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Bench-Scale Cross Flow Filtration of Tank S-107 Sludge Slurries and Tank C-107 Supernatant

J.G.H. Geeting
B. A. Reynolds

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Summary

Hanford tank waste filtration experiments were conducted using a bench-scale cross flow filter on 8 wt%, 1.5 wt%, and 0.05 wt% Tank S-107 sludge slurries and on Tank C-107 supernatant. For comparison, two simulants each with solids loadings of 8 wt% and 0.05 wt% were also tested. The purpose of the tests was to determine the efficacy of cross flow filtration on slurries of various solids loadings. In addition, filtrate flux dependency on axial velocity and transmembrane pressure was sought so that conditions for future experiments might be better selected. The data gathered are compared to the simulants and three cross flow filtration models.

A two-parameter central composite design which tested transmembrane pressure from 5 to 40 psig and axial velocity from 3 to 9 ft/s was used for all feeds. The cross flow filter effectively removed solids from the liquid, as 19 of 20 filtrate samples had particle concentrations below the resolution limit of the photon correlation spectrometer used in the Hanford Radiocolloid Laboratory. Radiochemical analysis indicate that all filtrate samples were below Class A waste classification standards for ^{90}Sr and transuranics.

The 8 wt% Tank S-107 filtrate flux rate was linear with velocity and independent of pressure above 20 psig (at 6 ft/s axial velocity) indicating that back mass transport limited filtrate flux rates. The filtrate flux rates ranged from approximately 0.04 to 0.06 gpm/ft² (excluding Conditions 10 and 11 where deagglomeration is suspected) which is consistent with the two 8 wt% simulants tested. The filtrate flux rate decreased to less than 1/4 the expected values after the highest axial flowrate condition (i.e., Conditions 10 and 11). Shear induced deagglomeration of the slurry is suspected of causing filter fouling at these last two conditions. Particle size analysis of the feed prior to and after testing support this hypothesis, as the mean particle size decreased from 0.5 microns prior to testing to 0.3 microns after testing.

The 8 wt% feed was subsequently diluted to produce the 1.5 wt% and 0.05 wt% feeds. These feeds both had lower than expected filtrate flux rates when compared with the simulants and the 8 wt% S-107 feed (excluding Conditions 10 and 11). The filtrate flux of the 1.5 wt% slurry decayed from 0.07 to 0.03 gpm/ft² during testing. Similarly, the 0.05 wt% slurry filtrate flux decayed from 0.06 to 0.03 gpm/ft². The later value being approximately 1/5 the rate measured in the two 0.05 wt% simulants. The C-107 supernatant also displayed a significant flux decline.

These results suggest the use of smaller-pore filter media. Filter media with larger pores facilitate the penetration of small particles in the pores and, therefore, promote internal fouling. Such fouling was not removed by back pulsing the filter and required the use of 2 wt% oxalic acid cleaning which restored the filtrate flux rates.

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1.0 Introduction

Past solid/liquid separation experience involving actual Hanford tank wastes includes settle/decant (Rasmussen 1980), centrifugation, and inverted pneumatic hydro pulse filtration (Kimura and Simmons 1987; Gerboth 1987). The first two methods were not always successful in removing the desired amount of solids, while the third method introduces a secondary waste by means of addition of body feed and/or precoat. A summary review of past solid/liquid separation (SLS) experience of alkaline tank wastes from the Hanford Site is contained in Geeting (1994)¹.

Figure 1.1 shows a simplified Hanford tank waste pretreatment flowsheet with the major solid/liquid separation (SLS) needs identified. Cross flow filtration is a candidate for all three of the SLS needs shown. SLS during the sludge leaching and washing steps will be required to remove leach and wash liquors from the bulk sludge. Feeds for this first need can be expected to have high solids concentrations, nominally 8 wt%. The leach and wash liquors would likely be sent to an evaporator to reduce their volume. Such a volume reduction may cause precipitates to form in the solution; therefore, the evaporator bottoms may require an additional SLS to reduce the solids content to prevent blinding or plugging of the Cs ion exchange column. Post ion exchange filtration may be required, particularly if a crystalline silico-titanates are used as the exchanger. The solids loading for this need should be low as solids above 0.05 wt% are not expected during normal operations.

West Valley Nuclear Services (WVNS) and Savannah River Site (SRS) both have cross flow filters which are used for the pretreatment of WVNS and SRS tank wastes. While there is considerable experience using cross flow filters around the U.S. Department of Energy (DOE) complex, gathering waste specific data for each feed to be processed is crucial, as each waste type can behave differently and it is not possible to predict how filtering behavior may differ a priori.

There is no previous cross flow filtration experience involving actual Hanford tank waste, despite successes met at WVNS and SRS. This report provides the results of cross flow filtration testing of Hanford Tank S-107 and Tank C-107 wastes.

¹ Geeting, J.G.H., Internal Memo to distribution entitled, *Summary Level Discussion and Meeting Minutes from the Solid/Liquid Separations Seminar held in Richland, Washington, December 7-9, 1994*. Pacific Northwest Laboratory, Richland, WA

Figure 1.1 Simplified Hanford Tank Pretreatment Train Showing Major Solid/Liquid Separation Needs

1.1 Objectives

The objective of this work was to determine the cross flow filtration solids removal efficiency for Hanford Tank S-107 sludge and Tank C-107 settle/decant supernatant (from enhanced sludge washing operations), and thereby provide a preliminary assessment of whether cross flow filtration may be implemented in the pretreatment of Hanford tank wastes. A secondary objective was to obtain initial data on filtrate flux as a function of axial velocity and pressure for scale up use.

1.2 Theory

Figure 1.2 schematically displays the difference between cross flow filtration and conventional dead-end filtration. Cross flow filtration uses velocity of the feed suspension to sweep away particles deposited on the filter media, thereby limiting the thickness of the filter cake.

Figure 1.2 Schematic Display of Fundamental Difference between Cross Flow Filtration and Conventional "Dead-End" Filtration (Murkes and Carlsson, 1988)

The two primary resistances to the filtrate flux are pressure filtration resistance and mass transport resistance. Back transport of solids away from the membrane and into the bulk stream is required to prevent the cake thickness from continually increasing. Both a filter cake and boundary layer may be present in a cross flow filtration system. Figure 1.3 shows a schematic representation of cross flow filtration showing the filter membrane, the filter cake, the boundary layer, and the bulk stream.

Figure 1.3 Schematic of Fluid Velocity, Pressure, and Particle Concentration Profiles for Cross Flow Filtration (Ripperger, 1988)

If the limiting resistance to filtrate flux is due to the back transport of solids away from the membrane, then

$$J_{mt} = k \ln(C_w/C_b) \quad (1)$$

where J_{mt} is the mass transfer limited flux, k is the back mass transfer coefficient, and C_w and C_b are the concentration at the wall and in the bulk, respectively. Porter (1972) observed that experimental flux values were often one to two orders of magnitude higher than those indicated by the mass transfer evaluated for laminar and turbulent flow using the Leveque and Dittus-Boelter relationships and the Stokes-Einstein relationship for Brownian motion diffusivity. Nevertheless, Equation 1 is thought to be valid with the correct mass transfer coefficient. Investigators (e.g., Zydney and Colton 1986) have suggested various particle transport augmentations to account for the difference in predicted vs. experimental fluxes.

If mass transport does not limit filtrate flow, then filtrate flux should vary in accordance with Darcy's equation for pressure filtration.

$$J_f = P / \mu (L/K + R_m) \quad (2)$$

where

J_f = pressure filtration limited flux ($m^3/m^2 \cdot S$)

P = filtration pressure (Pa)

μ = liquid viscosity (Pa·S)

R_m = filter media resistance (1/m)

L/K = filter cake resistance, where L = cake thickness (m) and K = cake permeability (m^2).

Equation 2 indicates the filtration rate J_f increases when P increases, K increases, or μ decreases. The filtration rate J_f decreases when L increases, and R_m increases.

Two operating regimes exist for cross flow filtration. In the first regime the filtrate flux is a function of pressure. In the second regime it is not. These two regimes are described as follows.

- **Regime I** - Suppose a given system at steady state with set axial velocity and constant filtration flux, J_{mt} , as described by Equation 1. If the filtration flux described by Equation 1 is greater than that described by Equation 2 (i.e., $J_{mt} > J_f$), then the filtrate flux will vary linearly with pressure because the flux will be limited as described by Darcy's Filtration equation (Equation 2). On the other hand, for the same system at set pressure with $J_{mt} > J_f$, an increase in velocity may or may not increase flux. An increase in axial velocity

will not result in higher filtrate flux unless it causes the cake resistance to decrease (thus increasing J_f). If the given axial velocity is effective at keeping the filter cake resistance low, axial velocity will not significantly effect filtrate flux.

- **Regime II** - Given the same system described, with conditions such that $J_{mt}=J_f$. In this regime the flux will no longer vary with pressure. Increased pressure will bring about an increase in cake resistance, R_c , by means of growth in cake thickness or decrease in the cake permeability (or both). While an increase in pressure may cause $J_{mt}<J_f$ temporarily, the cake resistance will increase until at steady state, $J_{mt}=J_f$. In this second regime velocity alone is effective in increasing the filtrate flux.

Porter (1972) divided cross flow filtration into two such regimes. At low transmembrane pressures the filtrate flux varies linearly with pressure, indicating that the filter cake limits the flux. While at high transmembrane pressures the filtrate flux is pressure independent indicating J_{mt} approximately equals J_f .

From equation (1) we see that increased solids loading in the feed, C_b , causes J_{mt} to decrease. Therefore, increasing solids loading decreases the pressure at which $J_{mt}=J_f$, and a given system can switch from Regime I to Regime II merely by increasing the solids loading in the feed.

Murkes and Carlsson (1988) discuss a physical limit on the filtrate flux rate for high flow rates, where (in theory) the cake thickness becomes infinitely thin and the flux is only limited by the resistance of the filter medium which gives a constant asymptote:

$$J=P/\mu R_m \quad (3)$$

While Murkes and Carlsson admit that this limit may never be achieved in practice it is, nevertheless, a useful limiting value of which to be aware.

1.3 Modeling

Numerous models have been proposed to predict filtrate flux rates. Zydney and Colton (1986) conducted a parametric review of existing models and found the models inadequate for correlating experimental observations. Even if it is not possible to use models to predict the flux of a crossflow unit it may, nevertheless, be useful for the understanding of the basic mechanisms of cross flow filtration. Two model categories predominate the literature.

- Gel Polarization Models which assume the form of Equation 1. Variations of these models focus on predicting the correct mass transfer coefficient from fundamental parameters.
- Lift Models which are based on a force balance between the hydrodynamic lift force and particle drag due to filtration. These models typically neglect diffusion as a driving force.

Both model types are developed to model Regime II where filtrate flux is independent of pressure. One representative model of each type is presented. In addition a third model, developed to model both Regime I and II, is also presented.

