrylic Acid - 7000 PPM	Z38	65.7	23.11	0.9840	50-300
Polyacrylic Acid - 10000 PPM	Z38	58.1	26.70	0.9919	50-300
Citric Acid - 1000 PPM	Z38	98.9	59.06	0.9707	50-300
Citric Acid - 3500 PPM	Z38	94.9	52.79	0.9767	50-300
Citric Acid - 7000 PPM	Z38	96.1	59.60	0.9610	50-300
Citric Acid - 10000 PPM	Z38	96.7	58.73	0.9711	50-300
Dolapix CE64 - 1000 PPM	Z38	79.4	65.39	0.9615	50-300
Dolapix CE64 - 6000 PPM	Z38	68.0	50.53	0.9811	50-300
Dolapix CE64 - 11000 PPM	Z38	49.1	42.24	0.9589	50-300
Dolapix CE64 - 16000 PPM	Z38	30.4	37.25	0.9778	50-300
ADVA FLEX - 1000 PPM	Z38	102.1	61.30	0.9800	50-300
ADVA FLEX - 6000 PPM	Z38	88.8	42.95	0.9923	50-300
ADVA FLEX - 11000 PPM	Z38	79.7	31.03	0.9953	50-300
ADVA FLEX- 16000 PPM	Z38	77.0	21.72	0.9993	50-300
ADVA CAST 555 - 1000 PPM	Z38	89.7	65.87	0.9582	50-300
ADVA CAST 555 - 6000 PPM	Z38	94.3	45.77	0.9841	50-300
ADVA CAST 555 - 10000 PPM	Z38	86.5	32.44	0.9924	50-300
ADVA CAST 555 - 16000 PPM	Z38	74.7	25.36	0.9937	50-300
Sugar - 1000 PPM	Z38	97.1	68.98	0.9625	50-300
Sugar - 3500 PPM	Z38	89.3	70.89	0.9421	50-300
Sugar - 7000 PPM	Z38	97.3	63.78	0.9742	50-300
Sugar - 10000 PPM	Z38	98.3	59.89	0.9752	50-300
Sodium Meta Silicate - 1000 PPM	Z38	92.7	70.13	0.9457	50-300
Sodium Meta Silicate - 3500 PPM	Z38	95.0	61.82	0.9770	50-300
Sodium Meta Silicate -7000 PPM	Z38	87.8	58.90	0.9781	50-300
Sodium Meta Silicate - 10000 PPM	Z38	79.5	65.23	0.9652	50-300
Phenylboric Acid - 1000 PPM	Z38	102.0	66.79	0.9760	50-300
Phenylboric Acid - 3500 PPM	Z38	102.0	66.33	0.9704	50-300
Phenylboric Acid -7000 PPM	Z38	90.2	68.42	0.9462	50-300
Phenylboric Acid - 10000 PPM	Z38	107.0	66.11	0.9774	50-300



RuRhHg 1-9 Decanted Z38 Baseline

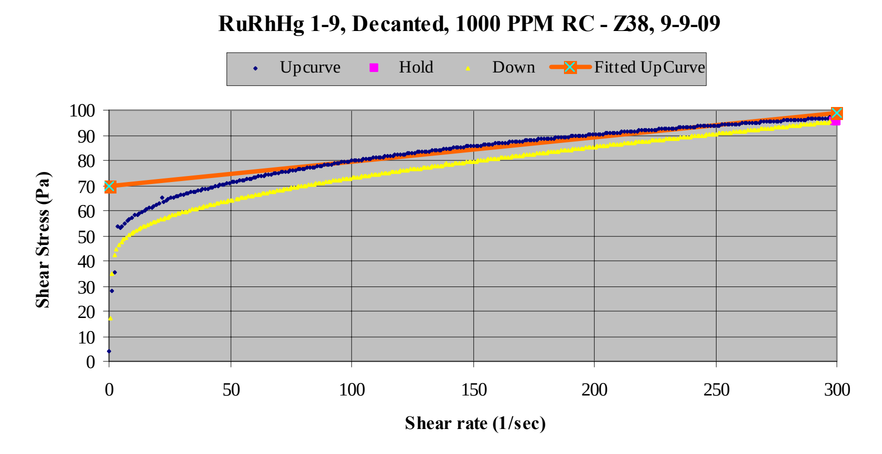


RuRhHg 1-9 Decanted Serrated Z38 Baseline R1

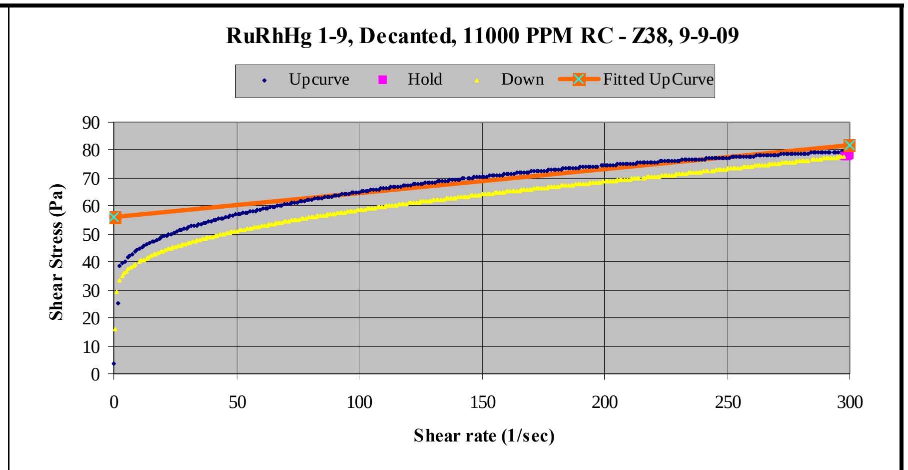


RuRhHg 1-9 Decanted Serrated Z38 Baseline R2

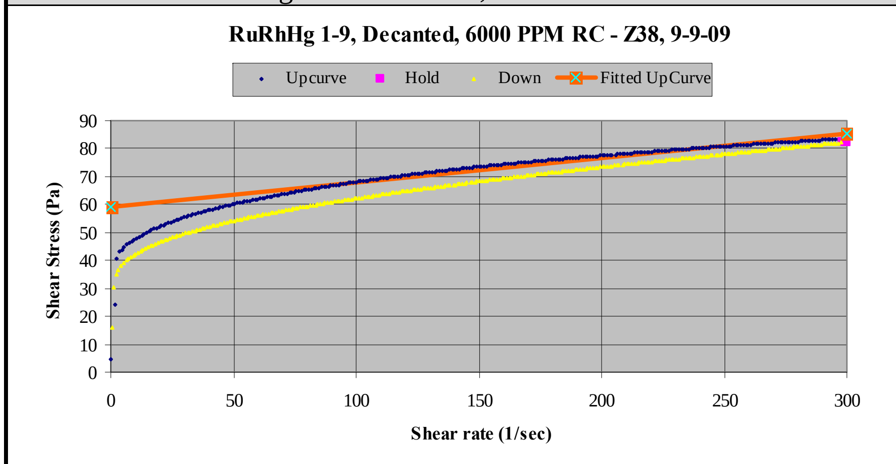
Figure C - 1 RuRhHg 1-9 SME Decanted Flow Curves: Baseline



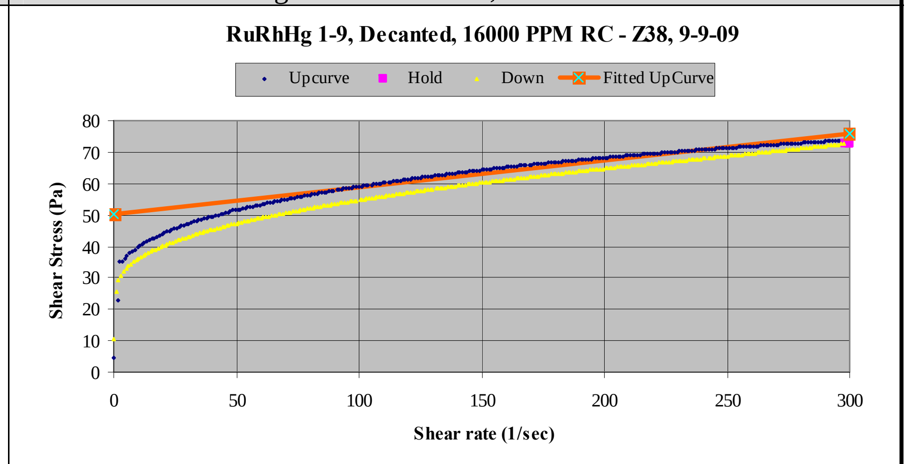
RuRhHg 1-9 Decanted 1,000 PPM Recover®



RuRhHg 1-9 Decanted 11,000 PPM Recover®

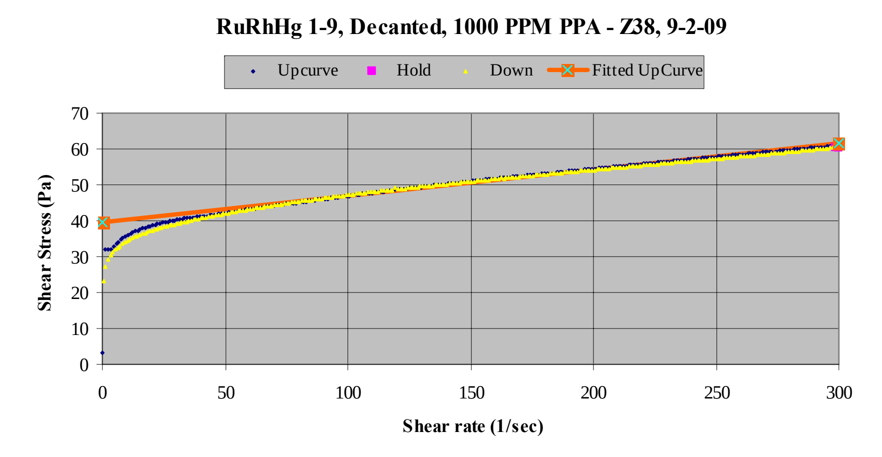


RuRhHg 1-9 Decanted 6,000 PPM Recover®

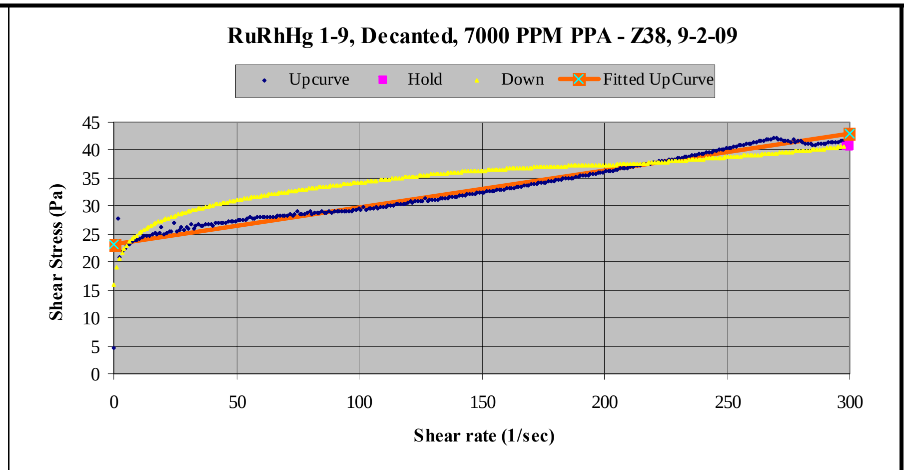


RuRhHg 1-9 Decanted 16,000 PPM Recover®

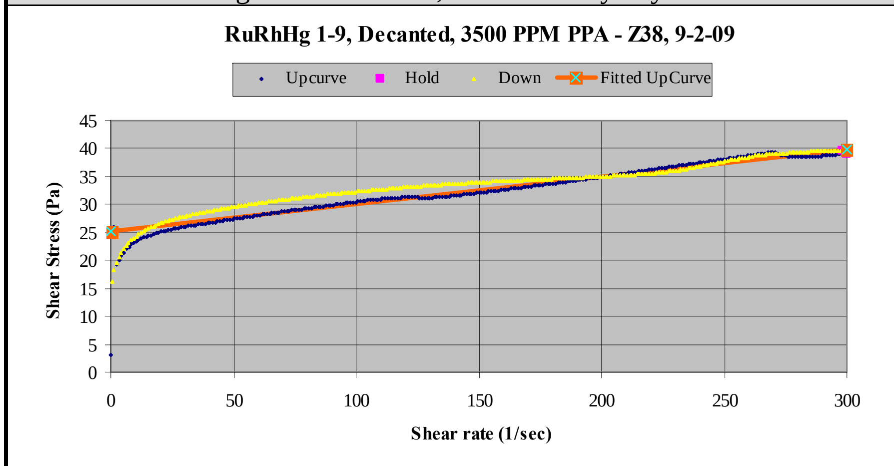
Figure C - 2 RuRhHg 1-9 Decanted SME Flow Curves: Grace Recover®



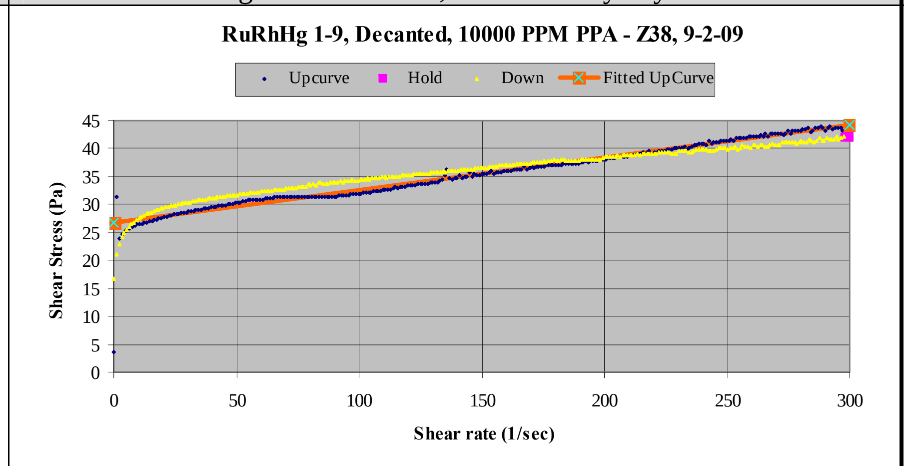
RuRhHg 1-9 Decanted 1,000 PPM Polyacrylic Acid



RuRhHg 1-9 Decanted 7,000 PPM Polyacrylic Acid

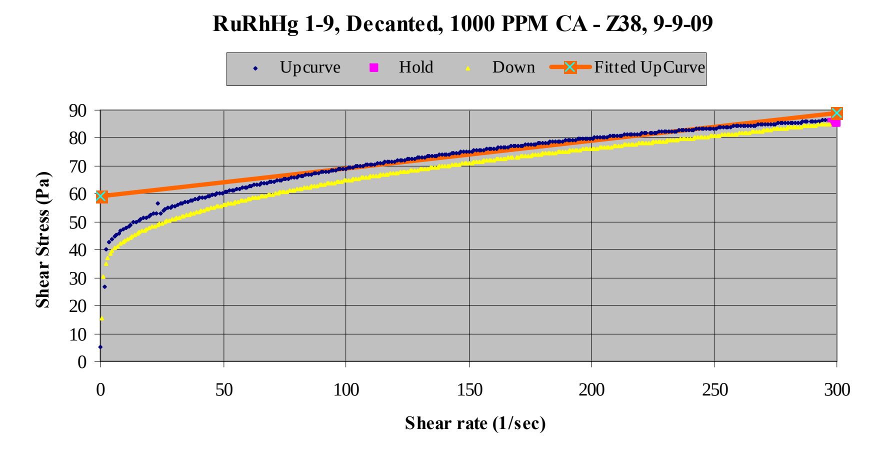


RuRhHg 1-9 Decanted 3,500 PPM Polyacrylic Acid

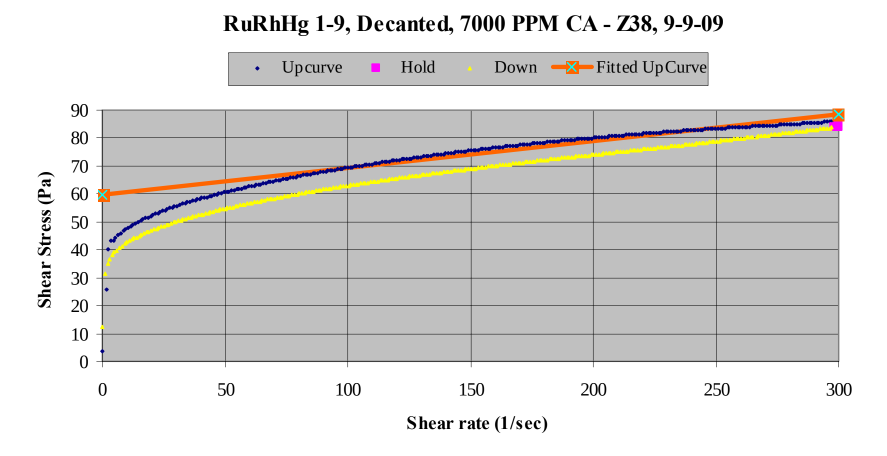


RuRhHg 1-9 Decanted 10,000 PPM Polyacrylic Acid

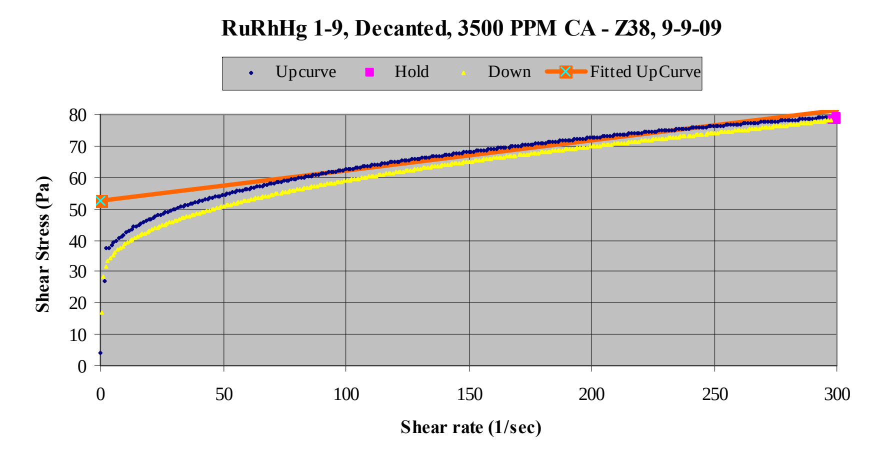
Figure C - 3 RuRhHg 1-9 Decanted SME Flow Curves: Polyacrylic Acid



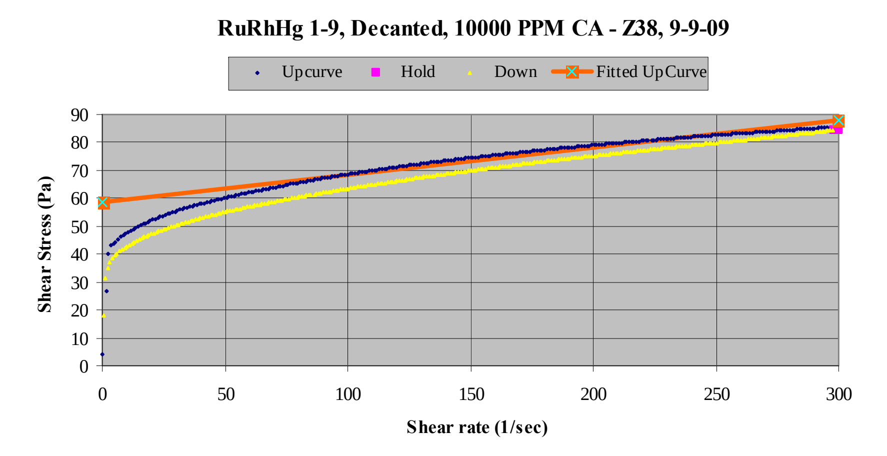
RuRhHg 1-9 Decanted 1,000 PPM Citric Acid



RuRhHg 1-9 Decanted 7,000 PPM Citric Acid

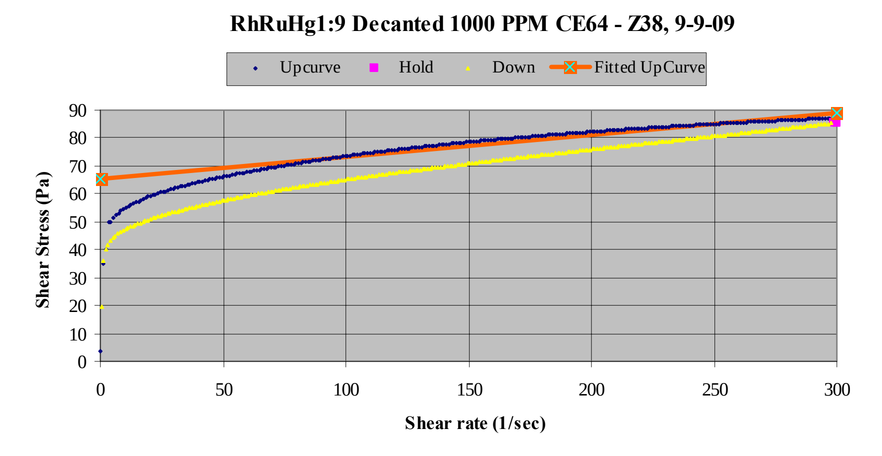


RuRhHg 1-9 Decanted 3,500 PPM Citric Acid

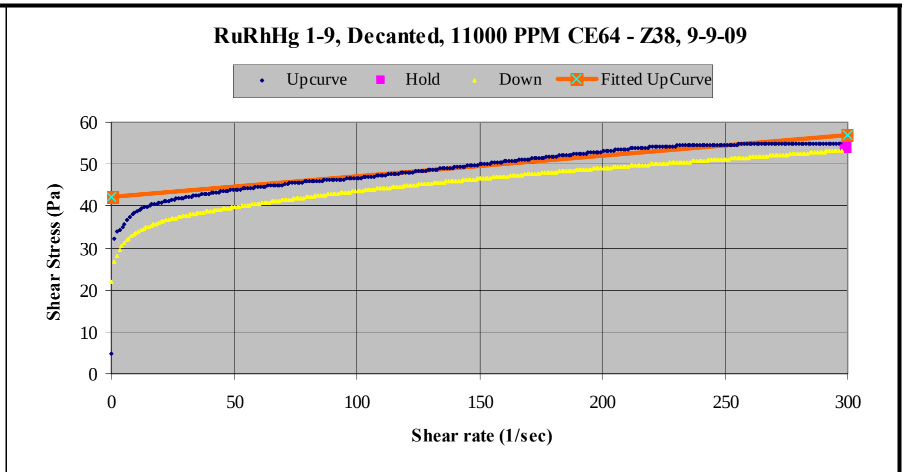


RuRhHg 1-9 Decanted 10,000 PPM Citric Acid

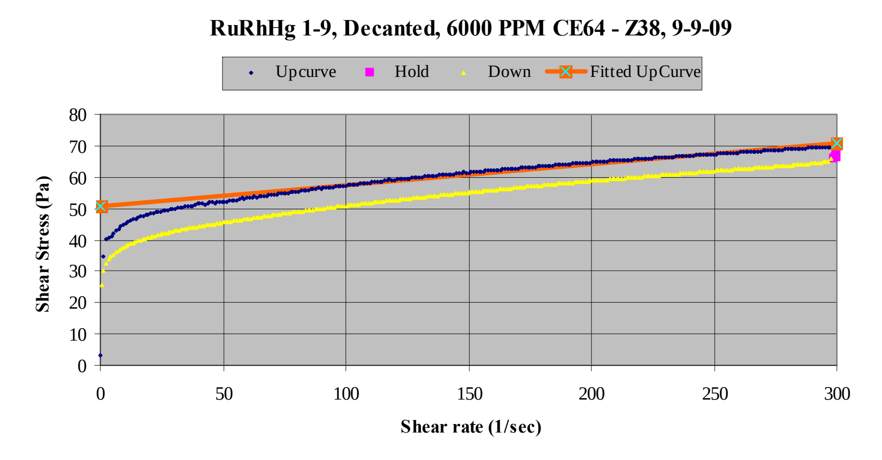
Figure C - 4 RuRhHg 1-9 Decanted SME Flow Curves: Citric Acid



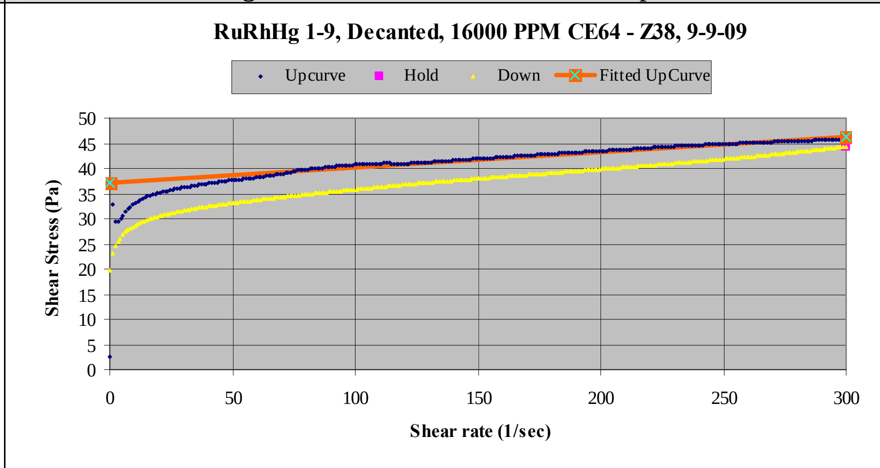
RuRhHg 1-9 Decanted 1,000 PPM Dolapix CE64



RuRhHg 1-9 Decanted 11,000 PPM Dolapix CE64

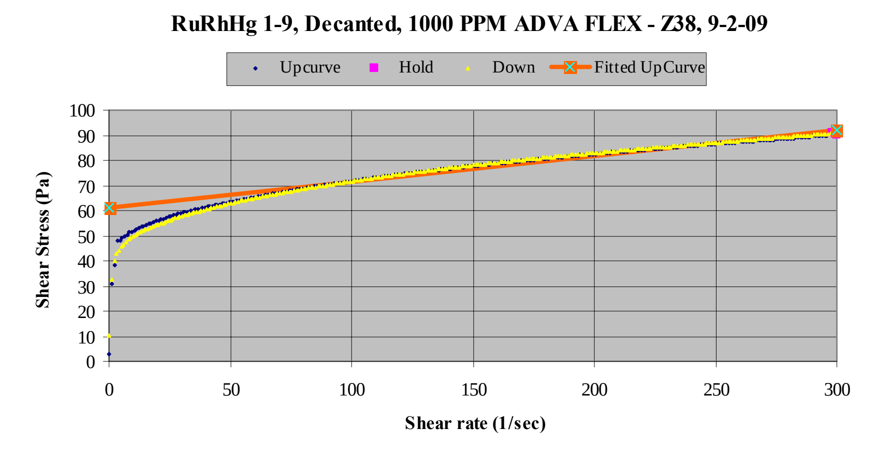


RuRhHg 1-9 Decanted 6,000 PPM Dolapix CE64

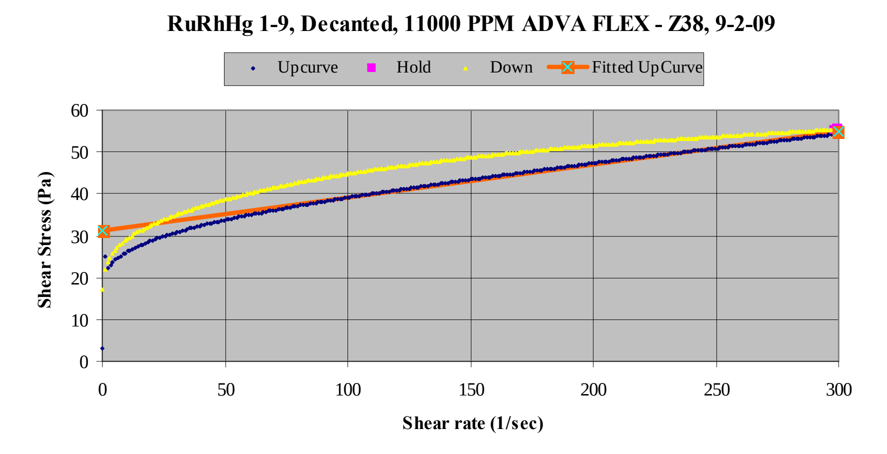


RuRhHg 1-9 Decanted 16,000 PPM Dolapix CE64

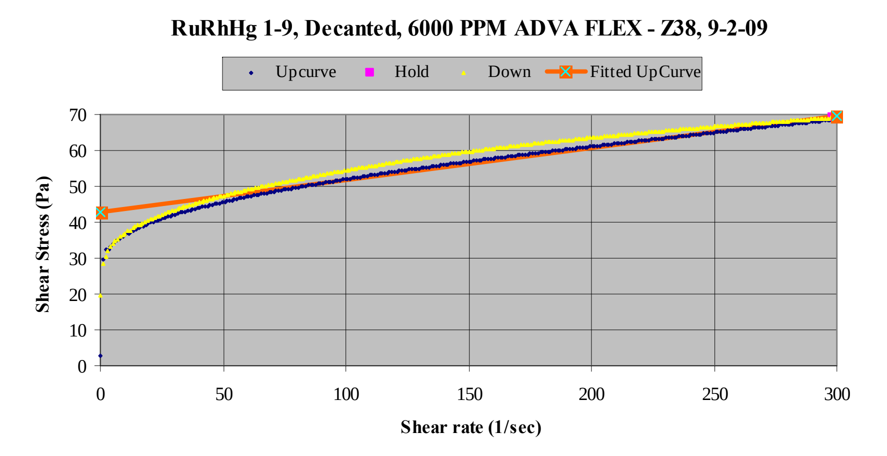
Figure C - 5 RuRhHg 1-9 Decanted SME Flow Curves: Dolapix CE64



