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Physical Property Measurements of Laboratory Prepared Saltstone Grout

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EXECUTIVE SUMMARY

The Saltstone Production Facility (SPF) built two new Saltstone Disposal Units (SDU), SDU 3 and SDU 5, in 2013. The variable frequency drive (VFD) for the grout transfer hose pump tripped due to high current demand by the motor during the initial radioactive saltstone transfer to SDU 5B on 12/5/2013. This was not observed during clean cap processing on July 5, 2013 to SDU 3A, which is a slightly longer distance from the SPF than is SDU 5B. Saltstone Design Authority (SDA) is evaluating the grout pump performance and capabilities to transfer the grout processed in SPF to SDU 3/5. To assist in this evaluation, grout physical properties are required. At this time, there are no rheological data from the actual SPF so the properties of laboratory prepared samples using simulated salt solution or Tank 50 salt solution will be measured.

The physical properties of grout prepared in the laboratory with de-ionized water (DI) and salt solutions were obtained at 0.60 and 0.59 water to premix (W/P) ratios, respectively. The yield stress of the DI grout was greater than any salt grout. The plastic viscosity of the DI grout was lower than all of the salt grouts (including salt grout with admixture). When these physical data were used to determine the pressure drop and fluid horsepower for steady state conditions, the salt grouts without admixture addition required a higher pressure drop and higher fluid horsepower to transport. When 0.00076 g Daratard 17/g premix was added, both the pressure drop and fluid horsepower were below that of the DI grout. Higher concentrations of Daratard 17 further reduced the pressure drop and fluid horsepower. The uncertainty in the single point Bingham Plastic parameters is $\pm$ 4% of the reported values and is the bounding uncertainty.

Two different mechanical agitator mixing protocols were followed for the simulant salt grout, one having a total mixing time of three minutes and the other having a time of 10 minutes. The Bingham Plastic parameters were essentially the same for the salt grout without admixture. When Daratard 17 was added, the Bingham Plastic yield stress increased for the 10 minute mix.

The simulant salt used in this task had similar physical properties of the Tank 50 3Q13 salt grout and is recommended for future use, if the salt solution in Tank 50 does not change.

The design basis physical properties used to size the pumps and mixers at SPF were obtained from DPST-85-312. The grouts characterized in this report are bounded by the design basis density and Bingham Plastic yield stress. The opposite is true for the plastic viscosity. Steady state pressure drop calculations were performed for the design basis values using the flow rate for the clean cap and salt grouts and they bound the pressure drop of the grouts characterized in this report.

A comparison of the lab prepared samples to PI ProcessBook data, specifically average pressure drop, indicate that the lab prepared samples are more viscous in nature than what is processed in the facility. This difference could be due to the applied shear rates which could be lower in the lab as compared to the facility and that fact the SPF added flush water, making this comparison more difficult.

A perfunctory review of the PI ProcessBook data used in Section 3.2 was discussed in Section 3.3. It may be possible that the frequency that the distributed control system alters the grout pump speed to maintain grout hopper volume can negatively affect the efficiency of the grout pump.

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LIST OF ABBREVIATIONS

ACTL	Aiken County Technical Laboratory
D17	Daratard 17
DI	De-ionized
EHP	Electric Horse Power
IW	Inhibited water
PV	Plastic Viscosity
SDA	Saltstone Design Authority
SDU	Saltstone Disposal Unit
SPF	Saltstone Production Facility
SRNL	Savannah River National Laboratory
VFD	variable frequency drive
W/P	Water to premix
WAC	Waste Acceptance Criteria
WHP	Fluid Horse Power
YS	Yield Stress

1.0 Introduction

The Saltstone Production Facility (SPF) built two new Saltstone Disposal Units (SDU), SDU 3 and SDU 5, in 2013. The variable frequency drive (VFD) for the grout transfer hose pump tripped due to high current demand by the motor during the initial radioactive saltstone transfer to SDU 5B on 12/5/2013. This was not observed during clean cap processing on July 5, 2013 to SDU 3A, which is a slightly longer distance from the SPF as compared SDU 5B.[1] Saltstone Design Authority (SDA) is evaluating the grout pump performance and capabilities to transfer the grout processed in SPF to SDU 3/5. To assist in this evaluation, grout physical properties are required. At this time, there are no rheological data from the actual SPF so the properties of laboratory prepared samples using simulated salt solution and Tank 50 salt solution were measured.

SDA requested the Savannah River National Laboratory (SRNL) to prepare and characterize laboratory scale prepared grout samples for rheology data to support this engineering evaluation and to determine the present SPF rheological basis used for sizing equipment in the SPF.[2]

2.0 Experimental Procedure

The experimental procedure consisted of the following items.

- Materials
  - Solutions
  - Premix
  - Admixture
- Grout Blends
  - Water to Premix Ratio
  - Batch Size and Mixing Methods
  - Number of Blends
- Physical Characterization
  - Rheology
  - Density
  - Gel Time
  - Bleed
- Analysis of Physical Data, PI Data, and Historical Data
  - Steady State Flow Analysis
  - Analysis of selected PI data
  - Historical Basis of Design

2.1 <u>Materials</u>

Materials used in this task consisted of solutions, premix, and admixture and are described in more detail below.

2.1.1 Solutions

Three different solutions were used in this task; Tank 50 3Q13 salt solution, simulant salt solution, and de-ionized (DI) water. A portion, approximately two liters of the Tank 50 3Q13 salt solution archived as part of the SDU sampling task[3] was made available for this work. The chemical analysis of this Tank 50 3Q13 salt solution is reported in Reference 4. A simulant salt solution of this composition was previously made to support Phase I of Saltstone Sampling and Analysis.[5] This simulant was requested in Reference 3 to support the activities in the sampling and analysis task. The composition of the simulant Tank 50 salt solution is provided in Table 2-1. The density and mass fraction of the solutions used in this task are provided in Table 2-2.

Table 2-1. Simulant Tank 50 Salt Solution Based On Tank 50 3Q13 Sample

Component	Concentration (g/L)
$NaNO_3$	145.2
$NaNO_2$	31.5
NaOH	99.9
Na_2CO_3	21.0
KNO_3	0.9
Na_2SO_4	7.5
$Al(NO_3)_3$-$9H_20$	55.5
Na_3PO_4-$9H_20$	1.7

Table 2-2. Density and Mass Fraction of Solids of Solutions

Solution	Density (g/ml)	Mass fraction solids - (g-solids/g-solution)
DI water	1.0000	0.0000
Simulant Tank 50	1.2336	0.2733
Actual Tank 50	1.2385	0.2877

2.1.2 Premix

Premix previously retrieved from the Saltstone Premix Feed Bin that was stored in a Level C storage facility was used to prepare all of the mixes in this task. It is assumed that the mass fraction composition of this premix is that stated in Table 2-3. The densities of the premix components were previously characterized using helium gas pycnometry.[6]

Table 2-3. Premix Composition and Density

Component	Source	Density (g/cm^3)	Mass fraction composition (g-component/g-premix)
Fly Ash	The SEFA Group, Lexington, SC	2.39	0.45
Blast Furnace Slag	Holcim (US) Birmingham, AL	2.85	0.45
Portland Cement	LaFarge, Pasco Station, WA	3.11	0.10

The density of the premix was determined using volume additivity,[7] equation (1).

$$\rho_{PM} = \left(\sum_{i=1}^{3} \frac{f_{PM,i}}{\rho_{PM.i}} \right)^{-1} \tag{1}$$

Where: $f_{PM,i}$ = mass fraction of premix component i (g-component/g-premix)
$\rho_{PM.i}$ = density of premix component i (g/cm^3)
ρ_{PM} = density of premix (g/cm^3)

2.1.3 Admixture

The admixture Daratard 17 (D17) is an ASTM C494[8] Type B and D set retarder/water reducer. In saltstone, Daratard 17 aids in the incorporation of premix into the salt solution and was added to the pump suction of the Salt Feed transfer pump. The use of Daratard 17 can alter the physical properties of the grout, reducing both the rheological properties (yield strength and plastic viscosity) and increasing the gel time.

In this task, fresh Daratard 17 admixture was obtained from the vendor, due to the decaying effectiveness of the Daratard 17 admixture as it ages.[9] Unlike the previous Daratard 17 used by SPF, this D17 does not contain the antimicrobial agent orthophenyl phenol. The quantity of admixture is based on the mass of premix and a review of SRNL data showed that the minimum recommended Daratard 17 addition was 0.00075 g-D17/g-premix[10]. The dosage was started at this minimum concentration and was increased in unitary quantities to reduce the plastic viscosity of the saltstone grout to approximate to that of the clean cap grout. The density and mass fraction solids of this D17 were characterized in this task and were 1.215 g/ml and 0.4475 g-solids/g-D17, respectively.

2.2 <u>Grout Blends</u>

The water to premix, batch size and mixing method, and number of blends are described below.

2.2.1 Water to Premix Ratio

Grout formulation is based on the water to premix (W/P) ratio. The W/P is the mass of the water in the solution to the mass of the premix. A W/P target of 0.59 and 0.60 was provided for this task in Reference 2 for salt solutions and clean cap grouts, respectively. This W/P value is used to determine the mass fraction of premix in the grout, mass fraction of solution in the grout, and density of the grout using equations (2), (3), and (4). In these calculations, the primary assumption is that there are no chemical reactions that take place during the measurements that would affect the calculated densities (used to determine batch size). This is a good assumption, given it takes time for the cementitious reactions to occur and this time is much greater than the time required in mixing the blend and obtaining the required physical properties of the fresh grout. Daratard 17, when added, was not considered in the W/P ratio used to determine the solution and premix masses.

$$f_{PMG} = \frac{1}{1 + \frac{W/P}{(1 - f_{SS})}} \tag{2}$$

$$f_{SSG} = 1 - f_{PMG} \tag{3}$$

$$\rho_{GT} = \left(\frac{f_{PMG}}{\rho_{PM}} + \frac{f_{SSG}}{\rho_{SS}}\right)^{-1} \tag{4}$$

Where: W/P = water to premix ratio (g-water/g-premix)
f_{SS} = mass fraction of solids in solution (g-solids/g-solution)
f_{PMG} = mass fraction of premix in grout (g-premix/g-grout)
f_{SSG} = mass fraction of solution in grout (g-solution/g-grout)
ρ_{SS} = density of salt solution (g/ml)
ρ_{GT} = theoretical density of grout (g/ml)

2.2.2 Batch Size and Mixing Methods

The physical properties, rheology, density, gel time, and bleed water require a minimum of 575 mL of grout. This volume is based on the methods used by SRNL to quantify these properties. The value for the mass of premix and solution are determined using equations (5) and (6). When Daratard 17 is used, the mass of Daratard addition was determined using equation (7).

$$m_{PM} = V_T \cdot \rho_{GT} \cdot f_{PMG} \quad (5)$$

$$m_{SS} = V_T \cdot \rho_{GT} \cdot f_{SSG} \quad (6)$$

$$m_{D17} = \psi \cdot f_{D17} \cdot m_{PM} \quad (7)$$

Where: V_T = volume of grout required (ml)
m_{PM} = mass of premix (g)
m_{SS} = mass of solution (g)
f_{D17} = minimum Daratard 17 mass fraction addition (g-D17/g-premix)
ψ = unitary multiplier (1, 2 or 3) for different Daratard 17 mass additions
m_{D17} = mass of Daratard 17 (g)

Three different mixing methods were used in this task as shown in Table 2-4. Two of the methods used a mechanical agitator and the third was hand blending. A modified impeller design was used for the mechanical agitator method and an off-the-shelf spatula was used for hand blending. The total mixing time of three minutes used in methods A and B is based on mixing times used by SRNL from recent Saltstone activities. The 10 minute mixing time for method C was based on the approximate time it would take for the grout to be blended in the READCO mixer, passed through the grout hopper, and transferred in the grout line to SDU 3/5.[11] In this case, the final mixing sequence was extended from 1.5 to 8.5 minutes. Method B is considered low shear as compared to the other two methods. Grout temperatures were measured/recorded when all the grout was added and upon completion of mixing.

Table 2-4. Mixing Methods

Method	Steps
A: Mechanical Agitator Total mixing time: 3 minutes	• Add liquid to 1L beaker. • Set speed to 200 RPM. • Add premix and increase speed to 300 RPM during addition. • Start mixing clock when all the premix has been added. • Mix at 300 RPM for 1.5 minutes. • Mix at 350 RPM for additional 1.5 minutes.
B: Hand Blending Total mixing time 3 minute	• Add liquid to 1L beaker. • Add premix. • Start mixing clock when all the premix has been added. • Mix for 3 minutes.
C: Mechanical Agitator Total mixing time: 10 minutes	• Same steps as method A, except for last step. • Mix at 350 RPM for additional 8.5 minutes.

The mixing methods have not been compared to the actual saltstone process data to determine if these laboratory mixing methods provide the same type and magnitude of shear rates and shear stresses as that in the actual SPF, resulting in grouts that have similar rheological properties. These data can be used to compare the potential impact of how changing process variables can affect the properties of fresh grout.

2.2.3 Number of Mixes

There were a total of 21 mixes made in this task and the batch #, solution, Daratard 17 addition, location, and mixing method are provided in Table 2-5.

Table 2-5. Batches Made

Mix #	Solution	D17	Location	Mixing Method	Mix #	Solution	D17	Location	Mixing Method
1	Simulant	-	ACTL	A	12	DI Water	-	ACTL	A
2	Simulant	-	ACTL	B	13	Simulant	1X	ACTL	A
3	Simulant	-	ACTL	B	14	Simulant	2X	ACTL	A
4	Simulant	-	ACTL	A	15	Simulant	3X	ACTL	A
5	Simulant	-	ACTL	A	16	DI Water	-	773A	A
6	Simulant	-	ACTL	B	17	Simulant	-	773A	A
7	Simulant	-	ACTL	A	18	Waste	-	773A	A
8	Simulant	-	ACTL	B	19	Waste	1X	773A	A
9	Simulant	-	ACTL	A	20	Simulant	-	ACTL	C
10	Simulant	-	ACTL	B	21	Simulant	1X	ACTL	C
11	DI Water	-	ACTL	A					

To generate the data necessary to satisfy the request, it was first necessary to determine the uncertainty in the fitted rheological parameters given single point measurements that typically occur with these fresh properties. To determine the uncertainties in the rheological properties and other physical properties for single point measurements, lab prepared mixes were made using the simulant Tank 50 salt solution at the W/P of 0.59 using the mixing methods A and B. The flow curve (rheological data), fresh density, gel, and bleed water were measured for mixes prepared by each method over five days (one mix by each method per day). The results were statistically analyzed, specifically to address the uncertainties in the fitted rheological parameters. The analysis is to determine if the errors are dominated by sample to sample variability, sample analysis, or both and to apply these if necessary to single point measurements.

Clean cap (DI water) mixes were performed to compare these results to the salt solution grouts, given that the clean cap transfer to SDU 3A was considered successful.

Simulant Tank 50 salt solution grouts were made to determine the impact of Daratard 17 on the rheological properties. Also, additional simulant Tank 50 salt solution grouts were made with extended mixing times to determine if the applied additional shear rate and stresses change the rheological properties.

To demonstrate consistency between preparation and analysis at the simulant facility and the radiological facility, the DI water and simulant Tank 50 salt solution grouts were also analyzed in the radiological environment. Two radioactive Tank 50 salt solutions grouts were analyzed, one without and one with Daratard 17.

2.3 Physical Characterization

Upon completion of mixing, the grout was analyzed for rheology, density, gel, and bleed water, in that order. This was done for all the mixes that were made at Aiken County Technical Laboratory (ACTL). For all the mixes that occurred in the radiological environment, density was not measured. The method used for these characterizations are provided below.

2.3.1 Rheology

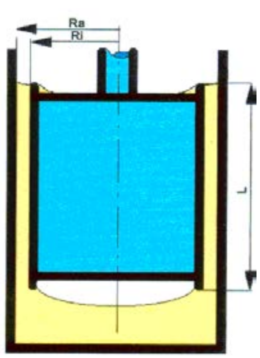
Rheological properties were determined using a Haake VT550 rotoviscometer to obtain the flow curves which are analyzed using rheological models. The VT550 is a Searle sensor system, where the bob rotates and the cup is fixed. The rotational speed and torque of the bob are measured. The speed of the bob is the controlled variable with the torque as the dependent variable. The heating or cooling of the cup, sample, and bob is through the heating jacket that supports the cup. The shear stress is determined from the torque measurement and is independent of rheological properties. The shear rate is geometrically determined using the equations of change (continuity & motion) and is that for a Newtonian fluid. This assumption assumes the flow field is fully developed and the flow is laminar. The shear rate can be calculated for non-Newtonian fluid using the measured data and fitting data to the rheological model or corrected as recommended by Darby.[12] In either case, for shear thinning non-Newtonian fluids, typical of grout, the corrected shear rates are greater than their corresponding Newtonian shear rates, resulting in a thinner fluid. The bob typically used for measuring grout is the MV2 rotor. The shape, dimensions, and geometric constants for the MV2 rotor are shown in Table 2-6. Prior to executing the measurements, the rotor and cup are inspected for physical damage. The torque/speed sensors and temperature bath are verified for functional operability using a bob/cup combination with a NIST traceable Newtonian oil standard. The resulting flow curves are fitted as a Newtonian fluid (equation (8)) and the calculated viscosity must be within $\pm$ 10% of the reported NIST viscosity. A N35 oil standard was used to verify system operability prior to the grout measurements on a daily basis. The flow curves for the grout are fitted using the Bingham Plastic rheological model, equation (9).

$$\tau = \mu \cdot \dot{\gamma} \tag{8}$$

$$\tau = \tau_o + \mu_\infty \cdot \dot{\gamma} \tag{9}$$

Where: τ = measured shear stress (Pa)
$\dot{\gamma}$ = measured shear rate (1/sec)
μ = viscosity (Pa-sec)
τ_o = Bingham Plastic Yield Stress (Pa)
μ_∞ = infinite viscosity (Pa-sec)

Table 2-6. Haake MV2 Rotor Dimensions and Flow Curve Program

MV2 Rotor	Dimensions and Flow Curve Program	
	Rotor radius (mm)	$R_i = 18.40$
	Cup Radius (mm)	$R_a = 21.0$
	Height of rotor (mm)	L = 60
	Sample Volume (cm^3)	50
	A factor (Pa/(N·cm))	76.8
	M factor (min/sec)	0.900
	Shear rate range (s^{-1})	0 – 300
	Ramp up time (seconds)	210
	Hold time (seconds)	30
	Ramp down time (seconds)	210

The rheological parameters were determined using Microsoft® Excel (2010). For the Newtonian fluids, the flow curves were plotted, the "Add Trendline" option selected and the data analyzed using the linear fit, forcing the data through the origin. The viscosity and R^2 factors were reported for both the up and down curves. For the Bingham Plastic fluids, the yield stress and plastic viscosity were determined using the "LINEST" Function.* The parameters were fitted for both the up (increasing shear) and down (decreasing shear) curve. The standard errors for the parameters were reported for the down curve. The up and down curves for the grouts were analyzed in the shear rate range of 0 to 300 sec^{-1} and 30 to 300 sec^{-1}. The 30 to 300 sec^{-1} shear rate range was selected given the data in this range was linear for most of the grouts for the down curves.

Regression analyses were conducted on the experimental results using JMP Version 9.0.0† to estimate the yield stress (YS) in Pascals (Pa) and the plastic viscosity (PV) in Pascal-seconds (Pa-s) for each batch run over two shear-stress intervals of the down curve testing.