Gel Polarization Model:

Porter (1972) developed a polarization model based on the assumption that the limiting resistance to filtrate flux was due to mass transport. The model is of the form of Equation 1, $J = k \ln(C_w/C_b)$, with the mass transfer coefficient, k , evaluated using Dittus and Boelter heat transfer correlation for turbulent flow, suitably modified for mass-transfer.

$$J = 0.0023 \left[\frac{v^{0.8} D^{0.67}}{d_h^{0.2} \nu^{0.47}} \right] \ln \left(\frac{C_w}{C_b} \right) \quad (4)$$

where

d_h = hydraulic diameter
 v = average fluid velocity
 ν = kinematic viscosity
 D = diffusivity

The diffusivity is evaluated using the Stokes-Einstein relationship. This model is applicable for turbulent flow in Regime II (where the flux is independent of pressure).

Lift Model.

Zawaicki (1981) developed a lift model, where particle diffusion is not taken into account, to rectify the discrepancies observed between the polarization model, Equation 4, and experimental data. The model is based on a force balance between the hydrodynamic lift force and drag on a particle due to filtration.

$$J = \frac{0.34 D_p^2 \gamma_w^{3/2}}{\lambda v^{1/2}} \quad (5)$$

where

D_p is the particle diameter, γ_w is the wall shear rate, and λ is a correction factor for the viscous drag force exerted on spherical particles in a slurry (Tam, 1969).

"Modified" Pressure Filtration Model

Scarlett and Treasure developed a model which covers both Regime I and II. The model takes into account the effects of pressure, as well as parameters typically used in models independent of pressure. The model uses sedimentary expressions to equate the cake thickness to axial velocity, transmembrane pressure, and slurry parameters. The cake thickness is introduced into Darcy's pressure filtration equation with the following result:

$$J = \frac{B \Delta P}{\mu \left[\frac{c^2 \Delta P}{(av^3 + bv^{3.5} + 0.28v^4)^{1/2}} + L_o \right]} \quad (6)$$

where

B = Darcy's permeability constant

ΔP = pressure drop across the filter membrane

μ = fluid viscosity

v = axial velocity

L_o = resistance of the filter medium expressed as an equivalent cake thickness

$a = 21\mu/D_p\rho_L$

$b = 6(a/21)^{1/2}$

$c = 2.43 C_v^{1/3} (2d_h / (1-\epsilon) \rho_L)^{1/2}$
 D_p = particle diameter
 ρ_L = density of liquid
 d_h = hydraulic diameter
 ϵ = filter cake porosity
 C_v = volumetric concentration of solids

A more complete development of the Scarlett and Treasure model is discussed in Murkes and Carlsson (1988).

2.0 Procedure

2.1 Radioactive Tests

A sample test procedure is contained in Appendix A. Below is a brief description of how the tests were conducted.

Radioactive filtration tests were conducted in the 325 Building C-cell with nominally 8 wt%, 1.5 wt%, and 0.05 wt% insoluble Tank S-107 sludge solids prepared by adding inhibited water (0.01 M NaOH, 0.01 M NaNO₂) to the sludge. A fourth filtration test was conducted with Tank C-107 decanted supernatant obtained from the Sludge Pretreatment Demonstration. The supernatant was a composite sample obtained from decanting leach and rinse liquors from enhanced sludge washing and rinsing operations demonstrated in the Sludge Pretreatment Pilot Plant.

Approximately 800 ml feed volume was required to fill the Cell Unit Filter (CUF). Each of eleven conditions were established by setting the desired axial velocity and transmembrane pressure (TMP). The experimental conditions were chosen based on a central composite response surface design. Figure 2.1 shows the conditions and run order used in the experimental design used for the 1.5 wt% and 0.05 wt% S-107 slurries. The center condition is tested three times: first, middle, and last.

Figure 2.1 Statistically Designed Experimental Conditions used in Testing

The design for the 8 wt% slurry was similar, but shifted down 5 psig and centered at 20 psig instead of 25 psig because the CUF was unable to meet the latter conditions at high solids loading. After establishing each condition, an initial back pulse was conducted and a clock was started. Each condition was run for at least 60 minutes measuring and recording transmembrane pressure, axial velocity, temperature, and filtrate flux data every 5 minutes. Slurry temperature was maintained between 28-38°C by adjusting the cell supplied heat exchanger as required. A back pulse was conducted after 30 minutes for each condition. Filtrate samples were taken at a total of five different conditions as described in Appendix A.

After completing testing, the CUF was drained and rinsed 3 times with deionized water. A feed sample of each feed was taken from a well mixed sample of the drained slurry. The test procedure was repeated for each of the four radioactive feeds.

2.2 Non-Radioactive Simulant Testing

Four simulants were tested in the CUF prior to its installation in the hot cell. Simulant S3 was composed of 9/1 gibbsite to boehmite by weight in 0.1 M NaOH. Simulant S103 was principally composed of precipitated $\text{Fe}(\text{OH})_3$, along with colloidal SiO_2 , gibbsite, and boehmite. Recipes for the 0.05 wt% and 8 wt% versions of each simulant are provided in Appendix B.

The testing procedure for the simulants was identical to the radioactive feeds. However, the test matrix for the simulant feeds were centered at 6 ft/s axial velocity (3 ft/s low, 9 ft/s high) and 15 psig transmembrane pressure (5 psig low, 25 psig high).

2.3 Apparatus

A CUF, shown schematically in Figure 2.2, was designed at the Savannah River Site and used for all testing. The CUF is principally connected with of stainless steel Swagelok fittings. The slurry feed is introduced into the CUF through the slurry reservoir. A Moyno progressive cavity pump powered by an air motor pumps the slurry from the slurry reservoir through the magnetic flowmeter and the nominally² 0.5" diameter x 6" long Mott 0.5 micron sintered metal filter. The axial velocity and transmembrane pressure are controlled by adjusting the pump speed and the throttle valve (V1). A back pressure (check) valve is installed to prevent over pressurization of the system. Filtrate passes through the Mott filter and is reconstituted with the slurry in the slurry reservoir. The filtrate flow rate is measured by means of a fill and drain graduated cylinder. Filtrate samples can be taken at the sampling valve (V6). The

²Measurement of the inside diameter of the filter with 3-pronged calipers revealed that the actual ID=0.475".

Figure 2.2 CUF Flow Diagram

slurry temperature is measured by a type J thermocouple installed in a temperature well in the slurry reservoir.

Filter back pulsing is conducted by opening the toggle valve (V3) and allowing the back pulse chamber to be filled with filtrate. The toggle valve is closed and the back pulse chamber is pressurized with air through a three way valve (V7). Once charged, the toggle valve is then opened allowing the pressurized filtrate to back pulse the filter element. After completing a run the system is drained through valves V2, V6, X1, and X2.

Upon receipt of the CUF, minor modifications were made by PNNL as follows:

- A cooling jacket was added to the outside of the slurry reservoir to control the slurry temperature because during simulant testing temperatures in excess of 80°C were observed;
- a single baffle was added to the slurry reservoir to prevent vortex formations observed in simulant testing;
- a larger Moyno pump (model SP-33304) with a nominal capacity of 7 gpm at 25 psig replaced the Moyno SP-23203 which had a nominal capacity of 4 gpm at 20 psig to permit testing at higher flowrates and transmembrane pressures;
- a 50 psig check valve replaced the 30 psig check valve to permit testing at higher transmembrane pressures;
- two drain valves were added to aid in draining between runs and thus minimize rinse volumes.

3.0 Results and Discussion

This section is arranged as follows. First the data from each of the four radioactive feeds tested are discussed individually and compared with pertinent simulant data. Then the data from the different runs are collectively reviewed and filtrate flux predictions using theoretical models are compared with the data. Finally filter performance data for the four different feeds are presented and discussed.

3.1 8 wt% Tank S-107 Slurry

Eleven conditions were established sequentially as shown in Table 3.1.

Table 3.1 Experimental Conditions

Condition	Axial Velocity (ft/s)	Transmembrane Pressure (psig)
Condition 1	6.0	20.0
Condition 2	7.5	27.5
Condition 3	3.0	20.0
Condition 4	6.0	5.0
Condition 5	7.5	12.5
Condition 6	6.0	20.0
Condition 7	4.5	27.5
Condition 8	6.0	35.0
Condition 9	4.5	12.5
Condition 10	9.0	20.0
Condition 11	6.0	20.0

Figure 3.1 displays the filtrate flux (gpm/ft²) for conditions 1, 6, and 11 as a function of time (minutes) since back pulse. One sees the typical flux decay as a function of time since back pulse. A striking result is that the flux at condition 11 is approximately 1/3 that of condition 1 or 6 indicating severe filter fouling that was not able to be cleared by means of a standard back

Figure 3.1 8 wt% Tank S-107: Filtrate Flux as a Function of Time (6 ft/s, 20 psig)

pulse. Inspection of the filtrate flux data (see Appendix C) indicate that back pulsing was unsuccessful at restoring the filtrate flux during and after condition 10. In fact the filtrate fouling was evident from the beginning of condition 10 as the flux rate declined noticeably during the first filtrate flux reading.

Poor back pulsing technique as a possible explanation for the flux decline is rejected because the same method was used successfully with the simulants. Improved back pulsing technique may be a means to improve filter performance, as no optimization has been attempted; however, the likelihood of back pulsing being the root cause of the sudden filtrate flux decline seems low. Increasing the back pulse pressure from 70 to 85 psig and duration by a factor of four did not improve the results of the back pulse.

A second explanation may be that air was entrained in the feed by means of a vortex in the feed reservoir and thereby blinding the filter. This explanation is unlikely as well. Vortexing in the feed reservoir was noted during shakedown testing, so a single baffle was installed and this problem was corrected prior to testing with simulants.

A third explanation is that the EPDM (ethylene-propylene-diene terpolymer) pump stator eroded causing filter blinding. Evidence for this explanation include the fact that the Tank C-

107 feed turned gray in color at the end of the testing.³ The pump stator is black EPDM, and small shavings from which would appear gray in a clear solution. However, one of the simulants (0.05 wt% S3 Simulant) also turned from white to grey during testing and no equivalent filtrate flux decline was measured.

In this author's opinion, the most likely hypothesis to explain the severe filtrate fouling during Conditions 10 and 11 is that high shear conditions broke up agglomerates thereby reducing the particle size and fouling the filter. Condition 10 is the highest shear condition and requires the highest pump rpm. A decrease in the filtrate flux was noted during the first reading of Condition 10. All subsequent flux readings were lower than expected.

Bunker (1995) reports of a semi-reversible shear breakdown of agglomerates induced by pumping which reduces 10 micron flocs to 2 micron flocs. While his data is from a simulant, it is suspected that actual tank waste exhibits similar behavior. If the primary particle diameter in the waste was smaller than the filter pore size, then such behavior explains the filter fouling. The agglomerate breakup in the actual tank waste, while induced at the highest shear conditions, appears to be partially reversible during subsequent conditions. The 1.5 wt% feed and the 0.05 wt% feed exhibited fouling at all conditions which makes sense because these feeds were diluted from the 8 wt% feed.

Avoiding the high shear conditions should significantly improve filtrate flux rates. Two obvious strategies are to limit shear by confining operating conditions or to acquire low shear equipment. The Moyno pump used in the CUF is a low shear pump, but perhaps a better pump exists. Such a pump would be of benefit because higher axial velocities reduce the cake thickness on the filter and generally improve filter performance.