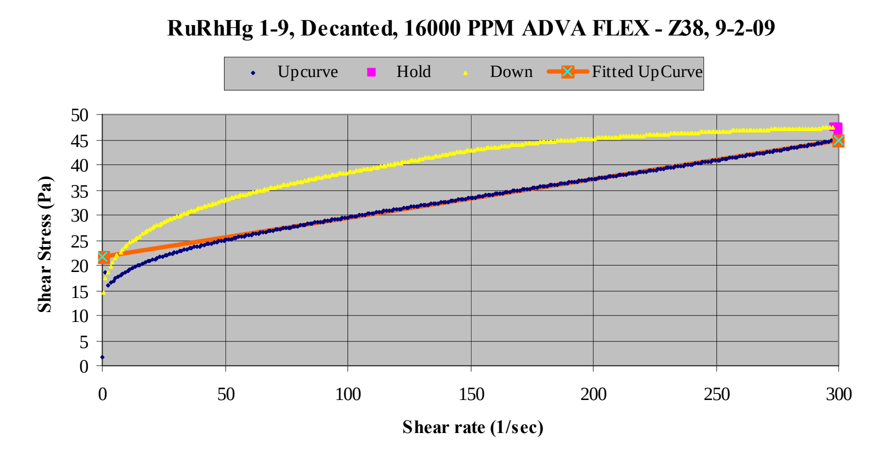
RuRhHg 1-9 Decanted 1,000 PPM ADVA Flex



RuRhHg 1-9 Decanted 11,000 PPM ADVA Flex



RuRhHg 1-9 Decanted 6,000 PPM ADVA Flex



RuRhHg 1-9 Decanted 16,000 PPM ADVA Flex

Figure C - 6 RuRhHg 1-9 Decanted SME Flow Curves: Grace ADVA Flex

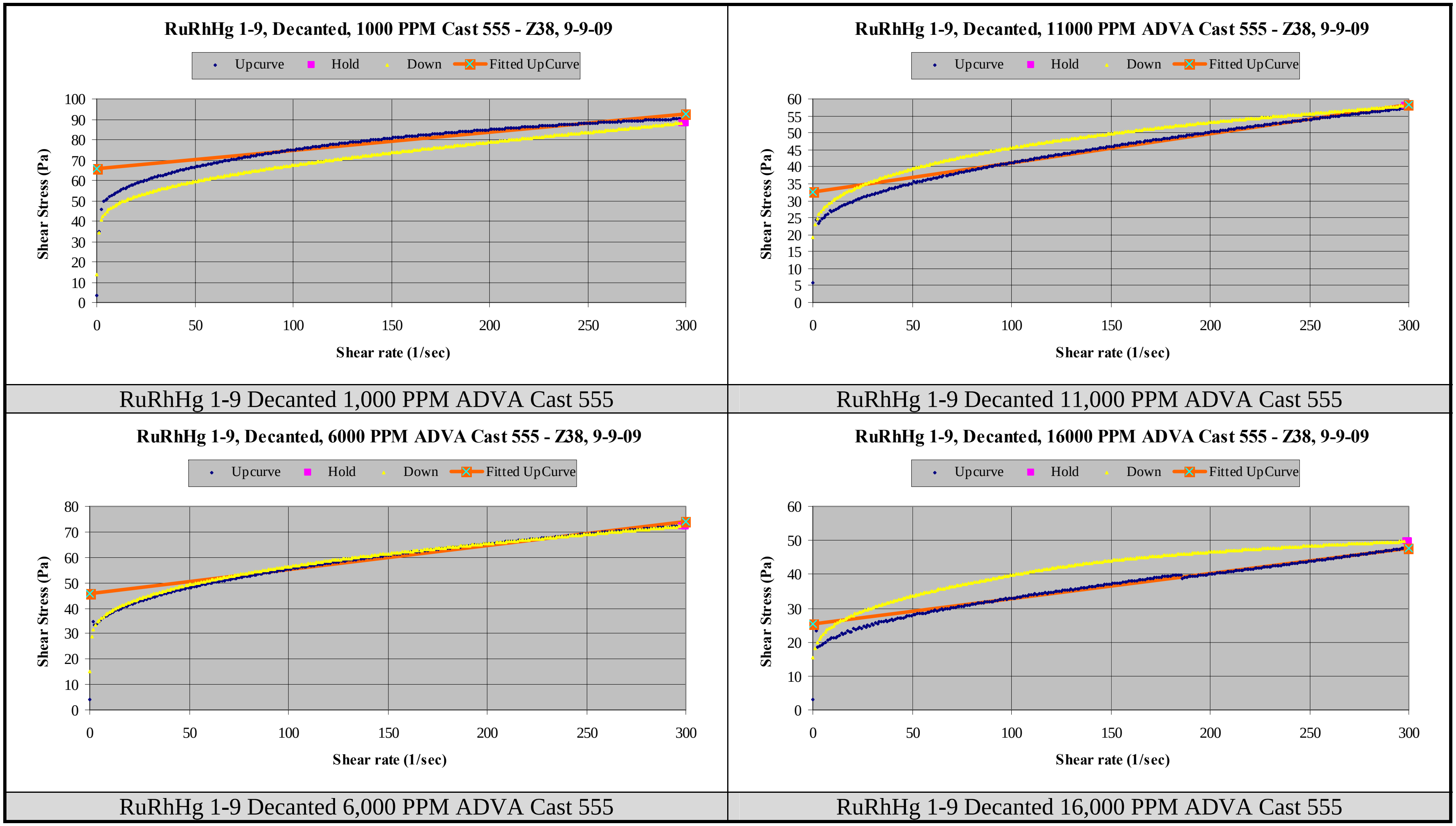
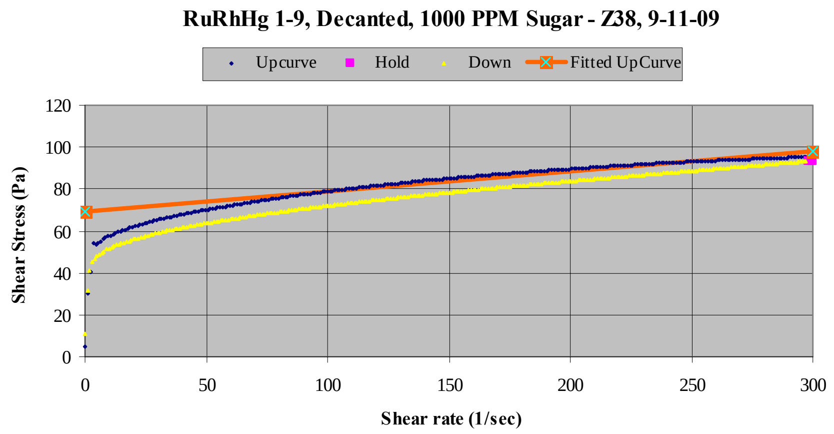
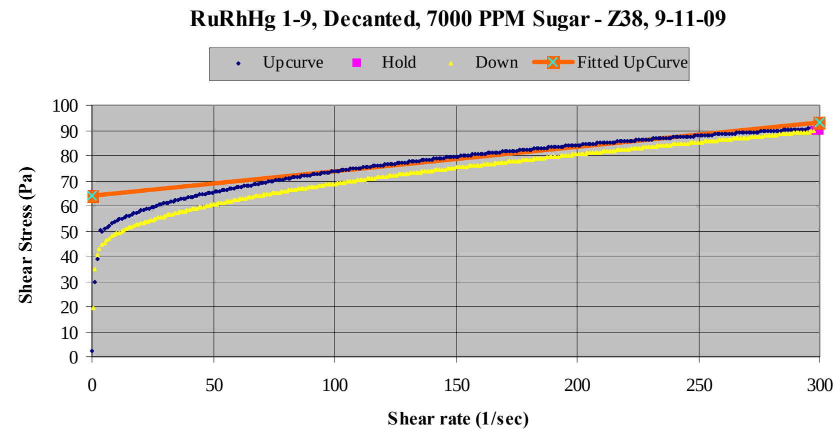


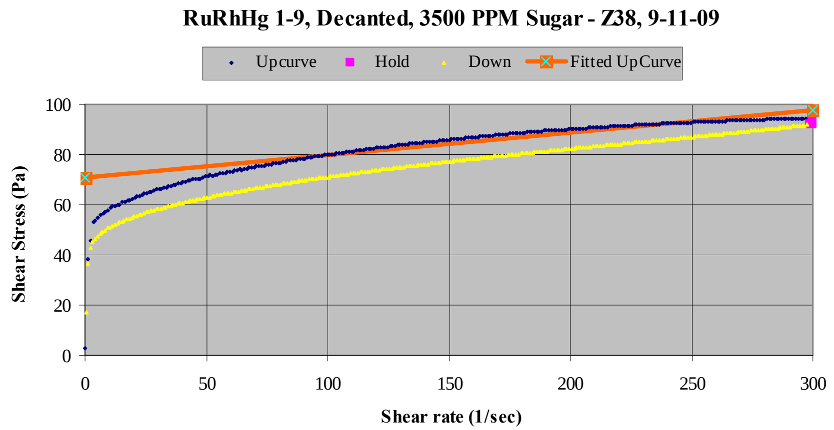
Figure C - 7 RuRhHg 1-9 Decanted SME Flow Curves: Grace ADVA Cast 555



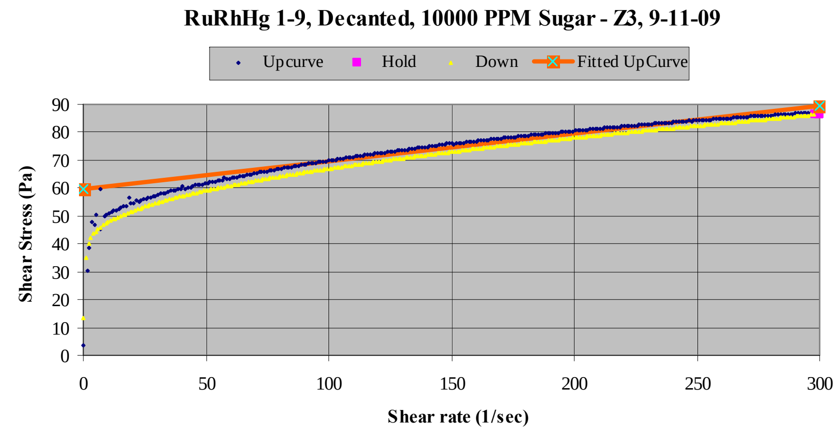
RuRhHg 1-9 Decanted 1,000 PPM Sugar



RuRhHg 1-9 Decanted 7,000 PPM Sugar

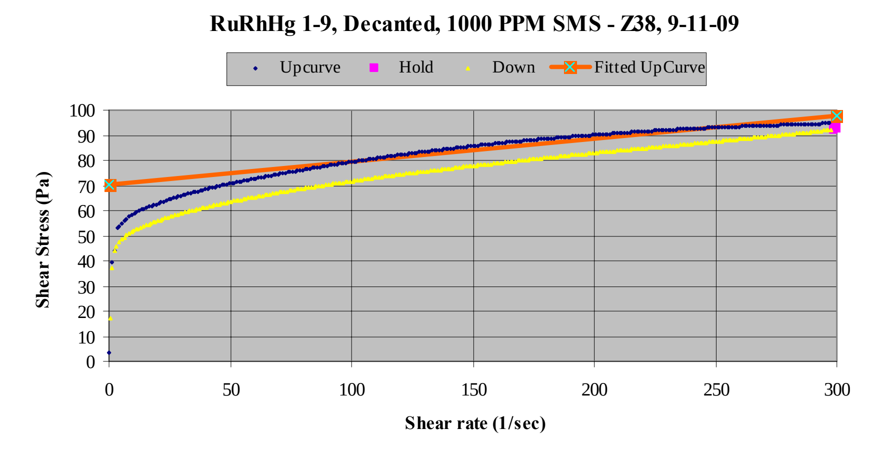


RuRhHg 1-9 Decanted 3,500 PPM Sugar

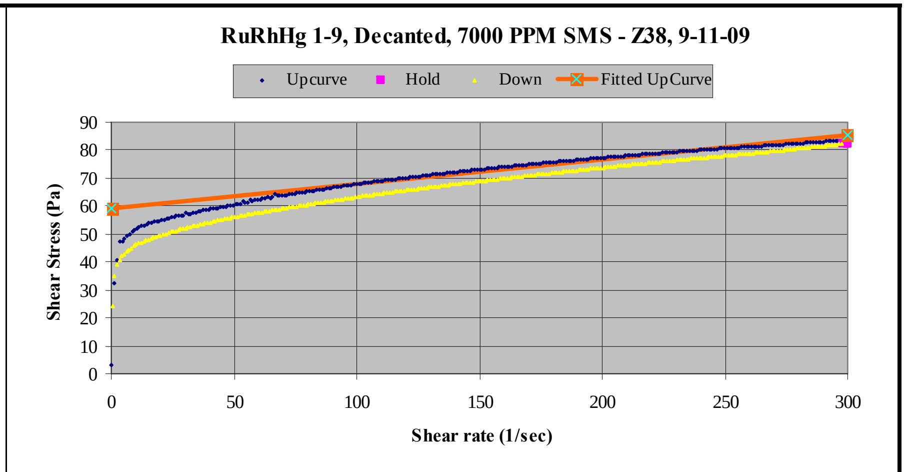


RuRhHg 1-9 Decanted 10,000 PPM Sugar

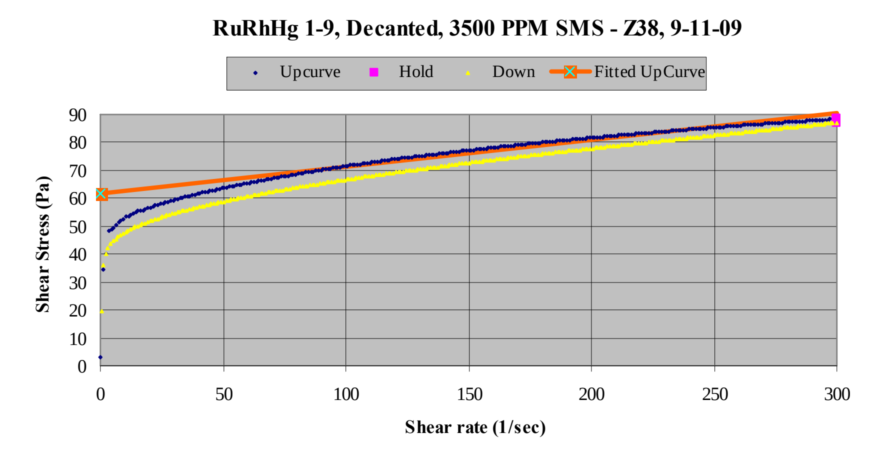
Figure C - 8 RuRhHg 1-9 Decanted SME Flow Curves: Sugar



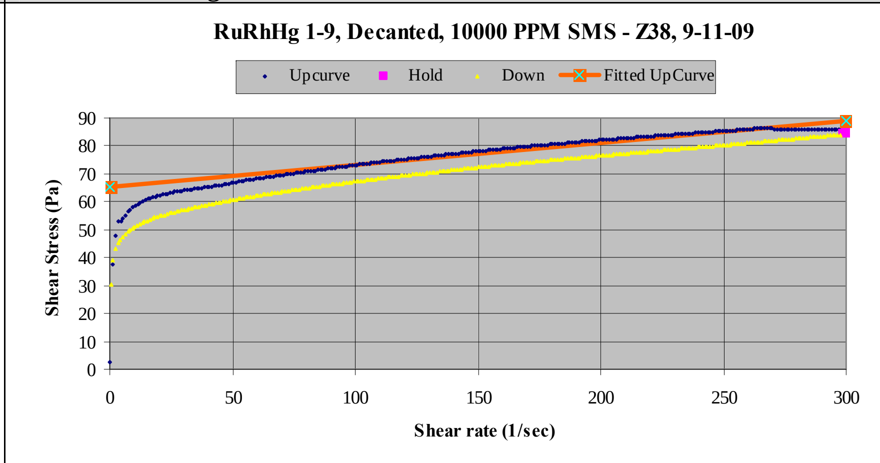
RuRhHg 1-9 Decanted 1,000 PPM Sodium Meta Silicate



RuRhHg 1-9 Decanted 7,000 PPM Sodium Meta Silicate

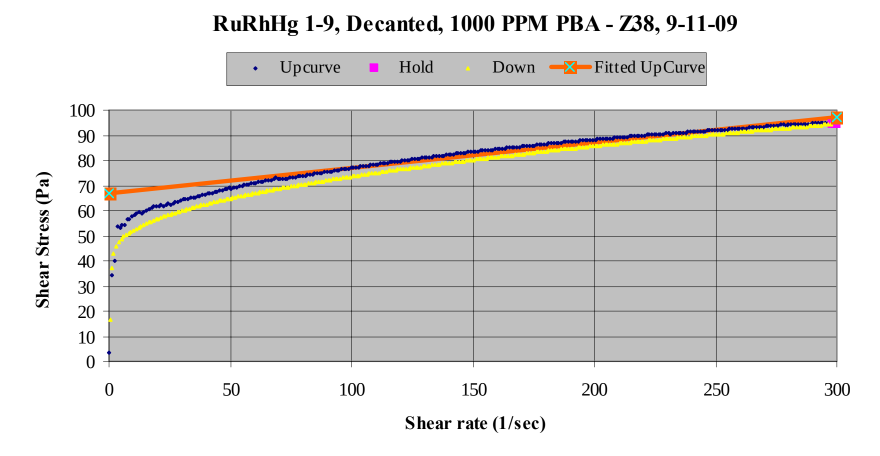


RuRhHg 1-9 Decanted 3,500 PPM Sodium Meta Silicate

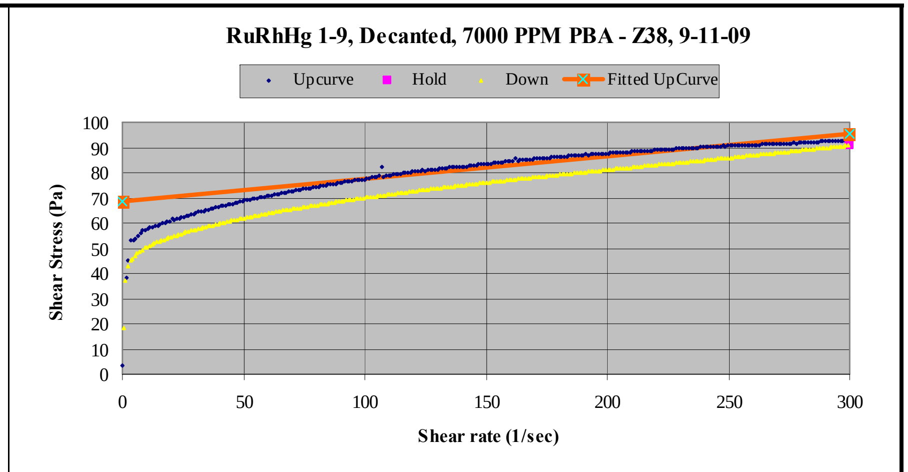


RuRhHg 1-9 Decanted 10,000 PPM Sodium Meta Silicate

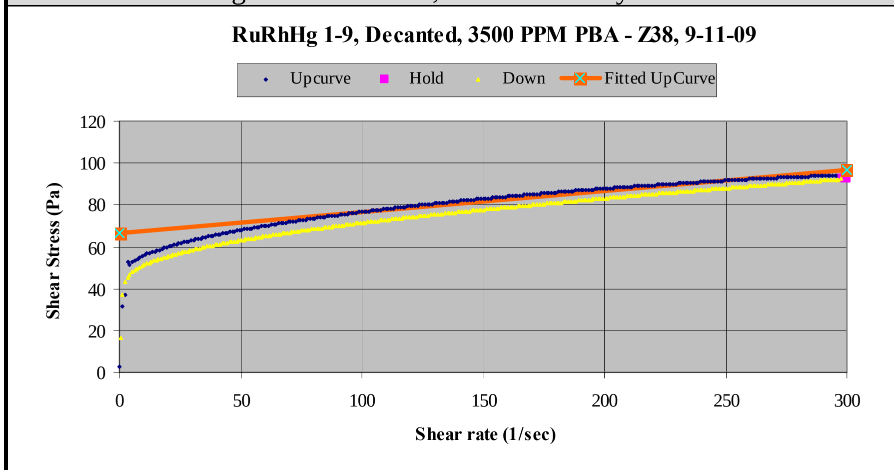
Figure C - 9 RuRhHg 1-9 Decanted SME Flow Curves: Sodium Meta Silicate



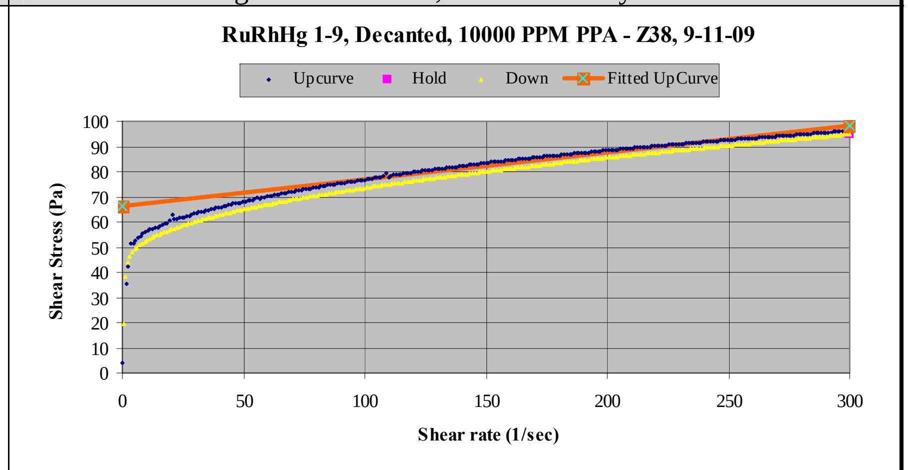
RuRhHg 1-9 Decanted 1,000 PPM Phenylboric Acid



RuRhHg 1-9 Decanted 7,000 PPM Phenylboric Acid



RuRhHg 1-9 Decanted 3,500 PPM Phenylboric Acid



RuRhHg 1-9 Decanted 10,000 PPM Phenylboric Acid

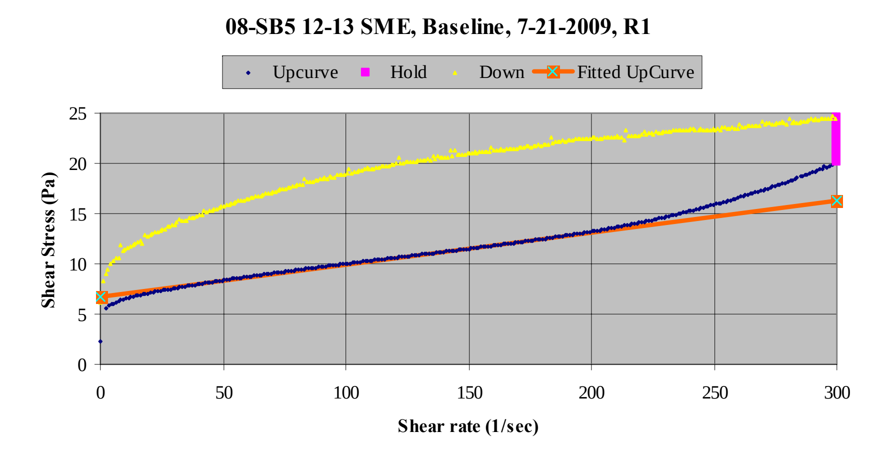
Figure C - 10 RuRhHg 1-9 Decanted SME Flow Curves: Phenylboric Acid

Appendix D SB5 12-13 SME Flow Curves

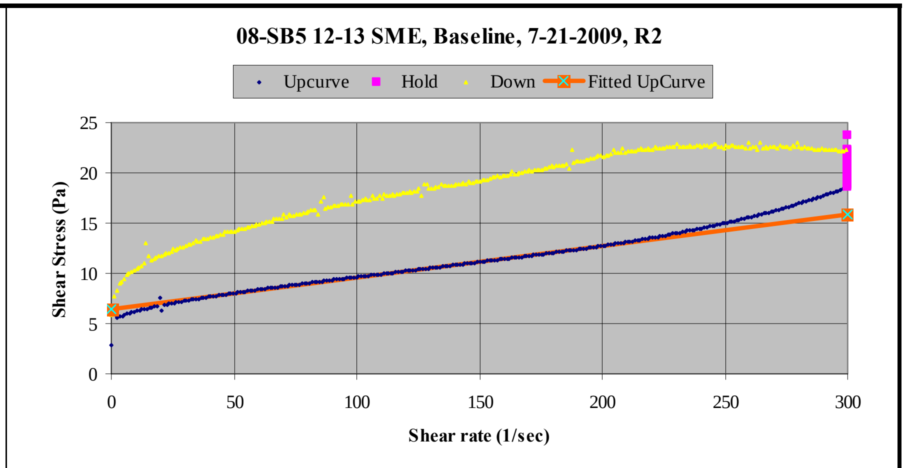
Table D - 1 08-SB5 12-13 SME: Bingham Plastic Results

Baseline Data, Sample ID	Rotor	Plastic Viscosity (cp)	Yield Stress (Pa)	R^2	Shear Rate Range (1/sec)
Baseline 5-4-2009, R1	Z38	32.0	6.74	0.9980	20-200
Baseline 5-4-2009, R2	Z38	31.5	6.42	0.9972	20-200
	Average	**31.7**	**6.58**		
	Std. Dev.	0.4	0.22		
	% Std. Dev.	1.2	3.4		