2.3.2 Density

The densities of the grouts were measured using a weight per gallon density cup (Gardco) that satisfies the intent of ASTM D 1475.[13] The volume of the cup is verified using DI water, per the ASTM. The density of the grout sample is then determined using equation (10).

$$\rho_{GT,m} = \frac{m_{cup+sample} - m_{cup}}{V_{cup}} \qquad (10)$$

Where: $m_{cup+sample}$ = mass of sample and cup (g)
m_{cup} = mass of cup (g)
V_{cup} = volume of cup (ml)
$\rho_{GT,m}$ = measured density of grout (g/ml)

2.3.3 Gel Time

The gel time was determined by placing approximately 60 mL of grout into a 75 mL plastic container having an inside diameter of approximately 1.32 inches. Four containers were filled for each mix. Periodically, a container was deliberately poured out and the flowability was evaluated. This process continued, with the time interval determined by the flowability of the prior pour, until it was determined that the grout was no longer flowable. Gel time measurements are subjective and are based on container diameter, sample mass, pour technique, and what the researcher considers is gel. In this case, gel was specified as when no grout was poured out of the container.

2.3.4 Bleed Volume Fraction

Bleed volume was determined by pouring approximately 60 mL of grout into a 75 mL plastic container and measuring the mass of bleed fluid after one and/or three days of curing. The mass of grout poured into the container is also measured. The bleed fraction is determined using equation (11). Two containers were filled for each mix.

$$f_{VB} = \frac{\left(\frac{m_{F,bleed}}{\rho_{SS}}\right)}{\left(\frac{m_{G,bleed}}{\rho_{GT}}\right)} \qquad (11)$$

Where: $m_{F,bleed}$ = mass of bleed (g)
$m_{G,bleed}$ = mass of grout (g)
f_{VB} = volume fraction bleed (volume bleed/volume grout)

* The LINEST function calculates the statistics for a line by using the "least squares" method to calculate a straight line that best fits the data, and then returns an array (coefficients, standard error values, coefficient of determination, F statistic, degrees of freedom, regression of sum squares, and residual sum of squares) that describes the line.
† SAS Institute, Inc., JMP™ Version 9.0.0, SAS Institute Inc., Cary, NC, 2010.

2.4 Analysis of Physical Data, PI Data and Historical Data

This section performs the following:

- Calculation of the steady state pressure drop and fluid horsepower of the various mixes made in section 2.2.
- Review and calculations of specific PI ProcessBook[‡] data for the 7/5/13 and 12/5/13 grout transfers.
- Documents used to determine the origin of the physical properties used for the design basis for pumps and mixers at SPF.

2.4.1 Steady State Flow Analysis

The physical properties (rheology and density) will be used to assess the steady state hydraulic conditions of the various mixes. This comparison looks at the pressure drop and horsepower requirements for the successful clean cap transfer and compares it to the salt solutions with and without Daratard 17.

The assumptions used in these calculations are that the fluid (grout) is homogeneous and incompressible and the flow is fully developed and at steady state. The grout can be modeled as a Bingham Plastic fluid. Bernoulli's equation is applicable to this application. This calculation will determine the pressure drop based on the equivalent length of piping (2583.5 feet) as determined by Jones[1] for the 3" schedule 40 piping[§], element C5 as defined in Table 2[1]. The equivalent length of piping for elbows and bends was determined for turbulent conditions.[14] Elevation change, exit or kinetic head of the fluid will not be considered in these calculations. These calculations are not used to support any pump calculations. It uses the physical data to determine the hydraulic loss and power, which are then compared to each other.

The friction factor for a Bingham Plastic fluid was determined using the method described by Darby.[12] Equations (12) through (18) are used to determine the friction factor.

$$f_B = \left(f_L^b + f_T^b\right)^{\frac{1}{b}} \tag{12}$$

$$f_L = \frac{16}{Re_B}\left[1 + \frac{1}{6}\frac{He}{Re_B} - \frac{1}{3}\frac{He^4}{f_L^3 Re_B^7}\right] \tag{13}$$

$$f_T = 10^a Re_B^{-0.193} \tag{14}$$

$$a = -1.47 \cdot \left[1 + 0.146 \cdot e^{-2.9\cdot 10^{-5}\cdot He}\right] \tag{15}$$

$$b = 1.7 + \frac{40{,}000}{Re_B} \tag{16}$$

$$He = \frac{D^2 \cdot \rho_{GT} \cdot \tau_o}{\mu_\infty^2} \tag{17}$$

$$Re_B = \frac{D \cdot V \cdot \rho_{GT}}{\mu_\infty} \tag{18}$$

Where: f_B = total friction factor (unitless)
f_L = laminar friction factor (unitless)

---

‡ PI ProcessBook Version 3.2.0.0 OSIsoft Inc. (2009)

§ Actual facility transfer line is constructed of API 5L galvanized steel pipe with a 3-inch internal diameter and a wall thickness of 1/4 inch. (G-SD-Z-00003, Revision 9)

f_T = turbulent friction factor (unitless)
a = calculated variable used in turbulent friction factor (unitless)
b = calculated variable used in turbulent friction factor (unitless)
He = Hedstrom number (unitless)
Re_B = Bingham Plastic Reynolds number (unitless)
D = pipe inside diameter (m)
V = average pipe line velocity (m/s)

The pressure drop for the equivalent feet of piping is determined using equation (19):[12]

$$\Delta P = 2 \cdot f_B \cdot \frac{L_{eq} \cdot \rho_{GT} \cdot V^2}{D} \tag{19}$$

Where: ΔP = Pressure drop (Pa) [Multiply by 145.038 x10^{-6} to obtain psi]
L_{eq} = Equivalent feet of piping (m)

The fluid horsepower (the power required to overcome the frictional losses in the piping system) can be calculated using equation (20):[15]

$$WHP = \frac{\dot{Q} \cdot \Delta P}{1714} \tag{20}$$

Where: WHP = fluid horsepower (HP)
$\dot{Q}$ = Volumetric Flow rate (GPM)
ΔP = Pressure drop (psi)

The average volumetric flow rate is obtained from the steady state regions of the PI ProcessBook data relative to the clean cap grout (July 5, 2013) and radioactive salt grout (December 5, 2013) runs using the mass flow rate of the premix. Equation (21) was used to calculate the grout volumetric flow rate for a specific time and Microsoft® Excel (2010) was used to determine the average volumetric flow rate ($\dot{Q}$). The average pipeline velocity was determined using equation (22) and is used in the above calculations.

$$\dot{Q} = 3.99 \frac{\frac{\sum_{j=1}^{n} \dot{m}_{PM,j}}{n}}{\rho_{GT} \cdot f_{PMG}} \tag{21}$$

$$V = 8.033 \cdot 10^{-5} \cdot \frac{\dot{Q}}{D^2} \tag{22}$$

Where:
$\dot{m}_{PM,j}$ = PI ProcessBook premix mass flow rate (Tag Name ZFIC1372/PV.CV) for time sequence j (tons/h)
n = number of data points

Microsoft® Excel (2010) was used to calculate the variables in the above equations. Fourteen iterations were used to solve for the laminar friction factor (equation (13)). Calculations were performed on the lab prepared simulant, water, and actual radioactive salt grout, given the average steady state premix feed rate used by the Saltstone facility during processing activities on July 5th and December 5th 2013. Details are provided in section 2.4.2 relating to PI ProcessBook data used in the above calculations.

2.4.2 Review of Selected PI ProcessBook Data For SDU-3 and SDU-5

SUD-3 and SDU-5 PI data were obtained on 7/5/2013 and 12/5/2013, respectively. Clean cap grout was processed from SPF to SDU-3; this transfer was considered a success. The SPF to SDU-5 operation was not considered successful while processing radioactive saltstone grout. Table 2-7 provides the range of PI obtained, and the time range of data that was averaged and the process variables that were downloaded. The averaged PI data was considered steady state data.

Table 2-7. PI Data Time and Process Variables

SDU	Date	PI Data Time Frame	Averaged PI Data Time Frame
3	7/5/2013	9:25:20 to 10:49:00	10:00:50 to 10:06:40 (2150 to 2500 seconds data) and 10:15:00 to 10:21:40 (3000 to 3400 seconds data)
5	12/5/2013	9:11:40 to 9:57:30	9:37:58 to 9:54:56 (3578 to 3596 seconds data)
Process Data			
Process Variable		**Tag Name**	
Grout Flow Rate (gpm)		ZFI1127/PV.CV	
Clean Cap (gpm)		ZFIC1118/PV.CV	
Salt Solution (gpm)		ZFIC1050/PV.CV	
Screw feeder flow (TPH)		ZFIC1372/PV.CV	
Xfer pressure (psig)		ZPI1129/PV.CV	
Pump speed (rpm)		ZSIC9001/PV.CV	
Grout SpG (measured)		ZDI1144/PV_FIELD.CV	
Grout SpG (Calculated)		ZDI1144/PV_CALC.CV	
Pump (Voltage)		ZEI9001/PV.CV	
Pump (amps)		ZII9001/PV.CV	
Grout Hopper (gallons)		ZLIC8003/PV.CV	

Additional calculations were performed on these data sets. It was assumed that for the salt solution, the density and mass fraction of solids obtained from the WAC Tank 50 3Q13 salt solution are representative of the salt processed in December 2013. Additionally, the density of the premix is that determined in section 2.1.2. In the calculations below, it is assumed that the PI ProcessBook Xfer pressure is due to the hydraulic pressure drop from the fluid alone. Process parameters for each time frame that were calculated from the PI ProcessBook data sets are provided below.

The total liquid flow rate is:

$$\dot{Q}_L = \dot{Q}_W + \dot{Q}_{SS} \quad (23)$$

Where: $\dot{Q}_W$ = Inhibited water (IW) flow rate (gpm)
$\dot{Q}_{SS}$ = Salt solution flow rate (gpm)
$\dot{Q}_L$ = Total liquid flow rate (gpm)

The average liquid density of the liquid flow is (no reactions):

$$\rho_L = \frac{\rho_W \cdot \dot{Q}_W + \rho_{SS} \cdot \dot{Q}_{SS}}{\dot{Q}_L} \quad (24)$$

Where: ρ_W = density of IW (g/mL) – **Assumed to be 1.000 in all calculations**.
ρ_L = average density of liquid (g/mL)

The mass fraction of soluble solids in the liquid is:

$$f_L = \frac{f_{SS} \cdot \rho_{SS} \cdot \dot{Q}_{SS}}{\rho_W \cdot \dot{Q}_W + \rho_{SS} \cdot \dot{Q}_{SS}} \tag{25}$$

Where: f_{SS} = fraction of soluble salts in salt solution (g-solids/g-solution)
f_L = fraction of soluble salts in the liquid (g-solids/g-solution)

The premix flow rate is (is used in section 2.4.1):

$$\dot{Q}_{PM} = 3.99 \frac{\dot{m}_{PM}}{\rho_{PM}} \tag{26}$$

Where: $\dot{m}_{PM}$ = mass flow rate of premix (tons/hr)
$\dot{Q}_{PM}$ = premix flow rate (GPM)

The grout flow is (assumes no air entrainment when the two streams are blended):

$$\dot{Q} = \dot{Q}_{PM} + \dot{Q}_L \tag{27}$$

The grout density is (same assumptions as in equation (4): no air and volume additivity):

$$\rho_G = \frac{\rho_L \cdot \dot{Q}_L + \rho_{PM} \cdot \dot{Q}_{PM}}{\dot{Q}_L + \dot{Q}_{PM}} \tag{28}$$

Where: ρ_G = grout density (g/ml)

The water to premix mass ratio is:

$$\left.\frac{w}{p}\right|_c = \frac{\rho_L \cdot \dot{Q}_L \cdot (1 - f_L)}{\rho_{PM} \cdot \dot{Q}_{PM}} \tag{29}$$

Where: $\left.\frac{w}{p}\right|_c$ = water to premix mass ratio (g-water/g-premix)

The fluid horsepower calculated from the PI ProcessBook data:

$$WHP_{PI} = \frac{\dot{Q}_{GT-PI} \cdot P_{PI}}{1714} \tag{30}$$

Where: $\dot{Q}_{GT-PI}$ = PI ProcessBook grout flow rate (GPM)
P_{PI} = Xfer pressure (psig)
WHP_{PI} = PI ProcessBook data fluid horsepower (HP)

The fluid horsepower calculated using PI ProcessBook pressure data and calculated grout flow rate is:

$$WHP_{PI} = \frac{\dot{Q}_{GT} \cdot P_{PI}}{1714} \tag{31}$$

Where: WHP_{GT} = fluid horsepower using calculated flow rate (HP)

The horsepower developed by the 3 phase motor is determined by:

$$EHP = \frac{\sqrt{3} \cdot V \cdot I \cdot \varepsilon \cdot PF}{746} \tag{32}$$

Where: V = Voltage (volts)
I = Current (amps)
ε = efficiency
PF = Power Factor
EHP = Electrical Horsepower

The product of $\varepsilon \cdot PF$ was taken to be 0.888 based using the above equation and taking the average of the mean motor load current at 48.3 Hz (this translates to 370 Volts) for the various HP/amp loadings.[16]

Grout flow rate based on pump rotation speed is:

$$\dot{Q}_{\Omega} = A \cdot \dot{\Omega} \tag{33}$$

Where: A = 10.56 gallon/revolution[**]
$\dot{\Omega}$ = revolution per minute
$\dot{Q}_{\Omega}$ = flow rate (gpm)

The average, standard deviation, minimum, and maximum were determined using the embedded functions in EXCEL (2010). Percent standard deviation and percent differences were calculated using equations (34) through (36).

$$\%STDEV = \frac{STDEV}{AVG} \cdot 100\% \tag{34}$$

$$\%max = \frac{(MAX - AVG)}{AVG} \cdot 100\% \tag{35}$$

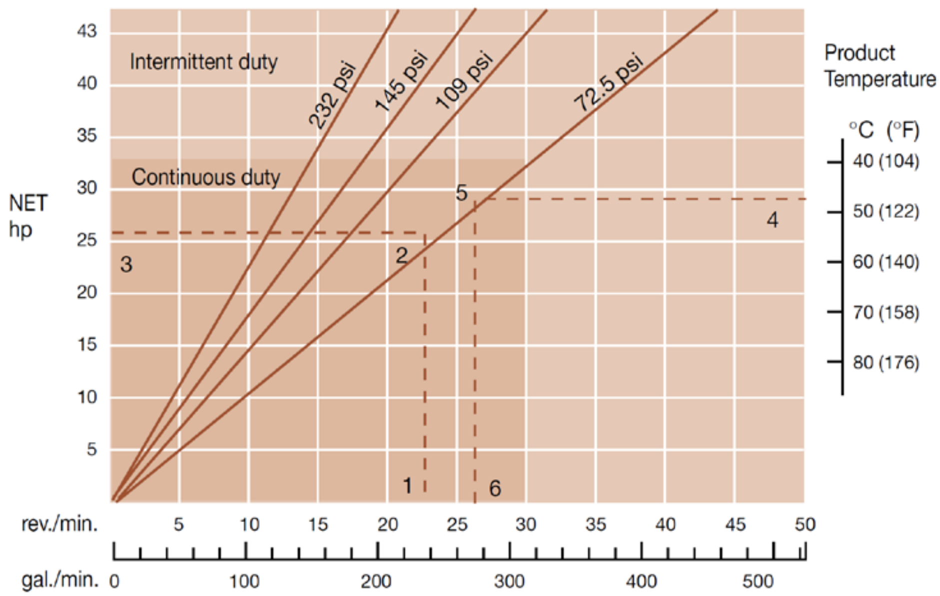
$$\%min = \frac{(MIN - AVG)}{AVG} \cdot 100\% \tag{36}$$

The capabilities of the Bredel 2100 hose pump are provided in Table 2-8.

[**] Data obtained from Bredel 2100 hose pump data sheet (http://www.watson-marlow.com/Documents/knowledge-hub/Brochures/us%20-%20USA/b-bredel-us-06.pdf).

Table 2-8. Bredel 2100 Capabilities

Performance	Value
Maximum Flow	400 gpm
Capacity	10.56 gal/rev
Starting Torque	80,000 in-lbs
Maximum Discharge Pressure	232 psi
Maximum Temperature	175 °F



2.4.3 Historical Basis of Design

A review of historical data was requested to determine the source of the density and Bingham Plastic rheological parameters that were used in pump and mixer specifications at SPF. The current basis of grout density of 1.8 to 1.82 g/ml, plastic viscosity of 42 to 42.5 cP, and yield stress of 21.5 Pa have been used.[17, 18] SRNL reviewed the following list of documents, Table 2-9, that were part of the early development of saltstone, given that the initial calculations that used these properties were performed in August 1985.[17]

Table 2-9. Historical Saltstone Documentation

Document #	Date Issued	Title
DPST-85-312	2/11/1985	Test Results --- Laboratory Testing On Saltstone by Halliburton
DPST-85-469	4/23/1985	Trip Report Slurry Property Evaluation at Halliburton February, 1985
DPST-85-469	4/29/1985	Slurry Data Collected By Halliburton For Full-Scale Mixing and Pumping Test

2.5 Quality Assurance

Requirements for performing reviews of technical reports and the extent of review are established in manual E7 2.60. SRNL documents the extent and type of review using the SRNL Technical Report Design Checklist contained in WSRC-IM-2002-00011, Rev. 2.

3.0 Results and Discussion

The results and discussions are presented in the following order:

Physical properties, averages, and uncertainties
Steady state pressure drop and horsepower
PI data review
Design Basis Document

3.1 Physical Properties

The density, gel time, and bleed water for all the mixes are provided in Table 3-1. The measured simulant salt grout average density is also reported in Table 3-1 and compares well to the calculated value of 1.748 g/ml. A color code system is used to distinguish between salt solution traditional mixed (black), salt solution hand mixed (green), clean cap (blue), and radioactive salt (red) grouts.

Table 3-1. Density, Gel Time, and % Bleed

Mix	Density (g/ml)	Gel Time (min)	% Bleed	Mix	Density (g/ml)	Gel Time (min)	% Bleed	Actual admixture addition (f_{D17})
1	1.731	10	0	12	n/m	n/m	n/m	-
2	1.723	5	0	13	1.730	8.75	0	0.000757
3	1.743	5	0	14	1.719	8.75	0	0.001614
4	1.720	4.75	0	15	1.720	17.5	0	0.002271
5	1.723	5	0	16	n/m	n/m	n/m	-
6	1.716	4.5	0	17	n/m	n/m	n/m	-
7	1.715	4.75	0	18	n/m	7.5	0	-
8	1.724	5	0	19	n/m	8.5[a]	0	0.000765
9	1.716	5	0	20	1.726	12[b]	0	-
10	1.722	3.75	0	21	1.723	18	0	0.000766
11	1.644	45 [b]	4.3					
Average Density and Standard Deviation of Simulant Salt Grout (g/ml)								
Average				1.723				
Std Dev				0.007				

n/m = not measured, a = 90% gel, b = did not gel – last data point

The flow curves for all of the mixes are provided in Appendix A. The flow curves, both up and down were analyzed using the Bingham Plastic model and the results are provided in Table 3-2. Table 3-2 also provides the type of solution used (and admixture + mixing time), batch mixing method, R^2 and the shear rate range in which the data were fitted. Review of the flow curves in Appendix A shows that the hand mixed grouts are more thixotropic than the mixer prepared grouts. Additionally, as both the mixing time and admixture concentrations increase, the thixotropic parameters are removed.