Partial least squares regression of the mean filtrate flux (gpm/ft^2) between back pulses for each condition fitted to the average axial velocity and transmembrane pressure indicates that the goodness of fit, R^2 , equals 0.19 with all the data included. Removal of Conditions 10 and 11 from the fit dramatically improves the R^2 to 0.72. Conditions 10 and 11 were excluded from the current model in order to prevent filter fouling from skewing the relationships between axial velocity and transmembrane pressure on filtrate flux.

The surface response plot which displays mean filtrate flux (gpm/ft^2) as a function of average axial velocity and transmembrane pressure is shown in Figure 3.2. One can see that the filtrate flux is a strong function of both axial velocity and transmembrane pressure. As mentioned, the fit for this two parameter linear model is fairly good and R^2 , which measures the variation around the mean explained by the model, is equal to 0.72. Leverage plots, located in Appendix D, indicate the axial velocity and transmembrane pressure are both

³ It is unlikely that the faint gray color would be seen in any of the Tank S-107 feeds as the gray color would be masked by the slurry color. Since the gray was seen in Tank C-107, it is suspected that it was also present, but not seen, in the other feeds as well.

Figure 3.2 8 wt% Tank S-107: Surface Response Plot Displaying Filtrate Flux as a Function of Velocity and Pressure

statistically significant in predicting the mean filtrate flux.

Figure 3.3a displays a plot of mean filtrate flux (gpm/ft^2) as a function of velocity. Mean filtrate flux values were adjusted with the partial least squares regression model to compensate for measurements at conditions other than 20 psig transmembrane pressure. The filtrate flux dependency on axial velocity is approximately linear over the range tested. Some data scatter is evident but not unexpected based on simulant cold testing. The scatter is not near the magnitude observed during condition 10 and 11, as can be seen by reviewing Figure 3.3b, which shows the same plot with Conditions 10 and 11 included.

Figure 3.3a 8 wt% Tank S-107: Filtrate Flux as a Function of Axial Velocity (Condition 10 and 11 excluded)

Figure 3.3b 8 wt% Tank S-107: Filtrate Flux as a Function of Axial Velocity

Likewise Figure 3.4a displays a plot of mean filtrate flux (gpm/ft^2) as a function of transmembrane pressure. Mean filtrate flux values were adjusted with the partial least squares regression model to compensate for measurements at conditions other than 6 ft/s. The data shown in the figure corresponds to that reported by other researchers (e.g., Porter 1972) where the filtrate flux loses dependency on the transmembrane pressure as the pressure increases beyond a certain critical value. For the 8 wt% Tank S-107 (at 6 ft/s axial velocity) pressure above 20 psig does not increase the filtrate flux, as the flux is controlled by mass transport away from the media. Without increasing J_{mt} , pressure increases merely cause the cake resistance to increase. Figure 3.4b shows the same data with Conditions 10 and 11 included.

Figure 3.4a 8 wt% Tank S-107: Filtrate Flux as a Function of Transmembrane Pressure
(Condition 10 and 11 excluded)

Figure 3.4b 8 wt% Tank S-107: Filtrate Flux as a Function of Transmembrane Pressure

3.1.1 Comparison with 8 wt% Simulant Data

Two 8 wt% simulants were tested prior to installing the CUF in the hot cell. The first simulant was composed of a 9:1 mass ratio of gibbsite to boehmite in 0.1 M NaOH (Simulant S3). The second was primarily composed of ferric hydroxide (Simulant S103). See Appendix B for recipes.

Figures 3.5a and 3.5b displays the filtrate flux (gpm/ft^2) for Conditions 1, 6, and 11 as a function of time (minutes) since back pulse for simulants S3 and S103, respectively. For both simulants the filtrate flux was approximately the same for each of the three conditions displayed. Contrast this to the severe filtrate flux decline noted in Condition 11 for the Tank S-107 waste (refer to Figure 3.1). Thus, one major difference between the simulant and the actual waste is that the simulant was not shear sensitive at the conditions tested, while the actual waste was.

Figure 3.5a 8 wt% S3 Simulant: Filtrate Flux as a Function of Time (6 ft/s, 15 psig)

Figure 3.5b 8 wt% S103 Simulant: Filtrate Flux as a Function of Time (6 ft/s, 15 psig)

Table 3.2 displays the nominal filtrate flux for the 8 wt% Tank S-107 waste and the S3 and S103 simulants at 6 ft/s and 20 psig. The filtrate flux for the actual waste fell between the two simulants tested.

Table 3.2 Comparison of Filtrate Flux Rates at 6 ft/s and 20 psig

	Nominal Filtrate Flux (gpm/ft ²) at 6 ft/s Axial Velocity and 20 psig transmembrane pressure
8 wt% S-107 Waste	0.045
8 wt% S3 Simulant	0.060
8 wt% S103 Simulant	0.035

Figures 3.6a and 3.6b display the filtrate flux (gpm/ft^2) as a function of axial velocity, for simulants S3 and S103, respectively. Mean filtrate flux values were adjusted for conditions other than 15 psig transmembrane pressure. The filtrate flux dependence on axial velocity is less for the S3 simulant (Figure 3.6a) than for the actual waste (Figure 3.3a). Simulant S103 and the actual waste had similar filtrate flux dependency on axial velocity over the range tested. The best fit line slope for the S103 simulant was 0.00546 vs. 0.00672 for the actual waste, while the slope for the S3 simulant was much less, 0.00269.

Figures 3.7a and 3.7b display the mean filtrate flux (gpm/ft^2) as a function of transmembrane pressure for simulants S3 and S103, respectively. Mean filtrate flux values were adjusted for conditions other than 6 ft/s. The data shown in figure 3.7b (S103 Simulant) corresponds well with the actual waste where the filtrate flux loses dependency on the transmembrane pressure as the pressure increases beyond a certain critical value. For the 8 wt% Tank S-107 (at 6 ft/s axial velocity) pressure above 20 psig does not increase the filtrate flux, while for the S103 simulant the pressure may be closer to 15 psig. The functionality of the S3 simulant, as seen in Figure 3.7a is different than the actual waste. In the range tested there is no point at which the filtrate flux loses dependency on the transmembrane pressure. One might speculate from looking at Figure 3.7a that the flux dependency on transmembrane pressure is lost around 25 psig, but without further testing the critical pressure cannot be definitively stated.

In conclusion the two simulants seem to bound the actual waste. Simulant S3 had a higher critical pressure than the actual waste, and different pressure/velocity relationships with filtrate flux. In addition, simulant S3 had a higher filtrate flux rate than did the actual waste at the same conditions. On the other hand, simulant S103 had a lower critical pressure than the actual waste, while the displayed pressure/velocity relationships with filtrate flux were similar. The S103 simulant filtrate flux was lower than the actual waste at the same conditions. One may conclude that of the two simulants, S103 appears to mimic Tank S-107 waste the closest at 8 wt% solids loading. However, neither simulant mimicked the fouling evident in the actual waste.

Figure 3.6a 8 wt% S3 Simulant: Filtrate Flux as a Function of Axial Velocity

Figure 3.6b 8 wt% S103 Simulant: Filtrate Flux as a Function of Axial Velocity

Figure 3.7a 8 wt% S3 Simulant: Filtrate Flux as a Function of Transmembrane Pressure

Figure 3.7b 8 wt% S103 Simulant: Filtrate Flux as a Function of Transmembrane Pressure

3.2 1.5 wt% Tank S-107 Slurry

Based on the 8 wt% feed data, significant filter fouling was expected. The nature of the fouling may provide insight as to the reversibility of the shear induced deagglomeration. Three main possibilities exist:

- If the breakup of agglomerates discussed in the Section 3.1 was irreversible, then we would expect to see a significant and immediate filter fouling of the 1.5 wt% slurry as this feed was diluted from an 8 wt% sample.
- If the break up of agglomerates was reversible we would expect a data set similar to the 8 wt% feed, where the worst fouling occurred at the most extreme shear.
- If the breakup of agglomerates was partially reversible we may expect to see significant filtrate flux decline as the pump shears particles that, having already been sheared apart, are more susceptible to shear induced deagglomeration.

Figure 3.8 seems to indicate that the last possibility is correct. Plotted are mean filtrate flux (gpm/ft^2) at the first, middle, and last condition all tested at 6 ft/s and 25 psig.⁴ The filtrate flux for Condition 1 is higher for the 1.5 wt% slurry than the 8 wt% slurry, indicating the filter was at least partially cleared between runs. As the solids concentration goes down in the feed, higher flux rates are expected. Since the flux decline between conditions is greater than that observed in simulant testing or seen in Figure 3.1 (Condition 1 and 6), it is evident that filter fouling is still a problem.

Partial least squares regression of the mean filtrate flux (gpm/ft^2) between back pulses for each condition fitted to the average axial velocity and transmembrane pressure indicates that the goodness of fit, R^2 , equals 0.17 with all the data included. Since the flux declined more or less gradually, the order in which the data were gathered was included as a parameter in the model. Including run order dramatically improves the R^2 for the model to 0.77. Therefore run order as a parameter was included in the current model in order to separate the effects of filter fouling from those of axial velocity and transmembrane pressure on the filtrate flux rate.

The surface response plot which displays mean filtrate flux (gpm/ft^2) as a function of average axial velocity and transmembrane pressure is shown in Figure 3.9. One can see that the filtrate flux is a strong function of transmembrane pressure, while almost independent of axial velocity. In fact the model indicates that the flux is actually a slightly negative function of the axial velocity, which could be explained if higher velocities induced shear deagglomeration, as suspected. Details of the entire model, including leverage plots, are located in Appendix D.

⁴ Condition 1 data were taken at 6 ft/s and 20 psig due to operator error. Therefore filtrate flux data plotted for condition 1 were modified to reflect 25 psig by applying the model described.

Figure 3.8 1.5 wt% Tank S-107: Filtrate Flux as a Function of Time (6 ft/s, 25 psig)

Figure 3.9 1.5 wt% Tank S-107: Surface Response Plot Displaying Filtrate Flux as a Function of Velocity and Pressure

Figure 3.10 displays a plot of mean filtrate flux (gpm/ft²) as a function of transmembrane pressure. Mean filtrate flux values were adjusted to compensate for run order (standardized to condition 6) and for axial velocities other than 6 ft/s. The filtrate flux data shown in the figure are approximately linear with pressure indicating that the data was taken below the critical pressure, at which the filtrate flux is pressure independent. These results correspond well to the literature in that it is known as the amount of solids in the slurry decreases the critical pressure increases. Thus, under these conditions the filtrate flux is controlled by Darcy's equation (Equation 2) rather than being limited by back mass transport (as described in Equation 1). Optimization testing should be conducted at higher transmembrane pressure in order to determine when filtrate flux and transmembrane pressure become independent.

Figure 3.11 displays a plot of mean filtrate flux (gpm/ft²) as a function of velocity. Mean filtrate flux values were adjusted to compensate for run order (standardized to Condition 6) and for transmembrane pressures other than 25 psig. Clearly there is no evident filtrate flux dependency on axial velocity. The model indicated that the axial velocity is not statistically significant in its ability to describe the variations in filtrate flux, and that result is borne out by review of Figure 3.11. Although the filtrate flux was described by the model as a slightly negative function of the axial velocity these results should be considered with caution, as some scatter in the data is evident.