Sample Identification	Rotor	Plastic Viscosity (cp)	Yield Stress (Pa)	R^2	Shear Rate Range (1/sec)
Recover® - 1000 PPM	Z38	32.8	6.34	0.9983	20-200
Recover® - 6000 PPM	Z38	35.5	5.30	0.9959	20-200
Recover® - 11000 PPM	Z38	32.0	4.68	0.9981	20-200
Recover® - 11000 PPM	Z38	29.7	4.20	0.9980	20-180
Polyacrylic Acid - 1000 PPM	Z38	34.4	7.56	0.9992	20-180
Polyacrylic Acid - 3500 PPM	Z38	28.6	8.74	0.9884	20-180
Polyacrylic Acid - 7000 PPM	Z38	25.7	6.50	0.9750	20-180
Polyacrylic Acid - 10000 PPM	Z38	23.7	3.35	0.9883	20-150
Citric Acid - 1000 PPM	Z38	32.5	5.53	0.9989	20-180
Citric Acid - 3500 PPM	Z38	29.8	4.26	0.9971	20-180
Citric Acid - 7000 PPM	Z38	26.5	3.91	0.9983	20-180
Citric Acid - 10000 PPM	Z38	28.7	3.24	0.9913	20-180
Sodium Pyrophosphate Tetrabasic – 1000 PPM	Z38	35.3	7.29	0.9965	20-200
Sodium Pyrophosphate Tetrabasic - 3500 PPM	Z38	34.5	7.71	0.9976	20-200
Sodium Pyrophosphate Tetrabasic - 7000 PPM	Z38	37.2	8.21	0.9958	20-200
Sodium Pyrophosphate Tetrabasic - 10000 PPM	Z38	41.3	8.39	0.9842	20-200
Dolapix A88 - 1000 PPM	Z38	36.5	8.67	0.9979	20-200
Dolapix A88 - 3000 PPM	Z38	36.2	10.38	0.9969	20-200
Dolapix A88 - 6000 PPM	Z38	31.7	13.91	0.9944	20-200
Dolapix A88 - 10000 PPM	Z38	32.0	16.99	0.9819	20-200
Dolapix CE64 - 1000 PPM	Z38	34.2	7.17	0.9991	20-200
Dolapix CE64 - 6000 PPM	Z38	33.5	8.95	0.9951	20-180
Dolapix CE64 - 11000 PPM	Z38	32.2	9.50	0.9906	20-180
Dolapix CE64 - 16000 PPM	Z38	29.3	8.52	0.9933	20-175
Dolapix PC75 - 1000 PPM	Z38	35.5	6.37	0.9991	20-200
Dolapix PC75 - 6000 PPM	Z38	33.4	5.87	0.9987	20-200
Dolapix PC75 - 11000 PPM	Z38	31.8	6.28	0.9994	20-200
Dolapix PC75 - 16000 PPM	Z38	34.2	6.60	0.9979	20-200
ADVA CAST 555 - 1000 PPM	Z38	32.2	6.65	0.9990	20-180
ADVA CAST 555- 6000 PPM	Z38	34.0	5.26	0.9971	20-180
ADVA CAST 555 - 11000 PPM	Z38	31.6	3.53	0.9947	20-180
ADVA CAST 555 - 16000 PPM	Z38	32.9	2.32	0.9873	20-175

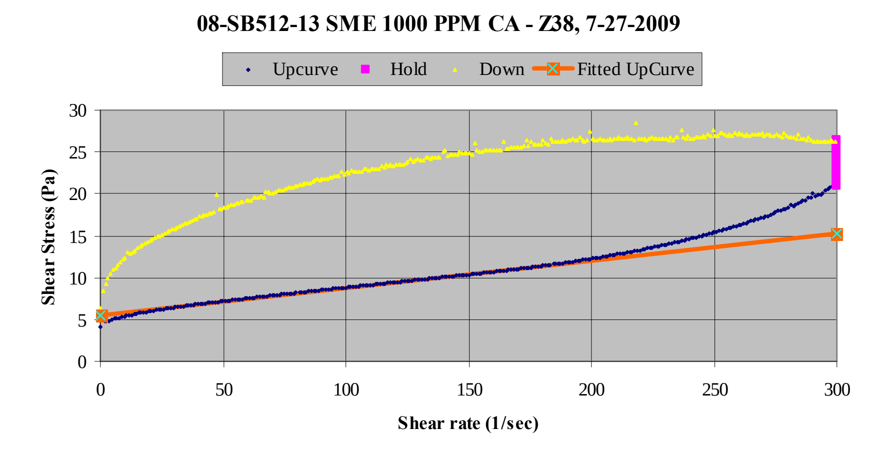


08-SB5 12-13 Baseline R1

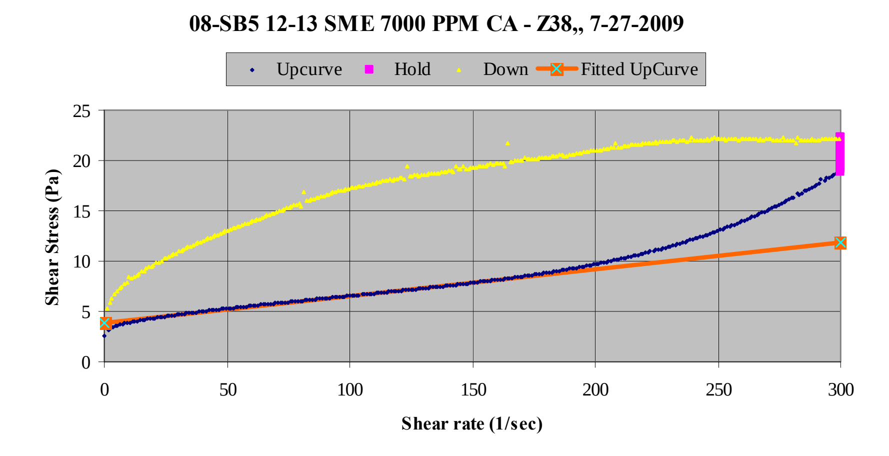


08-SB5 12-13 Baseline R2

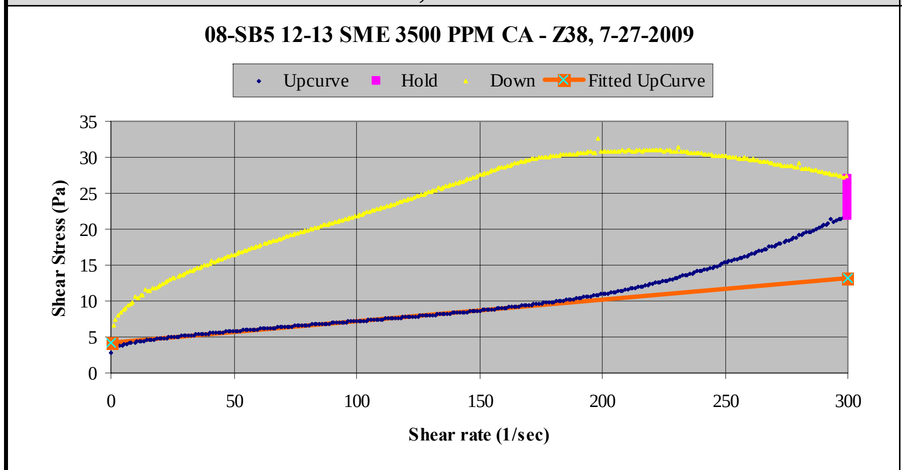
Figure D - 1 08-SB5 12-13 SME Flow Curves: Baseline



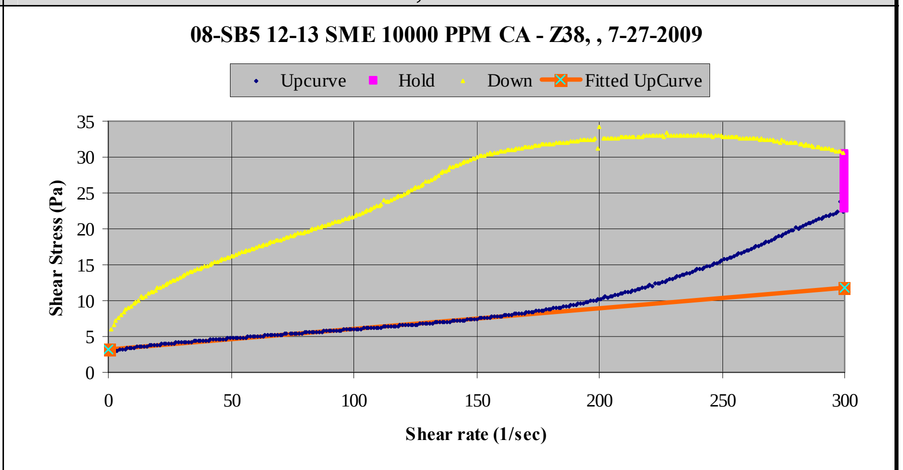
08-SB5 12-13 1,000 PPM Citric Acid



08-SB5 12-13 7,000 PPM Citric Acid

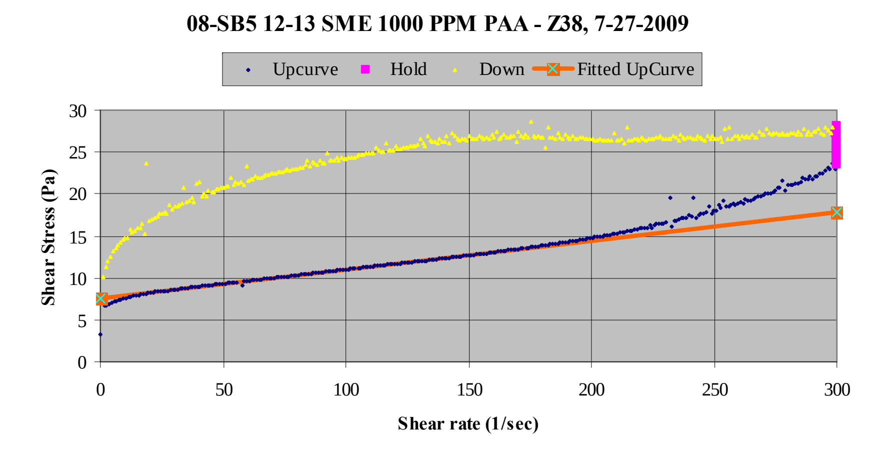


08-SB5 12-13 3,500 PPM Citric Acid

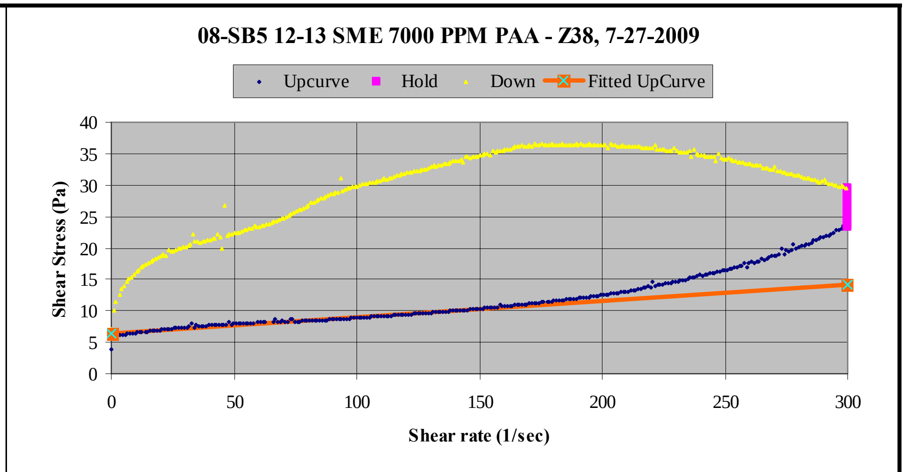


08-SB5 12-13 10,000 PPM Citric Acid

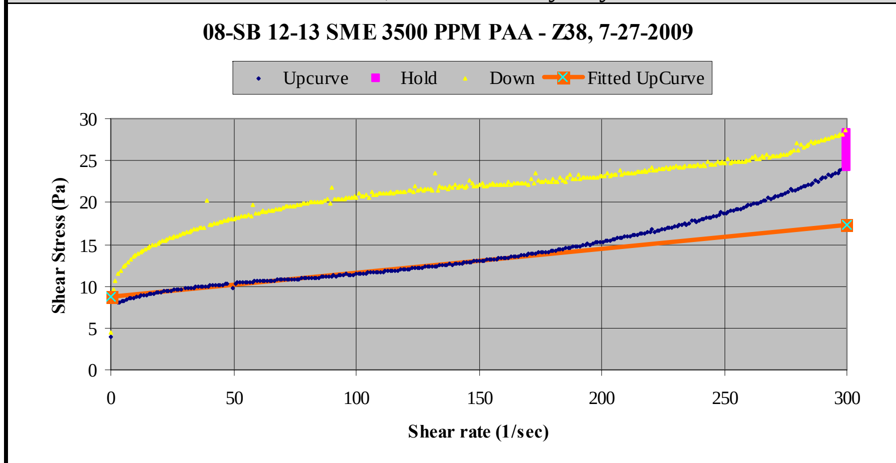
Figure D - 2 08-SB5 12-13 SME Flow Curves: Citric Acid Addition



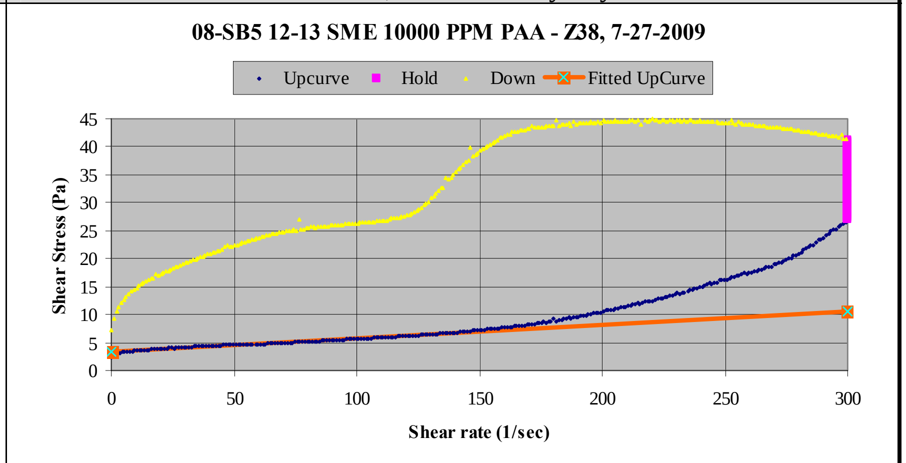
08-SB5 12-13 1,000 PPM Polyacrylic Acid



08-SB5 12-13 7,000 PPM Polyacrylic Acid

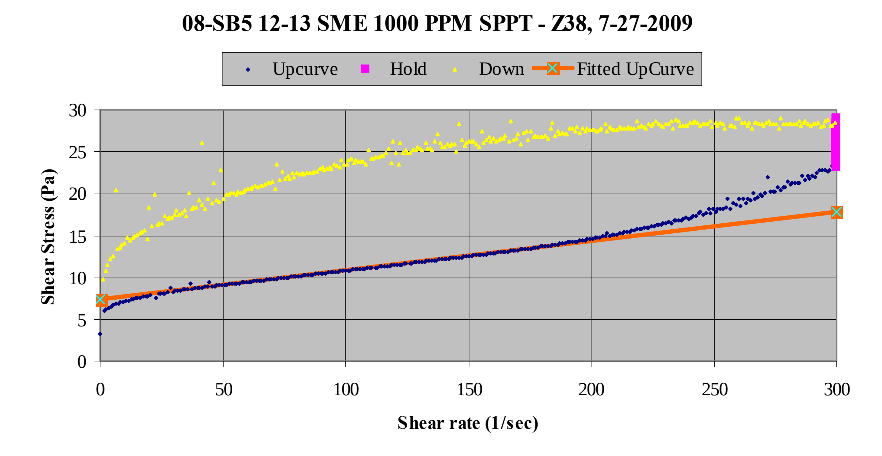


08-SB5 12-13 3,500 PPM Polyacrylic Acid

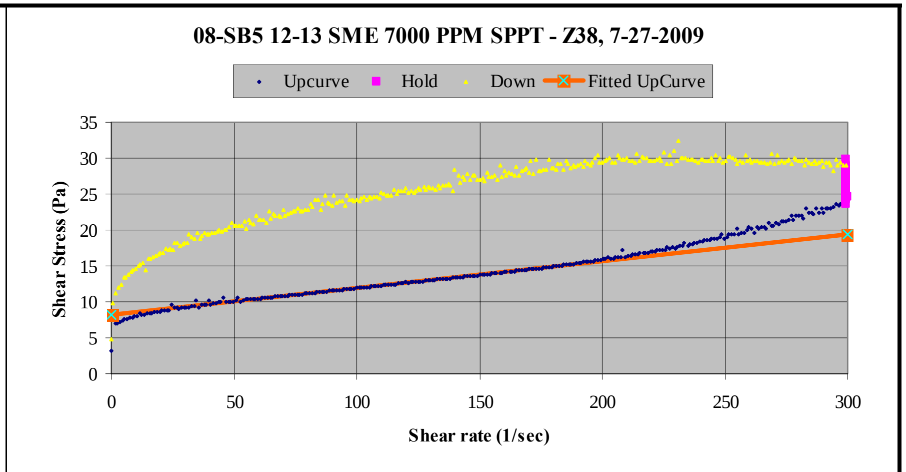


08-SB5 12-13 10,000 PPM Polyacrylic Acid

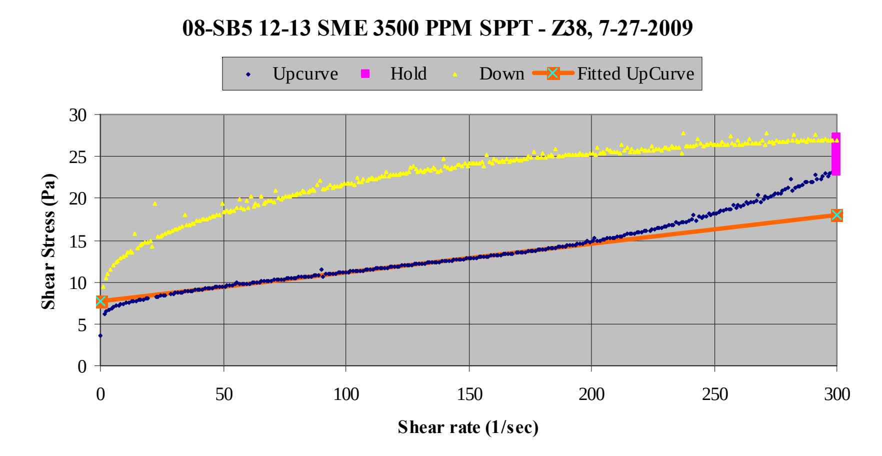
Figure D - 3 08-SB5 12-13 SME Flow Curves: Polyacrylic Acid Addition



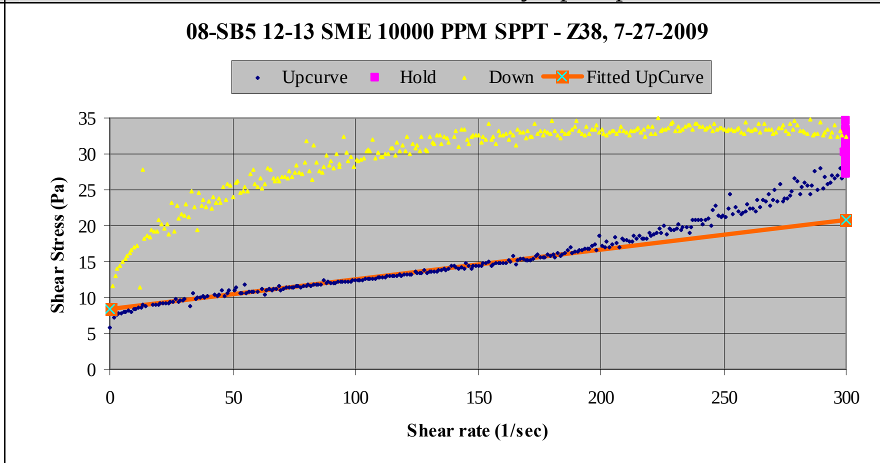
08-SB5 12-13 1,000 PPM Sodium Pyrophosphate Tetrabasic



08-SB5 12-13 7,000 PPM Sodium Pyrophosphate Tetrabasic

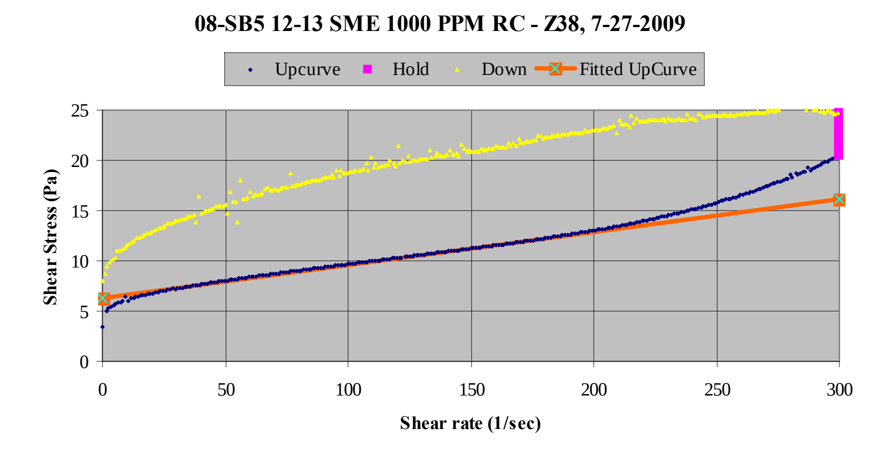


08-SB5 12-13 3,500 PPM Sodium Pyrophosphate Tetrabasic

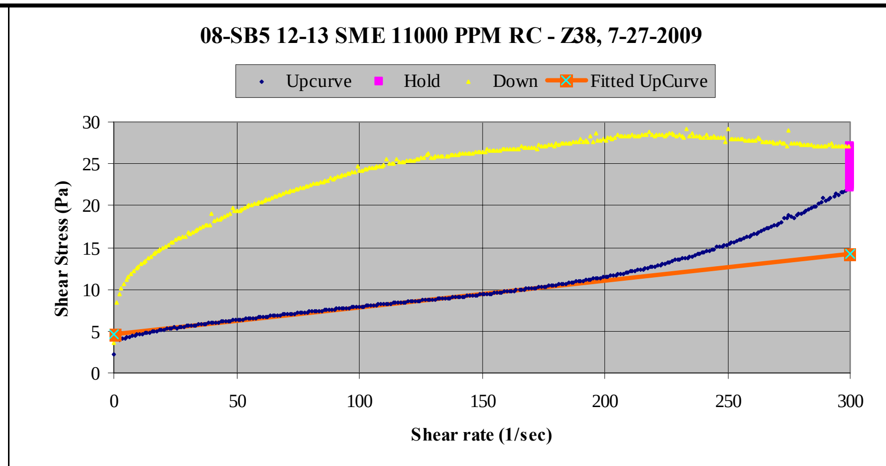


08-SB5 12-13 10,000 PPM Sodium Pyrophosphate Tetrabasic

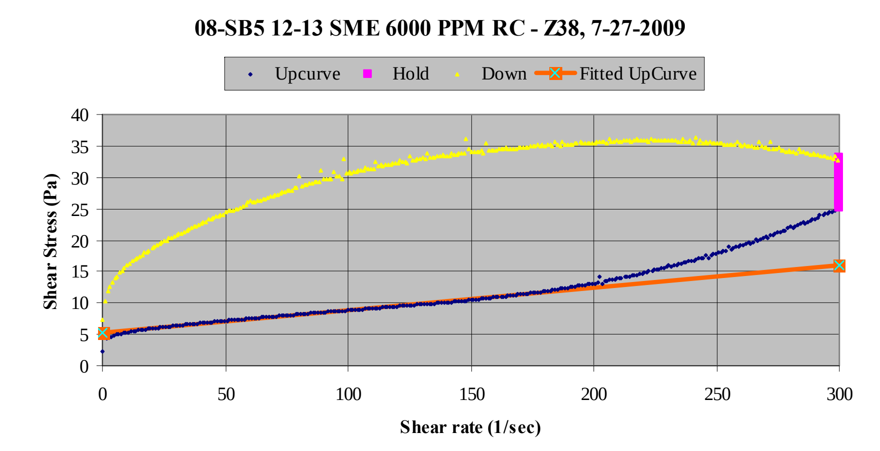
Figure D - 4 08-SB5 12-13 SME Flow Curves: Sodium Pyrophosphate Tetrabasic



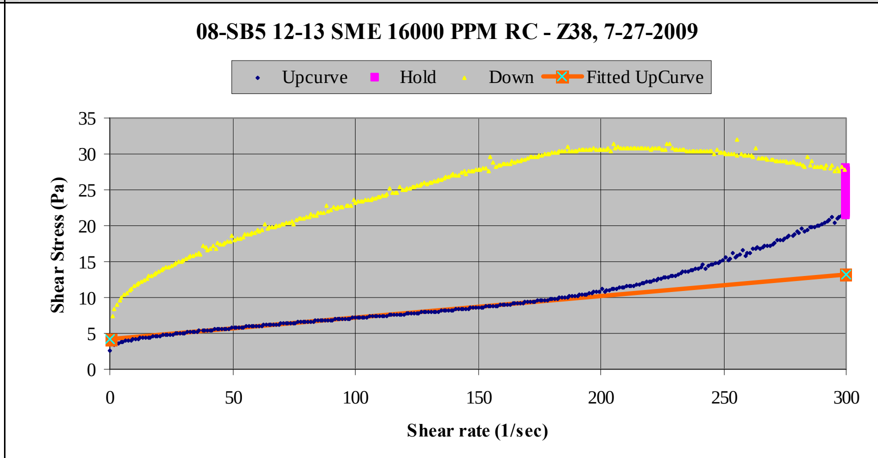
08-SB5 12-13 1,000 PPM Recover®



08-SB5 12-13 11,000 PPM Recover®

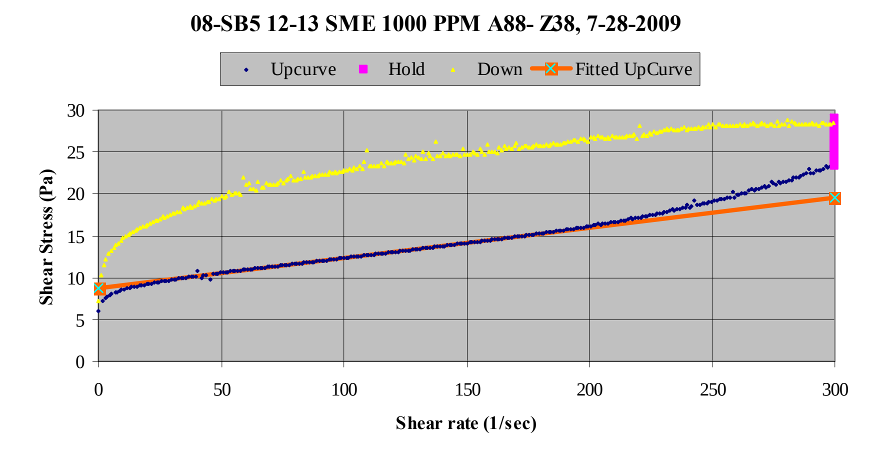


08-SB5 12-13 6,000 PPM Recover®

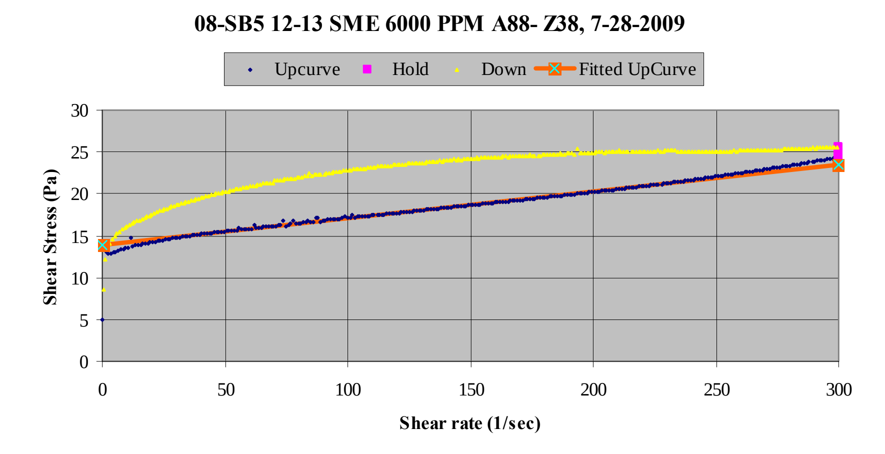


08-SB5 12-13 16,000 PPM Recover®

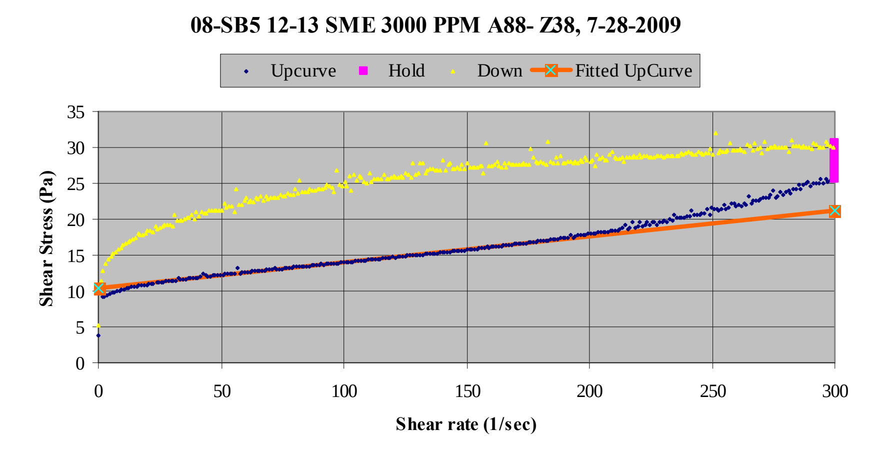
Figure D - 5 08-SB5 12-13 SME Flow Curves: Grace Recover®