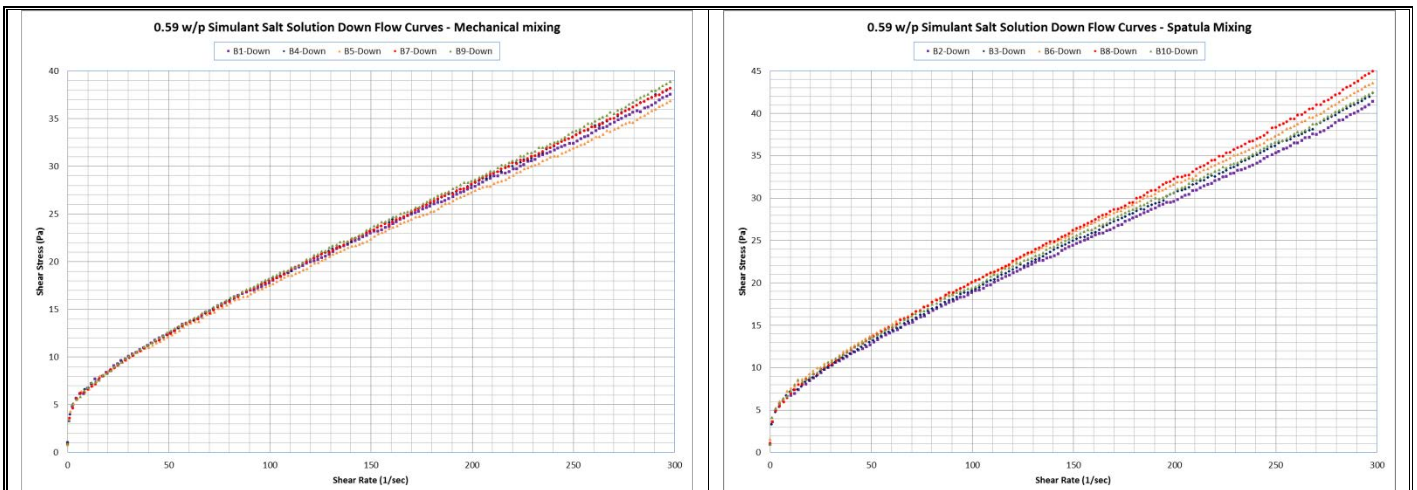
Table 3-2. Bingham Plastic Curve Fitted Data

Mix	Solution + admixture if used	Batch Mixing Method and Time	Bingham Plastic Model						
			Up Curve			Down Curve			Range (s^{-1})
			Plastic Viscosity (cP)	Yield Stress (Pa)	R^2	Plastic Viscosity (cP)	Yield Stress (Pa)	R^2	
1	Salt	Mixer 3 min	113.5	8.40	0.9858	104.0	6.90	0.9931	0-300
			100.3	10.29	0.9912	99.9	7.75	0.9993	30-300
2	Salt	Hand 3 min	109.1	15.32	0.9281	115.9	6.67	0.9952	0-300
			95.3	18.16	0.9558	112.1	7.44	0.9994	30-300
3	Salt	Hand 3 min	111.9	15.89	0.9263	119.4	6.68	0.9953	0-300
			97.9	18.77	0.9515	115.6	7.45	0.9995	30-300
4	Salt	Mixer 3 min	107.5	10.00	0.9767	106.6	6.79	0.9943	0-300
			100.1	11.53	0.9881	102.7	7.57	0.9992	30-300
5	Salt	Mixer 3 min	100.3	10.19	0.9828	101.7	6.81	0.9936	0-300
			94.6	11.36	0.9902	97.8	7.58	0.9992	30-300
6	Salt	Hand 3 min	0.7	41.24	0.0000	122.1	7.22	0.9953	0-300
			27.1	35.81	0.0912	118.2	8.01	0.9994	30-300
7	Salt	Mixer 3 min	106.7	10.29	0.9812	106.9	6.73	0.9938	0-300
			100.2	11.63	0.9899	102.9	7.55	0.9992	30-300
8	Salt	Hand 3 min	114.3	18.53	0.9118	127.9	6.66	0.9960	0-300
			98.8	21.73	0.9356	124.1	7.42	0.9994	30-300
9	Salt	Mixer 3 min	110.0	9.87	0.9797	108.6	6.75	0.9940	0-300
			103.2	11.25	0.9882	104.6	7.57	0.9993	30-300
10	Salt	Hand 3 min	111.3	16.02	0.9340	119.0	7.10	0.9948	0-300
			98.1	18.72	0.9580	115.0	7.91	0.9994	30-300
11	Water	Mixer 3 min	70.6	11.66	0.9463	74.0	10.31	0.9552	0-300
			63.1	13.20	0.9859	66.3	11.88	0.9904	30-300
12	Water	Mixer 3 min	66.9	11.05	0.9523	70.7	9.71	0.9557	0-300
			60.2	12.43	0.9852	63.3	11.21	0.9908	30-300
13	Salt + 1X	Mixer 3 min	98.2	5.69	0.9904	96.5	4.15	0.9960	0-300
			94.1	6.53	0.9941	93.6	4.73	0.9992	30-300
14	Salt + 2X	Mixer 3 min	91.2	3.34	0.9968	88.6	3.40	0.9963	0-300
			89.1	3.78	0.9980	85.9	3.94	0.9993	30-300
15	Salt + 3X	Mixer 3 min	81.7	2.75	0.9971	80.8	2.58	0.9979	0-300
			80.2	3.06	0.9976	79.1	2.91	0.9993	30-300
16	Water	Mixer 3 min	74.5	11.9	0.9615	79.3	10.5	0.9570	0-300
			67.7	13.3	0.9872	71.3	12.1	0.9904	30-300
17	Salt	Mixer 3 min	111.5	10.80	0.9806	113.4	6.51	0.9948	0-300
			104.6	12.22	0.9886	109.6	7.28	0.9992	30-300
18	Rad Salt	Mixer 3 min	112.4	10.14	0.9827	114.4	6.26	0.9951	0-300
			105.8	11.51	0.9904	110.5	7.04	0.9991	30-300
19	Rad Salt + 1X	Mixer 3 min	101.3	5.11	0.9946	100.4	4.47	0.9945	0-300
			98.1	5.76	0.9967	96.8	5.20	0.9985	30-300
20	Salt	Mixer 10 min	104.6	7.46	0.9939	102.8	6.83	0.9934	0-300
			101.1	8.17	0.9969	98.8	7.65	0.9993	30-300
21	Salt + 1X	Mixer 10 min	96.7	4.96	0.9973	95.4	5.07	0.9941	0-300
			94.9	5.34	0.9983	91.8	5.80	0.9988	30-300

Figure 3-1 shows the down curves for both the mixer and hand mixes, and visually there is more scatter with the hand mixes as compared to the mixer mixes. The down curve results of the simulated salts solution grouts (mixes 1 through 10) were further analyzed to determine the uncertainty in the reported rheological parameters. Appendix B provides the errors and uncertainty in fitting the down curves for both mixer and hand mixing grouts for the Bingham Plastic parameters. Appendix C is the statistical analysis of these data. The largest uncertainties were associated with sample to sample variability. The average and percent standard deviation of the averaged values for the different mixing methods are provided in Table 3-3. The results in this table also show that the two different types of mixing methods used resulted in about the same yield stress for the same range of data fitted, but the plastic viscosity for the hand mixes were larger than that of the mixer mixes. The difference in applied shear rate had little effect on the calculated yield stress. For single point data, the maximum standard deviation stated in Table 3-3 for the mixer results will be used, for the 30 to 300 sec^{-1} data.

Table 3-3. Average and Percent Standard Deviation For Down Curve Bingham Plastic Parameters

Type of Mixing	Shear rate range (1/s)	Yield Stress		Plastic Viscosity (cP)	
		Average (Pa)	% STD-Dev	Average (cP)	% STD-Dev
Mixer	0 - 300	6.79	1.0	105.6	2.6
	30 - 300	7.60	**1.1**	101.6	**2.6**
Hand	0 - 300	6.87	4.0	120.9	3.7
	30 - 300	7.65	3.7	117.0	3.9



Mixer	Hand

Figure 3-1. Down Curves for the Simulant Salt Grouts For Mixer and Hand

Table 3-4 is a summary of the rheological data that are used in section 3.2. For the salt grouts, the two rheological parameters are essentially the same, given the uncertainty ($\pm$ 4% of the value) in these calculated values, hence no differences in these properties due to the extended mixing time. When 1X Daratard 17 was added to the salt grout, there was no significant difference in the plastic viscosity, but this was not the case for the Bingham Plastic yield stress. SRNL does not have a technical reason why this is occurring. The density of the premix was calculated to be 2.643 g/cm^3 and was used to determine the grout density.

Table 3-4. Summarized Grout Physical Properties

Grout	W/P ratio	Supernate		Grout		
		Density (g/ml)	Fraction of solids	Density (g/ml)	Plastic Viscosity (cP)	Yield Stress (Pa)
Clean Cap	0.600	1.000	0.00	1.635	64.8	11.55
Salt	0.590	1.234	0.2733	1.748	101.6	7.60
Salt + 1X	0.590	1.234	0.2733	1.748	93.6	4.73
Salt + 2X	0.590	1.234	0.2733	1.748	85.9	3.94
Salt + 3X	0.590	1.234	0.2733	1.748	79.1	2.91
Rad Salt	0.590	1.239	0.2877	1.746	110.5	7.04
Rad Salt + 1X	0.590	1.239	0.2877	1.746	96.8	5.20
Salt + 10 Min	0.590	1.234	0.2733	1.748	98.8	7.65
Salt + 1X + 10 Min	0.590	1.234	0.2733	1.748	91.8	5.80

3.2 Steady State Data

The steady state pressure and fluid horsepower (WHP) are provided in Table 3-5. The fluid flow rate for the clean cap and salt solutions was determined using the average premix flow rate at steady state conditions for the clean cap run (7/5/2013) and salt run (12/5/2013), respectively. The piping length used in this calculation was 2583.5 feet. The condition flow for each grout is in the laminar region as shown in the system curves shown in Appendix D. In all cases, the salt grout without any Daratard 17 resulted in a higher pressure drop and more WHP than the clean cap run. The 1X addition of Daratard 17 to the salt grout reduced the pressure drop below that of the clean cap, but the WHP was essentially equivalent. Daratard 17 addition greater than 1X resulted in reduction of both the pressure drop and WHP as compared to the clean cap.

Table 3-5. Steady State Pressure Drop and Water Horsepower Requirements

Grout	Fluid Flow rate (GPM)	Reynolds Number	Hedstrom Number	Pressure Drop (psi)	WHP (HP)
Clean Cap	129.1	3356	27300	154.9	11.7
Salt	136.6	2422	7820	169.7	13.5
Salt + 1X	136.6	2628	5721	138.7	11.0
Salt + 2X	136.6	2864	5663	124.2	9.9
Salt + 3X	136.6	3109	4935	108.9	8.7
Rad Salt	138.1	2248	6110	176.4	14.2
Rad Salt + 1X	138.1	2566	2946	147.0	11.8
Salt + 10 Min	136.7	2683	8318	167.0	13.3
Salt + 1X + 10 Min	136.7	2683	7312	145.1	11.6

3.3 PI ProcessBook Data

The PI and calculated variables as defined in section 2.4.2 for the clean cap run during July 5, 2013 are presented in Table 3-6. The data are summarized:

- Volumetric feed rates for the clean cap water, screw feeder flow, and grout hopper volume are fairly constant, within the extremes being within $\pm$ 2.5% of the average values. The percent standard deviation for these variables are within 0.8% of their averages.

- The average calc grout density using the clean cap water and screw feeder feed rates is close to that calculated grout SpG in PI. The measured grout SpG in PI is higher than the calculated densities.
- The parameters that were highly variable were the xfer pressure, pump amperage, pump speed (and corresponding grout flow rate), and all horsepower calculations.
- The calculated W/P ratio was 0.59 compared to a target of 0.60 for the lab sample.
- The steady state pressure drop for the lab sample (155 psi, Table 3-5) is much higher than the average xfer pressure drop measured (112 psi). Lab grout samples were made using DI water. The applied shear rate and shear stress in the laboratory setting are lower than that in the field, given all else is equal (composition of the grout). As evident in Section 3.1, the agitator mixed grouts were rheologically thinner than the hand mixed grout, clearly showing the effect of the applied shear rate and shear stress on rheology. Such behavior to shear rate and shear stress was also noted by Langton.[19] The addition of water flushes in the actual SPF process also affects this comparison and its impact is unknown.

Table 3-6. PI and Calculated Variables For Clean Cap Grout Run on 7/5/2013

PI Data								
Parameter	Unit	Average	Stdev	% STD	Max	Min	% Max	% Min
grout flow rate	GPM	133.70	2.78	2.1	140.66	126.74	5.2	-5.2
clean cap water	GPM	77.79	0.64	0.8	79.72	75.77	2.5	-2.6
screw feeder flow	TPH	33.03	0.15	0.5	33.72	32.50	2.1	-1.6
xfer pressure	Psig	112.03	4.67	4.2	122.69	99.77	9.5	-10.9
pump speed	RPM	12.15	0.34	2.8	12.98	11.24	6.9	-7.4
grout SpG	Measured	1.720	0.007	0.4	1.729	1.702	0.5	-1.1
grout SpG	calculated	1.643	0.018	1.1	1.689	1.606	2.8	-2.3
pump	Voltage	326.8	6.4	2.0	342.9	309.0	4.9	-5.4
pump	Amps	30.2	4.1	13.6	40.0	22.8	32.7	-24.6
Grout hopper	Gallons	300.0	1.7	0.6	304.2	293.4	1.4	-2.2
Calculated Values								
Parameter	Unit	Average	Stdev	% STD	Max	Min	% Max	% Min
Total liquid flow rate	GPM	77.79	0.64	0.8	79.72	75.77	2.5	-2.6
Liquid Density	g/ml	1.000	0.000	0.0	1.000	1.000	0.0	0.0
mass frac soluble solids in liquid	g-sol/g-fl	0.000	0.000	-	0.000	0.000	-	-
Premix flow rate	GPM	49.93	0.23	0.5	50.97	49.14	2.1	-1.6
Calc grout flow	GPM	127.71	0.68	0.5	129.61	125.59	1.5	-1.7
Grout flow from pump speed	GPM	128.25	3.60	2.8	137.05	118.71	6.9	-7.4
Calc grout density	g/ml	1.642	0.004	0.2	1.656	1.631	0.8	-0.7
W/P ratio	g-H_20/g-P/M	0.589	0.006	0.9	0.606	0.570	2.8	-3.3
PI WHP	HP	8.73	0.52	5.9	10.02	7.44	14.7	-14.8
Calculated WHP	HP	8.35	0.35	4.2	9.24	7.41	10.7	-11.3
Motor EHP	HP	18.06	2.56	14.2	25.11	12.95	39.0	-28.3

Plotting of the grout hopper volume and grout flow from pump speed (volumetric flow rate), Figure 3-2, shows the pump speed lags the grout hopper volume and is consistent with how the speed of the pump is controlled, via the instantaneous change in grout hopper volume (or level).[18] This figure shows the grout flow rate and grout flow from pump speed are much more erratic than the feed used to make up the grout (clean cap water and screw feeder flow).

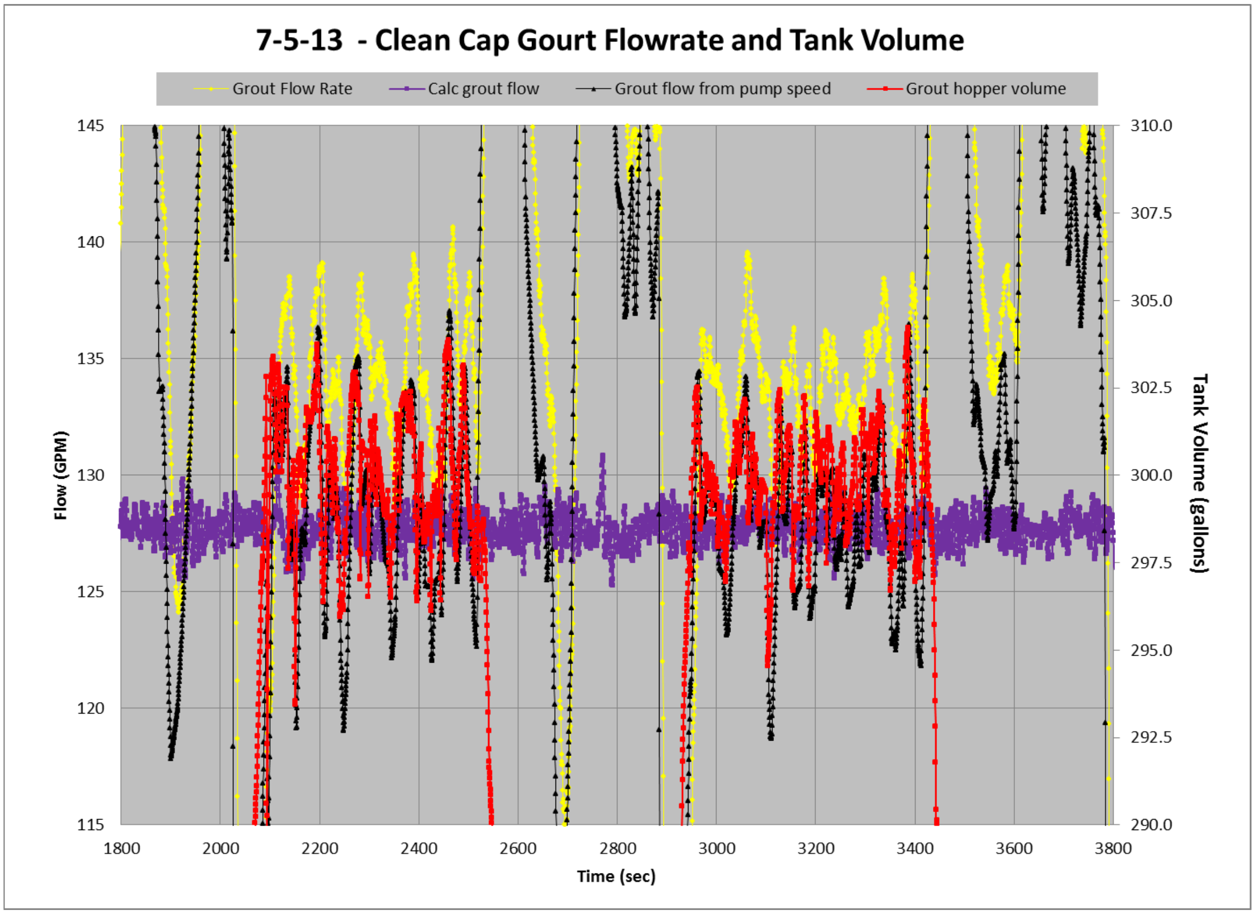


Figure 3-2. Clean Cap Grout Flow Rates and Tank Volume (7/5/2013)

Figure 3-3 is the calculated motor and PI WHP horsepower. The behavior of the two curves shows a good agreement with each other, with respect to change. For instance, when the PI WHP horsepower increases, so does the motor horsepower. The change in the motor horsepower is much greater in magnitude than that of the PI WHP horsepower. This indicates there are other inefficiencies or inertia effects that are being captured by the pump motor. The large increase in horsepower observed in this figure is due to the flushing activities, increasing HP demand by a factor of three as compared to the steady state values as observed in the peaks and valleys. The average PI WHP horsepower was 8.73 HP as compared to 18.06 HP for the average motor horsepower, indicating that 51.6% of the motor horsepower is to overcome losses other than hydraulic transfer.