Figure 3.10 1.5 wt% Tank S-107: Filtrate Flux as a Function of Transmembrane Pressure

Figure 3.11 1.5 wt% Tank S-107: Filtrate Flux as a Function of Axial Velocity

3.3 0.05 wt% Tank S-107 Slurry

Figure 3.12 is a plot of the mean filtrate flux (gpm/ft^2) at the first, middle, and last condition tested (all at 6 ft/s and 25 psig) as a function of time (minutes) after back pulse. As was seen for the 1.5 wt%, the flux decline is greater than that observed in simulant testing and it is evident that the deagglomeration is a problem. The filtrate flux for Condition 1 is less than that measured for the 1.5 wt% slurry at the same condition, indicating that filter fouling was immediate or the filter was not restored to its original condition between runs.

Partial least squares regression of the mean filtrate flux between back pulses for each condition fitted to the average axial velocity and transmembrane pressure indicates that the goodness of fit, R^2 , equals 0.59 with all the data included. Since the flux declined more or less gradually, the order in which the data were gathered was included as a parameter in the model. Including run order improves the R^2 for the model to 0.94. Therefore run order as a parameter was included in the current model in order to separate the effects of filter fouling from those of axial velocity and transmembrane pressure on the filtrate flux rate.

The surface response plot which displays mean filtrate flux (gpm/ft^2) as a function of average axial velocity and transmembrane pressure is shown in Figure 3.13. One can see that the filtrate flux is a strong function of transmembrane pressure, while almost independent of axial velocity. Both transmembrane pressure and run order were statistically significant in their ability to predict variation in the mean filtrate flux. As was the case for the 1.5 wt% slurry, axial velocity is only marginally significant. Details of the entire model, including leverage plots, are located in Appendix D.

Figure 3.12 0.05 wt% Tank S-107: Filtrate Flux as a Function of Time (6 ft/s, 25 psig)

Figure 3.13 0.05 wt% Tank S-107: Surface Response Plot Displaying Filtrate Flux as a Function of Velocity and Pressure

Figure 3.14 displays a plot of mean filtrate flux (gpm/ft²) as a function of transmembrane pressure. Mean filtrate flux values were adjusted to compensate for run order (standardized to Condition 6) and for axial velocities other than 6 ft/s. The filtrate flux data shown in the figure is approximately linear with pressure indicating that the data was taken below the critical pressure, at which the filtrate flux is pressure independent. Thus, under these conditions the filtrate flux is controlled by Darcy's equation (Equation 2) rather than being limited by back transport (as described in Equation 1). Optimization testing should be conducted at higher transmembrane pressure in order to determine when filtrate flux and transmembrane pressure become independent.

Figure 3.15 displays a plot of mean filtrate flux (gpm/ft²) as a function of velocity. Mean filtrate flux values were adjusted to compensate for run order (standardized to Condition 6) and for transmembrane pressures other than 25 psig. There is no clearly evident filtrate flux dependency on axial velocity indicating that the velocity was sufficient in removing filter cake. A mean fit line and a linear fit line are included in the figure to illustrate the fact that the filtrate flux is virtually independent of axial velocity at these conditions. Therefore, higher filtrate flux is not achievable without increasing transmembrane pressure, at which point theory tells us that filtrate flux will become a strong function of velocity.

Figure 3.14 0.05 wt% Tank S-107: Filtrate Flux as a Function of Transmembrane Pressure

Figure 3.15 0.05 wt% Tank S-107: Filtrate Flux as a Function of Axial Velocity

3.3.1 Comparison with Simulant Data

Two 0.05 wt% simulants were tested prior to installing the CUF in the hot cell. The first simulant was composed of a 9:1 mass ratio of gibbsite to boehmite in 0.1 M NaOH (Simulant S3). The second was primarily composed of ferric hydroxide (Simulant S103). See Appendix B for recipe.

Figures 3.16a and 3.16b display the filtrate flux for Conditions 1, 6, and 11 as a function of time (minutes) since back pulse for simulants S3 and S103, respectively. For both simulants the filtrate flux was approximately the same for each of the three conditions displayed (i.e., no filtrate flux decline with time is evident). Contrast this to the severe filtrate flux decline noted in Condition 11 for the Tank S-107 waste (refer to Figure 3.12). Thus, one major difference between the simulant and the actual waste is that the simulant was not shear sensitive at the conditions tested, while the actual waste was.

Figure 3.16a 0.05 wt% S3 Simulant: Filtrate Flux as a Function of Time (6 ft/s, 15 psig)

Figure 3.16b 0.05 wt% S103 Simulant: Filtrate Flux as a Function of Time (6 ft/s, 15 psig)

Because the two simulants were not shear sensitive, their filtrate flux rates did not decay with time as noted for the actual waste. This result is evident in reviewing the partial least squares regression of the mean filtrate flux between back pulses for each condition fitted to the average axial velocity, transmembrane pressure, and (optionally) run order. Table 3.3 displays the R^2 for models with and without run order in the model. For simulants, run order has a very minor effect in the model's ability to predict filtrate flux. Contrasted with the actual waste, where run order is a very important model parameter.

Table 3.3 Comparison of Model R² With and Without Run Order as a Parameter

Feed	Model R ² using Axial Velocity and transmembrane pressure, Only	Model R ² using Axial Velocity, transmembrane pressure, and Run Order
0.05 wt% S3 Simulant	0.98	0.98
0.05 wt% S103 Simulant	0.95	0.97
0.05 wt% S-107 Waste	0.59	0.94

Table 3.4 displays the nominal filtrate flux for the 0.05 wt% Tank S-107 waste and the S3 and S103 simulants at 6 ft/s and 25 psig. The filtrate flux for the actual waste was 1/3 to 1/5 the value of the two simulants tested. This result is surprising especially when compared to the 8 wt% data where the simulants bound the flux rates of the actual waste. This lower than expected filtrate flux for the actual waste is likely an artifact of the shear sensitivity of the Tank S-107 waste. The data in Table 3.4 indicate that chemical cleaning may be necessary to properly restore the filtrate flux.

Table 3.4 Comparison of Filtrate Flux at 6 ft/s Axial Velocity and 25 psig Transmembrane Pressure

Feed	Nominal Filtrate Flux (gpm/ft ²)
0.05 wt% S-107 Waste	0.04
0.05 wt% S3 Simulant	0.21
0.05 wt% S103 Simulant	0.12

Figures 3.17a and 3.17b display the filtrate flux (gpm/ft²) as a function of axial velocity for simulants S3 and S103, respectively. Mean filtrate flux values were adjusted for conditions other than 15 psig transmembrane pressure. The two simulants displayed no filtrate flux dependency on axial velocity. This is the same result seen for the actual waste (see Figure 3.15).

Figure 3.17a 0.05 wt% S3 Simulant: Filtrate Flux as a Function of Axial Velocity

Figure 3.17b 0.05 wt% S103 Simulant: Filtrate Flux as a Function of Axial Velocity

Figure 3.18a and 3.18b display the mean filtrate flux as a function of transmembrane pressure for simulants S3 and S103, respectively. Mean filtrate flux values were adjusted for conditions other than 6 ft/s. The two simulants displayed a linear filtrate flux dependency on axial velocity. This is the same result seen for the actual waste (see Figure 3.13). These data indicate that at low solids concentration, the transmembrane pressure should be higher than that tested.

In conclusion, while the two simulants displayed similar filtrate flux functionality to axial velocity and transmembrane pressure, the actual filtrate flux rate of the simulant was 3 to 5 times that seen for the actual waste. This result is in contrast to the 8 wt% slurry where the two simulants bound the filtrate flux rate of the actual waste. Fouling is suspected of causing the lower than expected flux rates for the 0.05 wt% Tank S-107 slurry.

Figure 3.18a 0.05 wt% S3 Simulant: Filtrate Flux as a Function of Transmembrane Pressure

Figure 3.18b 0.05 wt% S103 Simulant: Filtrate Flux as a Function of Transmembrane Pressure

3.4 Tank C-107 Supernatant

Figure 3.19 is a plot of the mean filtrate flux at the first, middle, and last condition tested (all 6 ft/s and 25 psig) as a function of time (minutes) after back pulse. The filtrate flux rate is approximately 5 times the rate observed for the 0.05 wt% slurry at similar conditions. The solids concentration in the C-107 was very low and solids were not visible to the eye. Higher filtrate flux rates are consistent with lower solids loading.

The flux decline observed as the run progressed was greater than simulant testing, but less than the 1.5 wt% and 0.05 wt% slurries. Table 3.5 shows the ratio of the mean filtrate flux at the first condition to the mean filtrate flux at the last condition tested.

Figure 3.19 Tank C-107 Supernatant: Filtrate Flux as a Function of Time (6 ft/s, 25 psig)

Table 3.5 Filtrate Flux Decline Observed for Various Feeds

Feed	Mean Filtrate Flux (Condition 1)/Mean Filtrate Flux (Condition 11)
8 wt% S-107	3.0
1.5 wt% S-107	3.5
0.05 wt% S-107	2.2
C-107 Supernatant	1.7
8 wt% S3 Simulant	0.94
8 wt% S103 Simulant	0.98
0.05 wt% S3 Simulant	0.92
0.05 wt% S103 Simulant	1.1

Tank C-107 supernatant feed, unlike the 8 wt% S-107 feed, did not have a sudden drop in filtrate flux. Rather the flux decline was gradual, as was observed for the 1.5 wt% and 0.05 wt% S-107 feeds (which were diluted from the 8 wt% feed and, consequently, would not necessarily display a sudden decline with shear if the deagglomeration was partially reversible). The flux decline exhibited in Figure 3.19, therefore, came as a surprise and cannot be readily explained. Possible explanations follow:

1. Tank C-107 gradually deagglomerated and caused filtrate fouling. This explanation is thought to be unlikely because prior to running the C-107 supernatant feed was clear to the eye. After running in the CUF the feed was cloudy indicating particulate in the feed. The visible particulate in the feed after testing is thought to be the result of pump stator erosion or S-107 solids which were not removed during the rinse.

2. The drop in filtrate flux was due to solids from erosion of the pump stator. Evidence for this explanation includes a) an increase in the TOC level of the C-107 feed after testing in the CUF relative to that prior to testing, and b) laboratory notes of a gray colored feed at the end of testing while at the beginning it was clear. The pump stator is composed of black EPDM rubber and fine shavings would appear gray in clear solution. While this tendency towards gray while running was not noticed for the other radioactive feeds it was noted for the 0.05 wt% S3 simulant. Evidence against EPDM rubber shaving causing the fouling is although the 0.05 wt% S3 Simulant turned gray during testing (indicating the presence of EPDM shavings), filter fouling was not experienced.

3. The rinse did not completely remove the S-107 feed. The C-107 feed was tested immediately after the 0.05 wt% S-107 feed. If tank S-107 solids hung up in the CUF and were not completely rinsed from the CUF, fouling would occur. The feed was clear during the first few conditions so if this explanation is correct a very small amount of solids caused the fouling. One of the reasons we tested from the most concentrated to the most dilute feed was to help rinse solids from the CUF while minimizing waste generated from rinse solutions. The 0.05 wt% slurry was rinsed three times prior to the introduction of the Tank C-107 supernatant feed.