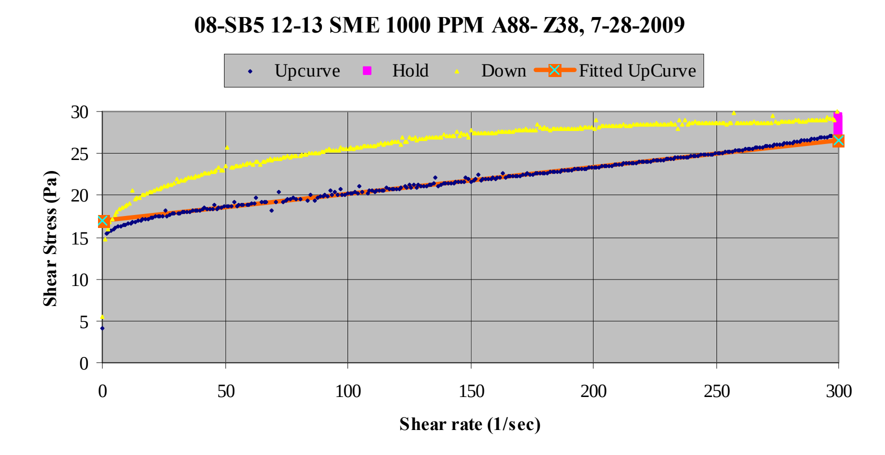
08-SB5 12-13 1,000 PPM Dolapix A88



08-SB5 12-13 6,000 PPM Dolapix A88

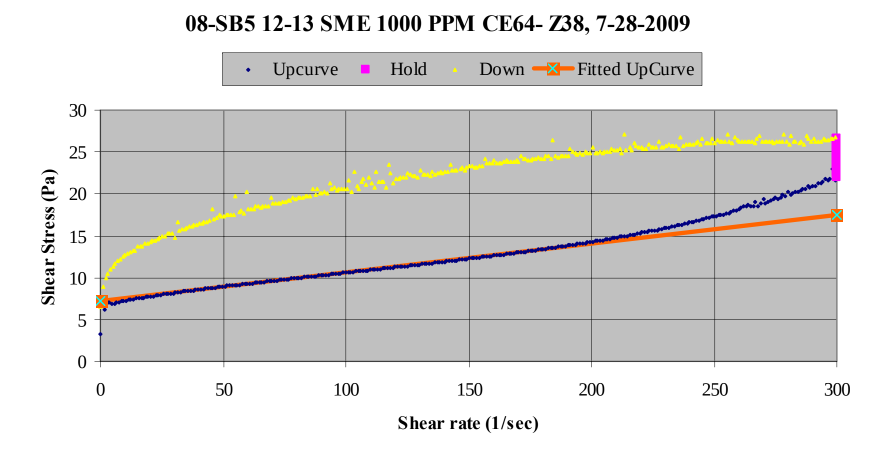


08-SB5 12-13 3,000 PPM Dolapix A88

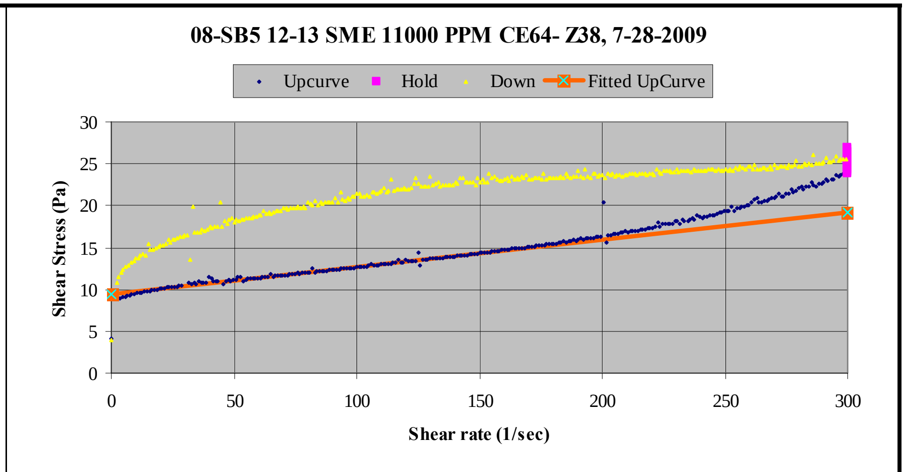


08-SB5 12-13 10,000 PPM Dolapix A88

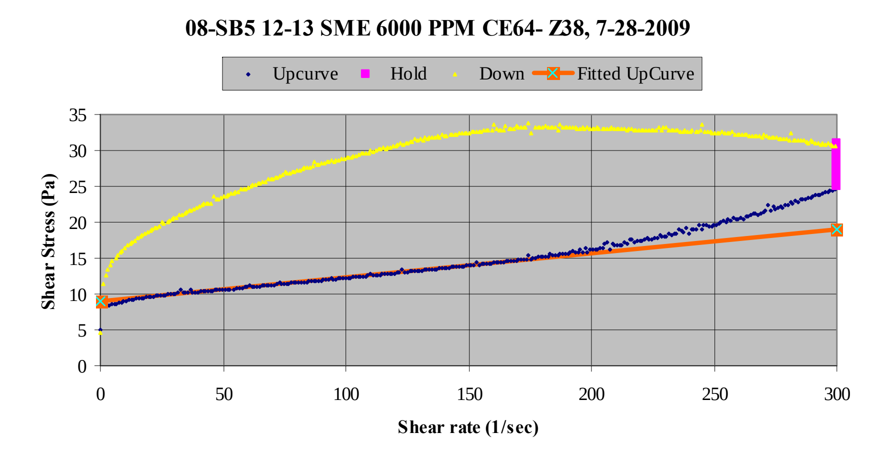
Figure D - 6 08-SB5 12-13 SME Flow Curves: Dolapix A88



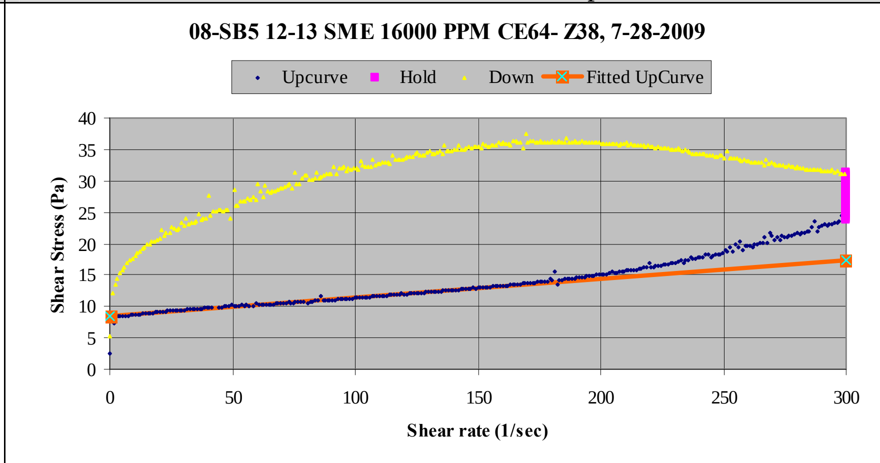
08-SB5 12-13 1,000 PPM Dolapix CE64



08-SB5 12-13 11,000 PPM Dolapix CE64

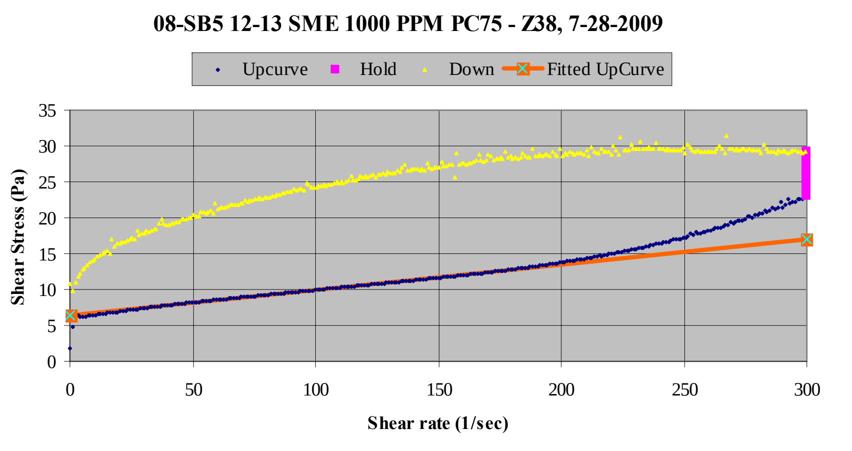


08-SB5 12-13 6,000 PPM Dolapix CE64

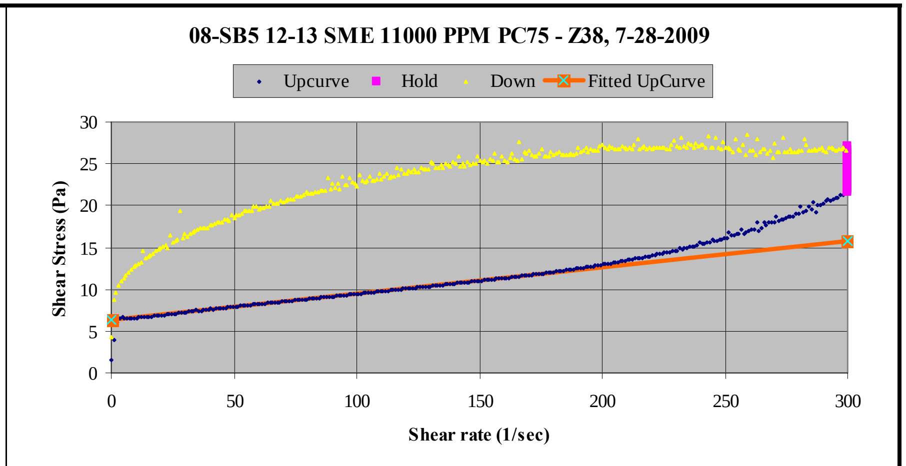


08-SB5 12-13 16,000 PPM Dolapix CE64

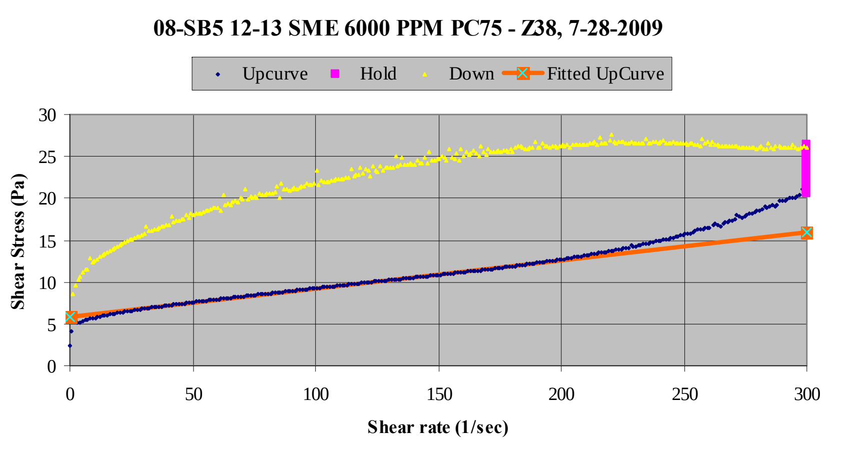
Figure D - 7 08-SB5 12-13 SME Flow Curves: Dolapix CE64



08-SB5 12-13 1,000 PPM Dolapix PC75



08-SB5 12-13 11,000 PPM Dolapix PC75



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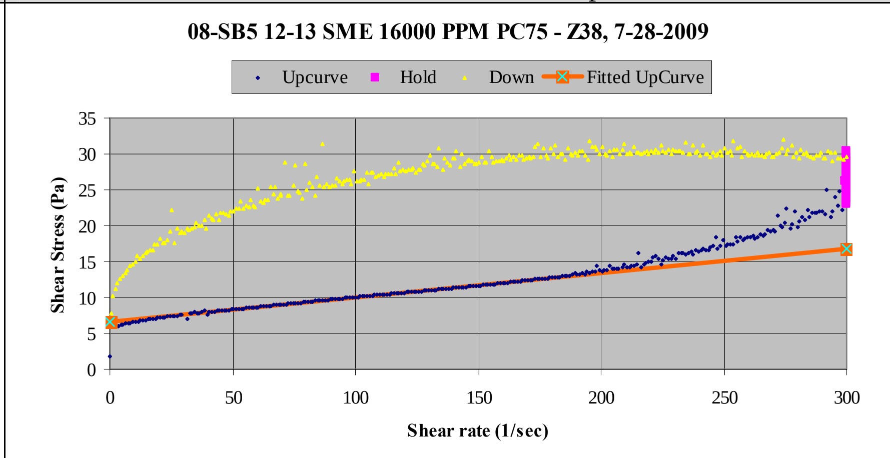
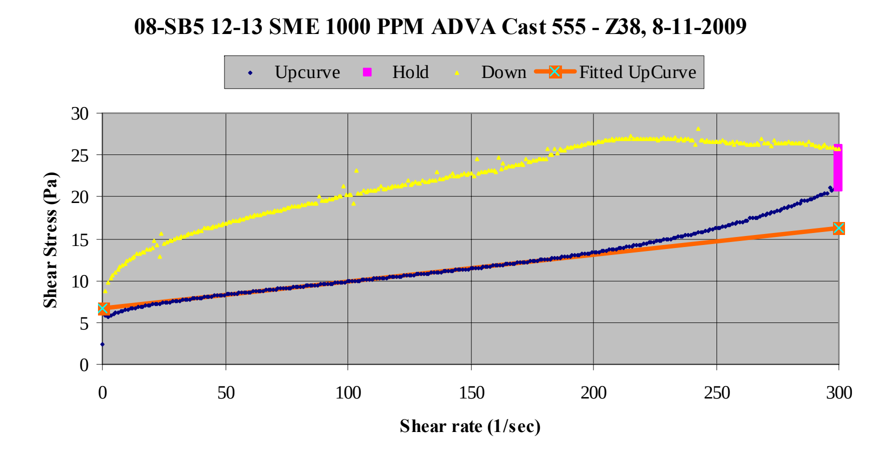
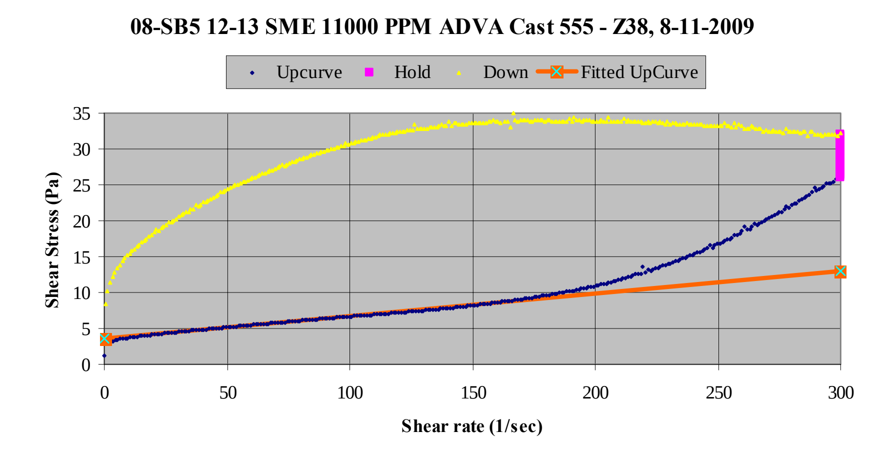


08-SB5 12-13 16,000 PPM Dolapix PC75

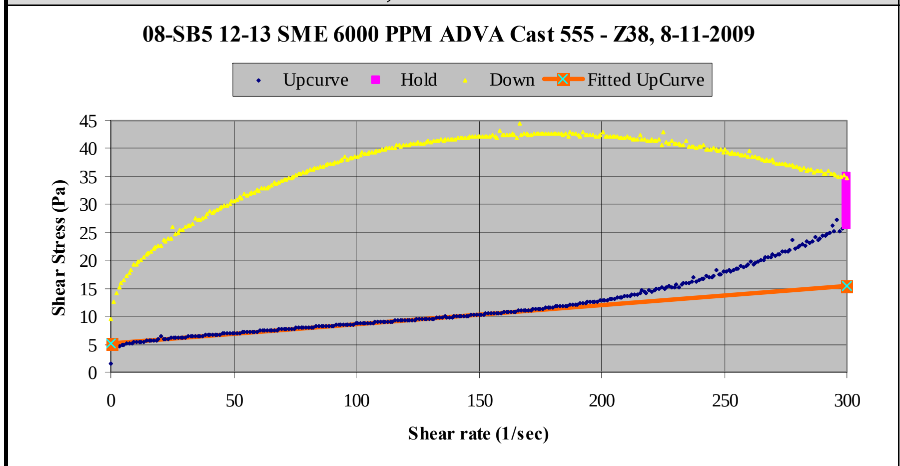
Figure D - 8 08-SB5 12-13 SME Flow Curves: Dolapix PC75



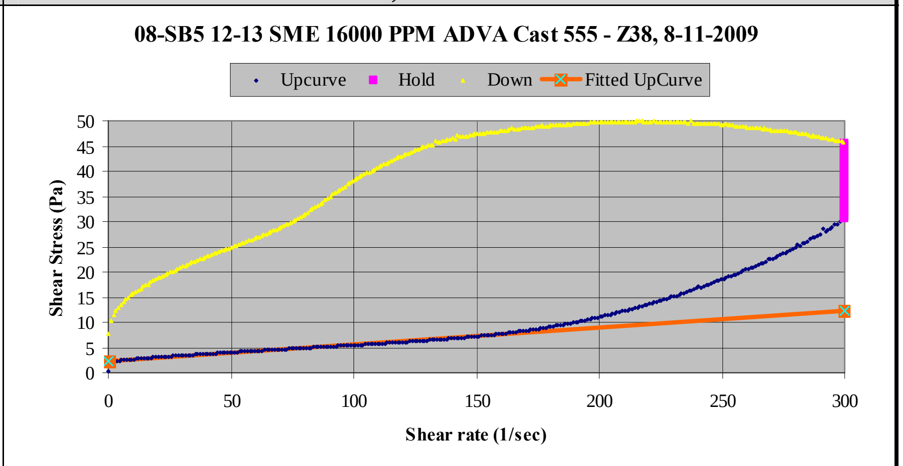
08-SB5 12-13 1,000 PPM ADVA Cast 555



08-SB5 12-13 11,000 PPM ADVA Cast 555



08-SB5 12-13 6,000 PPM ADVA Cast 555



08-SB5 12-13 16,000 PPM ADVA Cast 555

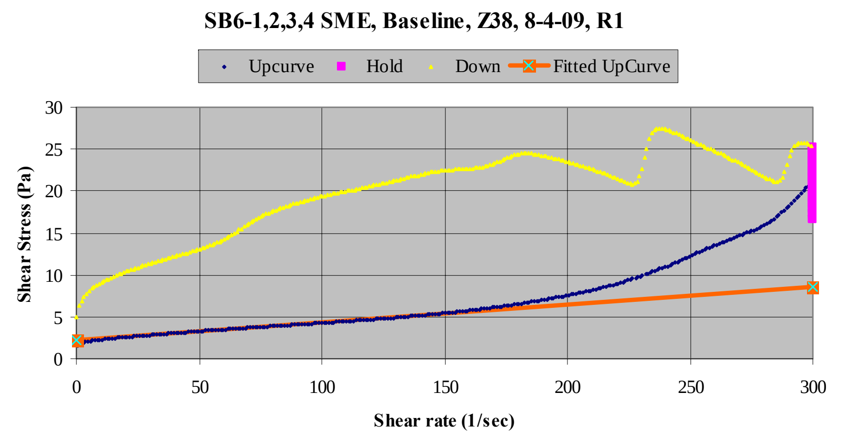
Figure D - 9 08-SB5 12-13 SME Flow Curves: ADVA Cast 555

Appendix E SB6-1,2,3,4 SME Flow Curves

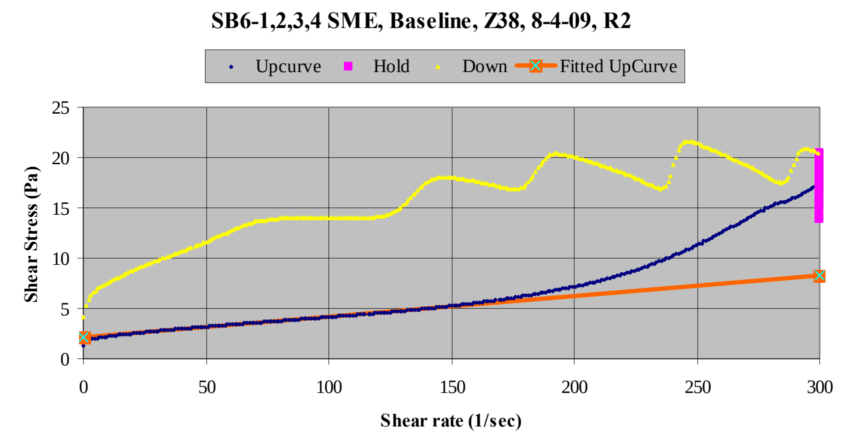
Table E - 1 SB6-1,2,3,4 SME: Bingham Plastic Results

Baseline Data, Sample ID	Rotor	Plastic Viscosity (cp)	Yield Stress (Pa)	R^2	Shear Rate Range (1/sec)
Baseline 8-4-2009, R1	Z38	21.6	2.16	0.9955	20-175
Baseline 8-4-2009, R2	Z38	20.7	2.12	0.9964	20-175
Baseline 8-5-2009, R1	Z38	21.0	2.23	0.9967	20-175
	Average	**21.1**	**2.17**		
	Std. Dev.	0.5	0.06		
	% Std. Dev.	2.4	2.57		

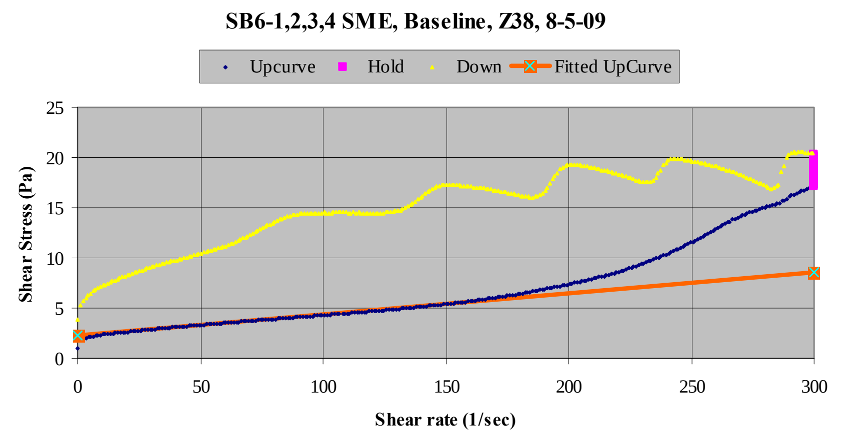
Sample Identification	Rotor	Plastic Viscosity (cp)	Yield Stress (Pa)	R^2	Shear Rate Range (1/sec)
Recover® - 1000 PPM	Z38	17.5	2.43	0.9910	20-140
Recover® - 6000 PPM	Z38	19.4	1.91	0.9980	20-140
Recover® - 11000 PPM	Z38	18.7	1.62	0.9972	20-140
Recover® - 11000 PPM	Z38	18.7	1.41	0.9956	20-140
Polyacrylic Acid - 1000 PPM	Z38	18.6	3.25	0.9882	20-175
Polyacrylic Acid - 3500 PPM	Z38	16.4	2.96	0.9876	20-140
Polyacrylic Acid - 7000 PPM	Z38	15.3	2.38	0.9777	20-140
Polyacrylic Acid - 10000 PPM	Z38	15.6	1.61	0.9700	20-140
Citric Acid - 1000 PPM	Z38	20.2	2.26	0.9973	20-175
Citric Acid - 3500 PPM	Z38	17.6	2.16	0.9752	20-140
Citric Acid - 7000 PPM	Z38	19.8	2.21	0.9995	20-140
Citric Acid - 10000 PPM	Z38	20.0	2.33	0.9992	20-140
Sodium Pyrophosphate Tetrabasic - 1000 PPM	Z38	19.5	2.44	0.9994	20-140
Sodium Pyrophosphate Tetrabasic - 3500 PPM	Z38	34.6	7.71	0.9949	20-140
Sodium Pyrophosphate Tetrabasic - 7000 PPM	Z38	21.8	2.46	0.9990	20-140
Sodium Pyrophosphate Tetrabasic - 10000 PPM	Z38	22.5	2.43	0.9990	20-140
Dolapix A88 - 1000 PPM	Z38	21.0	3.11	0.9944	45-175
Dolapix A88 - 3000 PPM	Z38	21.9	3.24	0.9922	45-175
Dolapix A88 - 6000 PPM	Z38	21.3	4.25	0.9899	50-175
Dolapix A88 - 10000 PPM	Z38	20.6	5.12	0.9898	45-175
Dolapix CE64 - 1000 PPM	Z38	20.3	2.91	0.9907	45-175
Dolapix CE64 - 6000 PPM	Z38	21.8	3.36	0.9867	45-175
Dolapix CE64 - 11000 PPM	Z38	22.0	3.23	0.9849	45-175
Dolapix CE64 - 16000 PPM	Z38	21.8	2.65	0.9913	45-175
Dolapix PC75 - 1000 PPM	Z38	18.3	2.12	0.9985	20-150
Dolapix PC75 - 6000 PPM	Z38	20.9	1.78	0.9963	20-150
Dolapix PC75 - 11000 PPM	Z38	20.4	1.84	0.9975	20-150
Dolapix PC75 - 16000 PPM	Z38	19.9	1.88	0.9975	20-150
Taylor 747 Antifoam - 1000 PPM	Z38	20.9	2.57	0.9953	20-170
Taylor 747 Antifoam - 3500 PPM	Z38	21.8	2.51	0.9962	20-170
Taylor 747 Antifoam - 7000 PPM	Z38	22.1	2.48	0.9973	20-170
Taylor 747 Antifoam - 10000 PPM	Z38	23.6	2.47	0.9966	20-170