It must be noted that the steady state conditions are those regions between the peaks and valleys, and given the time in these regions is approximately 400 seconds (6.5 minutes) and given the flushing activities, a steady condition in the transfer line most likely was never achieved. For a flow rate of 130 gpm, it takes approximately 8 minutes for a slug of material to travel the length of the transfer line.

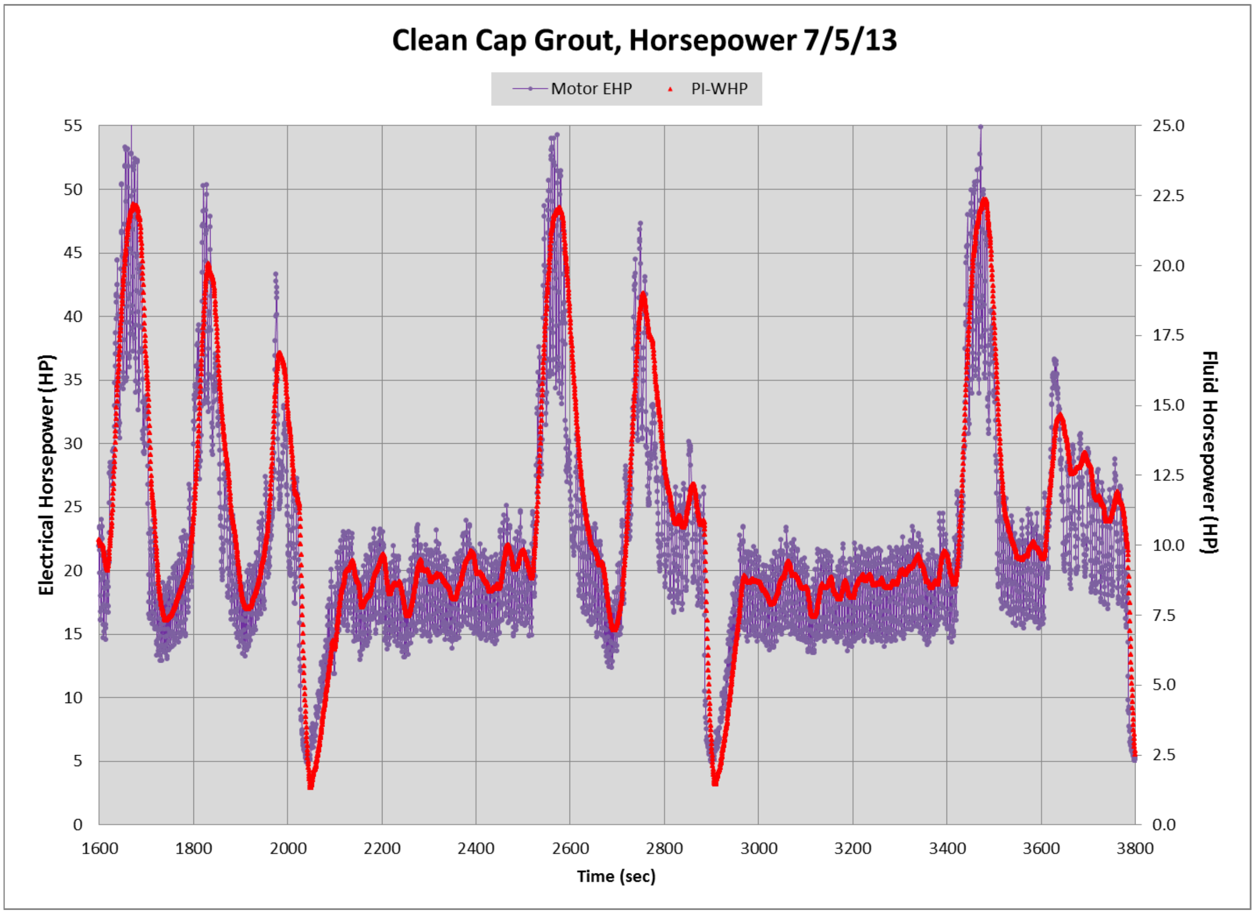


Figure 3-3. Clean Cap Grout Run Horsepower (7/5/2013)

The PI and calculated variables for the salt run during December 5, 2013 are presented in Table 3-7. The data are summarized:

- Volumetric feed rates for the salt solution, screw feeder flow, and grout hopper volume are fairly constant, within $\pm$ 2.2% of the average values.
- The grout flow rate and grout flow from pump speed volumetric flow rates are similar to each other but higher than the calc grout flow rate. The calc grout flow rate is the addition of the salt solution and screw feeder flow rates.
- The average calc grout density using the salt solution and screw feeder flow rates is close to the measured grout SpG. The calculated grout SpG is low and is comparable to the clean cap grout density. Calculated values should be close to each other.
- The parameters that were highly variable were the xfer pressure, pump amperage, pump speed (and corresponding grout flow from pump speed), and all horsepower calculations.
- The calculated W/P ratio was 0.589, comparable to that of the lab sample of 0.59.
- The calculated pressure drop for the lab samples (170 and 176 psi, section 3.2) is higher than the average xfer pressure drop measured in the field (156 psi). The applied shear rate and stress in the laboratory are lower than that in the field, given all else is equal (composition).

Table 3-7. PI and Calculated Variables For Salt Grout Run on 12/5/2013

PI Data								
Parameter	Unit	Average	Stdev	% STD	Max	Min	% Max	% Min
grout flow rate	GPM	146.74	2.56	1.75	153.66	139.37	4.7	-5.0
salt solution	GPM	88.07	0.53	0.60	89.61	86.20	1.8	-2.1
screw feeder flow	TPH	33.02	0.17	0.52	33.62	32.30	1.8	-2.2
xfer pressure	psig	155.51	3.93	2.53	164.14	145.00	5.6	-6.8
pump speed	RPM	13.74	0.31	2.26	14.51	12.75	5.6	-7.2
grout SpG	measured	1.781	0.012	0.67	1.803	1.759	1.3	-1.2
grout SpG	calculated	1.616	0.016	1.01	1.661	1.583	2.8	-2.1
Pump	voltage	367.2	6.9	1.88	384.0	347.9	4.6	-5.3
Pump	Amps	39.1	6.1	15.52	50.7	28.7	29.7	-26.6
Grout hopper	gallons	300.1	1.4	0.48	303.6	294.2	1.2	-2.0
Calculated Values								
Parameter	Unit	Average	Stdev	% STD	Max	Min	% Max	% Min
Total liquid flow rate	GPM	88.07	0.53	0.60	89.61	86.20	1.8	-2.1
Liquid Density	g/ml	1.238	0.000	0.00	1.239	1.239	0.0	0.0
mass frac soluble solids in liquid	g-sol/g-fl	0.288	0.000	0.00	0.288	0.288	0.0	0.0
Premix flow rate	GPM	49.92	0.26	0.52	50.82	48.83	1.8	-2.2
Calc grout flow	GPM	137.99	0.61	0.44	139.88	135.60	1.4	-1.7
Grout flow from pump speed	GPM	145.12	3.28	2.26	153.20	134.64	5.6	-7.2
Calc grout density	g/ml	1.747	0.002	0.14	1.756	1.737	0.5	-0.6
W/P ratio	g-H_20/g-P/M	0.589	0.005	0.77	0.607	0.573	3.0	-2.7
PI WHP	HP	13.29	0.49	3.70	14.69	12.04	10.5	-9.4
Calculated WHP	HP	12.52	0.33	2.62	13.28	11.62	6.1	-7.2
Motor EHP	HP	26.30	4.16	15.81	35.12	18.46	33.5	-29.8

Plotting of the grout hopper volume and grout flow rates, Figure 3-4, is to show the fluctuating functionality of the grout flow rate, grout flow from pump speed, and grout hopper volume as compared to the calc grout flow rate using the salt solution and screw feeder flow rates. This is consistent with the observations in the clean cap run. The grout hopper volume also became more erratic towards the latter half of the time frame.

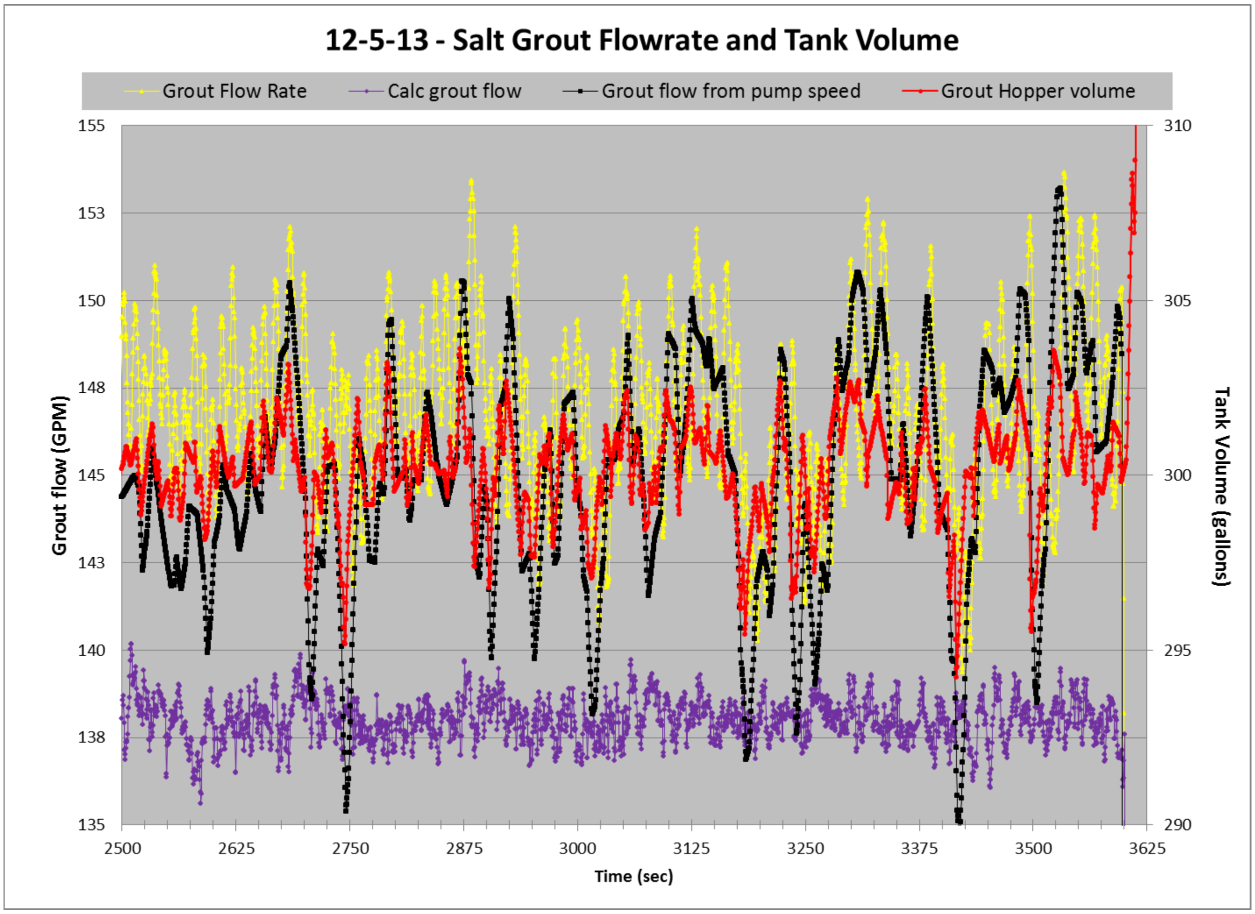


Figure 3-4. Salt Grout Flow Rates and Tank Volume (12/5/2013)

Figure 3-5 is the calculated motor and PI WHP horsepower. The behavior of the curves shows good agreement between the two, with respect to change, both the electrical and fluid horsepower are slightly increasing overtime. This seems to indicate that a steady state condition has yet to be reached, but it may be forthcoming, given that no flushing activities occurred during this time frame (18 minutes). The average PI WHP horsepower was 13.3 as compared to 26.3 for the average motor horsepower, indicating that 49.5% of the motor horsepower is to overcome losses other than hydraulic.

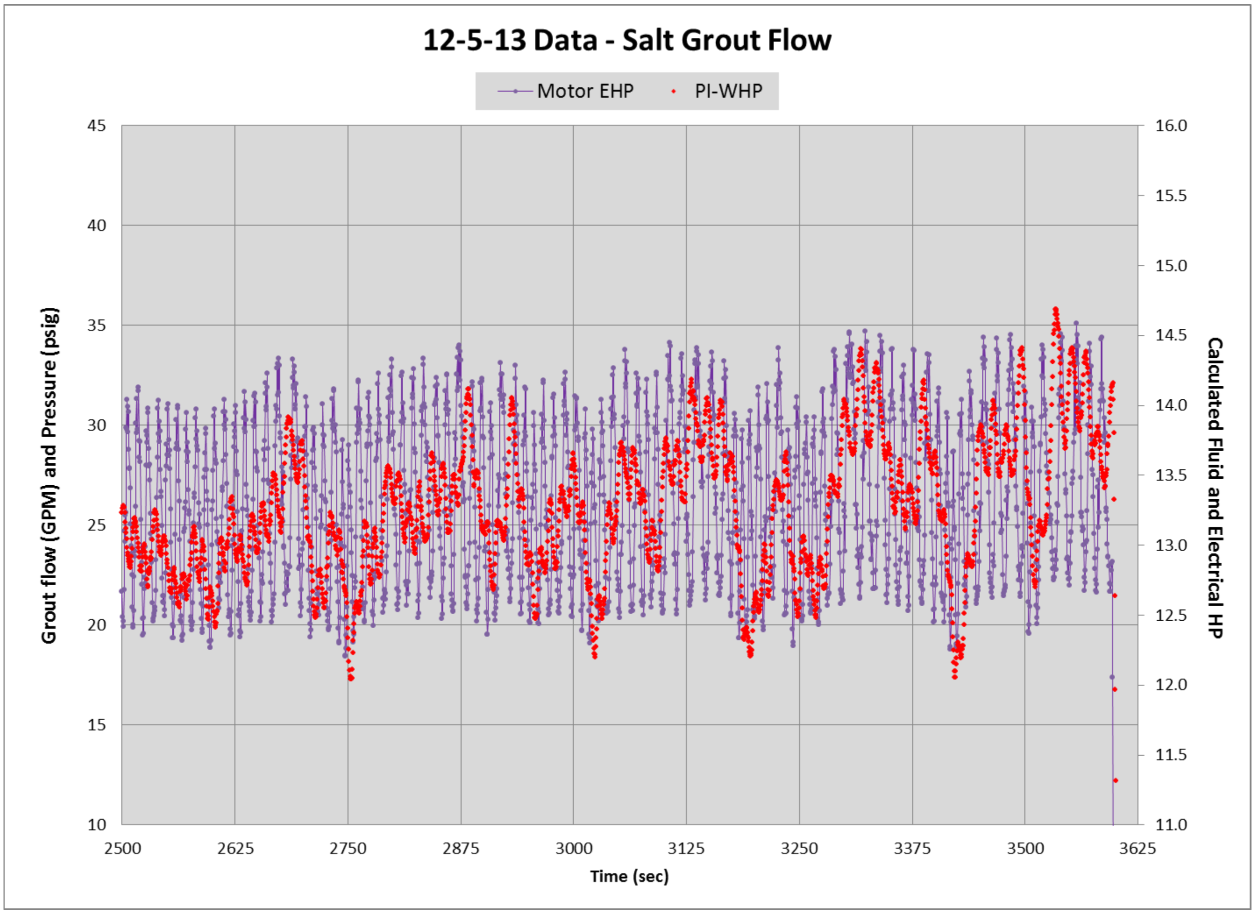


Figure 3-5. Salt Grout Run Horsepower (12/5/2013)

A comparison of the clean cap and salt grout runs is summarized:

- The logic used to control the hose pump speed should be reviewed. The immediate response in pump speed (rpm) is directly tied to the fluctuating behavior of the grout tank volume (or leve). A more averaged value could be used over a given time frame to control the speed of the hose pump and reduce these fluctuations.
- Given the extremes of the feed vectors coming into the grout hopper are within ± 2.5 % of the average, setting the pump speed could be a possible solution. This would be an input variable to the Distributed Control System.
  - This would have been excellent for the clean cap grout run.
  - A higher pump speed would be required for the salt grout. A technical reason for this could be that the pump hose does not pull in the same aliquot of volume as the pump speed increases or the grout is recirculating.
  - Setting the pump speed would reduce the erratic pump behavior, since the pump will be operating at a specific speed and the large pressure swings would be reduced.
- The December 5, 2013 run does not take into consideration the additional flow rate increase that would be observed during flush water addition. Given the large increase in pump power during the flush water addition for the clean cap run, this increase in HP must be considered. The electrical HP must take into consideration the hydraulic losses, inertia changes, and other losses such as mechanical and electrical losses associated with the pump/motor and these variables are a function of pump speed. Recommendations include but are not limited to:

- Decreasing the grout flow rate.
- Increase the horsepower of the motor to compensate for the increase in horsepower required. Such a recommendation was provided in Reference 16, but the increase in horsepower from water additions may not have been considered.

- As the pump speed increases, there is power draw in addition to the increase in hydraulic losses. This was observed in both the 7/5/2013 and 12/5/2013 data. Inspection of the figure in Table 2-8, given the continuous duty HP line of 33 HP and discharge pressure lines, as the flow rate increases, the power demand from other than hydraulic losses increases with pump speed.
- The measured grout SpG density is high compared to the calc grout density. The calculated SpG density compares well to the SRNL calculated density for the clean cap run but is low for the salt run. The algorithm for calculating the SpG density was not reviewed.

As previously discussed above, the pressure drop measured by PI includes both the frictional and inertia effects of the fluid. In this document, the fluid horsepower is calculated given the measured flow and pressure. The calculations do not take into consideration how to separate the inertia effects in the pressure measurement and to determine the power from the frictional and inertia effects. Such efforts would be time consuming, given the erratic behavior of the system, unknown physical properties of the actual grout and literature to support such efforts.