Partial least squares regression of the mean filtrate flux between back pulses for each condition fitted to the average axial velocity and transmembrane pressure indicates that the goodness of fit, R^2 , equals 0.73. Since the flux declined more or less gradually, the order in which the data were gathered was included as a parameter in the model. Including run order improves the R^2 for the model to 0.92. Therefore run order as a parameter was included in the current model in order to separate the effects of filter fouling from those of axial velocity and transmembrane pressure on the filtrate flux rate.

The surface response plot which displays mean filtrate flux (gpm/ft²) as a function of average axial velocity and transmembrane pressure is shown in Figure 3.20. One can see that the filtrate flux is a strong function of transmembrane pressure, while slightly negative in its dependence on axial velocity. Transmembrane pressure, run order, and axial velocity were all statistically significant in their ability to predict variation in the mean filtrate flux. Details of the entire model, including leverage plots, are located in Appendix D.

Figure 3.21 displays a plot of mean filtrate flux (gpm/ft²) as a function of transmembrane pressure. Mean filtrate flux values were adjusted to compensate for run order (standardized to Condition 6) and for axial velocities other than 6 ft/s. The filtrate flux data shown in the figure is approximately linear with pressure indicating that the data was taken below the critical pressure, at which the filtrate flux is pressure independent. Thus, under these conditions the filtrate flux is controlled by Darcy's equation (Equation 2) rather than being limited by back transport (as described in Equation 1). Optimization testing should be conducted at higher transmembrane pressure in order to determine when filtrate flux and transmembrane pressure become independent.

Figure 3.20 Tank C-107 Supernatant: Surface Response Plot Displaying Filtrate Flux as a Function of Velocity and Pressure

Figure 3.22 displays a plot of mean filtrate flux (gpm/ft^2) as a function of velocity. Mean filtrate flux values were adjusted to compensate for run order (standardized to Condition 6) and for transmembrane pressures other than 25 psig. Clearly increased axial velocity does not increase filtrate flux. The best fit line has a negative slope indicating that, for this feed, filtrate flux is a negative function of velocity. A possible explanation is that higher velocities caused more deagglomeration due to increased shear. Although the filtrate flux was described by the model as a negative function of the axial velocity these results should be considered with caution as some scatter in the data is evident.

Figure 3.21 Tank C-107 Supernatant: Filtrate Flux as a Function of Transmembrane Pressure

Figure 3.22 Tank C-107 Supernatant: Filtrate Flux as a Function of Axial Velocity

3.5 Comparison of Feeds

Figure 3.23 displays the filtrate flux as a function of transmembrane pressure for all the wastes tested and deionized water. The filtrate flux dependence on pressure is linear for all feeds except the 8 wt% S-107 indicating that operations were primarily in Regime I. The lines shown are constrained such that their intercept is the origin, as no flux is expected without pressure. Typically for such a plot, the more dilute feeds have a greater slope. At sufficiently high pressures, all feeds with solids will lose their filtrate flux pressure dependency. However we see that the flux rates for the 1.5 wt% and 0.05 wt% S-107 feeds are approximately the same as the 8 wt% feed. Filter fouling is suspected of causing the low filtrate fluxes.

The filtrate flux rate of deionized water is useful because it bounds the flux rate for fluids of the same viscosity. Data from the deionized water can also be used to determine the filter media resistance. Recall Darcy's pressure filtration equation:

$$J = P / \mu (R_{\text{total}})$$

where $R_{\text{total}} = R_{\text{media}} + R_{\text{fouling}} + R_{\text{cake}}$.

Hence in a plot of J vs. P the slope is $1/\mu(R_{\text{total}})$. For water, R_{fouling} and R_{cake} are assumed to be zero and all filtration resistance is from the media. For our case, the CUF filter media resistance, R_{media} , is equal to 1×10^{12} 1/meter.

Resistance due to fouling has been shown to be a function of time. Nevertheless it may be useful to estimate R_{fouling} for a particular time.⁵ The filtrate flux data for the 0.05 wt% slurry was linear with pressure indicating that Darcy's equation is applicable. Since higher velocity did not cause the filtrate flux to increase, we may be justified in assuming that R_{cake} was small compared with R_{media} and R_{fouling} . Doing so we find that the media resistance due to fouling is estimated at 7×10^{12} 1/m, for the conditions plotted. Thus the filtration resistance due to fouling is approximately 7 times the resistance due to the filtration media.

Also looking at the plot we see that the filtrate flux for the 8 wt% slurry is as much or more than the 0.05 wt% slurry, indicating that R_{fouling} (for the 0.05 wt% slurry) is the same order of magnitude as R_{cake} (for the 8 wt% slurry). (Recall that for the 8 wt% slurry significant fouling did not occur until Condition 10 and 11 and those two conditions were not included in the modeling of the data.)

Murkes and Carlsson (1988) report that filter media with larger pores facilitate the penetration

⁵ The data shown for the 0.05 wt% slurry have been adjusted to condition 6 by applying parameters from the partial least squares model discussed in Section 3.3.

Figure 3.23 Filtrate Flux Rates as a Function of Transmembrane Pressure

of small particles in the pores and, therefore, promote internal clogging. Opposite to what is normally valid in traditional filtration, more open media usually yield—after a certain initial time—a lower filtrate flux due to a higher degree of internal clogging.

These data suggest that exploring smaller pore sizes (e.g., 0.2 micron) may be appropriate in light of the fact that R_{cake} for the 8 wt% slurry is the same order of magnitude as $R_{fouling}$ for the 0.05 wt% slurry. If the deagglomerated particles in the feed are bigger than the filter pore size available, then a new filter media is recommended. If not, the best alternative to prevent fouling may be to avoid exposure of the feed to high shear unit operations. In either case the goal of keeping the resistance due to filter fouling low is the same.

3.5.1 Foaming

During testing of the 1.5 wt% S-107 feed, foaming was encountered at the two most extreme shear conditions:

- 6 ft/s axial velocity and 40 psig transmembrane pressure
- 9 ft/s axial velocity and 25 psig transmembrane pressure.

Foam came up out of the sight glass and onto the drip pan. It was estimated that 10 to 20 ml of feed was lost during the foaming conditions. The foaming that occurred during the 9 ft/s, 25 psig condition was so severe that the testing at this condition was stopped after 30 minutes (after the first back pulse). During the severe foaming it was very difficult to maintain the axial velocity at set point. As the feed foamed, it required higher pump rpm to maintain set point. But the higher pump rpm cause more foaming. For this reason the 9ft/s, 25 psig condition was aborted after 30 minutes.

The 0.05 wt% S-107 feed also foamed at 9 ft/s and 25 psig; however the foaming noted was significantly less, and perhaps 2 or 3 ml of foam came out of the sight glass at this condition. A method used to reduce foaming loses was to plug off the top of the sight glass. The small pressure generated by the foam rising against the plug was enough to significantly dampen the volume of foam lost.

Foaming has been reported for other Hanford feeds as well. For example, recently (August 1996) approximately a liter of C-106 sludge was leached with 3 M NaOH. When this feed was pumped around to homogenize the feed prior to settling, foaming was noted. Questions into foaming of the C-106 sludge should be directed toward KP Brooks of PNNL.

The 8 wt% S-107 feed and the C-107 supernatant did not foam at any condition tested.

3.5.2 Filter Cleaning

After testing the CUF filter was cleaned by running the system with 2 wt% oxalic acid for one hour. The acid cleaning cleared all filter fouling and the DI water filtrate flux rates were higher than those rates measured when the CUF was first put in the hot cell.

3.6 Modeling

Porter's gel polarization model (Equation 4) and Zawaicki's lift model (Equation 5) are developed to model Regime II where filtrate flux is independent of pressure. Of the radioactive feeds tested, only the 8 wt% S-107 data was gathered in Regime II. Therefore it is appropriate to compare these two models with the 8 wt% S-107 data only.

Figure 3.24 shows 8 wt% S-107 experimental data (taken from Figure 3.3a) plotted against theoretical predictions of the Porter and Zawaicki models. All parameters used in these models were derived from measurements from the 8 wt% S-107 slurry with one exception. The vol% solids in the filter cake was not measured in the radioactive waste. However, it was measured in the S103 simulant which best mimicked the S-107 filtration behavior at 8 wt%. The following lists the parameters used: $\mu = 0.73$ cp, $D_p = 0.5$ micron, $\rho_L = 1.04$ g/ml, $d_h = 0.475$ cm, temperature 32 °C, $C_B = 0.041$, $C_w = 0.55$, $\lambda = 1.7$.

The shear rate was estimated by assuming a velocity profile of a turbulent Newtonian fluid. It was further assumed that the turbulent core gives way to a boundary layer at a radius 0.05R (Bird et al. 1960, Figure 5.1-1). This boundary layer is responsible for most of the shear. The shear rate is approximated as the fluid velocity at 0.05R divided by the distance from the wall (0.05R). This estimate makes several assumptions which may not be rigorously correct for the slurry. Nevertheless the calculation is thought to provide a good first order shear estimate.

Figure 3.24 shows that both models underpredict the data in the range from 3 to 9 ft/s axial velocity. Porter's diffusion model gives the correct dependence on shear rate; however, the flux is low by a factor of 10. This result is in agreement with the literature which states that this model frequently underpredicts data by as much as an order of magnitude. The Zawaicki lift model gives a greater shear dependence than observed. Nevertheless, of the two models the Zawaicki lift model best predicts the experimental data for the 8 wt% S-107 feed.

Figure 3.24 8 wt% S-107 Data Compared with Theoretical Predictions from Models

Scarlett and Treasure's model (Equation 6) was developed for both the pressure dependent and pressure independent regimes and could be compared with all radioactive feeds; however, comparison with the experimental data is difficult because the filter resistance due to fouling was continually increasing. In addition, the cake permeability was not measured. Nevertheless useful insight may be made by fitting the model with actual data.

Two parameters were fit to the 8 wt% S-107 data: the filter resistance (which is the sum of the constant media resistance, R_{media} , and the variable fouling resistance, $R_{fouling}$) and the cake permeability (K). The cake permeability obtained from the 8 wt% S-107 was assumed to be constant⁶ and used in all subsequent data modeling. Hence for the 1.5 wt% S-107, 0.05 wt%

⁶The basis for this assumption is sound for filter cakes composed from the same feed. However this assumption was also used for C-107 feed and deagglomerated S-107 feed (which is essentially a different feedstock because deagglomeration will likely effect cake permeability). Nevertheless the assumption is sufficient for our purposes here and is considered to be better than the alternative of fitting a two parameter model to each data set.

Table 3.6 Best Fit Parameters used in the Scarlett and Treasure Model

Feed	Total Filter Resistance (1/m)	Cake Permeability (m ²)
8 wt% S-107	6.1×10^{11}	1.04×10^{-13}
1.5 wt% S-107	51.3×10^{11}	#
0.05 wt% S-107	79.4×10^{11}	#
C-107 Supernatant	24.2×10^{11}	#
8 wt% S103 Simulant	7.3×10^{11}	8.23×10^{-14}

- The cake permeability was not fit to the data for this feed. A constant value of 1.04×10^{-13} was used.

S-107, and C-107 supernatant data sets, Scarlett and Treasure's model was best fit to the data from each feed by adjusting the filter resistance only. Table 3.6 shows the best fit parameters obtained for each feed, including an 8 wt% S103 simulant feed whose data was fit in the same manner as the 8 wt% S-107 data (i.e., it was fit with two parameters). The simulant data was modeled for comparison purposes.