SB6-1,2,3,4 Baseline, R1

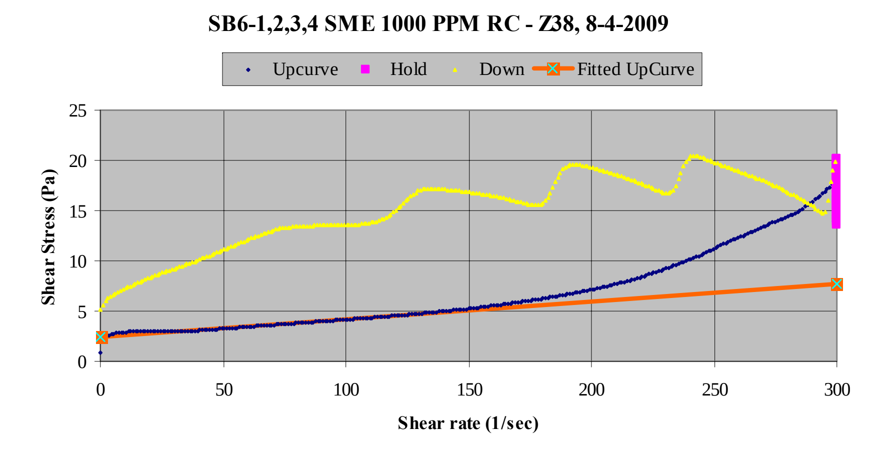


SB6-1,2,3,4 Baseline, R2

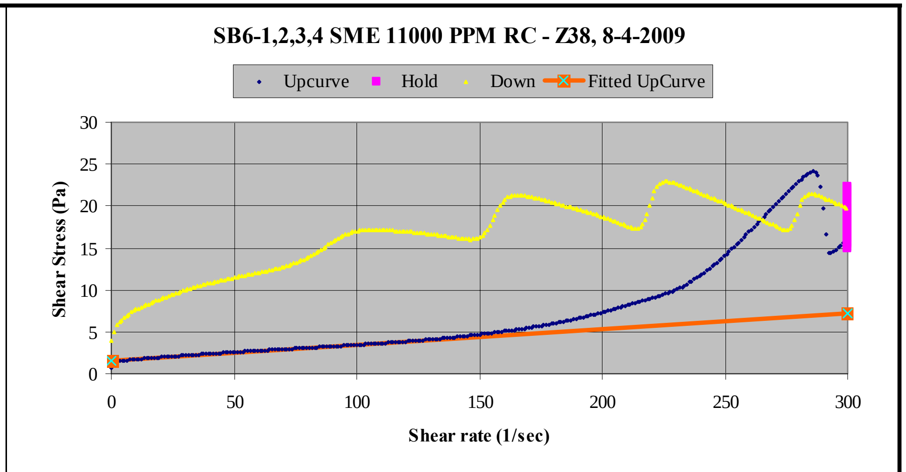


SB6-1,2,3,4 Baseline, R3

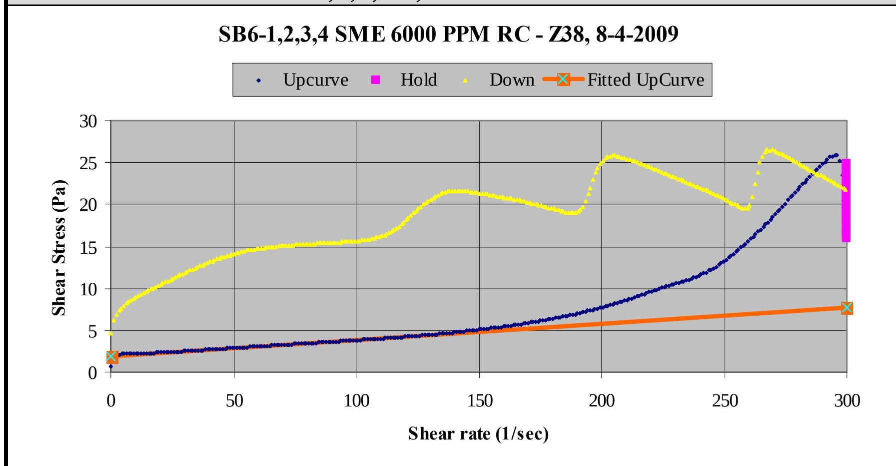
Figure E - 1 SB6-1,2,3,4 SME Flow Curves: Baseline



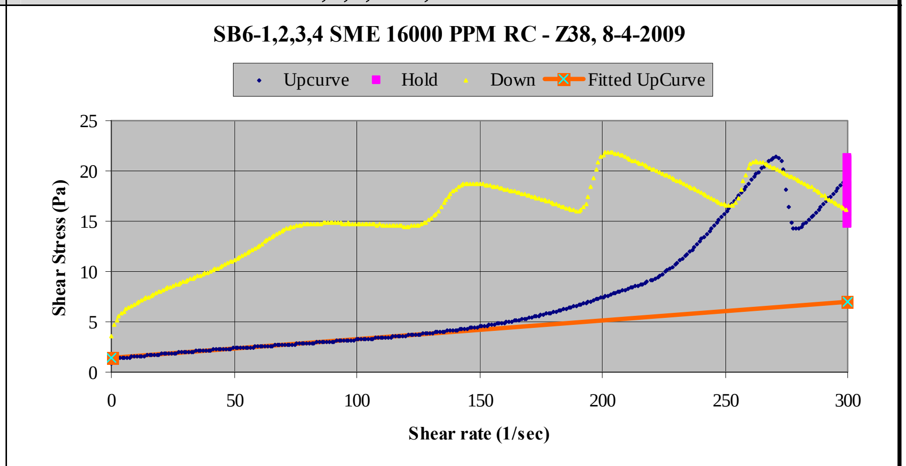
SB6-1,2,3,4 1,000 PPM Recover®



SB6-1,2,3,4 11,000 PPM Recover®

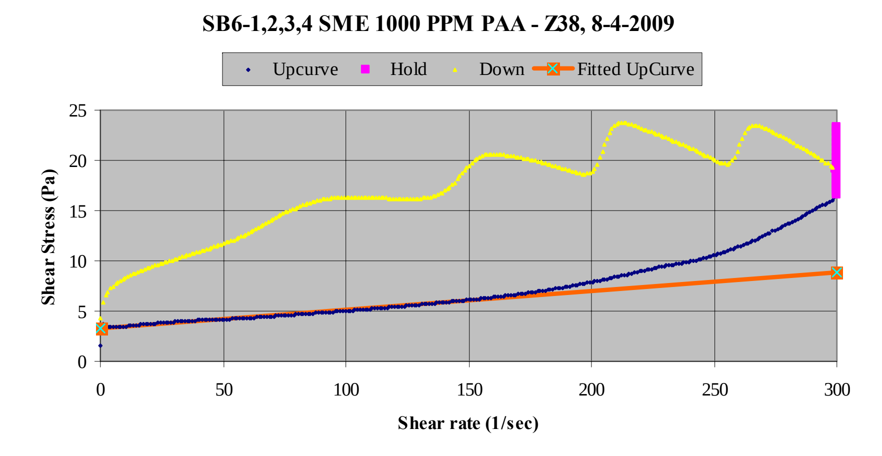


SB6-1,2,3,4 6,000 PPM Recover®

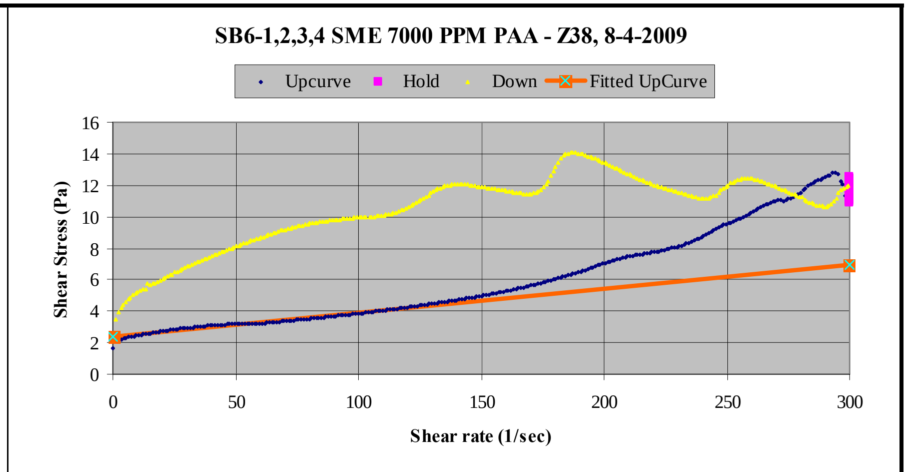


SB6-1,2,3,4 16,000 PPM Recover®

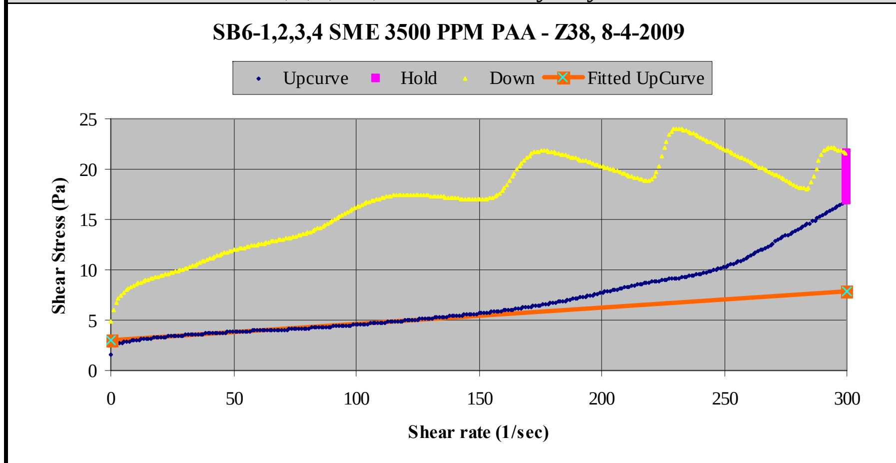
Figure E - 2 SB6-1,2,3,4 SME Flow Curves: Grace Recover®



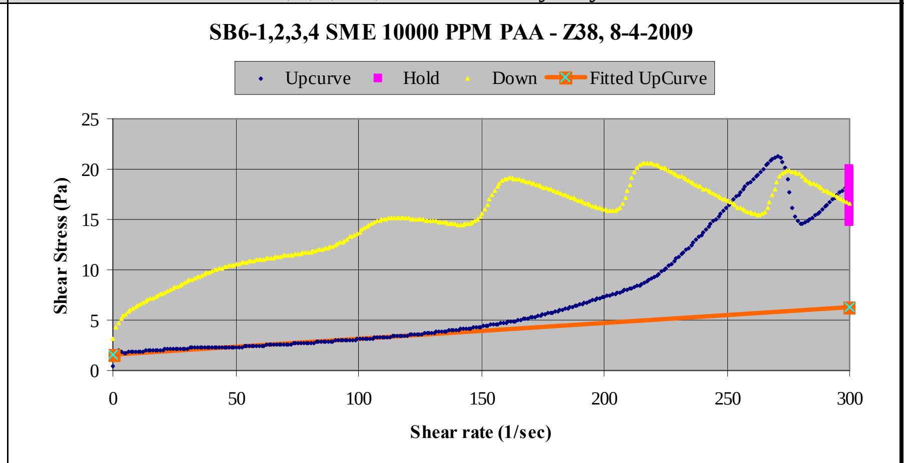
SB6-1,2,3,4 1,000 PPM Polyacrylic Acid



SB6-1,2,3,4 7,000 PPM Polyacrylic Acid

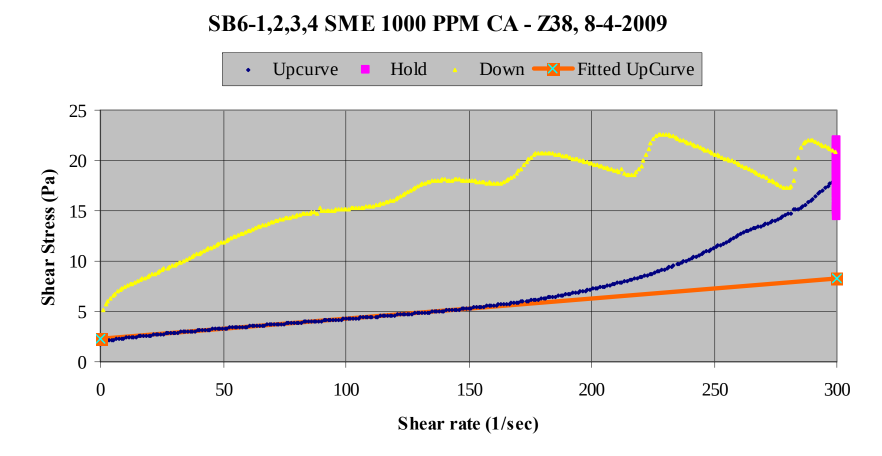


SB6-1,2,3,4 3,500 PPM Polyacrylic Acid

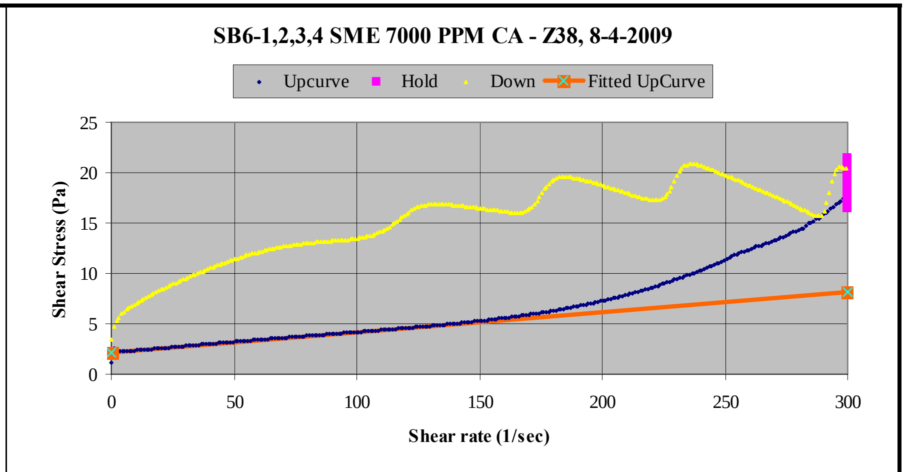


SB6-1,2,3,4 10,000 PPM Polyacrylic Acid

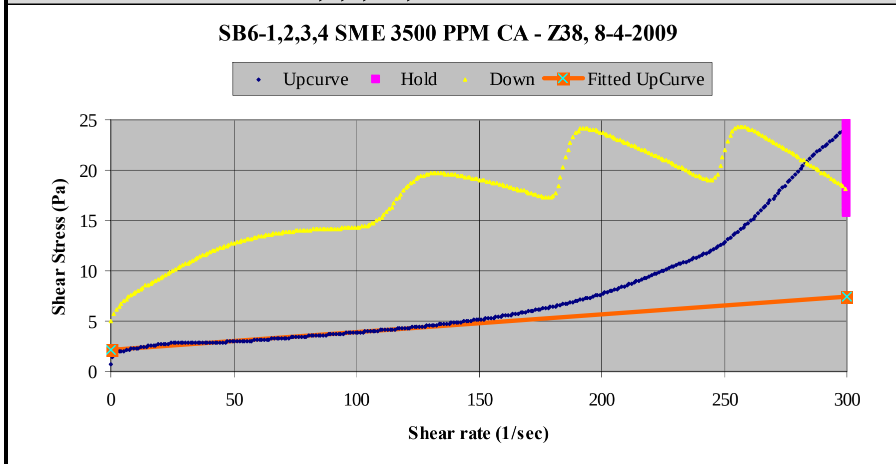
Figure E - 3 SB6-1,2,3,4 SME Flow Curves: Polyacrylic Acid



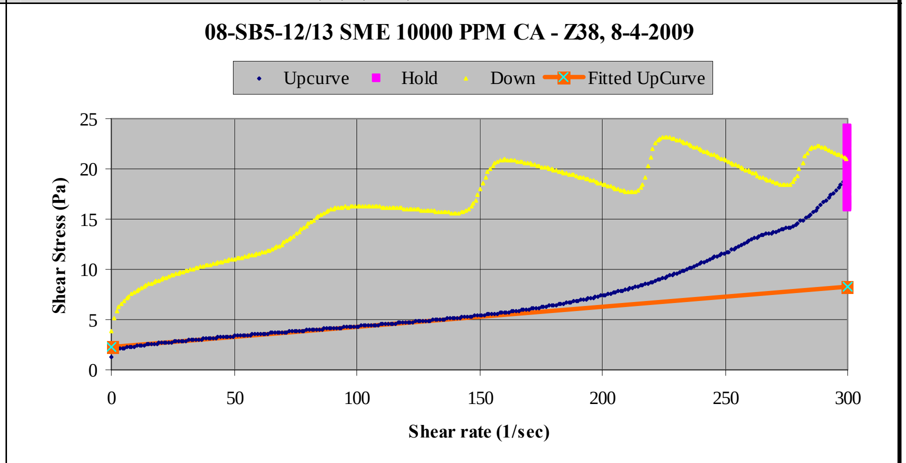
SB6-1,2,3,4 1,000 PPM Citric Acid



SB6-1,2,3,4 7,000 PPM Citric Acid

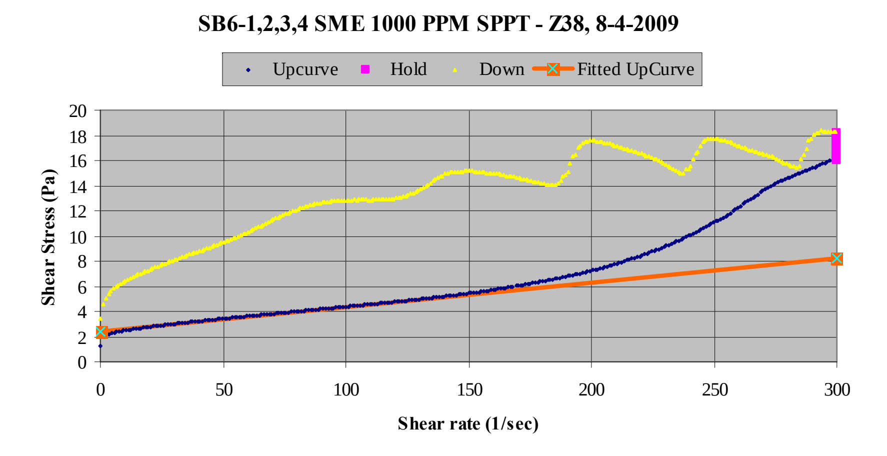


SB6-1,2,3,4 3,500 PPM Citric Acid

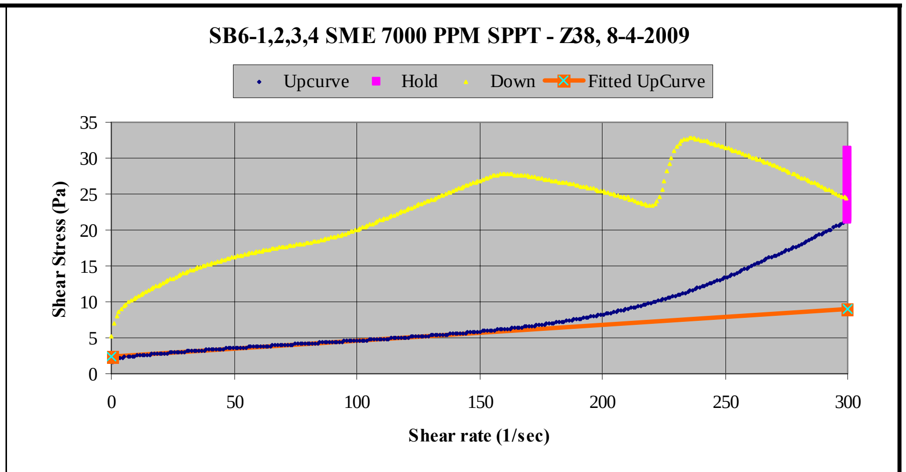


SB6-1,2,3,4 10,000 PPM Citric Acid

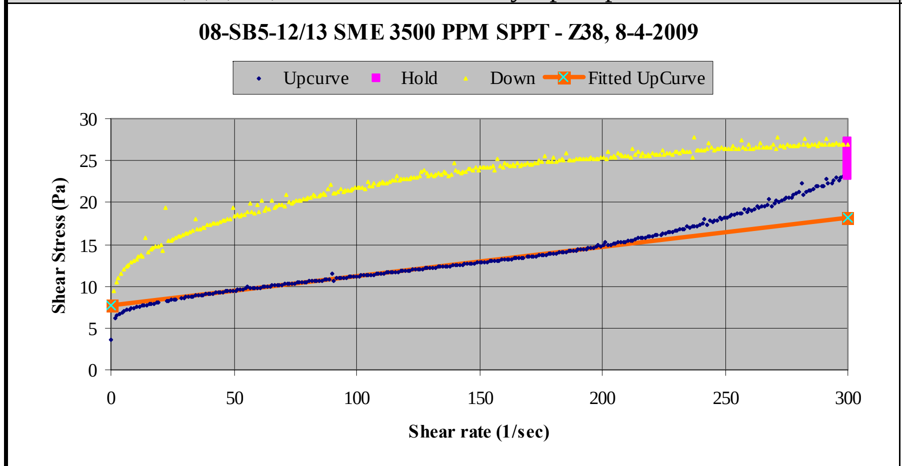
Figure E - 4 SB6-1,2,3,4 SME Flow Curves: Citric Acid



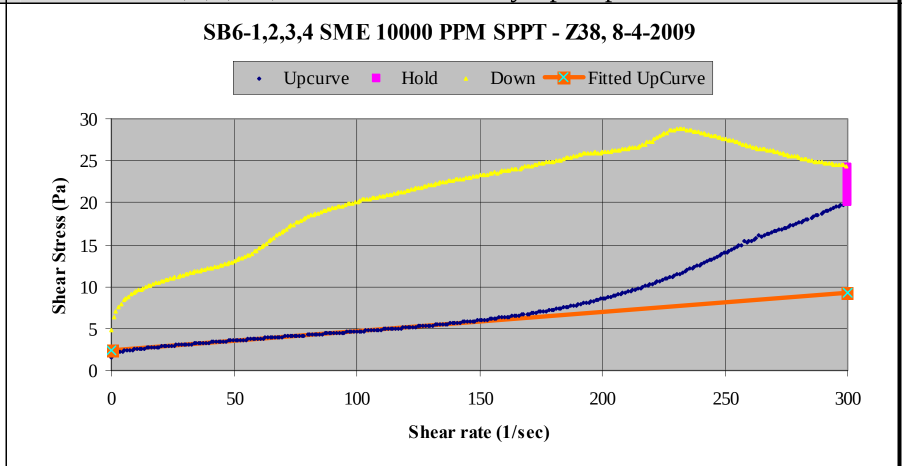
SB6-1,2,3,4 1,000 PPM Sodium Pyrophosphate Tetrabasic



SB6-1,2,3,4 7,000 PPM Sodium Pyrophosphate Tetrabasic

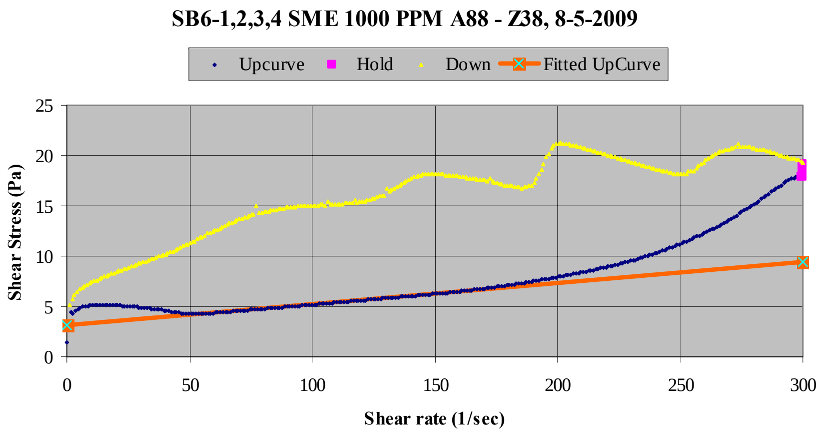


SB6-1,2,3,4 3,500 PPM Sodium Pyrophosphate Tetrabasic

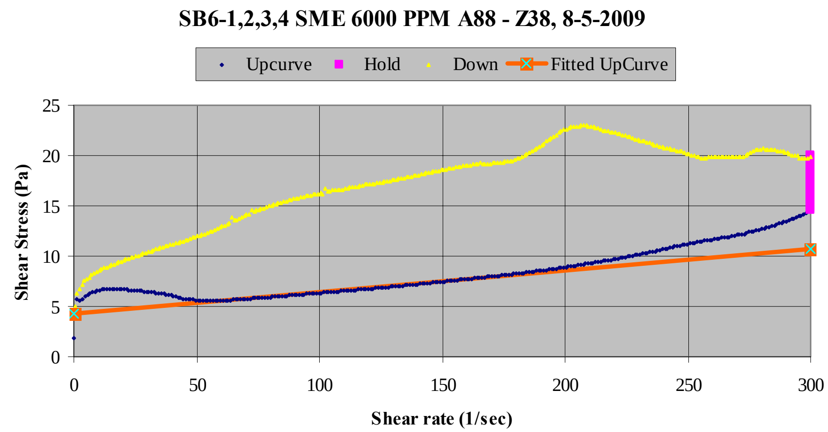


SB6-1,2,3,4 10,000 PPM Sodium Pyrophosphate Tetrabasic

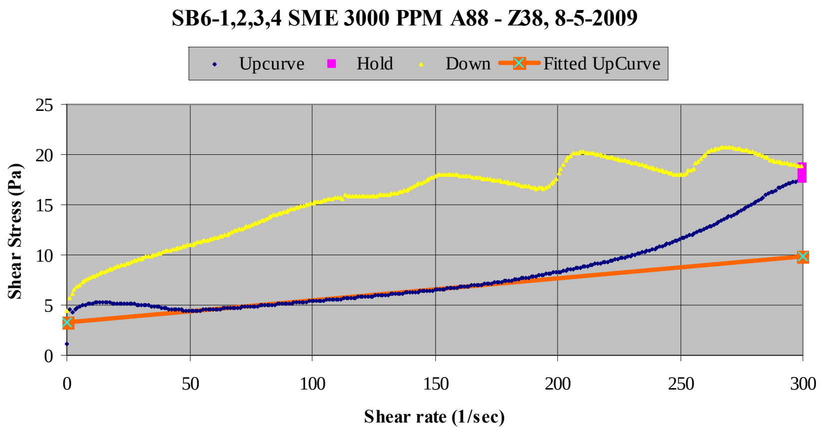
Figure E - 5 SB6-1,2,3,4 SME Flow Curves: Sodium Pyrophosphate Tetrabasic