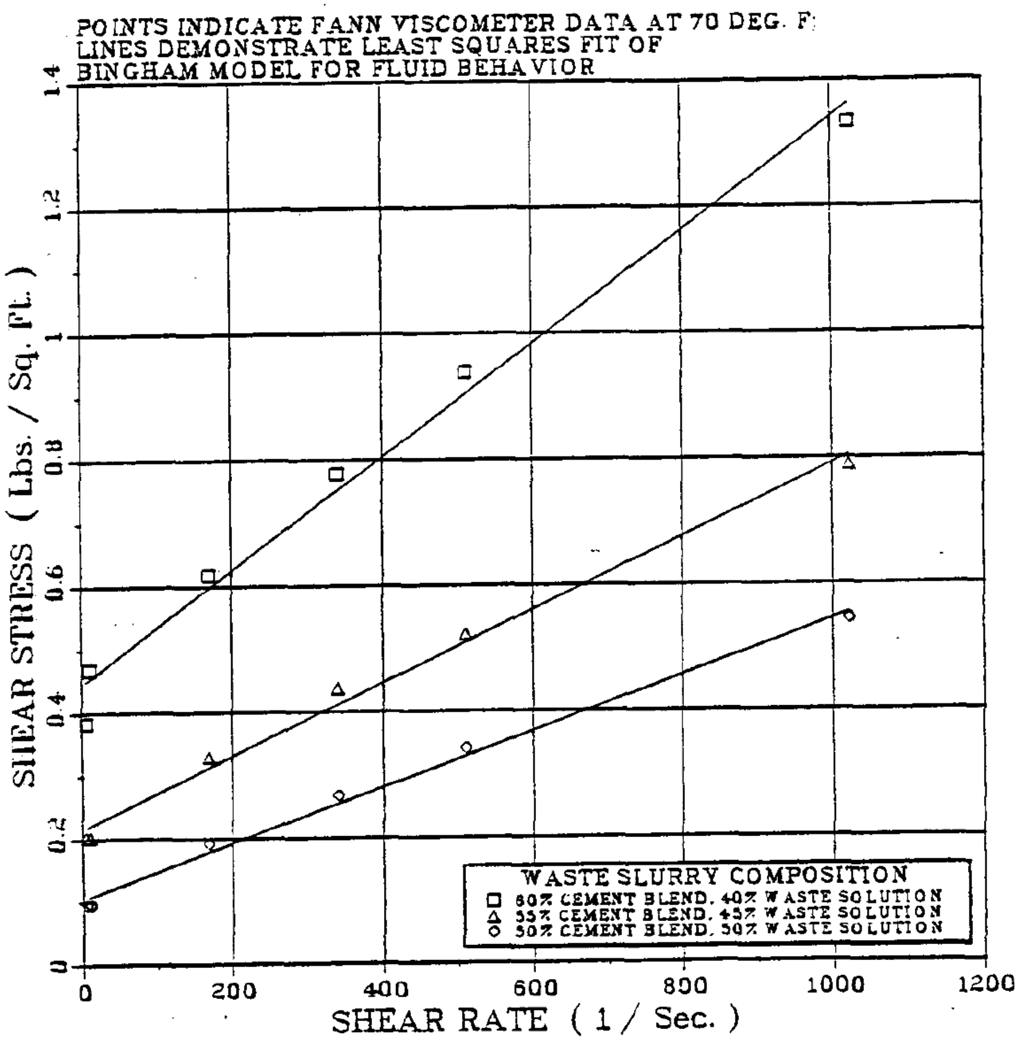
3.4 Physical Properties Basis For Design Calculations

Review of grout reports from the design stages of the Saltstone Facility indicates that Reference 20 is the basis for the density and rheological data that have been used to size the grout pumps and grout mixing systems at SDU. Table 3-8 is a summary of the simulant used, methods used to characterize the property of interest, and the values of the properties. The flow curve figure in Table 3-8 was fitted to a Bingham Plastic model, but no information on the Bingham Plastic yield stress or plastic viscosity was provided in this document. SRNL used two data points from the upper curve to determine these values: one being at the origin and having a shear stress of 0.45 lb_f/ft^2 and the other at the shear rate of 400 1/sec with a corresponding approximate shear stress of 0.805 lb_f/ft^2. Converting the shear stress to Pa and fitting these two points yield a ***Bingham Plastic yield stress of 21.54 Pa*** and plastic viscosity of ***42.5 cP***. The specific gravity reported in this reference was 1.82, essentially the same value used in the original pump calculations. The composition of the premix used in this report is different than the present premix composition. There was no information provided about the salt solution composition.

Comparing the grouts made in this task to the design basis values show that all the grout densities and yield stresses are bounded by the design basis. The opposite is true for the plastic viscosity. Steady state calculations using a density of 1.8 g/ml, plastic viscosity of 42.5 cP, and Bingham Plastic yield stress and 2583.5 feet of piping resulted in pressure drop of 210 and 213 psi for flow rates of 129.0 (for clean cap) and 136.6 (for salt grout) GPM respectively. These pressure drops bound those of the grouts characterized in this report.

Table 3-8. Information from DPST-85-312

Variable	Description
Simulated Waste Solution	Provided by Savannah River Laboratory. No specifics of the simulated waste solution provided, such as density and mass fraction of solids.
Premix	Provided by Savannah River Laboratory. 80 % fly ash and 20 % cement.
Mixer	Waring Blender. No specifics provided on the use of this blender.
Grout Blend	60% cement blend and 40% simulated waste solution. Two other blends are reported, with a higher mass fraction of simulant solution being used.
Grout Density	***Specific gravity = 1.82***. This value was calculated from the measured specific gravities of dry blend and simulated waste solution. See Table 1.1 of the report.
Viscometer	Fann Model 35 (6 speed). No specifics provided on geometry. SRNL has not obtained information about the Fann Model 35 and its operation.
Rheological Data	Sample from Waring blender was transferred directly to viscometer sample cup and analyzed. Data was obtained at 70 ^{o}F. Raw data for 60/40 sample (page 7) of report indicate shear stress data obtained from down curve measurement. Figure 1.4 show the flow curves and is provided below and the rheological data were obtained from the top curve.



WASTE GROUT RHEOLOGIES

4.0 Conclusions

The physical properties of lab prepared DI and salt grout were obtained at 0.60 and 0.59 W/P ratios, respectively. This data is located in Table 3-4. The yield stress of the DI grout was greater than any salt grout. The plastic viscosity of the DI grout was lower than all of the salt grouts (including salt grout with admixture). When this physical data was used to determine the pressure drop and fluid horsepower for steady state conditions, the salt grouts without admixture addition required a higher pressure drop and fluid horsepower to transport. When 0.00076 g Daratard 17/g premix was added, both the pressure drop and fluid horsepower were below that of the DI grout. Higher concentrations of Daratard 17 further reduced the pressure drop and fluid horsepower. The uncertainty in the single point Bingham Plastic parameters is $\pm$ 4% of the reported values and is the bounding uncertainty.

Two different mechanical agitator mixing protocols were followed, one having a total mixing time of three minutes and the other having 10 minutes for the simulant salt grout. The Bingham Plastic parameters were essentially the same for the salt grout without admixture. When Daratard 17 was used, the Bingham Plastic yield increased for the 10 minute mix.

The simulant salt used in this task had similar physical properties of the Tank 50 3Q13 salt grout and is recommend for future use, if the salt solution in Tank 50 does not change.

The design basis physical properties used to size the pumps and mixers at SPF were obtained from DPST-85-312. The grouts characterized in this report are bounded by the design basis density and Bingham Plastic yield stress. The opposite is true for the plastic viscosity. Steady state pressure drop calculations were performed for the design basis values using the flow rate for the clean cap and salt grouts and they bound the pressure drop of the grouts characterized in this report.

A comparison of the lab prepared samples to PI ProcessBook data, specifically average pressure drop, indicate that the lab prepared samples are more viscous in nature than what is processed in the facility This difference could be due to the applied shear rates are lower in the lab as compared to the facility and that fact the SPF adds flush water, making this comparison more difficult.

A perfunctory review of the PI ProcessBook data used in Section 3.2 was discussed in Section 3.3. It may be possible that the frequency that the distributed control system alters the grout pump speed to maintain grout hopper volume can negatively affect the efficiency of the grout pump.

5.0 References

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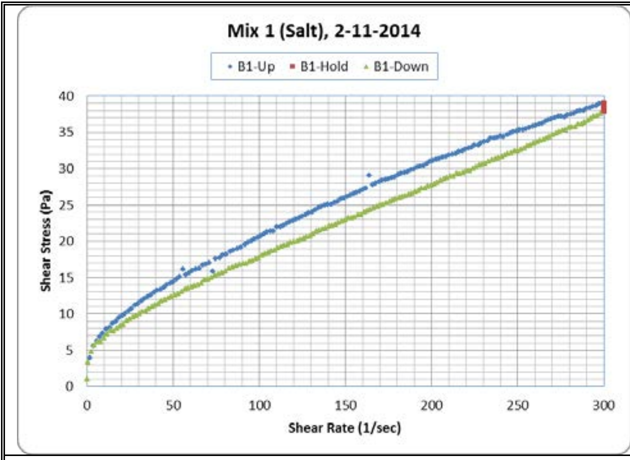
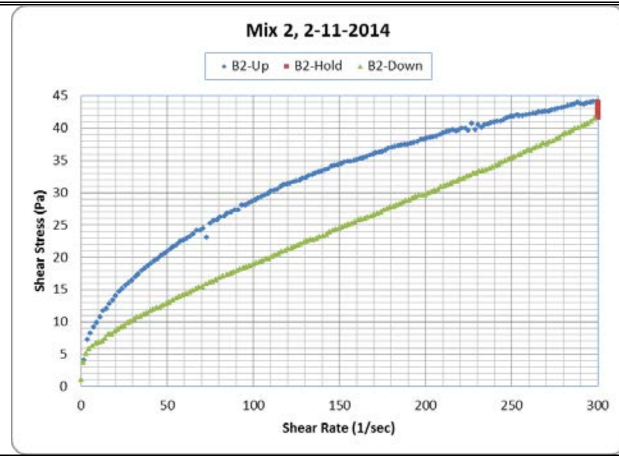
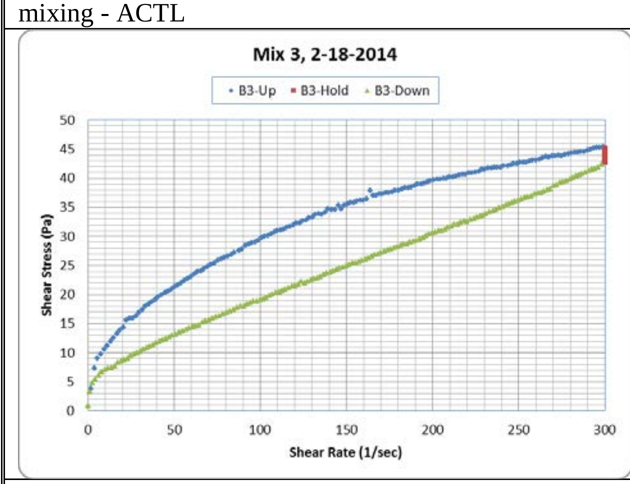
Appendix A. Up and Down Flow Curve Results



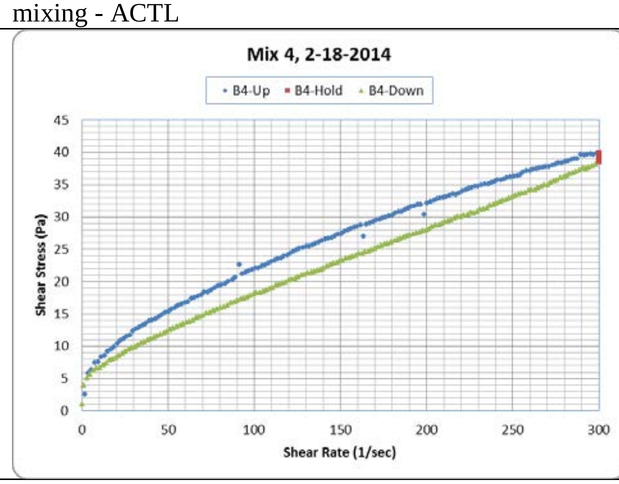
Mix 1 – Simulant Salt Solution – Mechanical – 3 min. mixing - ACTL



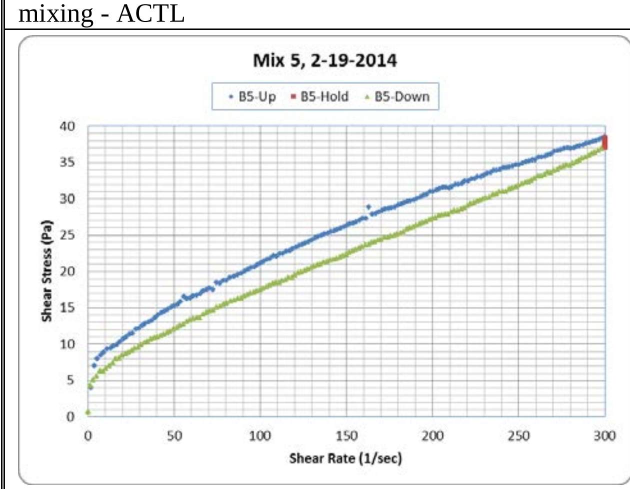
Mix 2 – Simulant Salt Solution – Spatula – 3 min. mixing - ACTL



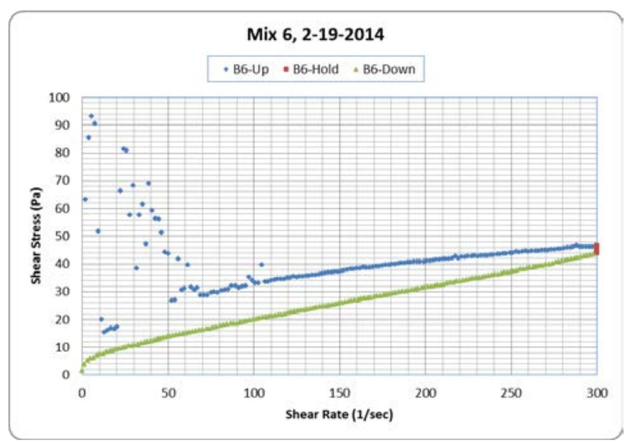
Mix 3 – Simulant Salt Solution – Spatula – 3 min. mixing - ACTL



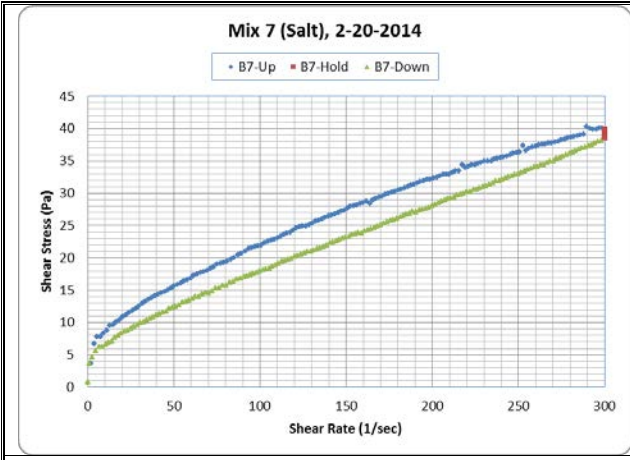
Mix 4 – Simulant Salt Solution – Mechanical – 3 min. mixing - ACTL



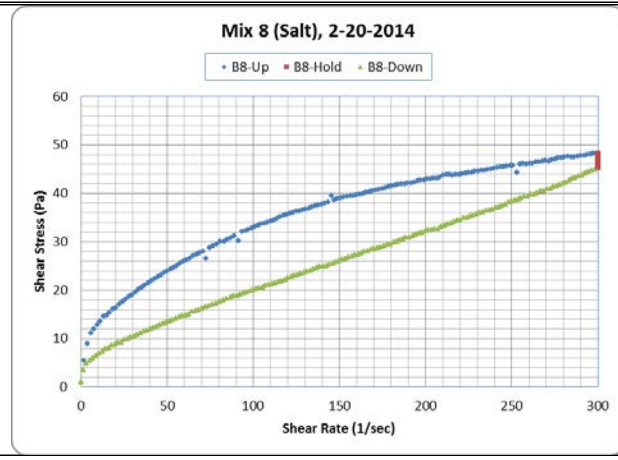
Mix 5 – Simulant Salt Solution – Mechanical – 3 min. mixing - ACTL



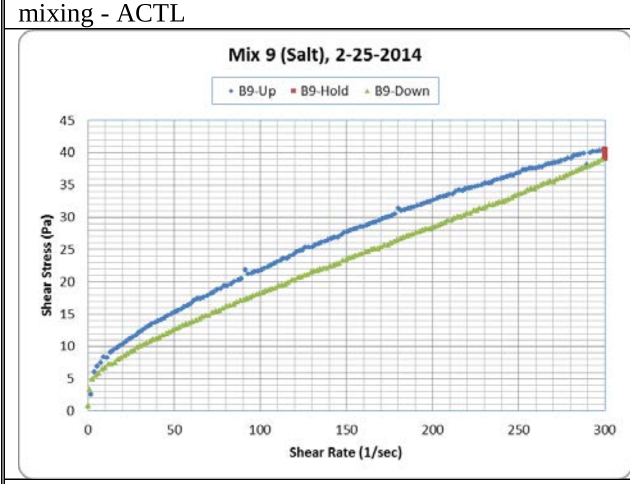
Mix 6 – Simulant Salt Solution – Spatula – 3 min. mixing - ACTL



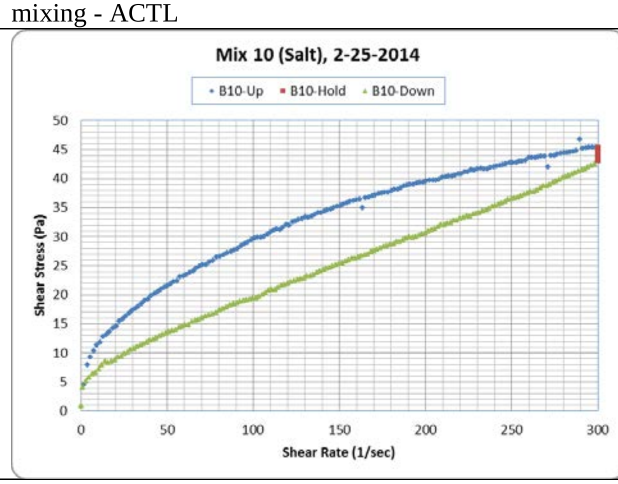
Mix 7 – Simulant Salt Solution – Mechanical – 3 min. mixing - ACTL



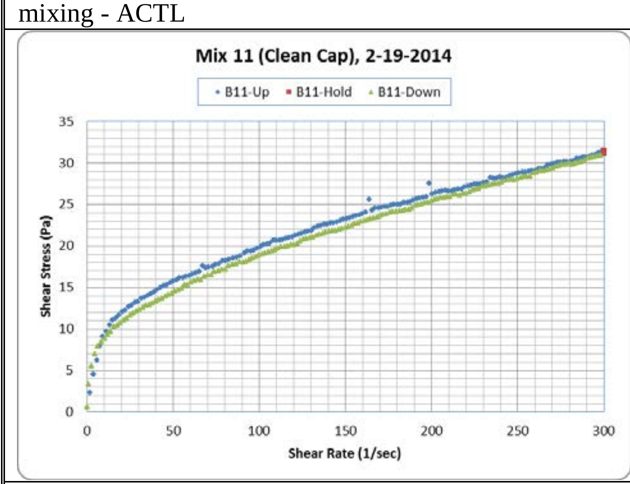
Mix 8 – Simulant Salt Solution – Spatula – 3 min. mixing - ACTL



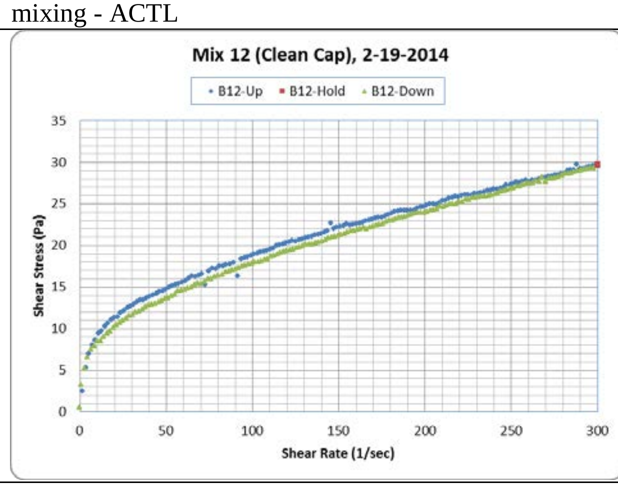
Mix 9 – Simulant Salt Solution – Mechanical – 3 min. mixing - ACTL