The total filtration resistances obtained from fitting the model are lower than those obtained in Section 3.5. Recall that the filter resistance was determined to be 1×10^{12} (1/m) with deionized water prior to testing. The value of filter resistance (6.1×10^{11} (1/m)) obtained from the Scarlett and Treasure model of the 8 wt% S-107 data is within a factor of 2 to that obtained for the 8 wt% simulant. According to the Scarlett and Treasure model, the total filter resistance increased for the 1.5 wt% S-107 feed and continued to increase for the 0.05 wt% S-107 feed, where as the total filter resistance reaches 13 times that of the 8 wt% S-107 feed. Qualitatively these results are consistent with the hypothesis of feed deagglomeration. The C-107 supernatant total filter resistance is 4 times that of the 8 wt% S-107 feed indicating that the fouling may have been partially cleared by back pulsing and rinsing.

The ease of filtration is directly related to the magnitude of the cake permeability, K. Table 3.7 provides some meaning to the magnitude of the cake permeability in a qualitative manner.

Table 3.7 Qualitative Assessment of Cake Permeability Values (Tiller and Anderson, 1994)

Ease of Filtration	Cake Permeability (m^2)
very easy	10^{-12}
easy	10^{-13}
moderate	10^{-14}
difficult	10^{-15}
very difficult	10^{-16}

Thus the Scarlett and Treasure model indicates that the cake permeability of the 8 wt% S-107 feed ($1.04 \times 10^{-13} \text{ m}^2$) is easy to filter, while the 8 wt% S103 simulant is moderately difficult to filter. In contrast the cake permeability of the S103 simulant was measured in the lab to be $1.3 \times 10^{-17} \text{ m}^2$, which is three orders of magnitude lower than that estimated by the model. The lab value obtained is consistent with the observation that a mere 1" cake of the S103 simulant would completely restrict flow through the pressure filter at 30 psig.

The value measured in the lab for the S103 simulant cake permeability ($1.3 \times 10^{-17} \text{ m}^2$) was tried in the Scarlett and Treasure and fit to the data; however, the resulting best fit for total resistance was not reasonable, as the value was negative. This result suggests that the cake thickness, L , calculated in the Scarlett and Treasure model is too high, thereby forcing the fit for the permeability to be too high as well. Indeed, inspection of the cake thickness, L , as a function of pressure reveals that the Scarlett and Treasure model calculates filter cake thicknesses larger than the pipe diameter. This result may explain why the model predicts permeabilities three orders of magnitude higher than that measured in the lab.

Figures 3.25 through 3.27 show the Scarlet and Treasure theoretical predictions plotted against experimental data for the 4 radioactive feeds and the 8 wt% S103 simulant.⁷

⁷ Data plotted in Figures 3.25 through 3.29 were taken from Figures 3.4a, 3.10, 3.14, 3.21, and 3.7b (respectively) at 6 ft/s axial velocity.

Figure 3.25 Scarlett and Treasure Model fit to 8 wt% S-107 Data

Figure 3.26 Scarlett and Treasure Model fit to 1.5 wt% S-107 Data

Figure 3.27 Scarlett and Treasure Model fit to 0.05 wt% S-107 Data

Figure 3.28 Scarlett and Treasure Model fit to C-107 Supernatant Data

Figure 3.29 Scarlett and Treasure Model fit to 8 wt% S103 Simulant Data

Despite the model's problems with the cake permeability and cake thickness, the Scarlett & Treasure model is of a form which can be fit well to all the experimental data. In every case both the pressure dependency and the flux rate can be matched to the data. It is doubtful, however, if such excellent agreement with the experimental data could be obtained without fitting the data. It has been shown that the model overcalculates the cake thickness and therefore overpredicts the cake permeability. Although the Scarlett and Treasure model may not give quantitatively exact results without fitting the data, it does seem to qualitatively describe the phenomena of cross flow filtration.

3.7 Analytical Results

The original intent of the radionuclide testing was to measure the radionuclide content for TRU, Sr, Cs, and Tc at the four extreme conditions and the center processing condition in the experimental test matrix. An analytical technique had been previously developed to support the one-liter enhanced sludge washing pilot plant to measure the colloidal and radionuclide properties of supernatants. This technique involved filtrate of the samples through two stages of millipore filtration to determine how much of the activity is from the solids, how much is due to the liquids, and how much is due to any radionuclide species that might adsorb onto the millipore filter element themselves.

This technique was expected to work equally well for the cross flow filtrate samples. However, the analytical testing in the hot colloids laboratory consumed more sample than anticipated. Consequently, there was not sufficient volumes of the samples to complete the analyses as originally planned and the available samples were composited for analysis.

3.7.1 Analytical Chemical Laboratory Results

Alpha/TRU

Samples of the filtrate feed and the composited filtrates sample were submitted for gross alpha according to PNL-ALO-4001 and PNL-ALO-421 (alpha counting) analysis. Preparation blanks, spiked blanks, and direct spiked samples were submitted. The spike recoveries are within the expected recovery range for the method tested. The feed values are directly reported from the radionuclide analyses. The filtrate values are calculated by adding the activity on the millipore filtration filters to the activity of the millipore filtration filtrates (see Table 3.8). A range of filtrate activities and decontamination factors is shown. The lower limit was determined by assuming that if the detection level was reached the value was zero, while the upper limit assumed that the value was the detection limit.

Table 3.8 Total Alpha Analysis

Feed Sample	Feed ($\mu\text{Ci/ml}$)	Filtrate Range ($\mu\text{Ci/ml}$)	Decontamination Factor Range
8 wt% S-107	0.215	$7.32\text{e-}6 < x < 8.7\text{e-}5$	$2460 < x < 29,400$
1.5 wt% S-107	0.0376	$2.6\text{e-}5 < x < 9.26\text{e-}5$	$391 < x < 1450$
0.05 wt% S-107	1.25e-3 (Calculated)	$2.6\text{e-}5 < x < 9.26\text{e-}5$	$12.9 < x < 47.5$
C-107	1.26e-4	$1.22\text{e-}5 < x < 9.2\text{e-}5$	$1.37 < x < 10.3$

The feed activity for the 0.05 wt% S-107 sample was calculated mathematically by diluting the 1.5 wt% sample because the sample was completely consumed in the radiocolloid analyses. This calculation was validated by checking in the 8 wt% vs 1.5 wt% S-107 samples and their activities.

The 8.0 wt% and 1.5 wt% S-107 feed samples are greater than the class A limit of $0.01 \mu\text{Ci/gram}$ (10 nCi/gram). The 0.05 wt% S-107 feed sample and the C-107 feed sample are both less than class A. All filtrates from all runs were approximately two orders of magnitude lower than the class A limits for TRU.

The results indicate that there is a small quantity (approximately $9.1\text{e-}5 \mu\text{Ci/ml}$) of TRU/alpha activity that remains in the filtrate in the form of either dissolved TRU species or the solid fines

too small to filter in a 0.5-micron filter tube. Since the filtration results at all three solids concentrations are relatively constant, the cross flow filtration appears to remove TRU/alpha equally well at all concentrations.

Cesium

Samples of the filtrate feed and the composited filtrates sample were submitted for gamma Spectral Analysis according to PNL-ALO-450 analysis. Preparation blanks, spiked blanks, and direct spiked samples were submitted. The spike recoveries are within the expected recovery range for the method tested. The feed values are directly reported from the radionuclide analyses. The filtrate values are calculated by adding the activity on the millipore filtration filters to the activity of the millipore filtration filtrates (see Table 3.9)..

Table 3.9 ^{137}Cs Analysis

Feed Sample	Feed ($\mu\text{Ci/ml}$)	Filtrate ($\mu\text{Ci/ml}$)	Decontamination Factor
8 wt% S-107	15.2	9.86	1.54
1.5 wt% S-107	3.01	1.49	2.02
0.05 wt% S-107	0.10 (Calculated)	0.145	0.69
C-107	7.48e-4	<5.06e-4	1.48

The feed activity for the 0.05 wt% S-107 sample was calculated mathematically by diluting the 1.5 wt% sample because there was not sufficient sample to measure it directly. This calculation was validated by checking in the 8 wt% vs 1.5 wt% S-107 samples and their activities

The results indicate that very little cesium is removed during cross flow filtration from the liquid stream. This is consistent with the expectation the cesium compounds are soluble in tank waste liquids.

Technetium

The technetium samples were prepared in the same manner as the TRU and cesium samples. Analyses were not performed on the feed samples. Table 3.10 shows the ^{99}Tc activities for the filtrates.

Table 3.10 ⁹⁹Tc Analysis

Feed Sample	Filtrate (ng/ml)
8 wt% S-107	706
1.5 wt% S-107	126
0.05 wt% S-107	20.3, 18.8
C-107	72.3

All filtrate values reported are less than the Class A limit of 17,600 ng/ml (0.3 Ci/m³) for technetium. If 98% of the technetium was in the liquid phase as has been reported by Lumetta (1996), the technetium activity of the 1.5 wt% S-107 sample filtrate can be calculated from the 8 wt% sample filtrate by dilution. This calculation predicts a technetium activity of 132 ng/ml and this agrees very well with the measured 126 ng/ml. The same logic applies to the 0.05 wt% sample as well; however, the results do not yield as good a comparison, (predicted of 4 ng/ml vs observed of 18.8 to 20.3 ng/ml). The implication is that the technetium in this tank waste is predominately in the liquid phase and consequently is not removed by cross flow filtration.

Strontium

The strontium samples were prepared in the same manner as the TRU and Cesium samples. Analysis were not performed on the feed samples; however Lumetta (1996) reports 437 µCi/g ⁹⁰Sr in the S-107 washed solids. All of the ⁹⁰Sr was reported to be insoluble. Table 3.11 shows the ⁹⁰Sr activities for the filtrates. All filtrate values reported are less than the Class A limit of 0.04 µCi/ml for strontium.

Table 3.11 ⁹⁰Sr Analysis

Feed Sample	Filtrate (µCi/ml)
8 wt% S-107	<0.007
1.5 wt% S-107	<0.008
0.05 wt% S-107	<0.007
C-107	<0.007

3.7.2 Radiocolloid Laboratory Results

Feed Samples

Portions of the slurry feeds were analyzed before and after introduction into the CUF cross flow filter. Particle size measurements were made using a Microtrac X100 particle size analyzer. Table 3.12 provides a summary of the mean particle diameter of the feeds. (Recall that the 1.5 wt% slurry was diluted from the 8 wt% slurry; therefore the post test 8 wt% slurry is the same as the pretest 1.5 wt% slurry. Likewise for the 1.5 wt% post test and the 0.05 wt% pre-test.) Data was not available for all samples because of procedural difficulties at the radiochemical laboratory.