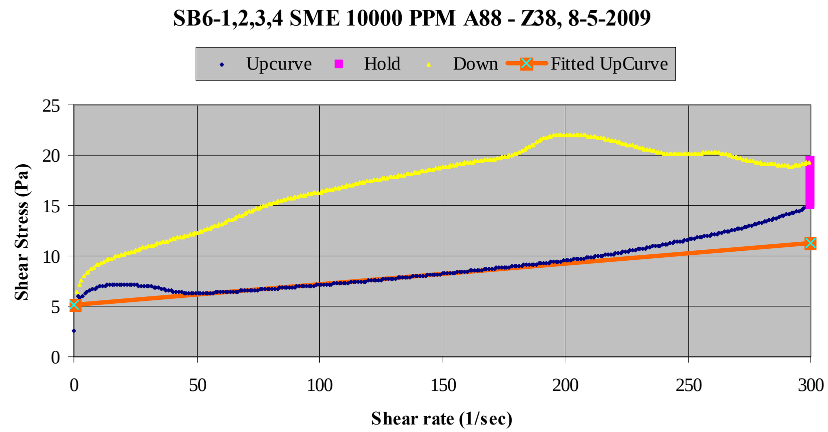
SB6-1,2,3,4 1,000 PPM Dolapix A88



SB6-1,2,3,4 6,000 PPM Dolapix A88

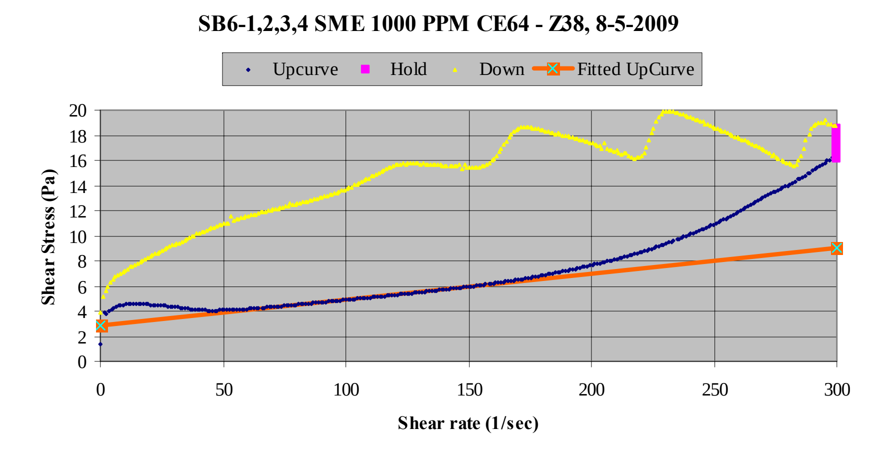


SB6-1,2,3,4 3,000 PPM Dolapix A88

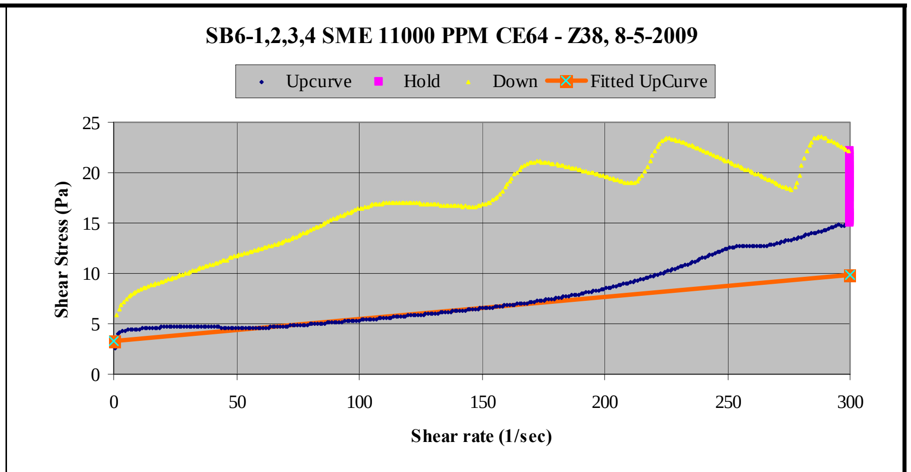


SB6-1,2,3,4 10,000 PPM Dolapix A88

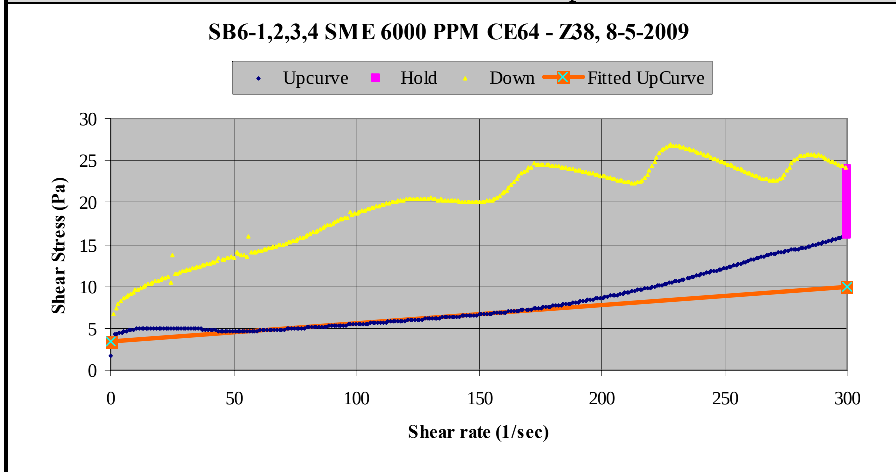
Figure E - 6 SB6-1,2,3,4 SME Flow Curves: Dolapix A88



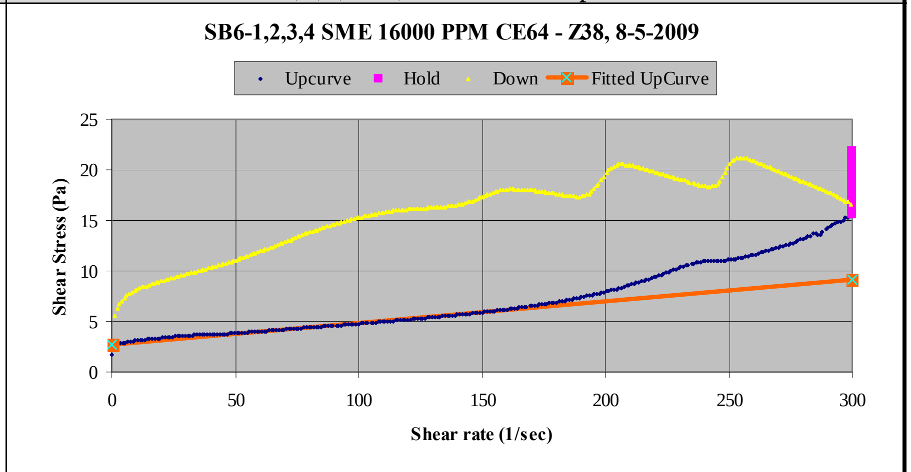
SB6-1,2,3,4 1,000 PPM Dolapix CE64



SB6-1,2,3,4 11,000 PPM Dolapix CE64

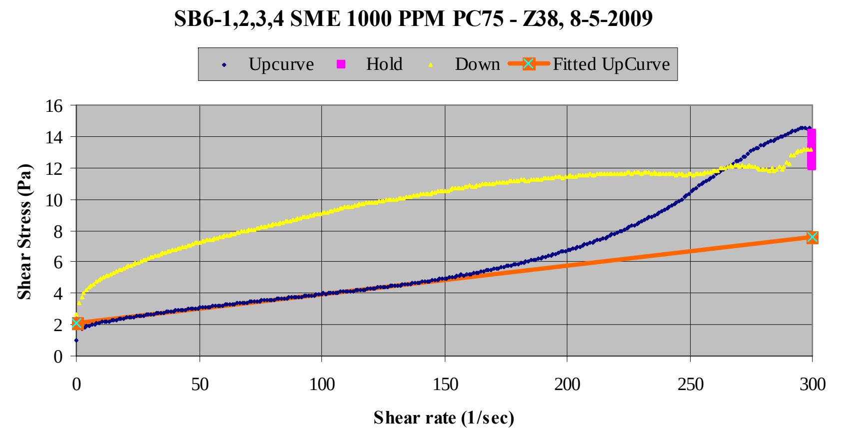


SB6-1,2,3,4 6,000 PPM Dolapix CE64

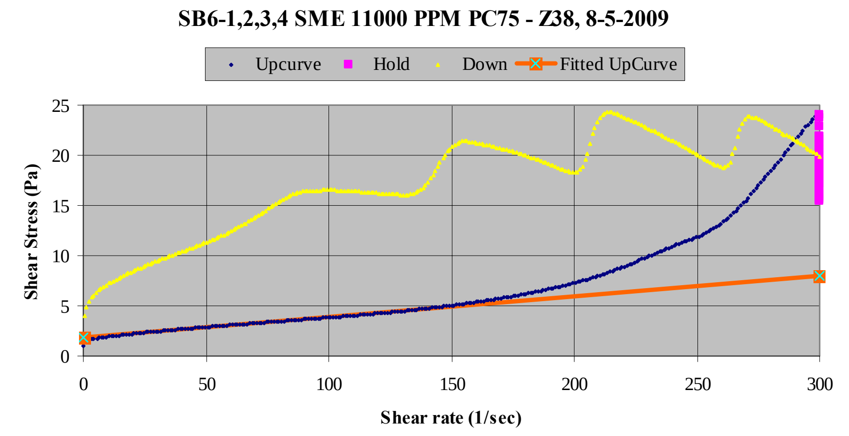


SB6-1,2,3,4 16,000 PPM Dolapix CE64

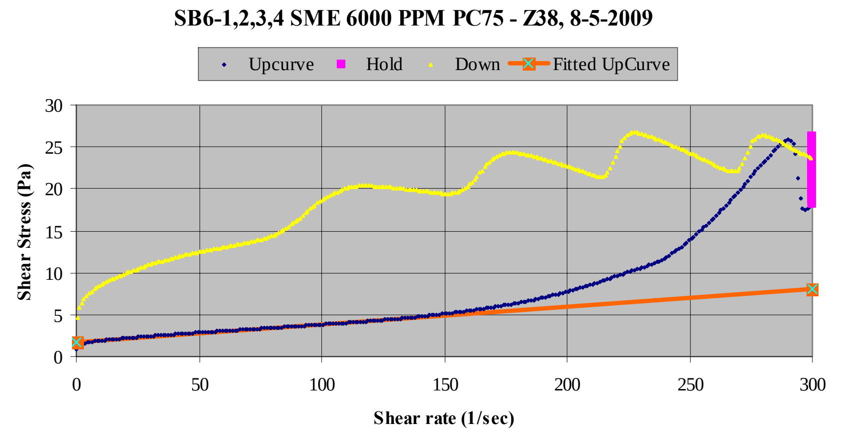
Figure E - 7 SB6-1,2,3,4 SME Flow Curves: Dolapix CE64



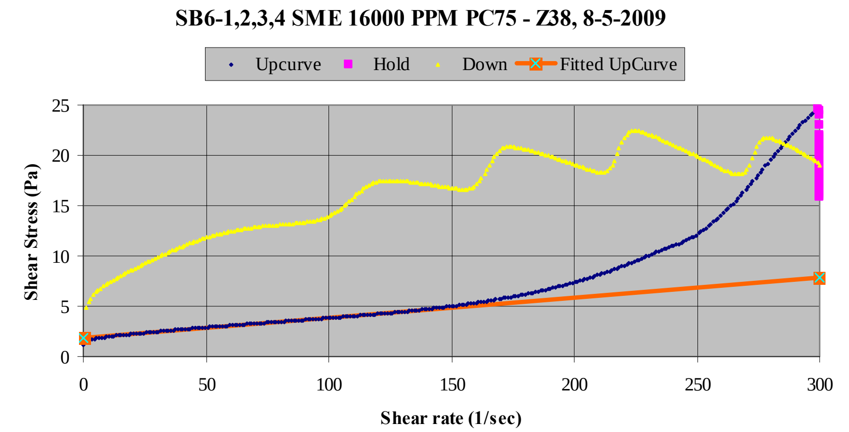
SB6-1,2,3,4 1,000 PPM Dolapix PC75



SB6-1,2,3,4 11,000 PPM Dolapix PC75

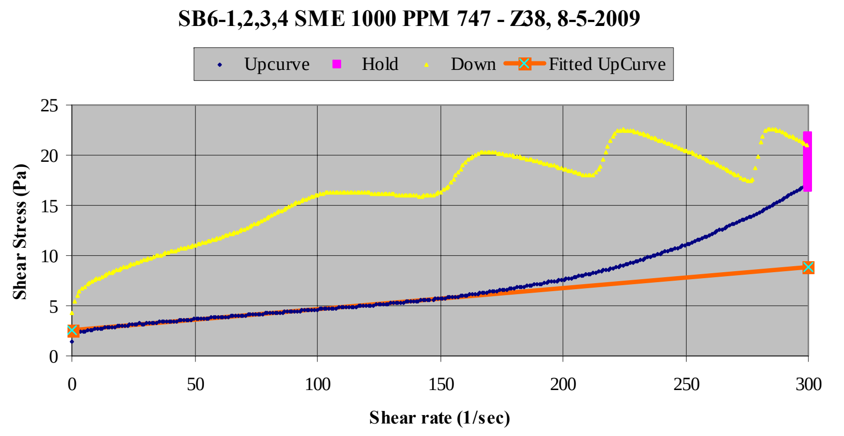


SB6-1,2,3,4 6,000 PPM Dolapix PC75

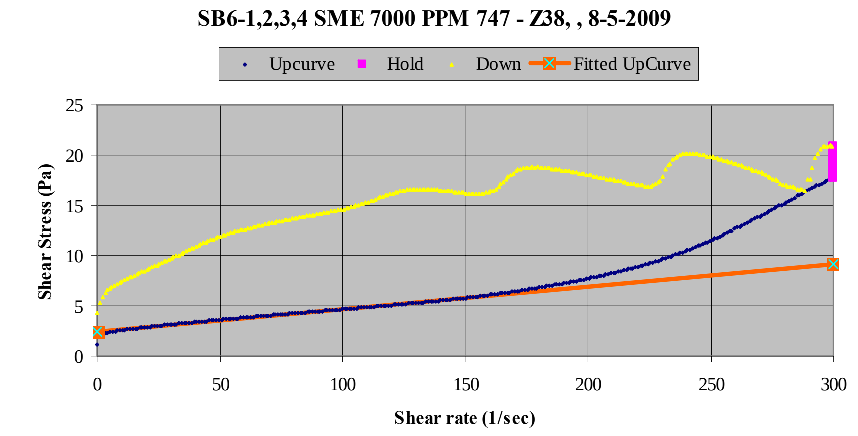


SB6-1,2,3,4 16,000 PPM Dolapix PC75

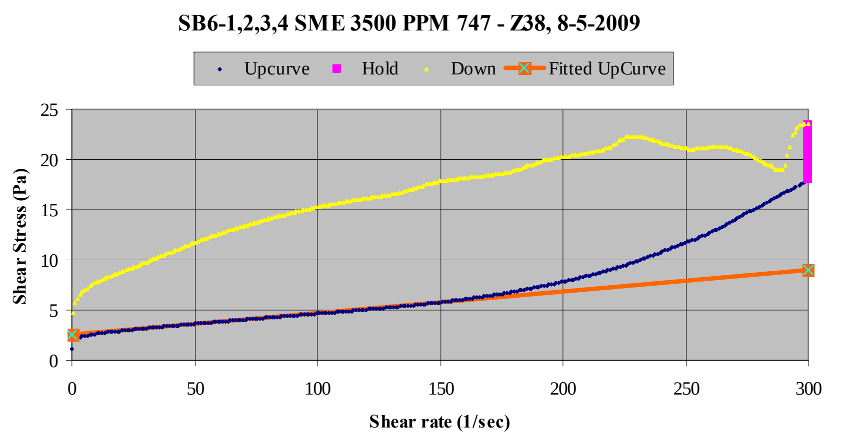
Figure E - 8 SB6-1,2,3,4 SME Flow Curves: Dolapix PC75



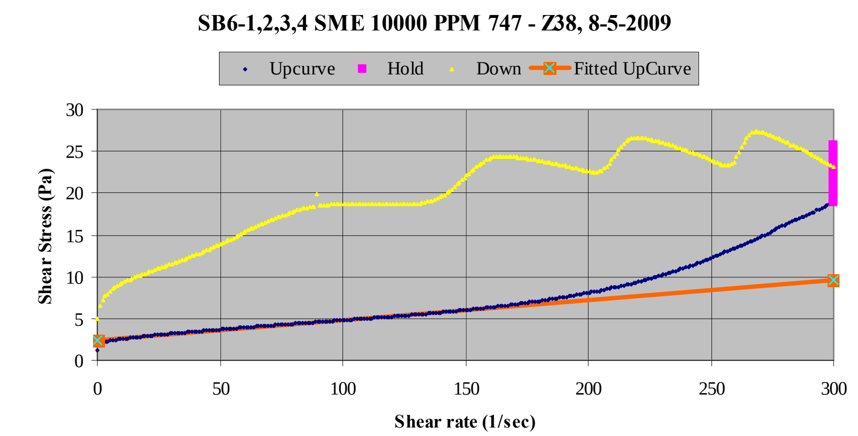
SB6-1,2,3,4 1,000 PPM Taylor 747 Antifoam



SB6-1,2,3,4 7,000 PPM Taylor 747 Antifoam



SB6-1,2,3,4 3,500 PPM Taylor 747 Antifoam



SB6-1,2,3,4 10,000 PPM Taylor 747 Antifoam

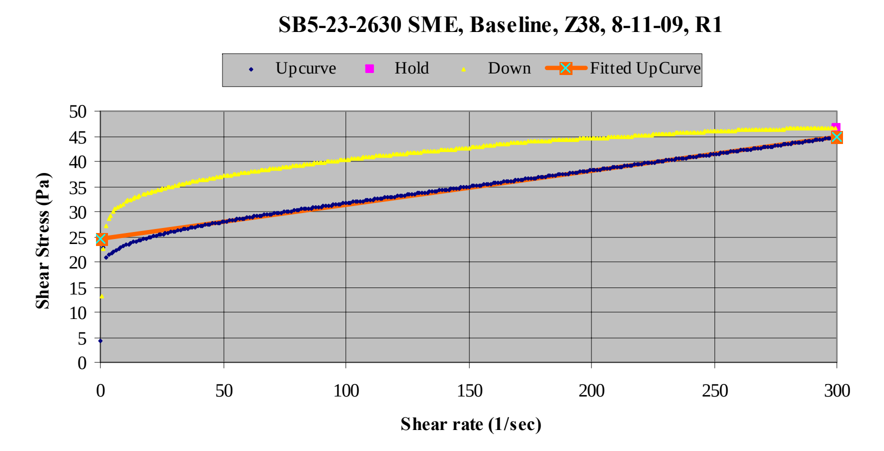
Figure E - 9 SB5 1,2,3,4 SME Flow Curves: Taylor 747 Antifoam

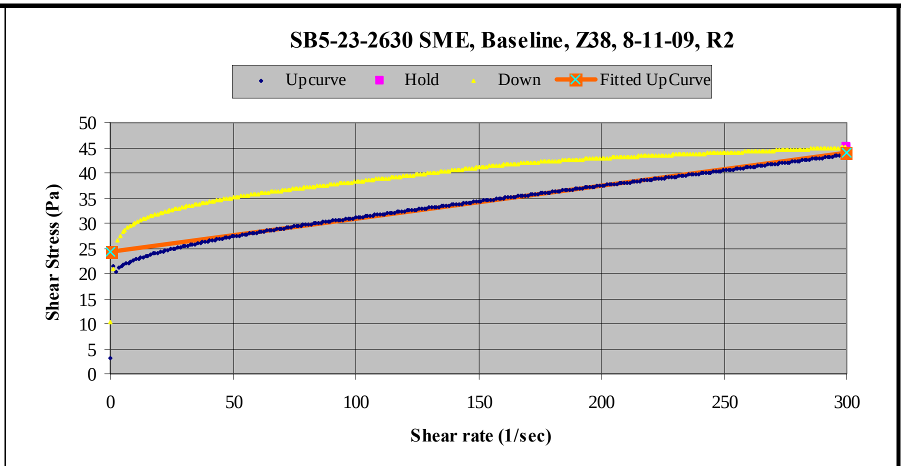
Appendix F 09-SB5-23-2630 SME Flow Curves

Table F - 1 09-SB5-23-2630 SME: Bingham Plastic Results

Baseline Data, Sample ID	Rotor	Plastic Viscosity (cp)	Yield Stress (Pa)	R^2	Shear Rate Range (1/sec)
Baseline 8-11-2009, R1	Z38	67.5	24.7	0.9980	20-300
Baseline 8-11-2009, R2	Z38	65.7	24.2	0.9966	20-300
	Average	**66.6**	**24.4**		
	Std.	1.3	0.3		
	% Std. Dev.	1.9	1.4		

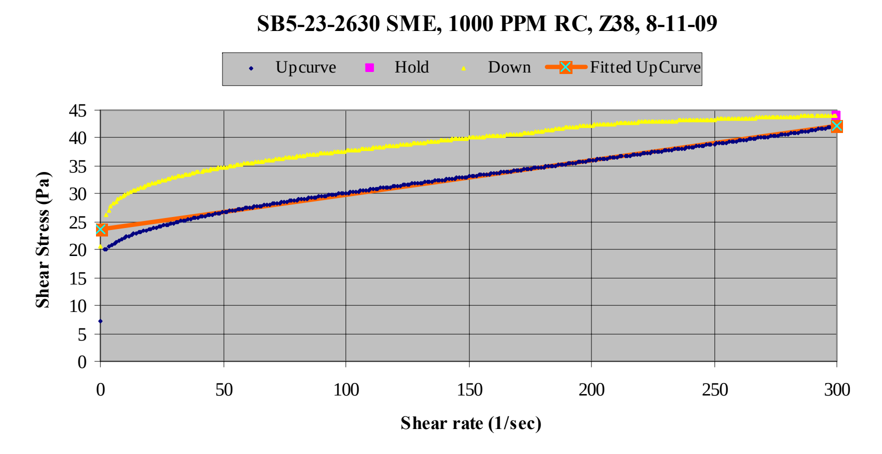
Sample Identification	Rotor	Plastic Viscosity (cp)	Yield Stress (Pa)	R^2	Shear Rate Range (1/sec)
Recover® - 1000 PPM	Z38	61.3	23.7	0.9969	20-300
Recover® - 6000 PPM	Z38	56.7	19.5	0.9955	20-300
Recover® - 11000 PPM	Z38	59.6	16.5	0.9972	20-300
Recover® - 16000 PPM	Z38	57.7	15.1	0.9974	20-300
Polyacrylic Acid - 1000 PPM	Z38	57.9	24.8	0.9993	20-300
Polyacrylic Acid - 3500 PPM	Z38	42.3	20.6	0.9978	20-180
Polyacrylic Acid - 7000 PPM	Z38	28.4	12.5	0.9893	20-150
Polyacrylic Acid - 10000 PPM	Z38	27.7	5.7	0.9898	20-140
Citric Acid - 1000 PPM	Z38	57.8	19.4	0.9940	20-300
Citric Acid - 3500 PPM	Z38	59.0	17.7	0.9954	20-300
Citric Acid - 7000 PPM	Z38	54.0	11.6	0.9977	20-300
Citric Acid - 10000 PPM	Z38	42.5	8.5	0.9996	20-180
ADVA FLEX - 1000 PPM	Z38	57.7	21.6	0.9953	20-300
ADVA FLEX - 6000 PPM	Z38	50.2	15.2	0.9972	20-200
ADVA FLEX - 11000 PPM	Z38	40.7	12.1	0.9989	20-200
ADVA FLEX - 16000 PPM	Z38	40.2	9.4	0.9985	20-200
ADVA CAST 555 - 1000 PPM	Z38	65.8	22.4	0.9982	20-300
ADVA CAST 555 - 6000 PPM	Z38	58.8	18.2	0.9988	20-300
ADVA CAST 555 - 11000 PPM	Z38	56.0	15.4	0.9991	20-200
ADVA CAST 555 - 16000 PPM	Z38	55.2	13.3	0.9996	20-200



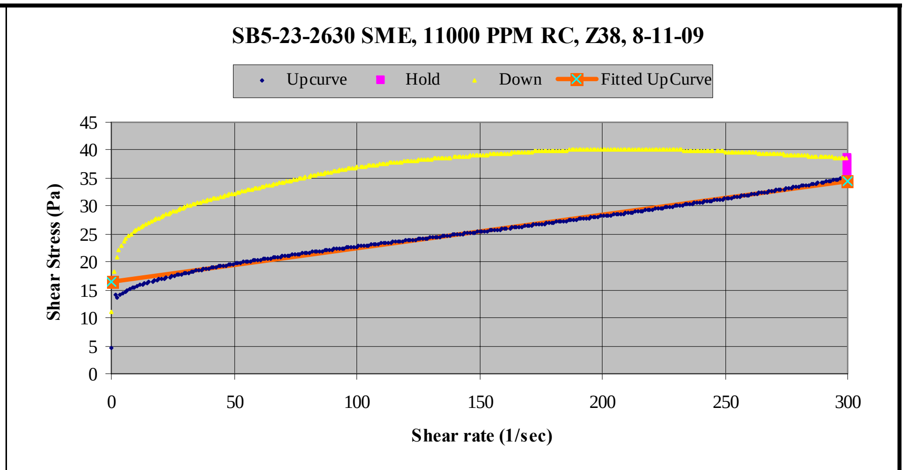


09-SB5-23-2630 Z38 Baseline	09-SB5-23-2630 Z38 Baseline R1

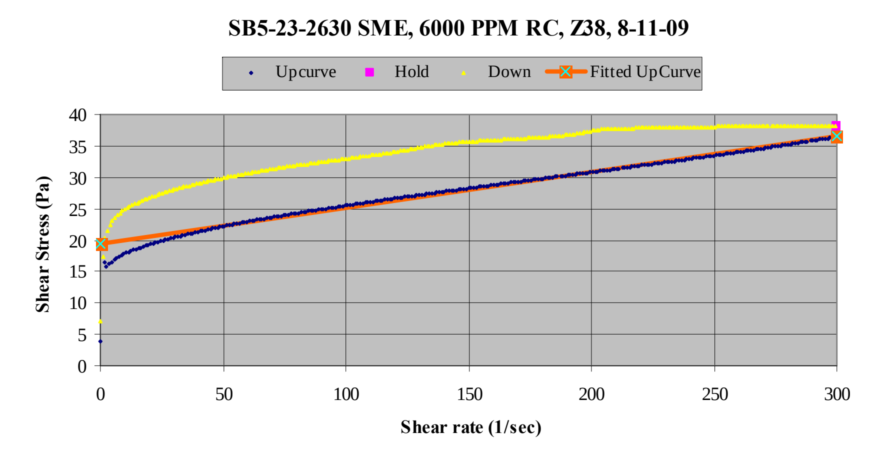
Figure F - 1 09-SB5-23-2630 SME Flow Curves: Baseline