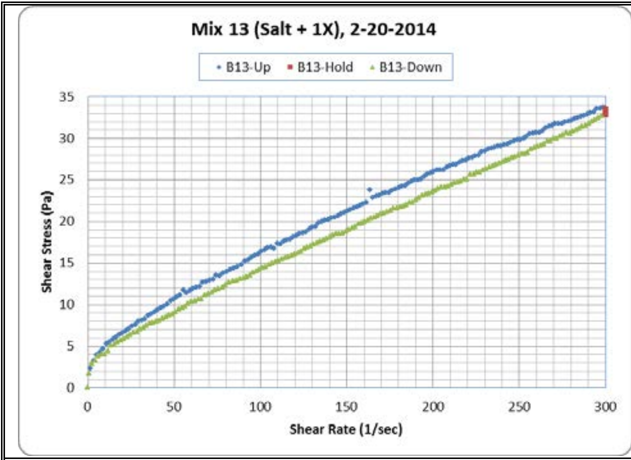
Mix 10 – Simulant Salt Solution – Spatula – 3 min. mixing - ACTL



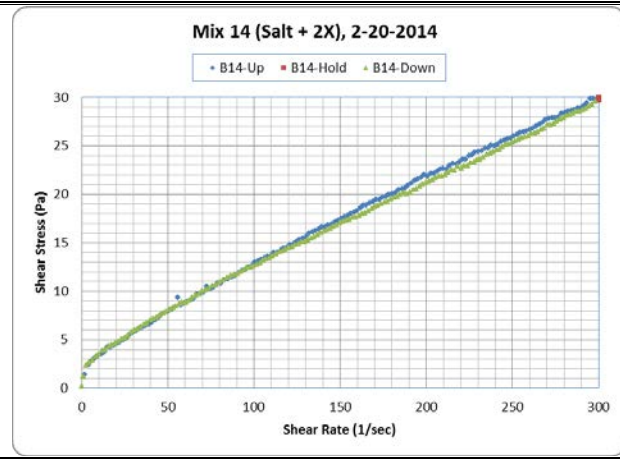
Mix 11 – DI Water – Mechanical – 3 min. mixing - ACTL



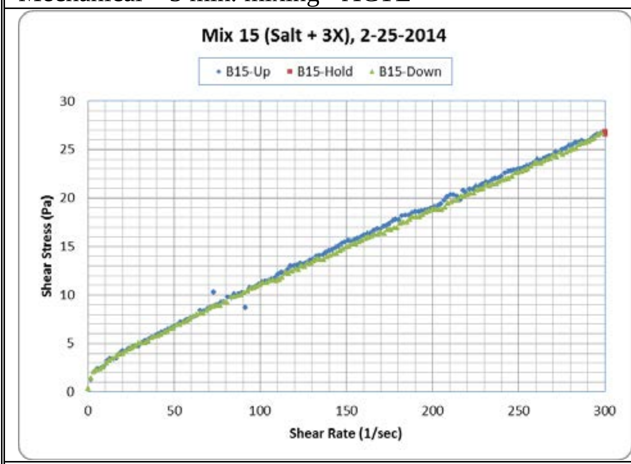
Mix 12 – DI Water – Spatula – 3 min. mixing - ACTL



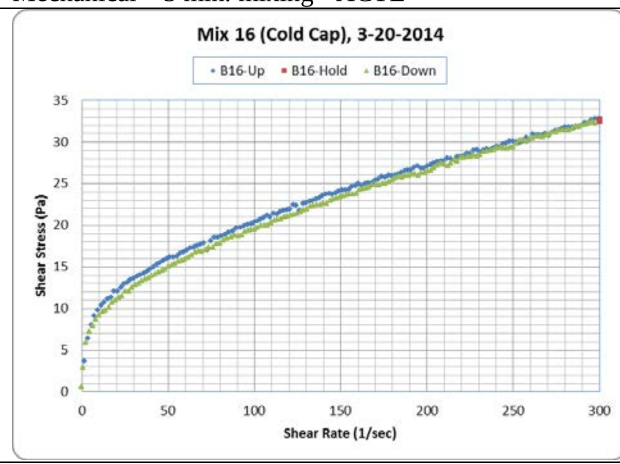
Mix 13 – Simulant Salt Solution + 1X Daratard 17 – Mechanical – 3 min. mixing - ACTL



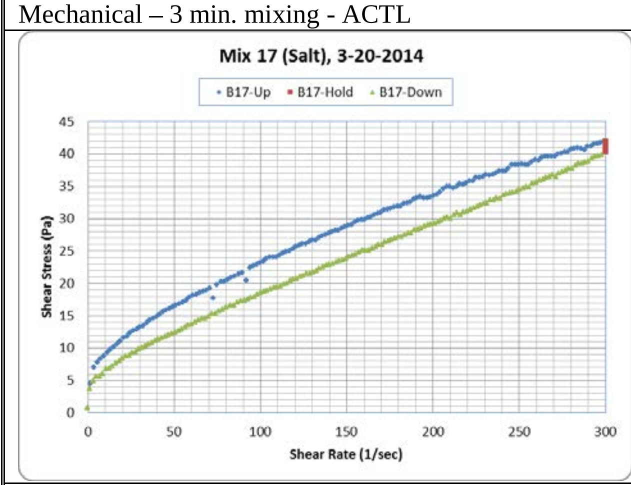
Mix 14 – Simulant Salt Solution + 2X Daratard 17 – Mechanical – 3 min. mixing - ACTL



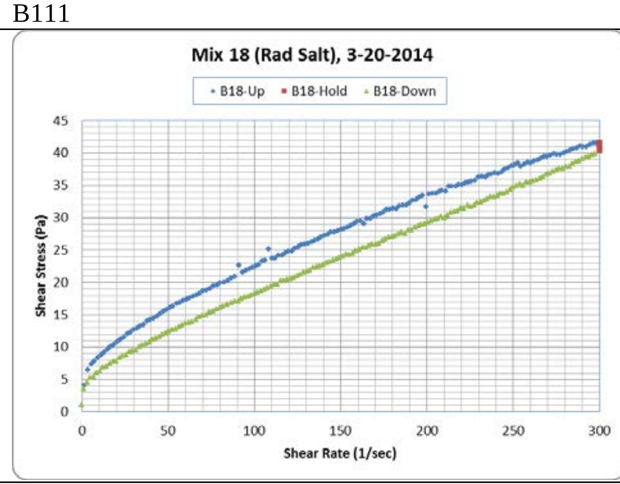
Mix 15 – Simulant Salt Solution + 3X Daratard 17 – Mechanical – 3 min. mixing - ACTL



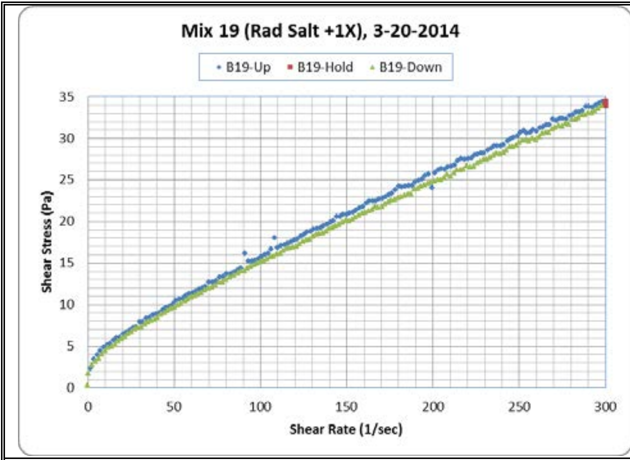
Mix 16 – Clean Cap – Mechanical – 3 min. mixing - B111



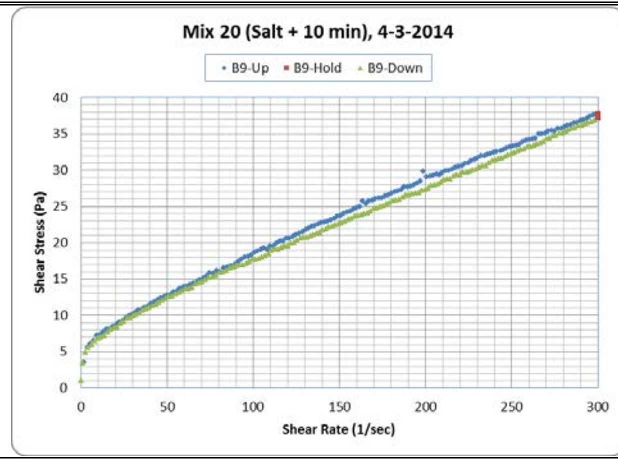
Mix 17 – Simulant Salt Solution – Mechanical – 3 min. mixing - B111



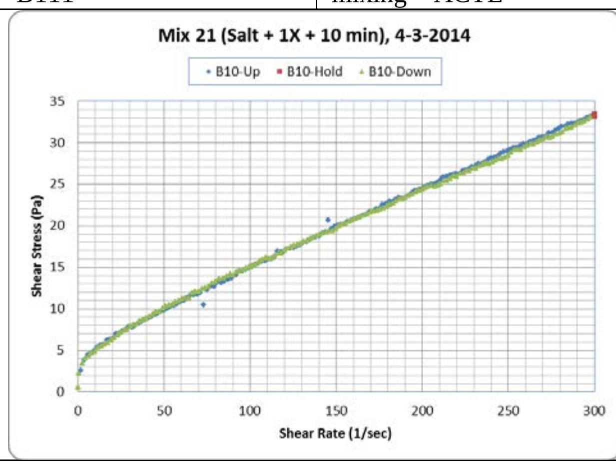
Mix 18 – Radioactive Salt Solution – Mechanical – 3 min. mixing - B111



Mix 19 – Radioactive Salt Solution + 1X Daratard 17 – Mechanical – 3 min. mixing - B111



Mix 20 – Simulant Salt Solution – Mechanical – 10 min. mixing – ACTL



Mix 21 – Simulant Salt Solution + 1X Daratard 17 – Mechanical – 10 min. mixing - ACTL

Appendix B. Errors Associated with Down Curve Bingham Plastic Parameters

Mixer Data Only (0 -300)

Sample	Down Curve			
	Plastic Viscosity (cP)		Yield Stress (Pa)	
	Average	Standard Error	Average	Standard Error
B-1	104.0	1.2	6.90	0.17
B-4	106.6	1.3	6.79	0.23
B-5	101.7	1.1	6.81	0.18
B-7	106.9	1.2	6.73	0.21
B-9	108.6	1.3	6.75	0.22
AVG	105.6		6.79	
STD DEV	2.73		0.07	

Mixer Data Only (30 -300)

Sample	Down Curve			
	Plastic Viscosity (cP)		Yield Stress (Pa)	
	Average	Standard Error	Average	Standard Error
B-1	99.9	0.8	7.75	0.14
B-4	102.7	0.9	7.57	0.17
B-5	97.8	0.8	7.58	0.14
B-7	102.9	0.8	7.55	0.15
B-9	104.6	1.3	7.57	0.22
AVG	101.6		7.60	
STD DEV	2.68		0.08	

Hand Blend Only (0 - 300)

Sample	Down Curve			
	Plastic Viscosity (cP)		Yield Stress (Pa)	
	Average	Standard Error	Average	Standard Error
B-2	115.9	2.4	6.67	0.42
B-3	119.4	2.5	6.68	0.44
B-6	122.1	10.8	7.22	1.90
B-8	127.9	2.8	6.66	0.49
B-10	119.0	2.3	7.10	0.41
AVG	120.9		6.87	
STD DEV	4.50		0.27	

Hand Blend Only (30 - 300)

Sample	Down Curve			
	Plastic Viscosity (cP)		Yield Stress (Pa)	
	Average	Standard Error	Average	Standard Error
B-2	112.1	1.7	7.44	0.31
B-3	115.6	1.8	7.45	0.34
B-6	118.2	7.1	8.01	1.31
B-8	124.1	2.2	7.42	0.40
B-10	115.0	1.7	7.91	0.31
AVG	117.0		7.65	
STD DEV	4.54		0.29	

Appendix C. Statistical Analysis of the Down Curve Bingham Plastic Parameters

The results generated by the fitting process in Section 2.3.1 are provided in Table 1. The standard error (Std Error) of each of the estimated parameters is provided along with the estimate of the parameter.

Table 1. Regression Results

Label	select 0-300 / 30-300	Batch	Mixing	down	Soln	Estimate YS (Pa)	Estimate PV (Pa-s)	Std Error YS (Pa)	Std Error PV (Pa-s)
A	0-300	B#1	Mixer	down	salt	6.904	0.104	0.11834	0.00069
A	30-300	B#1	Mixer	down	salt	7.749	0.100	0.04179	0.00023
B	0-300	B#2	Hand	down	salt	6.669	0.116	0.11080	0.00064
B	30-300	B#2	Hand	down	salt	7.445	0.112	0.04151	0.00023
C	0-300	B#3	Hand	down	salt	6.682	0.119	0.11173	0.00065
C	30-300	B#3	Hand	down	salt	7.454	0.116	0.04025	0.00022
D	0-300	B#4	Mixer	down	salt	6.787	0.107	0.11089	0.00064
D	30-300	B#4	Mixer	down	salt	7.571	0.103	0.04406	0.00024
E	0-300	B#5	Mixer	down	salt	6.807	0.102	0.11181	0.00065
E	30-300	B#5	Mixer	down	salt	7.584	0.098	0.04251	0.00023
F	0-300	B#6	Hand	down	salt	7.218	0.122	0.11449	0.00066
F	30-300	B#6	Hand	down	salt	8.007	0.118	0.04338	0.00024
G	0-300	B#7	Mixer	down	salt	6.727	0.107	0.11538	0.00067
G	30-300	B#7	Mixer	down	salt	7.547	0.103	0.04352	0.00024
H	0-300	B#8	Hand	down	salt	6.662	0.128	0.11066	0.00064
H	30-300	B#8	Hand	down	salt	7.423	0.124	0.04525	0.00025
I	0-300	B#9	Mixer	down	salt	6.746	0.109	0.11574	0.00067
I	30-300	B#9	Mixer	down	salt	7.571	0.105	0.04215	0.00023
J	0-300	B#10	Hand	down	salt	7.102	0.119	0.11732	0.00068
J	30-300	B#10	Hand	down	salt	7.911	0.115	0.04393	0.00024

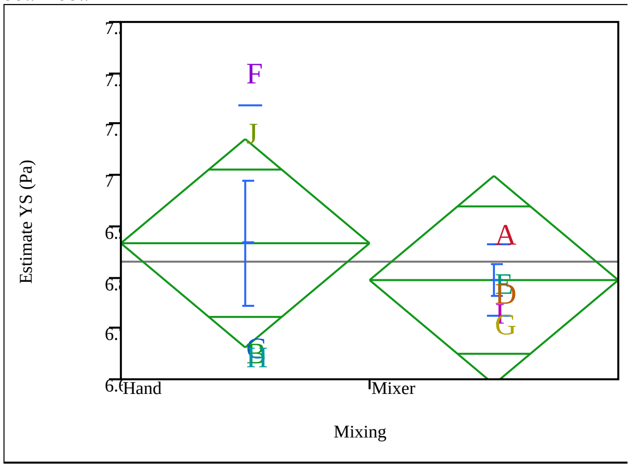
Comparisons between the results for the two mixing protocols (hand-mixing and mixing using a mixer) were of interest in this study. The comparisons to be conducted include those for the YS test results (both parameter estimates and the standard errors of the estimates) and those for the PV test results (both parameter estimates and the standard errors of the estimates). Exhibit A1 in the Appendix provides an investigation into the comparisons between the two mixing protocols for the YS values and for PV values both parameter estimates and standard errors of estimates, for results grouped by the selection of the 0 to 300 or 30 to 300 shear-stress intervals. The plotted points in this exhibit utilize the labels provided in Table 1 to represent the groupings of the test results. One of the statistical tests for each grouping of data provided in this JMP output was a test for equal variances in the results for the two mixing protocols. Several test statistics are provided for this variance test, and the Levene result is the one that is to be used to interpret the outcome of this test. If the p-Value indicated for this test is 0.05 or smaller, then there is an indication of a statistically significant difference for the data grouping between the variance of the hand-mixed test results and the variance of the mixer test results. As an example, consider the YS, 0-300, down results: the Levene p-Value is 0.0008, which is flagged with an asterisk in the exhibit to indicate that the difference in variances is statistically significant at the 5% level. From these results, it is seen that the variation in the hand-mixed results is significantly higher than the variation in the mixer test results.

In addition to the tests for equal variances, tests are conducted to investigate for statistically significant differences in the means of the two sets of results as well. There are two versions of these tests: one assuming that the variances of the two groups are equal and the other assuming that the variances or unequal. The result from the Levene test is to be used to select the appropriate test in comparing the means. For each of these tests, if the p-value of the result, labeled in the exhibit by “Prob > |t|” is 0.05 or smaller, then there is an indication of a statistically significant difference between the mean of the hand-mixed results and the mean of the mixer test results. Once again, consider the example of the YS, 0-300, down results: the appropriate t-test for equal means is the unequal variances case. For this case, the p-value is “Prob > |t|” = 0.5917, which indicates that the means of the estimated YS values for the hand-mixed tests and for the mixer tests are not statistically different at the 5% level.

Other conclusions for the 0 to 300 shear-stress groupings from Exhibit A1 are: (1) for estimated PV values, there is no indication of a difference in the variances between the hand-mixed results and the mixer test results. However, the mean estimated PV value for the hand-mixed results is statistically larger than the mean estimated PV value for the mixer test results, and (2) for the standard errors (for both the YS and PV estimates), there do not appear to be statistically significant differences between the variances nor between the means of the results for the two mixing protocols.

The conclusions for the 30 to 300 shear-stress groupings from Exhibit A1 are: (1) for estimated YS values, there is an indication of a difference between the variances for the hand-mixed results and the mixer test results. Specifically, it is seen that the variation in the hand-mixed results is significantly higher than the variation in the mixer test results. In addition, the results indicate that the means of the estimated YS values for the hand-mixed tests and for the mixer tests are not statistically different at the 5% level., (2)) for estimated PV values, there is no indication of a difference in the variances between the hand-mixed results and the mixer test results. However, the mean estimated PV value for the hand-mixed results is statistically larger than the mean estimated PV value for the mixer test results, and (3) for the standard errors (for both the YS and PV estimates), there do not appear to be statistically significant differences between the variances nor between the means of the results for the two mixing protocols.