Table 3.12 Particle Diameter Analysis of the Feeds

Sample	Fraunhofer mass number, m_n (microns)
8 wt% S-107 pre-test	0.5
8 wt% S-107 post test/ 1.5 wt% S-107 pre-test	0.3
1.5 wt% S-107 post test/ 0.05 wt% S-107 pre-test	0.3
0.05 wt% S-107 post test	na
C-107 Supernatant pre-test	nd
C-107 Supernatant post-test	2.1

na-not available due to procedural difficulties at the radiochemical laboratory.

nd-not detected, i.e. the concentration of solids was below the detection limit

The data indicate that the mean particle diameter decreased from 0.5 microns prior to testing to 0.3 microns after testing at 8 wt% solids. All subsequent S-107 feeds were composed of dilutions from the 8 wt% feeds. After the initial deagglomeration there is no measurable decrease in average particle diameter in subsequent testing. Such a decrease is consistent with the hypothesis of deagglomeration causing filter fouling. The fouling was noted at the end of the 8 wt% slurry testing and during all subsequent S-107 feed testing.

TOC analysis of the pre and post C-107 feed indicate that the feed may have been contaminated with some organic. The organic is suspected of coming from particulate EPDM rubber shavings. The results are not conclusive as the TOC levels are close to the detection limit of (80 ug/g). The TOC level in the pretest C-107 was below the detection limit in both samples analyzed, while the post test TOC level was below the detection limit in the first sample, and

at 120 ug/g in the second (see Table 3.13). This data does not exclude the possibility that the S-107 feed (possibly hung up in the CUF and not completely rinsed away) caused the particulate contamination. Unfortunately the post-test C-107 feed was not analyzed for radiochemicals. Comparison with pre-test C-107 feed and S-107 feed would likely indicate if the S-107 feed was a source of the particulate contamination.

Table 3.13 TOC Analysis

Feed	TOC Analysis	Duplicate Analysis
C-107 Pre-test	BDL	BDL
C-107 Post-test	BDL	120 ug/g

BDL-below the detection limit (80 ug/g)

Filtrate Samples

Photon correlation spectroscopy (PCS) analysis was performed on the filtrate samples taken from each feed. Nineteen of twenty samples analyzed had particle concentrations below the instrument resolution limit, indicating no appreciable quantity of solids in the sample. The one sample with solids concentration above the PCS unit resolution had a particle diameter of 0.6 microns. The sample was taken from the first filtrate sample from the 0.05 wt% S-107. sampled with conditions of 6 ft/s axial velocity and 25 psig transmembrane pressure. The determination of separation efficiency as a function of particle size (typically called grade efficiency) could not be determined.

4.0 Conclusions and Recommendations

1. Cross flow filtration was effective at filtering 8 wt%, 1.5 wt% and 0.05 wt% S-107, sludge slurries and C-107 supernatant, as judged by filtrate clarity, and should be considered a candidate solid-liquid separation method in the pretreatment of Hanford tank wastes.
2. Radiochemical analysis of the filtrate indicate cross flow filtration was effective in removing both TRU and ^{90}Sr below Class A disposal criteria standards for all wastes tested.
3. Although the filtrate fouling observed was reversible with a 2 wt% oxalic acid cleaning, the use of smaller pore filter media and alternate low shear pumps should be explored. Filter media with larger pores facilitate the penetration of small particles in the pores and, therefore, promote internal clogging. Alternate low-shear pumps should be considered which reduce shear (if possible), while avoiding the use of rubber which will alter the feed properties should it erode.
4. The 8 wt% tank S-107 filtrate flux rate was linear with velocity and independent of pressure above 20 psig (at 6 ft/s axial velocity) indicating that back mass transport limited filtrate flux rates. The filtrate flux rates ranged from approximately 0.04 to 0.06 gpm/ft² (excluding conditions 10 and 11 where deagglomeration is suspected) which is consistent with the two 8 wt% simulants tested. Of the two simulants, S103 appears to mimic Tank S-107 the closest at 8 wt% loading, although neither simulant mimicked the filtrate fouling evident during Conditions 10 and 11.
5. The 1.5 wt%, 0.05 wt% S-107 and C-107 supernatant feed filtrate fluxes varied linearly with transmembrane pressure but independent of velocity, indicating that the filtrate flux is controlled by Darcy's Equation and the axial velocity was effective in removing the filter cake. Therefore, higher transmembrane pressures are required to optimize the low solids loading feeds.
6. The 0.05 wt% S103 filtrate flux rates were approximately 1/4 that of the two 0.05 wt% simulants at the same conditions. These lower rates are indicative of the filtrate fouling and indicate that back pulsing was not able to restore the filtrate flux despite the use of higher back pulsing pressure and increased duration.
7. Porter's diffusion model gave the correct dependence on shear rate; however, the flux was low by a factor of 10. This result is in agreement with the literature which states that this model frequently under predicts data by as much as an order of magnitude. The Zawaicki lift model gives a greater shear dependence than observed. Nevertheless, of the two models the Zawaicki lift model best predicts the experimental data for the 8 wt% S-107 feed. Scarlett and Treasure's model was unable to provide quantitatively correct results because the model was found to over predict cake thickness. When the model was fit to the data, it provided a correct qualitative description of crossflow filtration.

8. It is recommended that one of the tank wastes tested with the 0.5 micron filter be retested using a smaller pore size filters (e.g. 0.2 micron). Such a test would clearly indicate any advantages associated with the smaller pore filter.

9. It is recommended that tank wastes with different processing histories (i.e. different waste types) should be tested to verify the efficacy of crossflow filtration for other Hanford waste types.

5.0 References

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Appendix A

Sample Test Procedure

TEST PLAN- #TFA-CUF-001

Cross Flow Filtration of Hanford Tank Sludges using the Cell Unit Filter (CUF)

John G. H. Geeting

Pacific Northwest Laboratory
Richland, Washington 99352

May 20, 1996

1.0 Applicability

This plan is to be used to perform small scale filtration tests of S-107 Hanford tank sludge, and other tank sludges with the approval of the lead engineer or project manager.

2.0 Supporting Documents

This test plan is not a stand-alone document. It is linked to operating procedure number CUF-325-001, *Operation of the Cell Unit Filter*, which contains the necessary procedural information for the safe operation of the CUF.

2.1 Quality Assurance

This project is IL-III, work authorized by this test plan will be conducted in accordance with the requirements of Quality Assurance manual, PNL-MA-70, Part 2 Good Practices Standard. All measuring and test equipment shall be controlled in accordance with PAP-70-1201, Calibration Control. Calibration controls include labeling instruments with calibration due dates and maintaining a list of calibrated equipment.

3.0 Responsible Staff

The staff responsible for executing this test plan are as follows.

- Project Manager
- Principal Investigator/Lead Engineer
- Technician

4.0 Materials, Equipment, and Reagents Needed

4.1 Materials

1. Fifteen 20 ml glass scintillation vials for filtrate samples, pre-labeled as follows:
 - CUF-H1-001 through CUF-H1-015.
2. Three 10 ml glass scintillation vials for feed (slurry) samples pre-labeled as follows:
 - CUF-H1-016 through CUF-H1-018.
3. One 1-liter volumetric container for adding inhibited and rinse water to the CUFs.
4. Two 1-liter glass containers. The first to be used for receiving the drained 8 wt% slurry after testing (labeled S-107, ~ 8 wt % slurry). The second to be used for receiving the drained 1.5 wt% slurry after testing (labeled S-107, ~ 1.5 wt % slurry).
5. Two 100 ml containers polyethylene containers for draining CUF. Labeled "Drain"
6. One 250 ml polyethylene bottle to be used for mixing the sludge slurry and draining CUF. [Polycarbonate Bottle, 250-ml Capacity (Nalgene No. 3140-0250)] Labeled "Drain"
7. Container for storing alkaline rinse solutions, minimum volume 2 gallons. Labeled "Alkaline rinse" and "Radioactive".

4.2 Equipment

1. 4000 gram balance (provided in hot cell).
2. Hand held periscope. To be used during testing for reading filtrate flowmeter.

4.3 Reagents

The following reagents will be needed to perform the test.

- 0.95 g NaOH
- 1.8 g NaNO₂
- 189 grams S-107 sludge (70 g insoluble solids, dry basis).

5.0 Procedure

The technician will initial in the left hand margin of each step below with time and date when completed. The laboratory notebook (LRB) shall be used to record other testing information as required by this procedure and all test conditions not stated by this procedure.

5.1 Prestart

5.1.1 Inventory materials, equipment, and reagents to ensure all required items are available.

5.1.2 Prepare required amount (805g+710g+846g) of inhibited water in a fume hood. Inhibited water is composed of 0.01 M NaOH and 0.011 M NaNO₂. Record preparation of inhibited water in LRB.

5.1.3 Ensure technicians are thoroughly familiar with this test plan and operating procedure number CUF-325-001, *Operation of the Cell Unit Filter*. If personnel have any questions or uncertainties have them taken care of before commencing test.

5.1.4 Conduct CUF-325-001 *Prestart* operations.

5.1.5 Conduct CUF-325-001 *Start up* operations, steps 2.2.1 through 2.2.3 only.

5.1.6 Turn on heat exchanger in accordance with CUF-325-001, *Operation of A-Cell Heat Exchanger*.

5.2 Preparation of 8 wt% slurry

The 8 wt% slurry consists of 189 grams S-107 (70 g insoluble solids, dry basis) and 805 grams inhibited water.

5.2.1 Weigh 250 polyethylene bottle with cap and record in LRB.

5.2.2 Remove cap and place 189 g of S-107 sludge into polyethylene bottle. This shall be done by using approximately equal masses from containers 8786, 8787, and 8789. Replace cap. Weigh and record weight in LRB.

5.2.3 Weigh out 805 g of inhibited water and pour into the chem add funnel (penetration 108).

5.2.4 From chem add funnel, pour inhibited water into polyethylene bottle with sludge until it is approximately 4/5 full. Weigh polyethylene bottle and record mass in LRB.

5.2.5 With cap secured to polyethylene bottle, repeatedly invert bottle to mix solids and liquid. When contents are well mixed, pour contents into slurry reservoir in accordance with CUF-325-001 *Startup*, step 2.2.4.

5.2.6 Add remainder of inhibited water from chem add funnel (for a total of 805 g inhibited water) to the slurry reservoir in accordance with CUF-325-001 *Startup*, step 2.2.4. Weigh container with inhibited water before and after adding inhibited water to the slurry reservoir. Record mass added in the LRB.

5.2.7 Complete steps 2.2.5 through 2.2.9 in CUF-325-001 *Startup*.

5.3 Conditions to be tested

8 wt% Slurry:

Condition	Axial Velocity (ft/s)	Trans-membrane Pressure (psig)	Technicians initial and date indicating condition completed for 8 wt% slurry
1#	6.0	20	
2	7.5	27.5	
3#	3.0	20	
4#	6.0	5	
5	7.5	12.5	
6	6.0	20	
7	4.5	27.5	
8#	6.0	35	
9#	9.0	20	
10	4.5	12.5	
11	6.0	20	
12*			
13*			
14*			

#-Filtrate sample required during conditions so indicated.

*-Optional conditions which may be set at the time of testing by the test engineer.

1.5 wt% Slurry:

Condition	Axial Velocity (ft/s)	Trans-membrane Pressure (psig)	Technicians initial and date indicating condition completed for <u>1.5 wt%</u> slurry
1#	6.0	25	
2	7.5	32.5	
3#	3.0	25	
4#	6.0	10	
5	7.5	17.5	
6	6.0	25	
7	4.5	32.5	
8#	6.0	40	
9#	9.0	25	
10	4.5	17.5	
11	6.0	25	
12*			
13*			
14*			

#-Filtrate sample required during conditions so indicated.