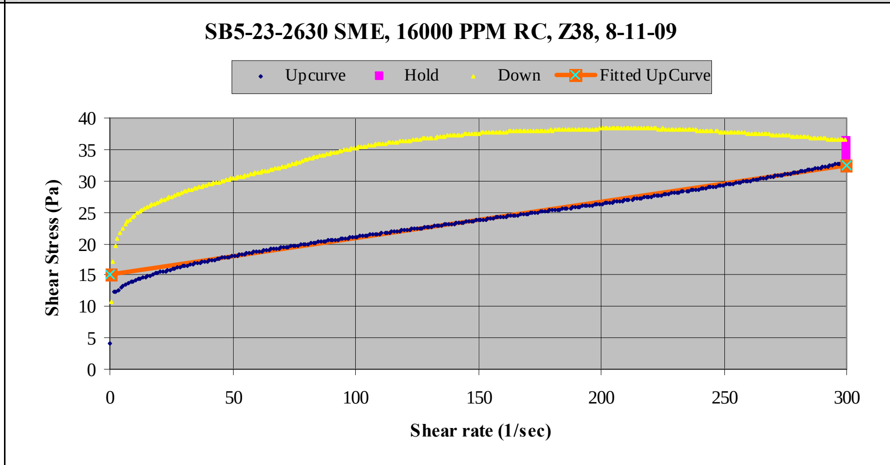
09-SB5-23-2630 1,000 PPM Recover®



09-SB5-23-2630 11,000 PPM Recover®

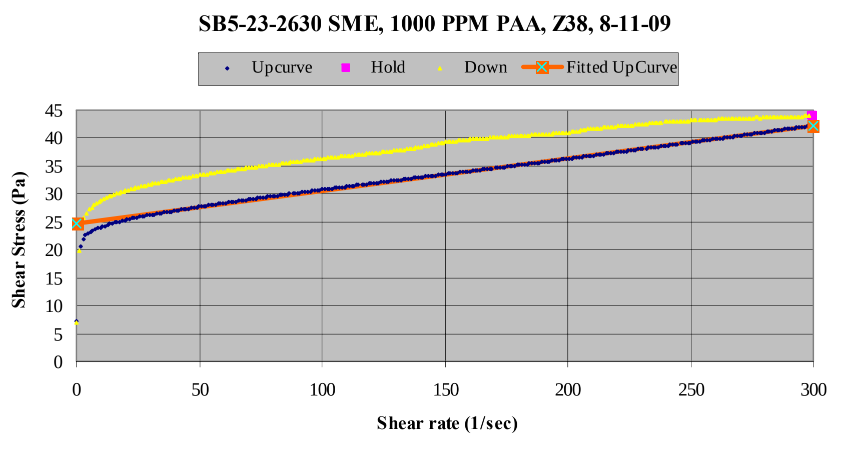


09-SB5-23-2630 6,000 PPM Recover®

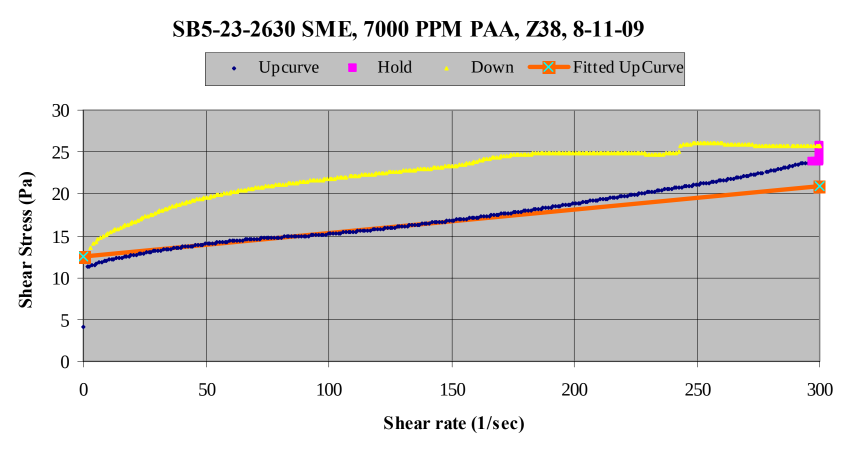


09-SB5-23-2630 16,000 PPM Recover®

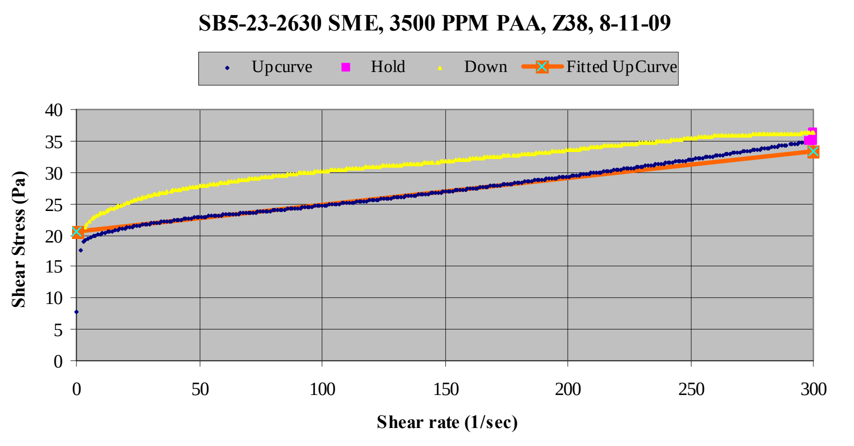
Figure F - 2 09-SB5-23-2630 SME Flow Curves: Grace Recover®



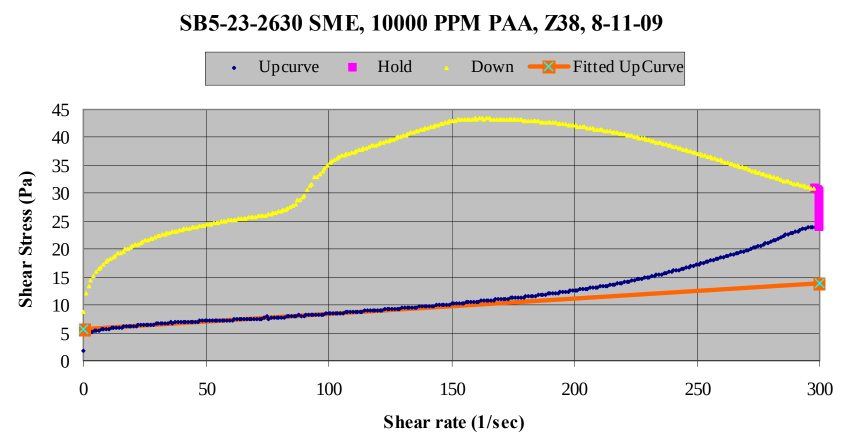
09-SB5-23-2630 1,000 PPM Polyacrylic Acid



09-SB5-23-2630 7,000 PPM Polyacrylic Acid

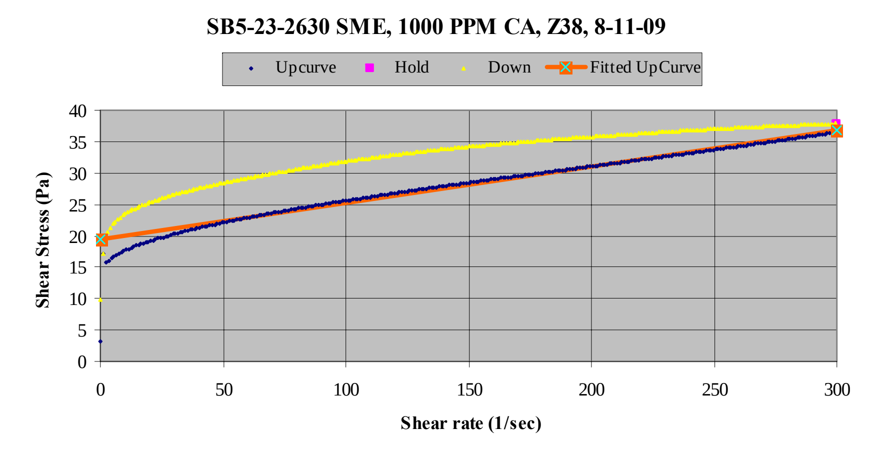


09-SB5-23-2630 3,500 PPM Polyacrylic Acid

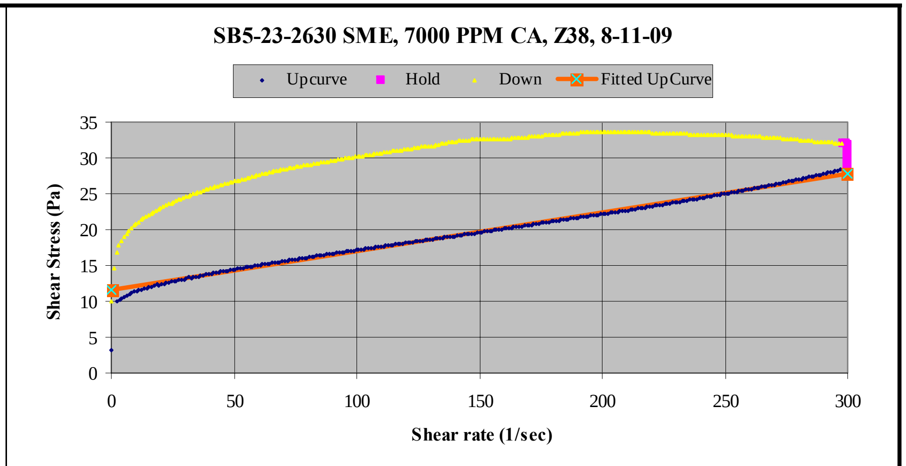


09-SB5-23-2630 10,000 PPM Polyacrylic Acid

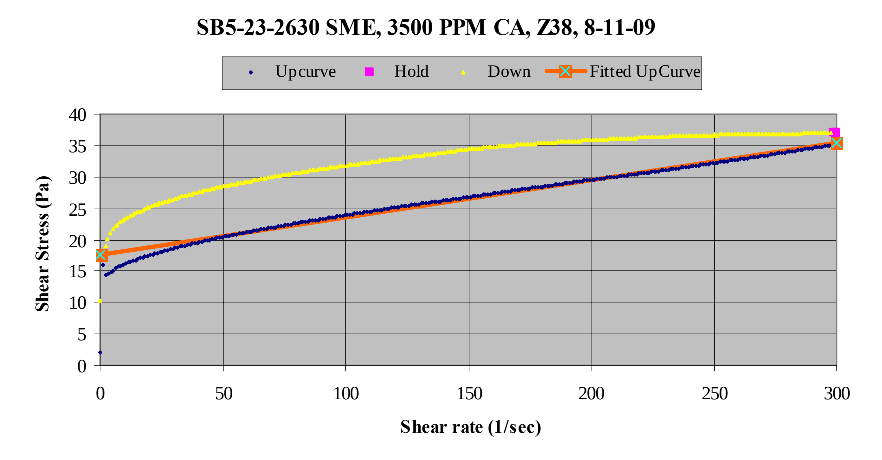
Figure F - 3 09-SB5-23-2630 SME Flow Curves: Polyacrylic Acid



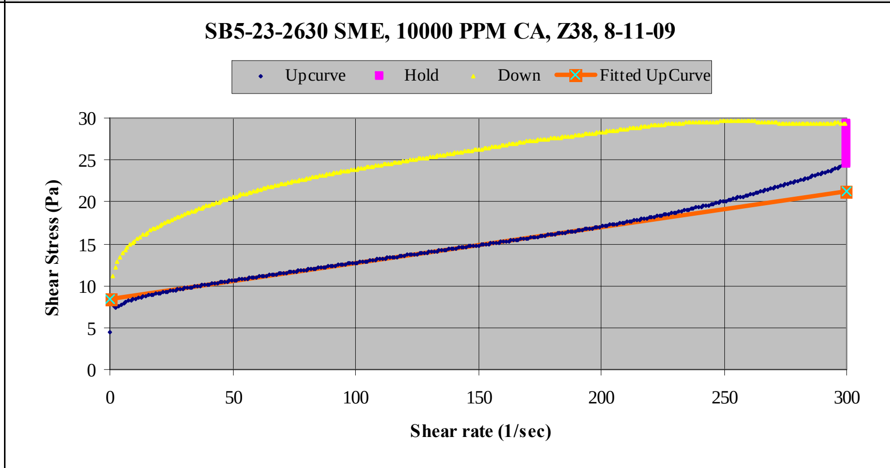
09-SB5-23-2630 1,000 PPM Citric Acid



09-SB5-23-2630 7,000 PPM Citric Acid

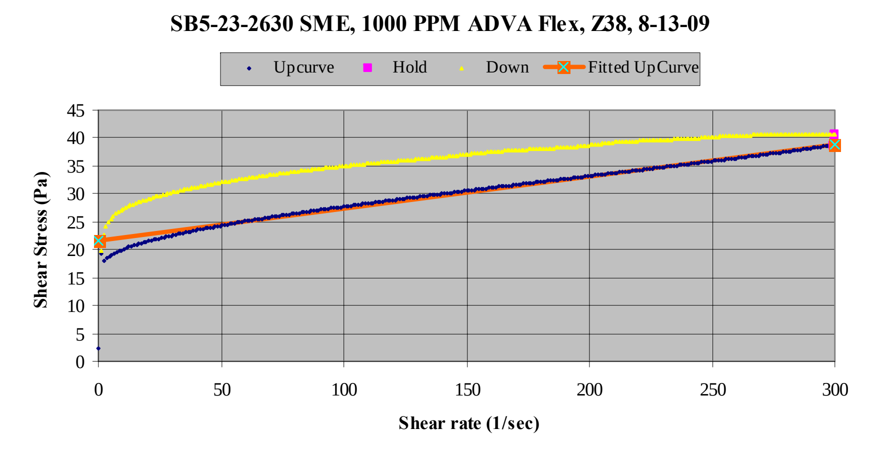


09-SB5-23-2630 3,500 PPM Citric Acid

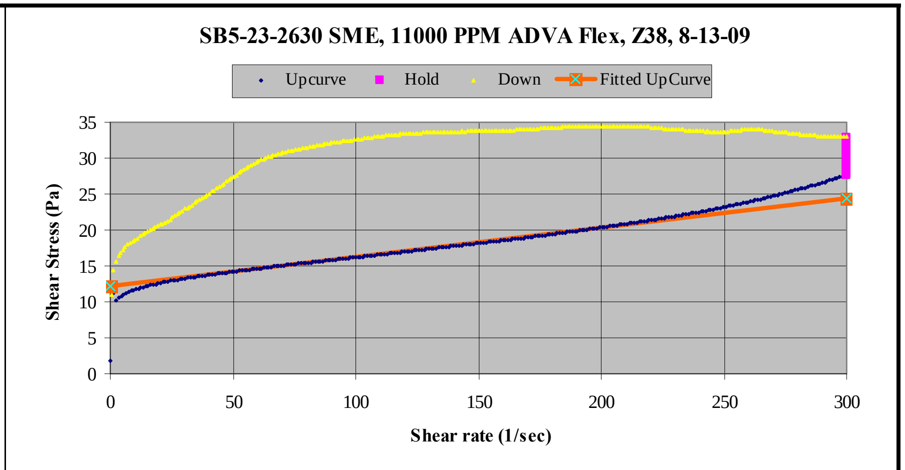


09-SB5-23-2630 10,000 PPM Citric Acid

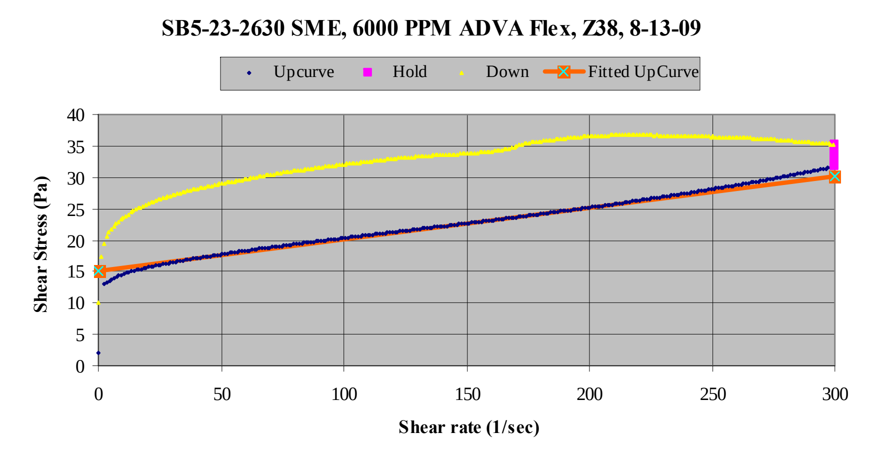
Figure F - 4 09-SB5-23-2630 SME Flow Curves: Citric Acid



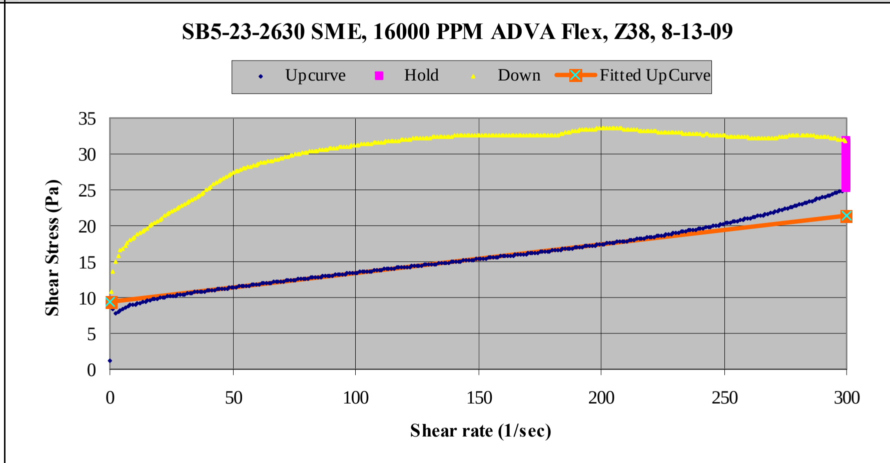
09-SB5-23-2630 1,000 PPM ADVA Flex



09-SB5-23-2630 11,000 PPM ADVA Flex

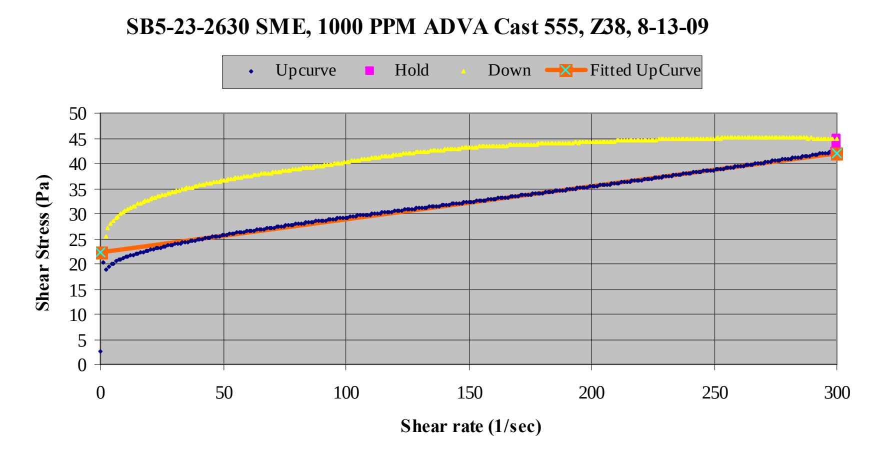


09-SB5-23-2630 6,000 PPM ADVA Flex

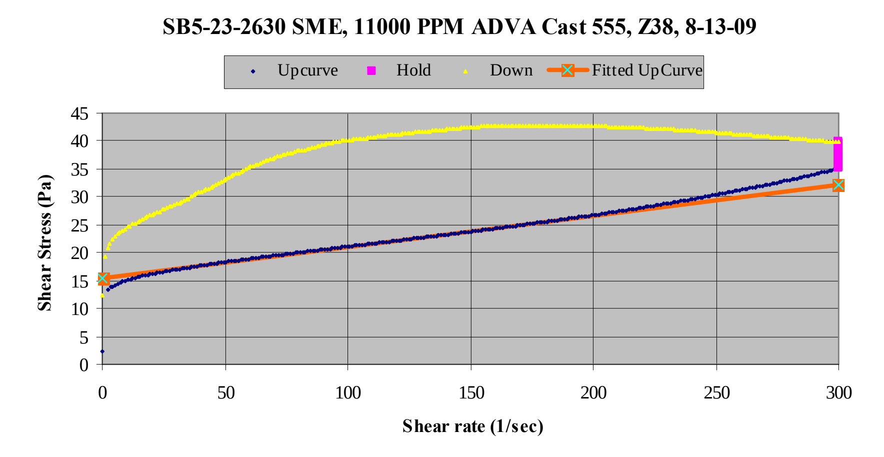


09-SB5-23-2630 16,000 PPM ADVA Flex

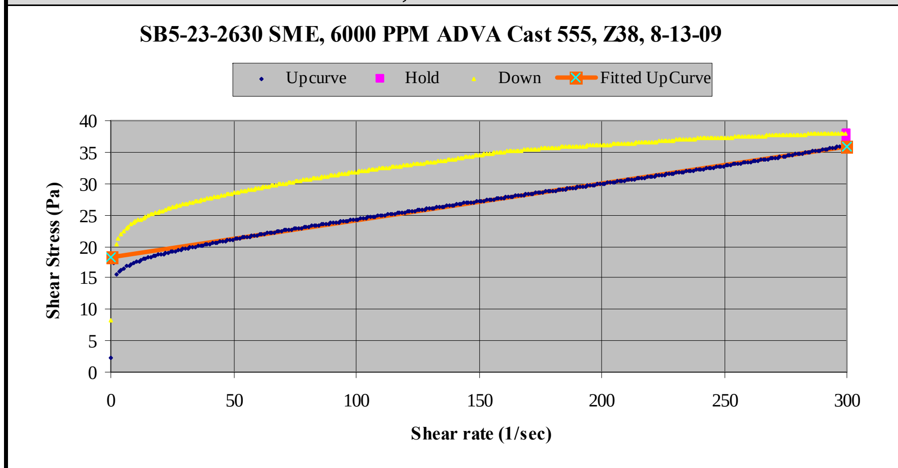
Figure F - 5 09-SB5-23-2630 SME Flow Curves: Grace ADVA Flex



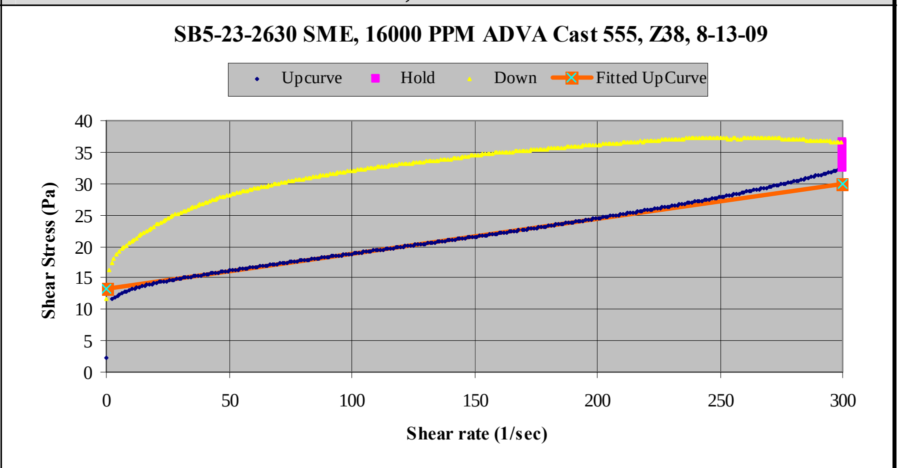
09-SB5-23-2630 1,000 PPM ADVA Cast 555



09-SB5-23-2630 11,000 PPM ADVA Cast 555



09-SB5-23-2630 6,000 PPM ADVA Cast 555



09-SB5-23-2630 16,000 PPM ADVA Cast 555

Figure F - 6 09-SB5-23-2630 SME Flow Curves: Grace ADVA Cast 555

Appendix G 09-SB5-24-2640 SME Flow Curves

Table G - 1 09-SB5-24-2640 SME: Bingham Plastic Results

Baseline Data, Sample ID	Rotor	Plastic Viscosity (cp)	Yield Stress (Pa)	R^2	Shear Rate Range (1/sec)
Baseline 8-12-2009, R1	Z38	34.0	5.29	0.9983	20-200
Baseline 8-11-2009, R2	Z38	31.6	5.15	0.9985	20-200
	Average	**32.8**	**5.22**		
	Std.	1.7	0.10		
	% Std. Dev.	5.2	1.9		

Sample Identification	Rotor	Plastic Viscosity (cp)	Yield Stress (Pa)	R^2	Shear Rate Range (1/sec)
Recover® - 1000 PPM	Z38	32.7	4.98	0.9986	20-200
Recover® - 6000 PPM	Z38	31.9	4.06	0.9982	20-180
Recover® - 11000 PPM	Z38	31.5	3.64	0.9983	20-180
Recover® - 11000 PPM	Z38	30.8	3.28	0.9974	20-180
Polyacrylic Acid - 1000 PPM	Z38	30.5	6.45	0.9995	20-180
Polyacrylic Acid - 3500 PPM	Z38	28.3	6.08	0.9956	20-180
Polyacrylic Acid - 7000 PPM	Z38	28.2	4.12	0.9954	20-180
Polyacrylic Acid - 10000 PPM	Z38	25.4	2.67	0.9948	20-150
Citric Acid - 1000 PPM	Z38	31.1	3.96	0.9983	20-180
Citric Acid - 3500 PPM	Z38	29.1	3.70	0.9985	20-150
Citric Acid - 7000 PPM	Z38	28.2	4.24	0.9979	20-150
Citric Acid - 10000 PPM	Z38	28.7	4.65	0.9976	20-150
ADVA FLEX - 1000 PPM	Z38	31.8	4.99	0.9974	20-180
ADVA FLEX - 6000 PPM	Z38	29.3	4.04	0.9953	20-180
ADVA FLEX - 11000 PPM	Z38	29.3	4.29	0.9943	20-180
ADVA FLEX - 16000 PPM	Z38	32.0	4.78	0.9954	20-180
ADVA CAST 555 - 1000 PPM	Z38	31.6	4.78	0.9979	20-180
ADVA CAST 555 - 6000 PPM	Z38	32.4	3.94	0.9975	20-180
ADVA CAST 555 - 11000 PPM	Z38	33.6	3.42	0.9969	20-180
ADVA CAST 555 - 16000 PPM	Z38	32.2	4.25	0.9963	20-180

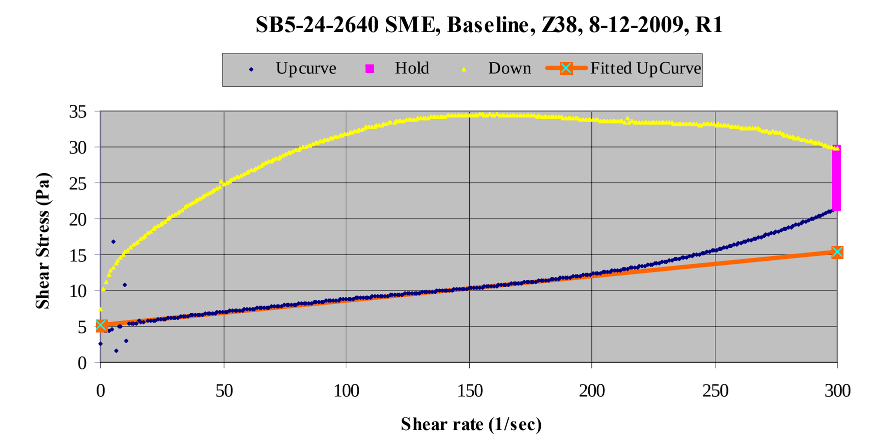
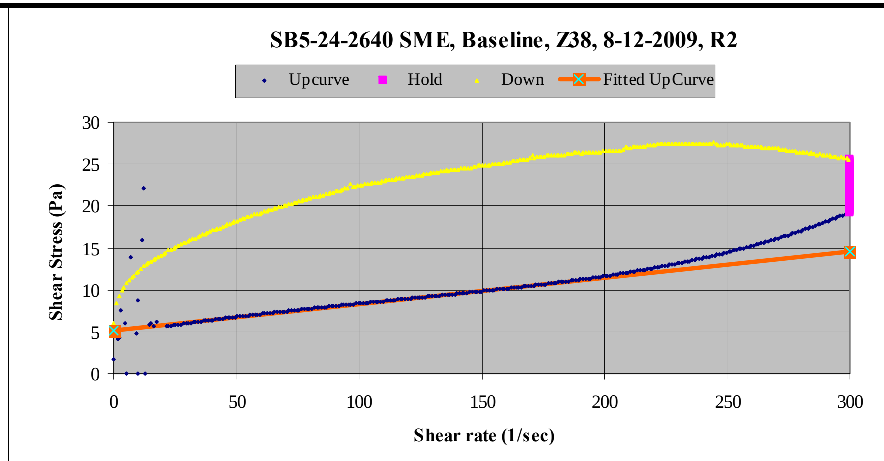
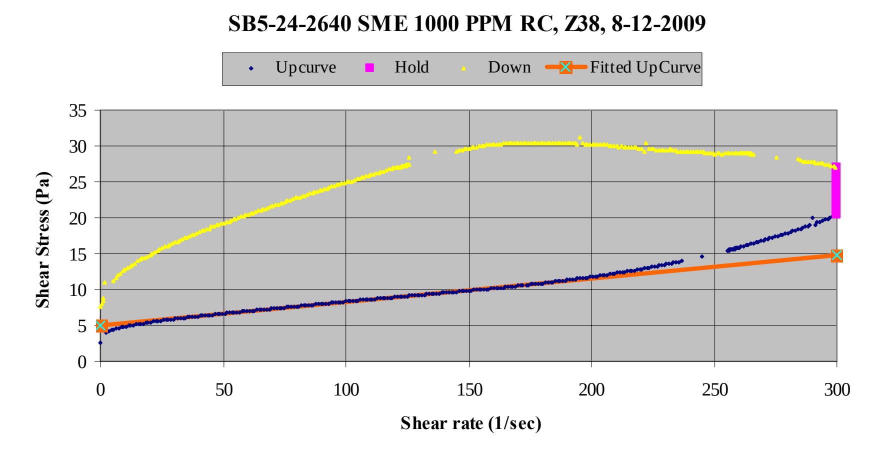
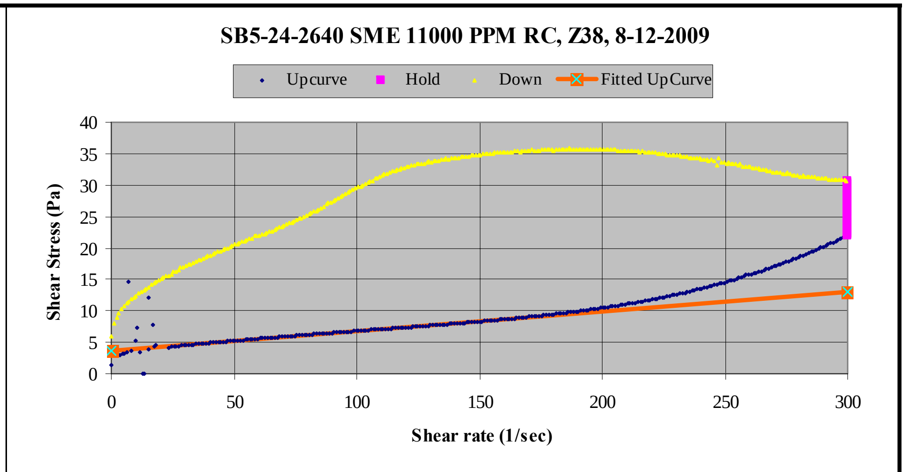
	