Fit Y by X Group
Oneway Analysis of Estimate YS (Pa) By Mixing select 30-300=0-300, down=down



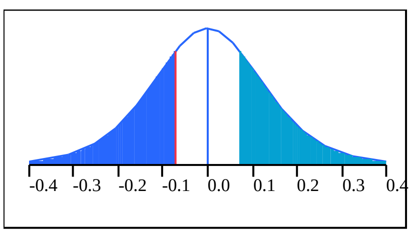
Oneway Anova
Summary of Fit

Rsquare	0.039902
Adj Rsquare	-0.08011
Root Mean Square Error	0.197968
Mean of Response	6.830385
Observations (or Sum Wgts)	10

t Test
Mixer-Hand

Assuming equal variances

Difference	-0.07220	t Ratio	-0.57661
Std Err Dif	0.12521	DF	8
Upper CL Dif	0.21653	Prob > |t|	0.5801
Lower CL Dif	-0.36092	Prob > t	0.7100
Confidence	0.95	Prob < t	0.2900



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Mixing	1	0.01303040	0.013030	0.3325	0.5801
Error	8	0.31352986	0.039191		
C. Total	9	0.32656027			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Hand	5	6.86648	0.08853	6.6623	7.0706
Mixer	5	6.79429	0.08853	6.5901	6.9984

Std Error uses a pooled estimate of error variance

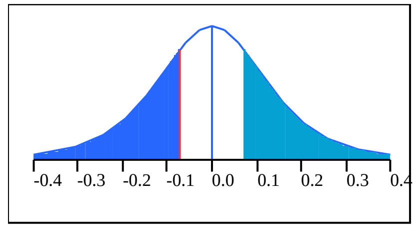
Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Hand	5	6.86648	0.271238	0.12130	6.5297	7.2033
Mixer	5	6.79429	0.069373	0.03102	6.7081	6.8804

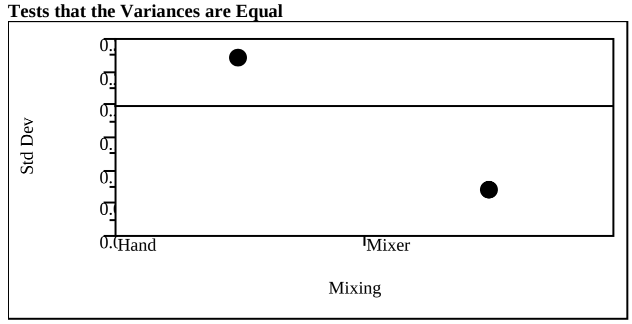
t Test
Mixer-Hand

Assuming unequal variances

Difference	-0.07220	t Ratio	-0.57661
Std Err Dif	0.12521	DF	4.521092
Upper CL Dif	0.26019	Prob > |t|	0.5917
Lower CL Dif	-0.40458	Prob > t	0.7041
Confidence	0.95	Prob < t	0.2959



Tests that the Variances are Equal



Level	Count	Std Dev	MeanAbsDif to Mean	MeanAbsDif to Median
Hand	5	0.2712377	0.2348961	0.2005837
Mixer	5	0.0693728	0.0492935	0.0519310

Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	7.9638	1	8	0.0224*
Brown-Forsythe	1.6349	1	8	0.2369
Levene	27.0187	1	8	0.0008*
Bartlett	5.2175	1	.	0.0224*
F Test 2-sided	15.2870	4	4	0.0217*

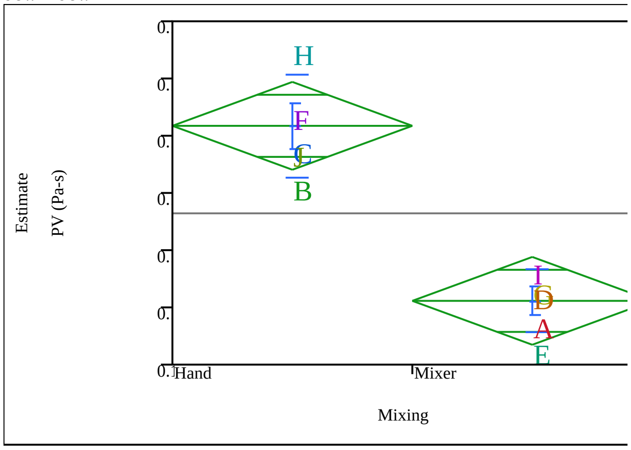
Warning: Small sample sizes. Use Caution.

Welch's Test
Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
0.3325	1	4.5211	0.5917

t Test
0.5766

Oneway Analysis of Estimate PV (Pa-s) By Mixing select 30-300=0-300, down=down



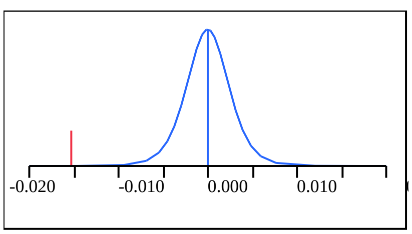
Oneway Anova
Summary of Fit

Rsquare	0.840748
Adj Rsquare	0.820842
Root Mean Square Error	0.003721
Mean of Response	0.113218
Observations (or Sum Wgts)	10

t Test
Mixer-Hand

Assuming equal variances

Difference	-0.01529	t Ratio	-6.49885
Std Err Dif	0.00235	DF	8
Upper CL Dif	-0.00987	Prob > |t|	0.0002*
Lower CL Dif	-0.02072	Prob > t	0.9999
Confidence	0.95	Prob < t	<.0001*



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Mixing	1	0.00058470	0.000585	42.2350	0.0002*
Error	8	0.00011075	0.000014		
C. Total	9	0.00069546			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Hand	5	0.120864	0.00166	0.11703	0.12470
Mixer	5	0.105571	0.00166	0.10173	0.10941

Std Error uses a pooled estimate of error variance

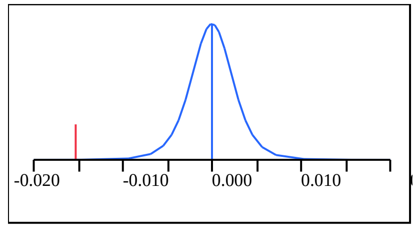
Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Hand	5	0.120864	0.004497	0.00201	0.11528	0.12645
Mixer	5	0.105571	0.002732	0.00122	0.10218	0.10896

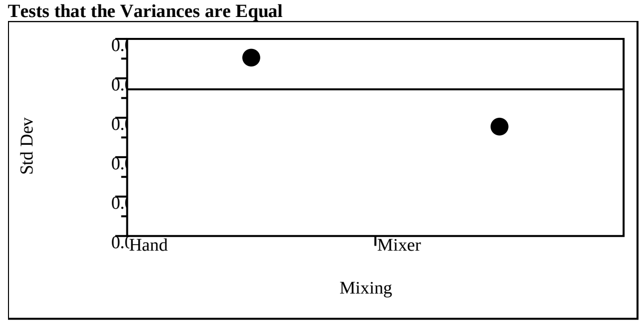
t Test
Mixer-Hand

Assuming unequal variances

Difference	-0.01529	t Ratio	-6.49885
Std Err Dif	0.00235	DF	6.598247
Upper CL Dif	-0.00966	Prob > |t|	0.0004*
Lower CL Dif	-0.02093	Prob > t	0.9998
Confidence	0.95	Prob < t	0.0002*



Tests that the Variances are Equal



Level	Count	Std Dev	MeanAbsDif to Mean	MeanAbsDif to Median
Hand	5	0.0044972	0.0033051	0.0030928
Mixer	5	0.0027319	0.0021719	0.0020410

Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	0.8060	1	8	0.3955
Brown-Forsythe	0.3803	1	8	0.5546
Levene	0.7891	1	8	0.4003
Bartlett	0.8491	1	.	0.3568
F Test 2-sided	2.7100	4	4	0.3576

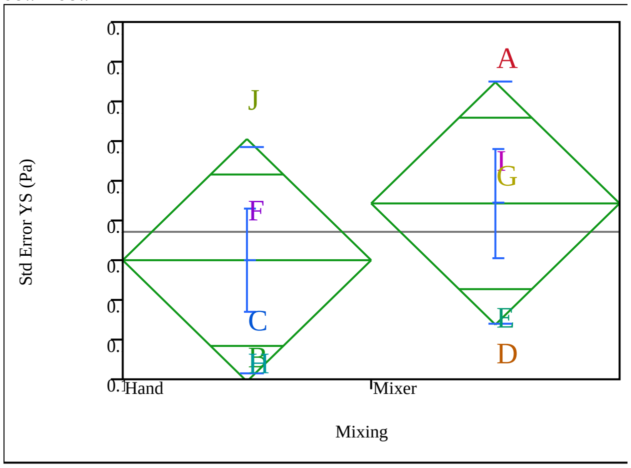
Warning: Small sample sizes. Use Caution.

Welch's Test
Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
42.2350	1	6.5982	0.0004*

t Test
6.4988

Oneway Analysis of Std Error YS (Pa) By Mixing select 30-300=0-300, down=down



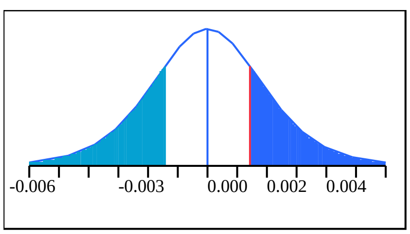
Oneway Anova
Summary of Fit

Rsquare	0.067974
Adj Rsquare	-0.04853
Root Mean Square Error	0.002961
Mean of Response	0.113715
Observations (or Sum Wgts)	10

t Test
Mixer-Hand

Assuming equal variances

Difference	0.00143	t Ratio	0.763842
Std Err Dif	0.00187	DF	8
Upper CL Dif	0.00575	Prob > |t|	0.4669
Lower CL Dif	-0.00289	Prob > t	0.2334
Confidence	0.95	Prob < t	0.7666



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Mixing	1	0.00000511	5.1145e-6	0.5835	0.4669
Error	8	0.00007013	8.7659e-6		
C. Total	9	0.00007524			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Hand	5	0.113000	0.00132	0.10995	0.11605
Mixer	5	0.114430	0.00132	0.11138	0.11748

Std Error uses a pooled estimate of error variance

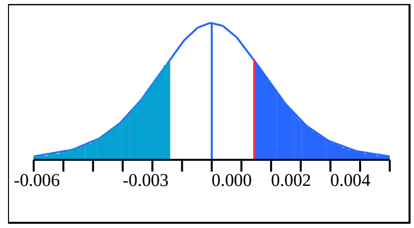
Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Hand	5	0.113000	0.002866	0.00128	0.10944	0.11656
Mixer	5	0.114430	0.003052	0.00136	0.11064	0.11822

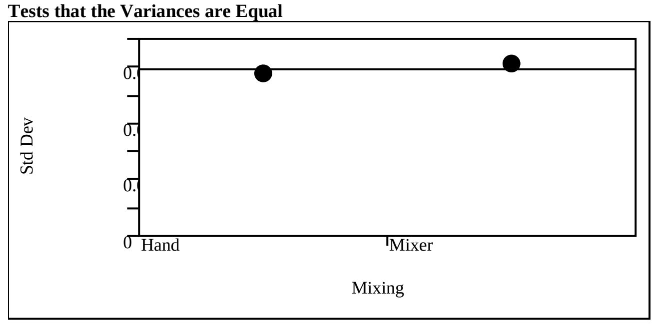
t Test
Mixer-Hand

Assuming unequal variances

Difference	0.00143	t Ratio	0.763842
Std Err Dif	0.00187	DF	7.968709
Upper CL Dif	0.00575	Prob > |t|	0.4670
Lower CL Dif	-0.00289	Prob > t	0.2335
Confidence	0.95	Prob < t	0.7665



Tests that the Variances are Equal



Level	Count	Std Dev	MeanAbsDif to Mean	MeanAbsDif to Median
Hand	5	0.0028665	0.0023263	0.0022587
Mixer	5	0.0030521	0.0024641	0.0023478

Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	0.0318	1	8	0.8630
Brown-Forsythe	0.0052	1	8	0.9444
Levene	0.0299	1	8	0.8670
Bartlett	0.0140	1	.	0.9058
F Test 2-sided	1.1337	4	4	0.9061

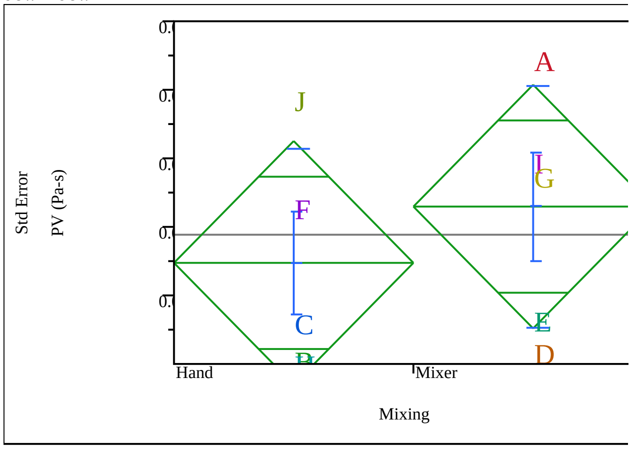
Warning: Small sample sizes. Use Caution.

Welch's Test
Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
0.5835	1	7.9687	0.4670

t Test
0.7638

Oneway Analysis of Std Error PV (Pa-s) By Mixing select 30-300=0-300, down=down



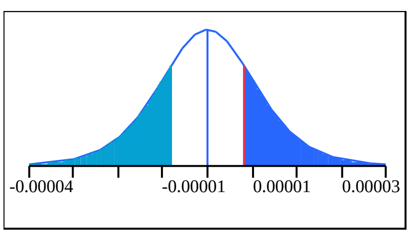
Oneway Anova
Summary of Fit

Rsquare	0.066229
Adj Rsquare	-0.05049
Root Mean Square Error	1.724e-5
Mean of Response	0.000659
Observations (or Sum Wgts)	10

t Test
Mixer-Hand

Assuming equal variances

Difference	8.212e-6	t Ratio	0.753267
Std Err Dif	0.000011	DF	8
Upper CL Dif	3.335e-5	Prob > |t|	0.4729
Lower CL Dif	-1.69e-5	Prob > t	0.2364
Confidence	0.95	Prob < t	0.7636



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Mixing	1	1.6857e-10	1.686e-10	0.5674	0.4729
Error	8	2.37674e-9	2.971e-10		
C. Total	9	2.54531e-9			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Hand	5	0.000655	7.7083e-6	0.00064	0.00067
Mixer	5	0.000663	7.7083e-6	0.00065	0.00068

Std Error uses a pooled estimate of error variance

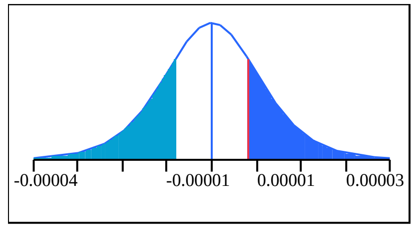
Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Hand	5	0.000655	0.000017	7.4913e-6	0.00063	0.00068
Mixer	5	0.000663	0.000018	7.9194e-6	0.00064	0.00068

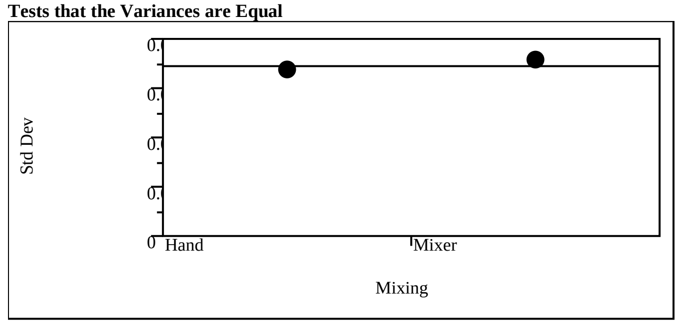
t Test
Mixer-Hand

Assuming unequal variances

Difference	8.212e-6	t Ratio	0.753267
Std Err Dif	0.000011	DF	7.975415
Upper CL Dif	3.336e-5	Prob > |t|	0.4729
Lower CL Dif	-1.69e-5	Prob > t	0.2365
Confidence	0.95	Prob < t	0.7635



Tests that the Variances are Equal



Level	Count	Std Dev	MeanAbsDif to Mean	MeanAbsDif to Median
Hand	5	0.0000168	0.0000136	0.0000133
Mixer	5	0.0000177	0.0000143	0.0000136

Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	0.0258	1	8	0.8763
Brown-Forsythe	0.0021	1	8	0.9648
Levene	0.0236	1	8	0.8818
Bartlett	0.0110	1	.	0.9166
F Test 2-sided	1.1176	4	4	0.9168

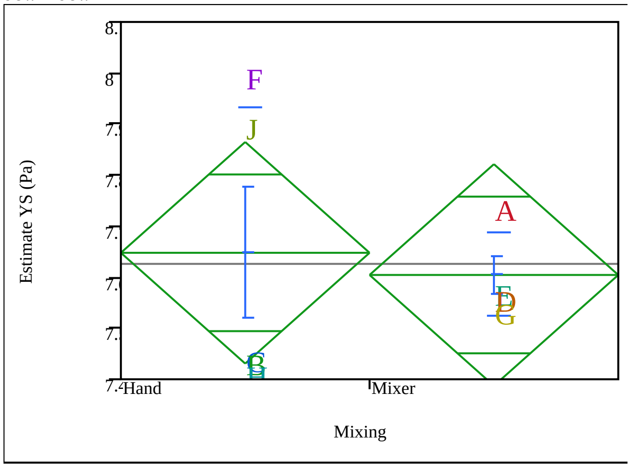
Warning: Small sample sizes. Use Caution.

Welch's Test
Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
0.5674	1	7.9754	0.4729

t Test
0.7533

Fit Y by X Group
Oneway Analysis of Estimate YS (Pa) By Mixing select 30-300=30-300, down=down



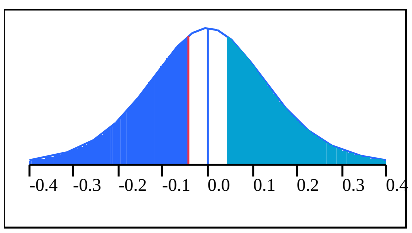
Oneway Anova
Summary of Fit

Rsquare	0.013129
Adj Rsquare	-0.11023
Root Mean Square Error	0.210476
Mean of Response	7.626044
Observations (or Sum Wgts)	10

t Test
Mixer-Hand

Assuming equal variances

Difference	-0.04343	t Ratio	-0.32624
Std Err Dif	0.13312	DF	8
Upper CL Dif	0.26354	Prob > |t|	0.7526
Lower CL Dif	-0.35040	Prob > t	0.6237
Confidence	0.95	Prob < t	0.3763



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Mixing	1	0.00471499	0.004715	0.1064	0.7526
Error	8	0.35440178	0.044300		
C. Total	9	0.35911677			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Hand	5	7.64776	0.09413	7.4307	7.8648
Mixer	5	7.60433	0.09413	7.3873	7.8214

Std Error uses a pooled estimate of error variance

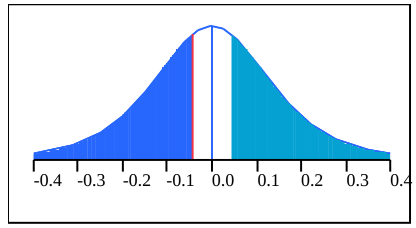
Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Hand	5	7.64776	0.286217	0.12800	7.2924	8.0031
Mixer	5	7.60433	0.081732	0.03655	7.5028	7.7058

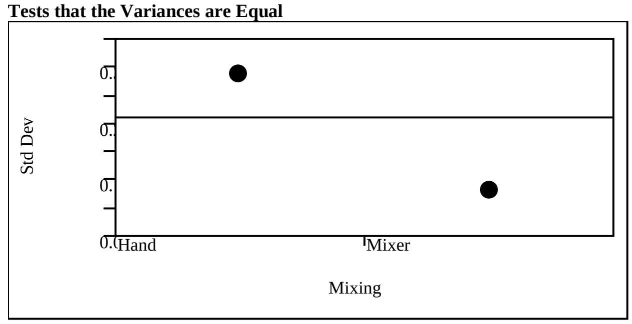
t Test
Mixer-Hand

Assuming unequal variances

Difference	-0.04343	t Ratio	-0.32624
Std Err Dif	0.13312	DF	4.648036
Upper CL Dif	0.30670	Prob > |t|	0.7584
Lower CL Dif	-0.39356	Prob > t	0.6208
Confidence	0.95	Prob < t	0.3792



Tests that the Variances are Equal



Level	Count	Std Dev	MeanAbsDif to Mean	MeanAbsDif to Median
Hand	5	0.2862174	0.2488431	0.2117177
Mixer	5	0.0817315	0.0576988	0.0429607

Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	8.9503	1	8	0.0173*
Brown-Forsythe	1.8067	1	8	0.2158
Levene	25.9660	1	8	0.0009*
Bartlett	4.5408	1	.	0.0331*
F Test 2-sided	12.2635	4	4	0.0324*

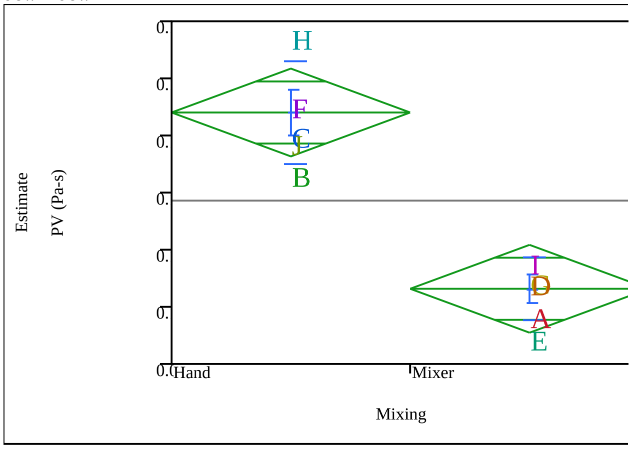
Warning: Small sample sizes. Use Caution.

Welch's Test
Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
0.1064	1	4.648	0.7584

t Test
0.3262

Oneway Analysis of Estimate PV (Pa-s) By Mixing select 30-300=30-300, down=down



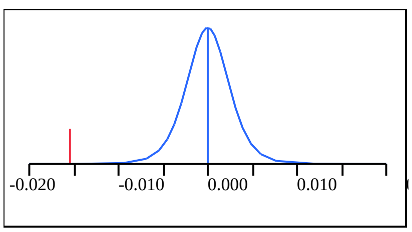
Oneway Anova
Summary of Fit

Rsquare	0.842664
Adj Rsquare	0.822997
Root Mean Square Error	0.003728
Mean of Response	0.109297
Observations (or Sum Wgts)	10

t Test
Mixer-Hand

Assuming equal variances

Difference	-0.01543	t Ratio	-6.54574
Std Err Dif	0.00236	DF	8
Upper CL Dif	-0.01000	Prob > |t|	0.0002*
Lower CL Dif	-0.02087	Prob > t	0.9999
Confidence	0.95	Prob < t	<.0001*



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Mixing	1	0.00059539	0.000595	42.8467	0.0002*
Error	8	0.00011117	0.000014		
C. Total	9	0.00070656			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Hand	5	0.117013	0.00167	0.11317	0.12086
Mixer	5	0.101580	0.00167	0.09774	0.10542

Std Error uses a pooled estimate of error variance

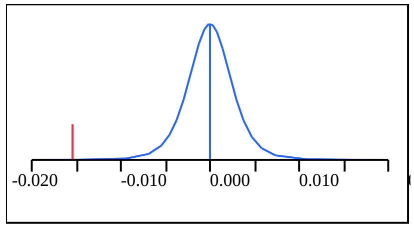
Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Hand	5	0.117013	0.004537	0.00203	0.11138	0.12265
Mixer	5	0.101580	0.002684	0.00120	0.09825	0.10491

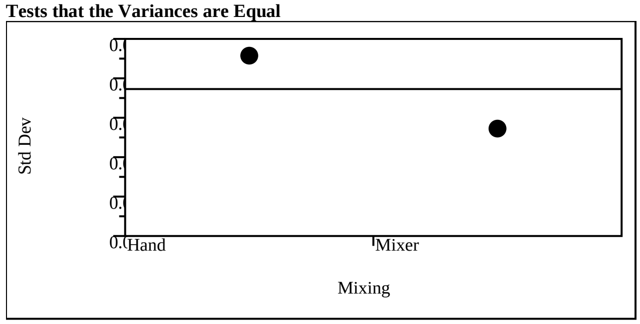
t Test
Mixer-Hand

Assuming unequal variances

Difference	-0.01543	t Ratio	-6.54574
Std Err Dif	0.00236	DF	6.493905
Upper CL Dif	-0.00977	Prob > |t|	0.0004*
Lower CL Dif	-0.02110	Prob > t	0.9998
Confidence	0.95	Prob < t	0.0002*



Tests that the Variances are Equal



Level	Count	Std Dev	MeanAbsDif to Mean	MeanAbsDif to Median
Hand	5	0.0045374	0.0033291	0.0031621
Mixer	5	0.0026840	0.0021731	0.0019799

Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	0.8610	1	8	0.3806
Brown-Forsythe	0.4782	1	8	0.5088
Levene	0.8316	1	8	0.3885
Bartlett	0.9382	1	.	0.3327
F Test 2-sided	2.8579	4	4	0.3335

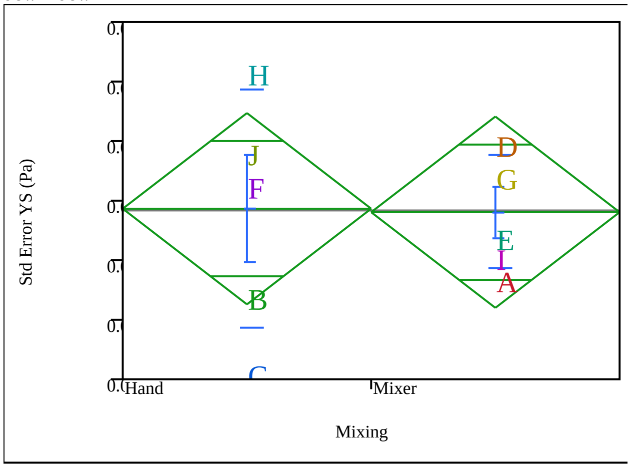
Warning: Small sample sizes. Use Caution.

Welch's Test
Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
42.8467	1	6.4939	0.0004*

t Test
6.5457

Oneway Analysis of Std Error YS (Pa) By Mixing select 30-300=30-300, down=down



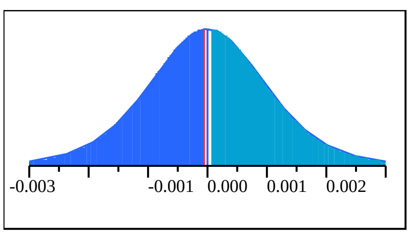
Oneway Anova
Summary of Fit

Rsquare	0.000443
Adj Rsquare	-0.1245
Root Mean Square Error	0.001558
Mean of Response	0.042835
Observations (or Sum Wgts)	10

t Test
Mixer-Hand

Assuming equal variances

Difference	-5.87e-5	t Ratio	-0.05955
Std Err Dif	0.00099	DF	8
Upper CL Dif	0.00221	Prob > |t|	0.9540
Lower CL Dif	-0.00233	Prob > t	0.5230
Confidence	0.95	Prob < t	0.4770



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Mixing	1	8.60232e-9	8.6023e-9	0.0035	0.9540
Error	8	0.00001941	2.4259e-6		
C. Total	9	0.00001942			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Hand	5	0.042865	0.00070	0.04126	0.04447
Mixer	5	0.042806	0.00070	0.04120	0.04441

Std Error uses a pooled estimate of error variance

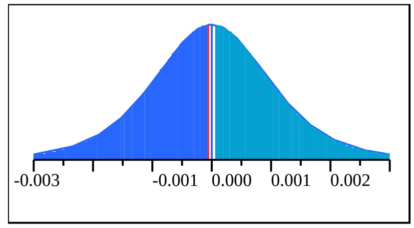
Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Hand	5	0.042865	0.001987	0.00089	0.04040	0.04533
Mixer	5	0.042806	0.000951	0.00043	0.04162	0.04399

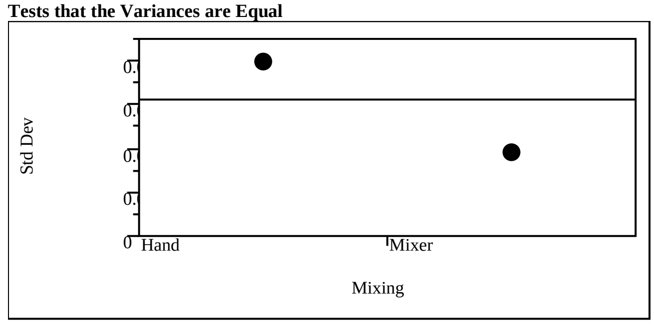
t Test
Mixer-Hand

Assuming unequal variances

Difference	-5.87e-5	t Ratio	-0.05955
Std Err Dif	0.00099	DF	5.742587
Upper CL Dif	0.00238	Prob > |t|	0.9545
Lower CL Dif	-0.00250	Prob > t	0.5227
Confidence	0.95	Prob < t	0.4773



Tests that the Variances are Equal



Level	Count	Std Dev	MeanAbsDif to Mean	MeanAbsDif to Median
Hand	5	0.0019867	0.0015872	0.0015962
Mixer	5	0.0009513	0.0007853	0.0007998

Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	2.4334	1	8	0.1574
Brown-Forsythe	2.2489	1	8	0.1721
Levene	3.4505	1	8	0.1003
Bartlett	1.7756	1	.	0.1827
F Test 2-sided	4.3616	4	4	0.1828

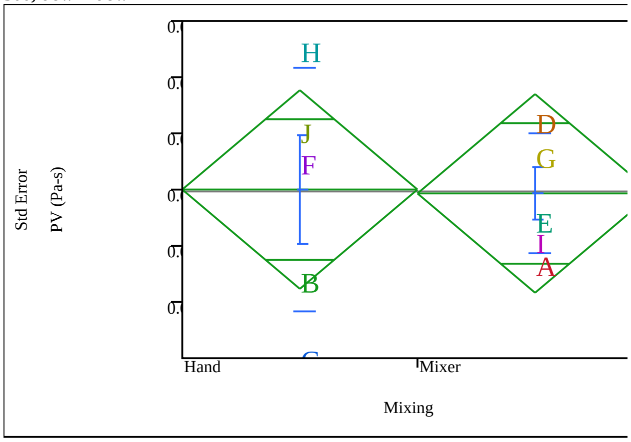
Warning: Small sample sizes. Use Caution.

Welch's Test
Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
0.0035	1	5.7426	0.9545

t Test
0.0595

Oneway Analysis of Std Error PV (Pa-s) By Mixing select 30-300=30-300, down=down



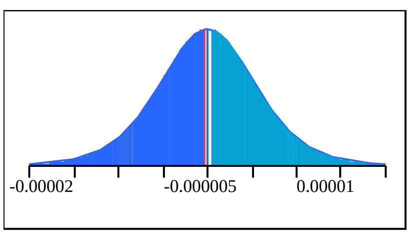
Oneway Anova
Summary of Fit

Rsquare	0.000516
Adj Rsquare	-0.12442
Root Mean Square Error	8.569e-6
Mean of Response	0.000235
Observations (or Sum Wgts)	10

t Test
Mixer-Hand

Assuming equal variances

Difference	-3.48e-7	t Ratio	-0.06424
Std Err Dif	5.419e-6	DF	8
Upper CL Dif	1.215e-5	Prob > |t|	0.9504
Lower CL Dif	-1.28e-5	Prob > t	0.5248
Confidence	0.95	Prob < t	0.4752



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Mixing	1	3.03e-13	3.03e-13	0.0041	0.9504
Error	8	5.8738e-10	7.342e-11		
C. Total	9	5.8768e-10			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Hand	5	0.000235	3.832e-6	0.00023	0.00024
Mixer	5	0.000235	3.832e-6	0.00023	0.00024

Std Error uses a pooled estimate of error variance

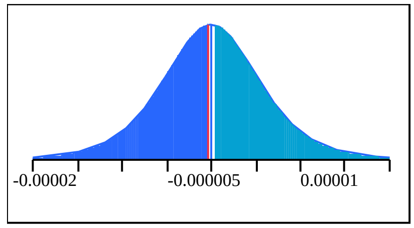
Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Hand	5	0.000235	0.000011	4.8794e-6	0.00022	0.00025
Mixer	5	0.000235	5.273e-6	2.3581e-6	0.00023	0.00024

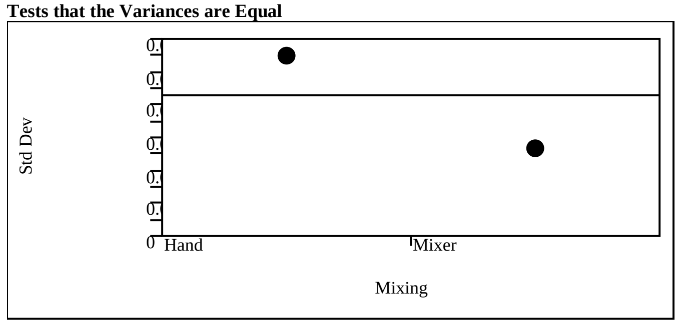
t Test
Mixer-Hand

Assuming unequal variances

Difference	-3.48e-7	t Ratio	-0.06424
Std Err Dif	5.419e-6	DF	5.771889
Upper CL Dif	0.000013	Prob > |t|	0.9509
Lower CL Dif	-1.37e-5	Prob > t	0.5245
Confidence	0.95	Prob < t	0.4755



Tests that the Variances are Equal



Level	Count	Std Dev	MeanAbsDif to Mean	MeanAbsDif to Median
Hand	5	0.0000109	8.7428e-6	8.7455e-6
Mixer	5	0.0000053	4.3685e-6	4.3875e-6

Test	F Ratio	DFNum	DFDen	p-Value
O'Brien[.5]	2.4407	1	8	0.1568
Brown-Forsythe	2.1234	1	8	0.1832
Levene	3.4859	1	8	0.0989
Bartlett	1.7344	1	.	0.1878
F Test 2-sided	4.2814	4	4	0.1880

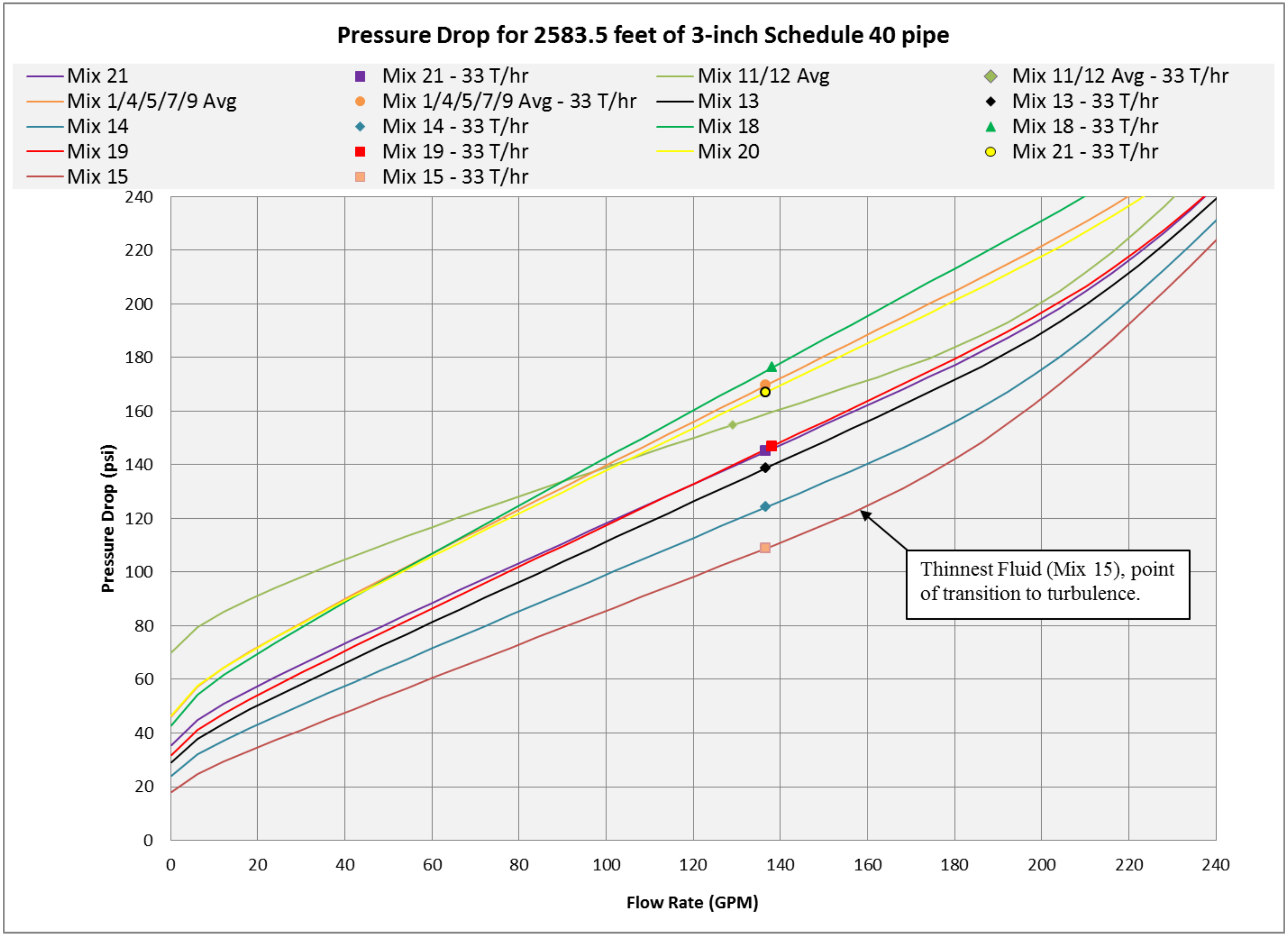
Warning: Small sample sizes. Use Caution.

Welch's Test
Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
0.0041	1	5.7719	0.9509

t Test
0.0642

Appendix D. System Curves for Grout Mixtures


Pressure Drop for 2583.5 feet of 3-inch Schedule 40 pipe
Mix 21
Mix 21 - 33 T/hr
Mix 11/12 Avg
Mix 11/12 Avg - 33 T/hr
Mix 1/4/5/7/9 Avg
Mix 1/4/5/7/9 Avg - 33 T/hr
Mix 13
Mix 13 - 33 T/hr
Mix 14
Mix 14 - 33 T/hr
Mix 18
Mix 18 - 33 T/hr
Mix 19
Mix 19 - 33 T/hr
Mix 20
Mix 21 - 33 T/hr
Mix 15
Mix 15 - 33 T/hr
Pressure Drop (psi)
Flow Rate (GPM)
0
20
40
60
80
100
120
140
160
180
200
220
240
Thinnest Fluid (Mix 15), point of transition to turbulence.

Distribution:

S. L. Marra, 773-A
T. B. Brown, 773-A
D. H. McGuire, 999-W
S. D. Fink, 773-A
C. C. Herman, 773-A
E. N. Hoffman, 999-W
F. M. Pennebaker, 773-42A
W. R. Wilmarth, 773-A
Records Administration (EDWS)

J. M. Bricker, 704-30S
J. S. Contardi, 766-H
V. Jain, 704-Z
J. N. Leita, 210-S
S. P. Simner, 249-8H

P. R. Jackson, DOE-SR, 703-46A
K. H. Subramanian, 241-156H

M. R. Bodine, 704-26S

B.C. Hodges, 704-30S

S. C. Shah, 704-30S

M. E. Smith, 704-30S