09-SB5-24-2640 Z38 Baseline	09-SB5-24-2640 Z38 Baseline R1

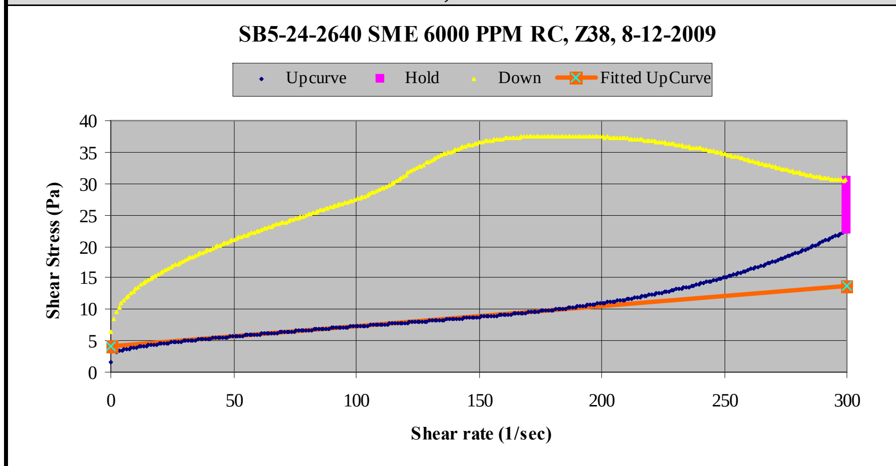
Figure G - 1 09-SB5-24-2640 SME Flow Curves: Baseline



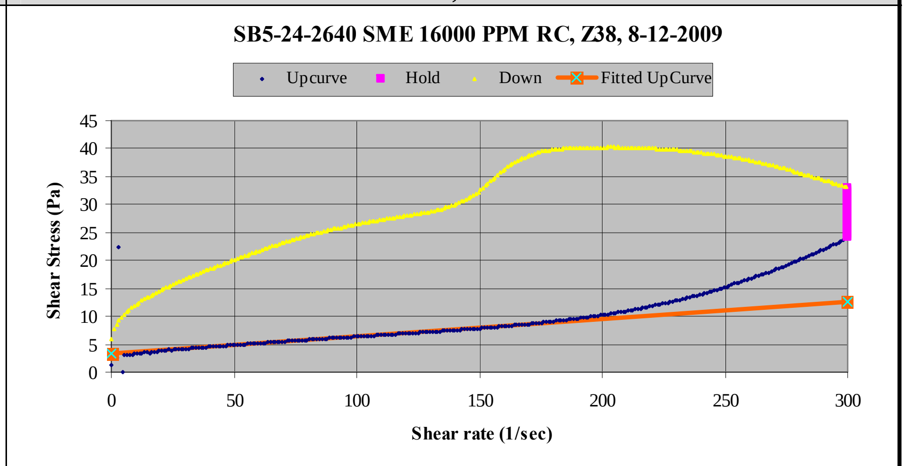
09-SB5-24-2640 1,000 PPM Recover®



09-SB5-24-2640 11,000 PPM Recover®

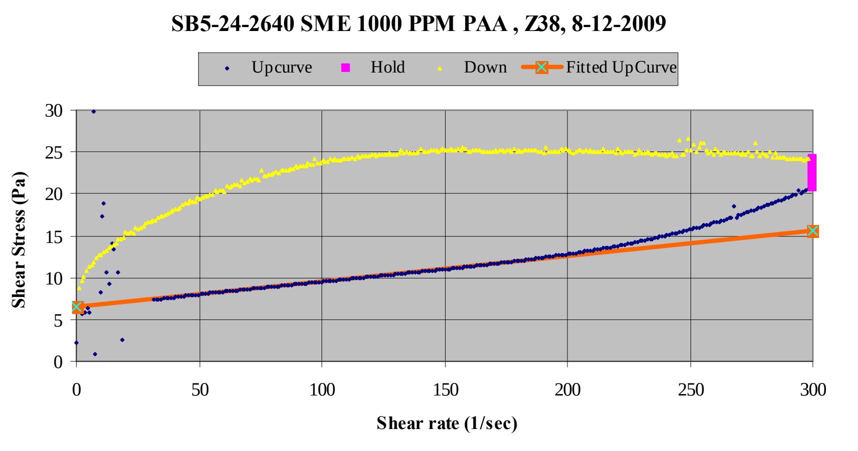


09-SB5-24-2640 6,000 PPM Recover®

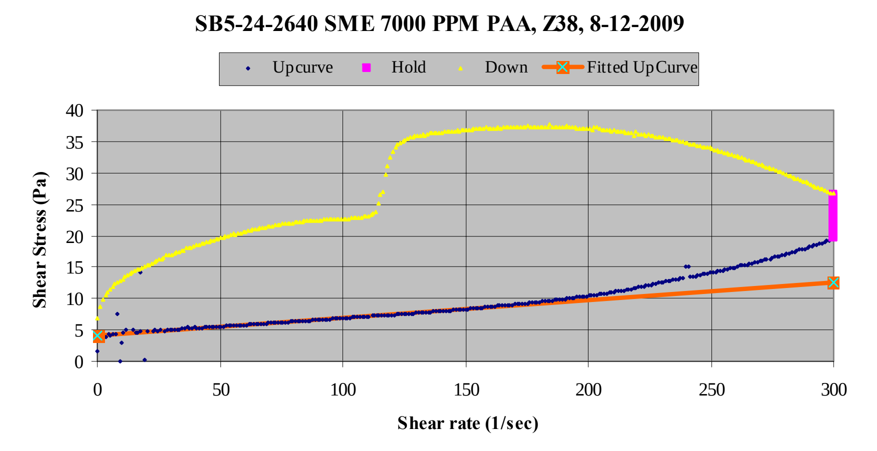


09-SB5-24-2640 16,000 PPM Recover®

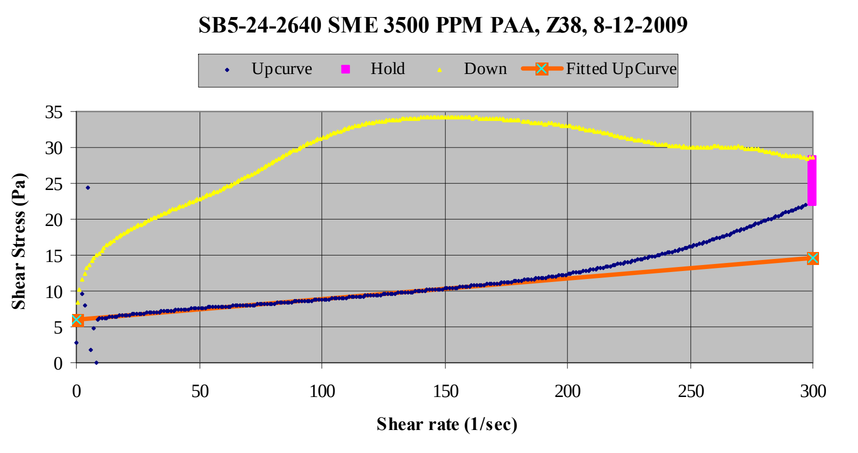
Figure G - 2 09-SB5-24-2640 SME Flow Curves: Grace Recover®



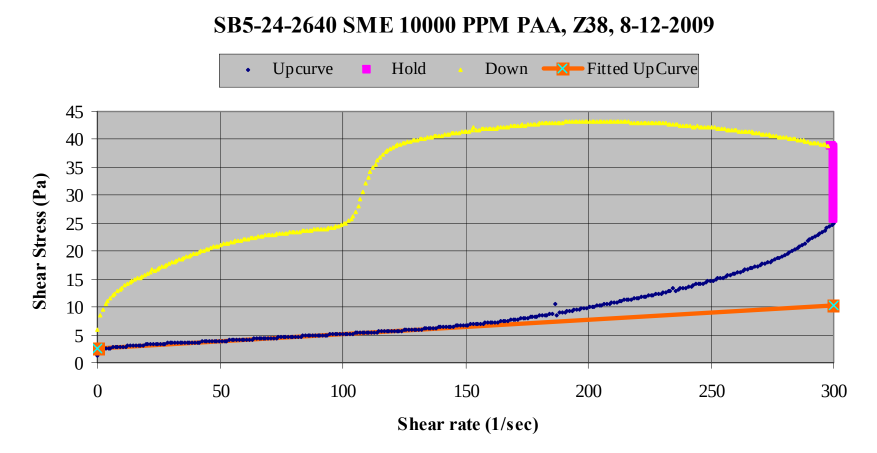
09-SB5-24-2640 1,000 PPM Polyacrylic Acid



09-SB5-24-2640 7,000 PPM Polyacrylic Acid

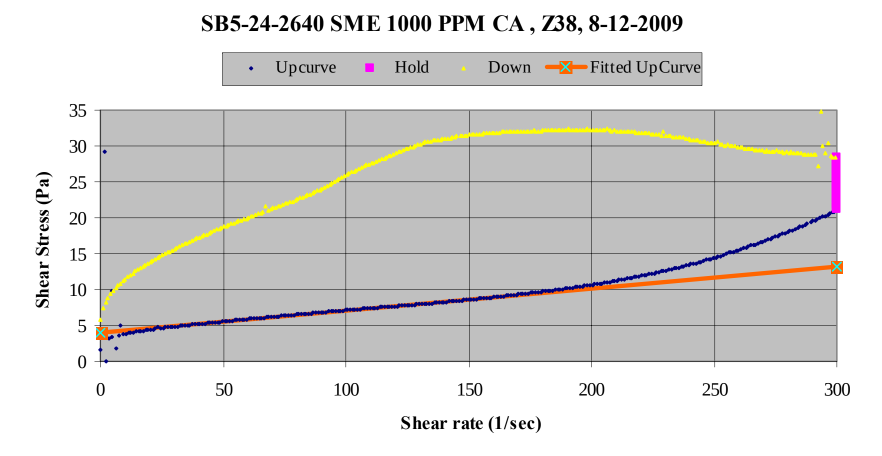


09-SB5-24-2640 3,500 PPM Polyacrylic Acid

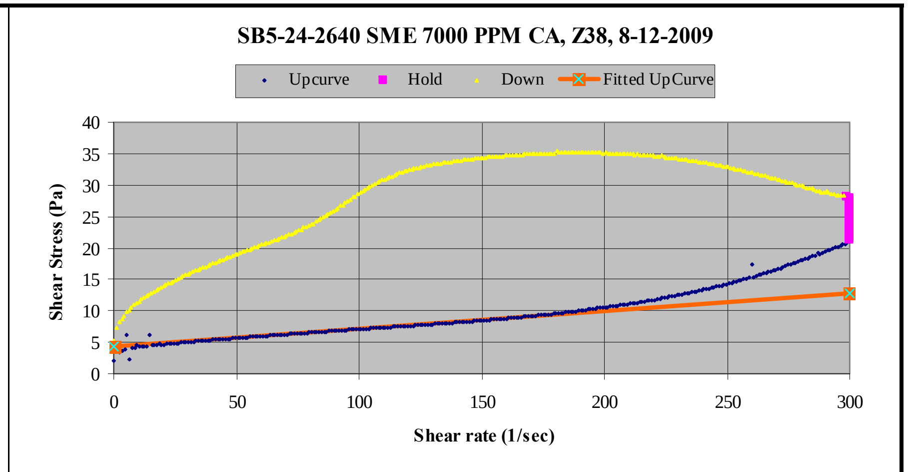


09-SB5-24-2640 10,000 PPM Polyacrylic Acid

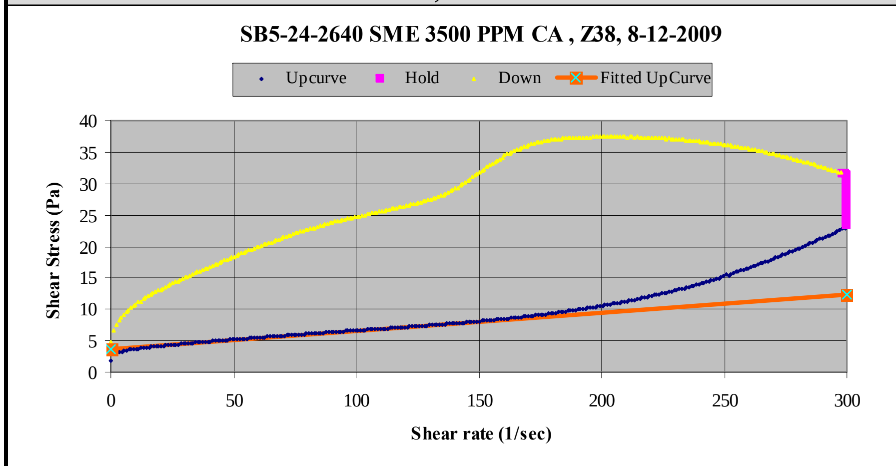
Figure G - 3 09-SB5-24-2640 SME Flow Curves: Polyacrylic Acid



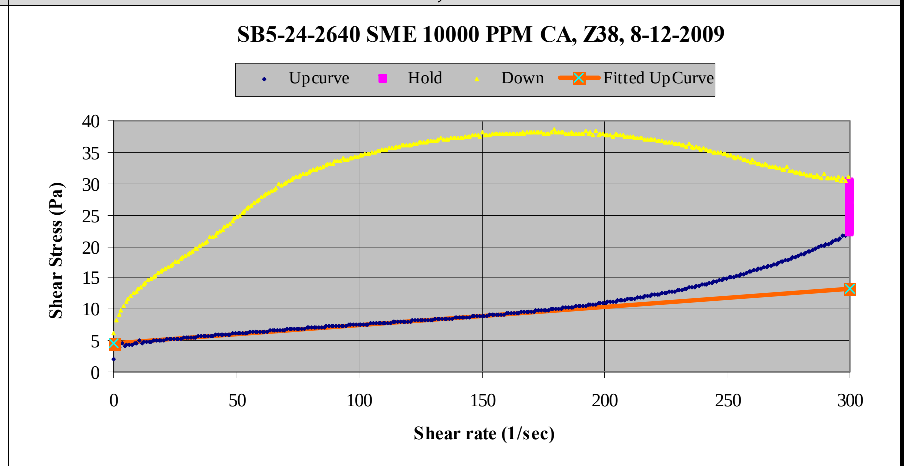
09-SB5-24-2640 1,000 PPM Citric Acid



09-SB5-24-2640 7,000 PPM Citric Acid

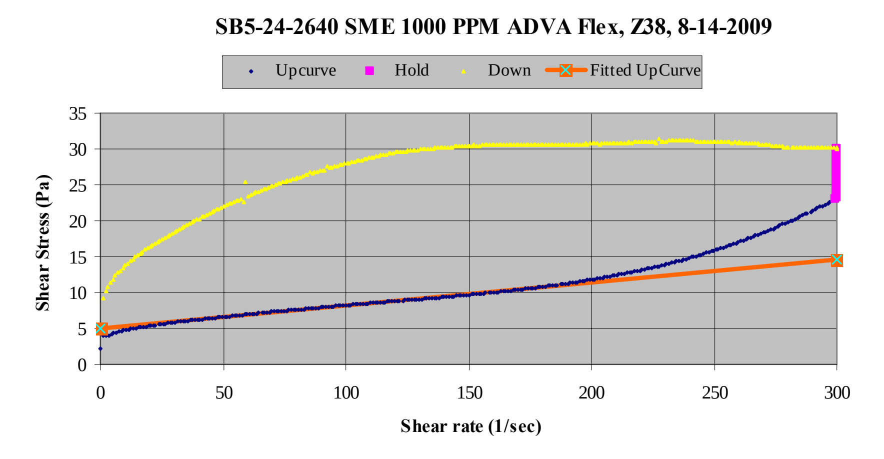


09-SB5-24-2640 3,500 PPM Citric Acid

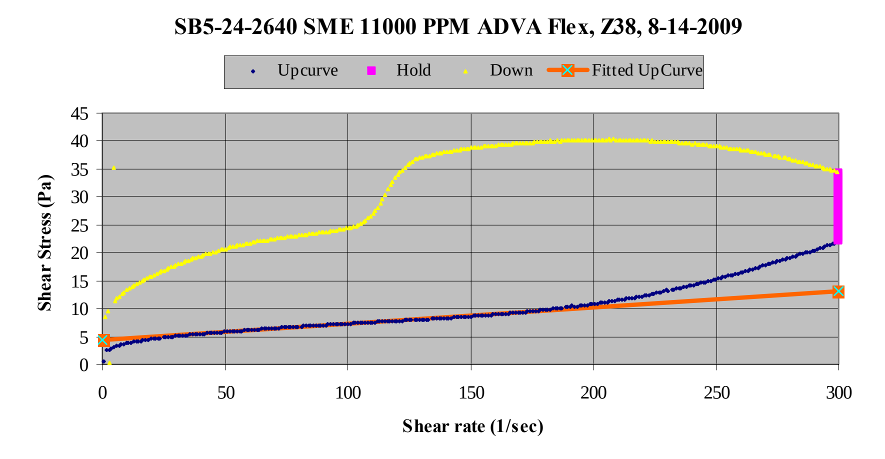


09-SB5-24-2640 10,000 PPM Citric Acid

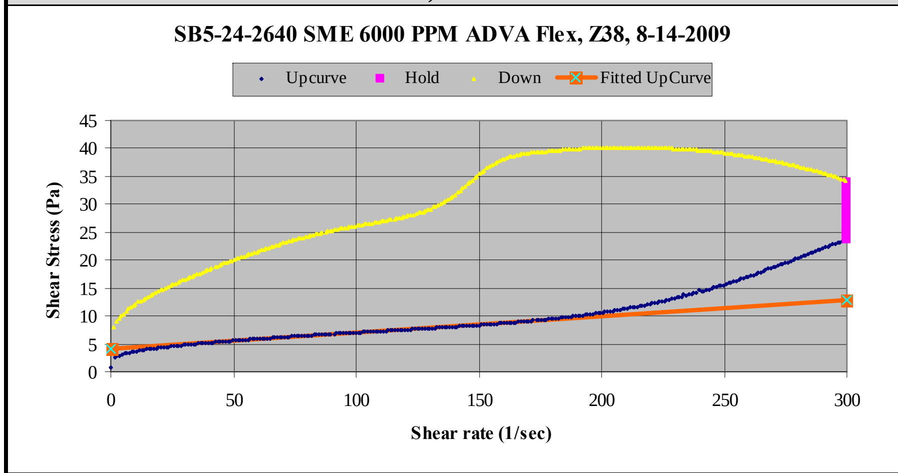
Figure G - 4 09-SB5-24-2640 SME Flow Curves: Citric Acid



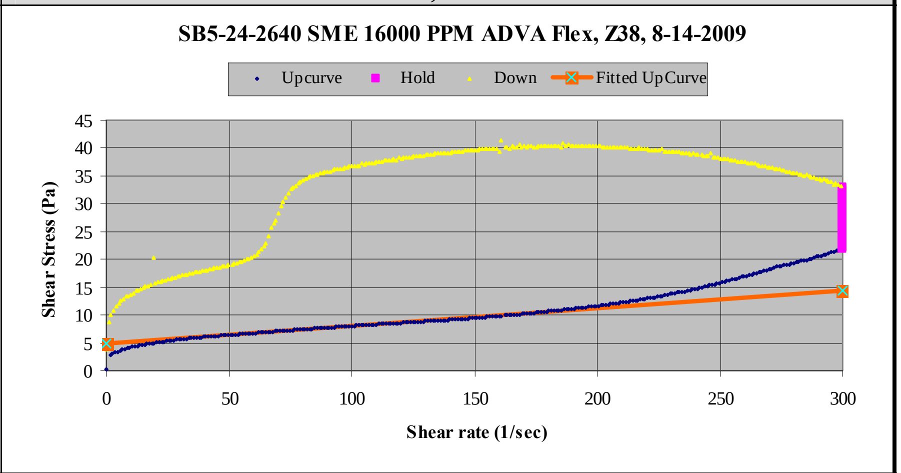
09-SB5-24-2640 1,000 PPM ADVA Flex



09-SB5-24-2640 11,000 PPM ADVA Flex

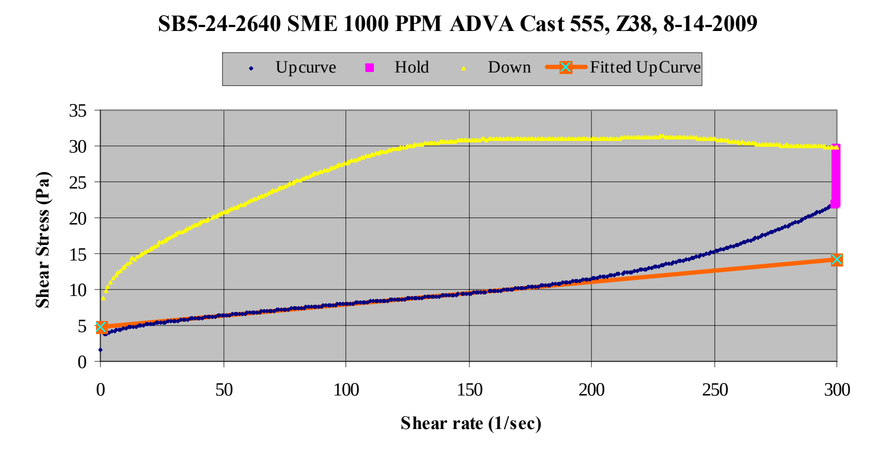


09-SB5-24-2640 6,000 PPM ADVA Flex

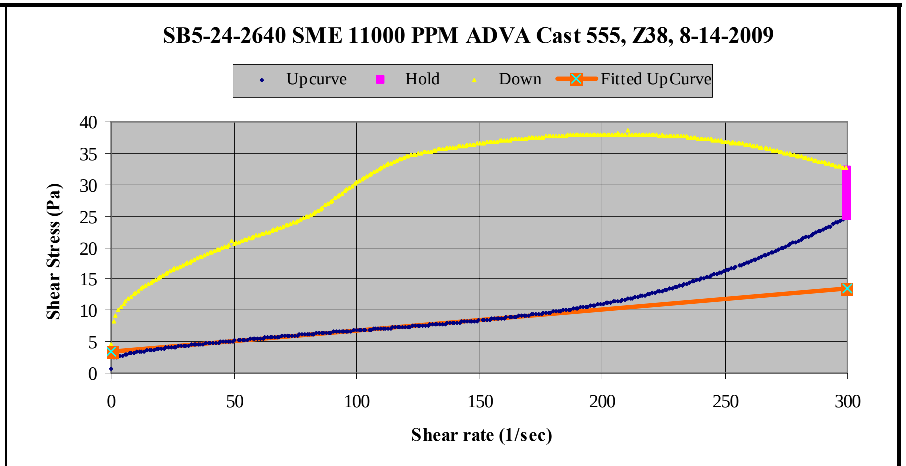


09-SB5-24-2640 16,000 PPM ADVA Flex

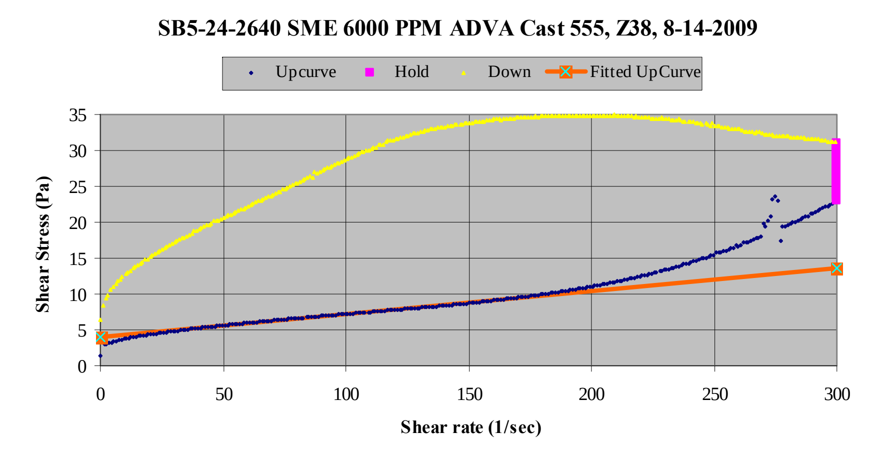
Figure G - 5 09-SB5-24-2640 SME Flow Curves: Grace ADVA Flex



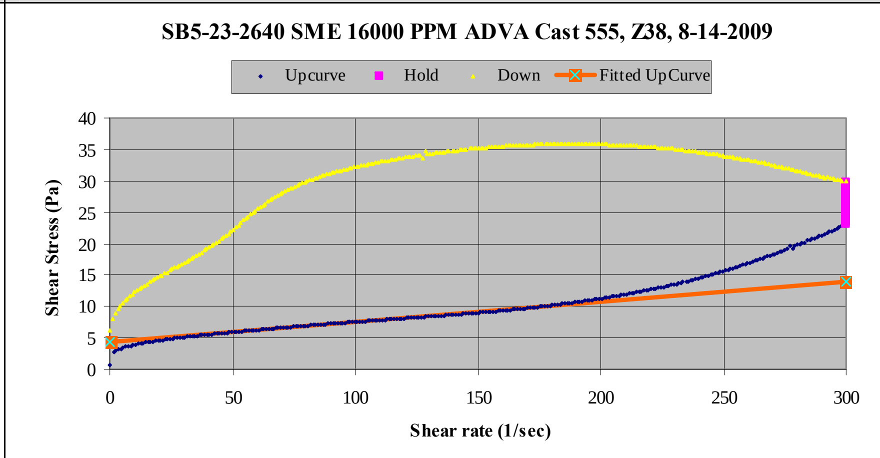
09-SB5-24-2640 1,000 PPM ADVA Cast 555



09-SB5-24-2640 11,000 PPM ADVA Cast 555



09-SB5-24-2640 6,000 PPM ADVA Cast 555



09-SB5-24-2640 16,000 PPM ADVA Cast 555

Figure G - 6 09-SB5-24-2640 SME Flow Curves: Grace ADVA Cast 555