*-Optional conditions which may be set at the time of testing by the test engineer.

0.05 wt% Slurry:

Condition	Axial Velocity (ft/s)	Trans-membrane Pressure (psig)	Technicians initial and date indicating condition completed for <u>0.05 wt% slurry</u>
1#	6.0	25	
2	7.5	32.5	
3#	3.0	25	
4#	6.0	10	
5	7.5	17.5	
6	6.0	25	
7	4.5	32.5	
8#	6.0	40	
9#	9.0	25	
10	4.5	17.5	
11	6.0	25	
12*			
13*			
14*			

#-Filtrate sample required during conditions so indicated.

*-Optional conditions which may be set at the time of testing by the test engineer.

For each condition listed the following instructions apply:

5.3.1 Briefly establish conditions 8 and 9 by following CUF-325-001 *Operation* to ensure the CUFs can pump slurry at these most extreme conditions. If conditions 8 and 9 can be met, establish each condition to be tested (sequentially), setting the indicated axial velocity and TMP by following CUF-325-001 *Operation*. If conditions cannot be the test engineer shall modify conditions before continuing.

5.3.2 After establishing each condition conduct initial back pulse (designated time 0) in accordance with CUF-325-001 *Back pulse*.

5.3.3 Run each condition for at least 60 minutes recording data every 5 minutes (starting at time 0) on data sheet provided in CUF-325-001. Maintain slurry temperature between 25-35 °C by adjusting the cell supplied heat exchanger as required.

5.3.4 Back pulse after time=30 minutes for each condition in accordance with CUF-325-001 *Back pulse*.

5.3.5 Take 5 ml filtrate samples during condition 1, 3, 4, 8, 9. Samples are to be taken in accordance with CUF-325-001 *Sampling*. Use labeled containers made in advance. Record sample number and time in LRB.

5.3.6 The test engineer reserves the right to add in optional conditions (conditions 12, 13, or 14) which shall be completed after executing the test plan on conditions 1 through 11.

5.3.7 When all conditions have been tested drain system in accordance with CUF-325-001 *Draining the System*. Store drained slurry in 1 liter container labeled "8 wt% slurry" Sample ~2 ml of slurry being drained using containers made in advance. Record sample number and time in LRB. [Note: 1.5 wt% slurry will be stored in an 1-liter container labeled "1.5 wt% slurry." The 0.05 wt% slurry will be stored in the container marked "alkaline rinse" for eventual disposal down the RLWS.

5.4 Rinsing System between Runs

5.4.1 Pour approximately 800 ml of deionized water (obtained from VA-14, penetration 110) into the slurry reservoir, bumping pump as needed to fill the lines, in accordance with CUF-325-001 *Startup*.

5.4.2 Run system for approximately 3 minutes before draining rinse in accordance with CUF-325-001 *Draining the System*.

5.4.3 Repeat steps 5.4.1 and 5.4.2 for a total of 3 rinses (if necessary).

5.4.4 If system is to be shut down for longer than a week the final rinse should contain 1-5 ppm hypochlorite (bleach). Do not drain lay up solution until ready to commence testing again. If the system is going to be laid up, the 1-5 ppm hypochlorite solution shall be prepared in advance in a fume hood and added to the cell via the chem add funnel (penetration 108).

5.5 Preparation of 1.5 wt% slurry

The 1.5 wt% slurry consists of approximately 165 g of the 8 wt% slurry and 710 g of inhibited water.

5.5.1 Weigh 250 polyethylene bottle with cap and record in LRB.

5.5.2. Remove cap and place 165 g of well mixed S-107 8 wt% slurry into polyethylene bottle. Replace cap. Weigh and record weight in LRB. Pour contents into slurry reservoir in accordance with CUF-325-001 *Startup*, step 2.2.4.

5.5.3 Add 710 g inhibited water to the chem add funnel (penetration 108).

5.5.4 Add inhibited water from the chem add funnel to the slurry reservoir in accordance with CUF-325-001 *Startup*, step 2.2.4. Weigh container before and after adding inhibited water to the slurry reservoir. Record mass in LRB.

5.5.5 Complete steps 2.2.5 through 2.2.9 in CUF-325-001 *Startup*.

5.5.6 Repeat section 5.3 (*Conditions to be Tested*) and 5.4 (*Rinsing System between Runs*) using the 1.5 wt% slurry.

5.5.7 When complete proceed to Section 5.6, *Preparation of 0.05 wt% Slurry*.

5.6 Preparation of 0.05 wt% slurry

The 0.05 wt% slurry consists of approximately 29 g of the 1.5 wt% slurry and 846 g of inhibited water.

5.6.1 Weigh 250 polyethylene bottle with cap and record in LRB.

5.6.2. Remove cap and place 29 g of well mixed S-107 1.5 wt% slurry into polyethylene bottle. Replace cap. Weigh and record weight in LRB. Pour contents into slurry reservoir in accordance with CUF-325-001 *Startup*, step 2.2.4.

5.5.3 Add 846 g inhibited water to the chem add funnel (penetration 108).

5.5.4 Add inhibited water from the chem add funnel to the slurry reservoir in accordance with CUF-325-001 *Startup*, step 2.2.4. Weigh container before and after adding inhibited water to the slurry reservoir. Record mass in LRB.

5.5.5 Complete steps 2.2.5 through 2.2.9 in CUF-325-001 *Startup*.

5.5.6 Repeat section 5.3 (*Conditions to be Tested*) and 5.4 (*Rinsing System between Runs*) using the 0.05 wt% slurry.

5.7 Waste Disposal

1. Rinse Solutions (including 0.05 wt% feed): Rinse solutions are principally composed of water with small amounts of solids resulting from rinsing out the CUF system between runs. The 0.05 wt% solids feed will also be included with the rinse solutions because 0.05 wt% solids is the amount of solids expected in these rinse solutions. The pH of the rinse solutions should range between 7-12 pH and will be acceptable for the RLWS. For each waste type (e.g. S-107) approximately 2 gallons of rinse solution will be generated. The expected dose rate for S-107 rinse was calculated to be approximately 190 mrem/hour.

Disposal path:

a) The principal disposal path for these rinse solutions will be the same as that for the extrusion rinse solutions generated by J. Tingey in 325 Bldg., and will be disposed through the HLRS RLWS drain system.

b) If for some reason this disposal pathway is taken away, the rinse solutions will be sent to Wayne Larson (contact handled) or Rick Steele (remote handled) for disposal in the RLWS. Wayne generally takes waste with dose of <100 mrem/hour.

2. Cleaning Solutions: Cleaning solutions are composed of 2 wt% NaOH or 2 wt% oxalic acid. These solutions are generated infrequently when chemical cleaning of the filter is required.

Disposal path:

a) These wastes will be segregated (acidic and alkaline) and sent to Wayne Larson (contact handled) or Rick Steele (remote handled) for neutralization in one of the permitted units at 325 Bldg. and disposed of in the RLWS.

3. Solids: The CUFs filter system will not chemically alter the sludge solids other than simple water washing. Sludge solids are not considered a waste and will be saved for use in other projects. If for some reason the solids need to be disposed, the following is applicable. The liquid will be allowed to evaporate from the solids leaving a dry cake. These solids will then be packaged for disposal in the 200 Area Central Waste Complex.

5.8 Sample Analysis

The point of contact for sample transfer is Pete Smith (375-4537) or Bob Elovich (373-0953). Samples should be submitted in small glass scintillation vials.

5.8.1 Filtrate Samples

Filtrate samples (5 ml) will be submitted to the colloids laboratory for the following analysis:

1. Photo correlation spectroscopy- This analytical technique uses light scattering to tell you
 - Are there colloids present ?
 - How many? Counts/second can be used to solids volume/volume sample.
 - How big? PCS uses light scattering techniques to provide PSD in the range from 5 nm to 2 microns.
2. If colloids are present in the feed then the filtrate will be run through 2 filters. The first will contain colloids and any ions sorbed onto the filter medium. The second will contain only ions sorbed on the medium. Radiochemical analysis of each filter should tell us what radioactivity is attributable to the ions and (by difference) colloids. Radiochemical analysis of the leached filter will include:
 - Gross alpha
 - Chemical separations to quantify ^{99}Tc and ^{90}Sr present.
3. Concentration of OH^- in the filtrate.

5.8.2 Feed (Slurry) Samples

Feed samples (2 ml) will be submitted to the colloids laboratory and will have all the analysis provided to the filtrate samples. In addition the following analytical techniques shall be performed.

1. Upper range particle size analyzer (range 0.5 micron to 200 micron)
2. Thermogravimetric analysis of the supernate and the slurry. (The difference between the two and measuring the volume of liquid in the slurry should provide total suspended solids.)

Appendix B
Simulant Recipe

Make-up Procedures:

Simulant S3 8 wt%

1. To 920 grams of 0.1M sodium hydroxide add 72 grams of $\text{Al}(\text{OH})_3$ (Alcoa, spacerite S-3)
2. Add 8.0 grams of AlOOH (Vista, Catapal D).
3. Stir slurry 12 hours.

Simulant S3 0.05wt%

1. To 999.5 grams of 0.1M sodium hydroxide add 0.450 grams of $\text{Al}(\text{OH})_3$ (Alcoa, Spacerite S-3)
2. Add 0.05 grams AlOOH (Vista, Catapal D).
3. Stir slurry 12 hours.

Simulant S103 8wt%

1. To 400g deionized water add 134.9 grams of ferric nitrate $[\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}]$. Stir until dissolved.
2. Add 5M sodium hydroxide while stirring until a pH of 7-8 is indicated.
3. Add 71.6 grams of 50wt% colloidal silica (Nycol Silica Solution). Continue stirring the slurry.
4. Add quantities indicated of the following chemicals and stir:
 - $\text{Al}(\text{OH})_3$ (Alcoa, Spacerite S-11): 7.76 grams
 - AlOOH (vista, Catapal D): 2.29 grams
 - $\text{Ca}_{10}(\text{OH})_2(\text{PO}_4)_6$ (Aldrich): 14.3 grams
5. Add 5M sodium hydroxide slowly while stirring until a pH of 12 is reached. Allow slurry to stir vigorously for 24 hours.
6. Slowly add 5M nitric acid while stirring until a pH of 10 is reached.
7. Bring net mass of slurry to 1200 grams by adding distilled water, then stir for 3 hours.

Simulant S103 0.05wt%

1. To 400 grams of ionized water add 0.84 grams of ferric nitrate $[\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}]$. Stir until dissolved.
2. Add 5M sodium hydroxide while stirring until a pH of 7-8 is indicated.
3. Add 0.45 grams of 50wt% colloidal silica (Nycol Silica Solution). Continue stirring the slurry.
4. Add quantities indicated of the following chemicals while continually stirring:
 - $\text{Al}(\text{OH})_3$ (Alcoa, spacerite S-11): 0.050 grams
 - AlOOH (Vista, Catapal D): 0.015 grams
 - $\text{Ca}_{10}(\text{OH})_2(\text{PO}_4)_6$ (Aldrich): 0.090 grams
5. Add 5M sodium hydroxide slowly while stirring until a pH of 12 is reached. Allow slurry to stir vigorously for 24 hours.
6. Slowly add 5M nitric acid while stirring until a pH of 10 is indicated.
7. Bring net mass of slurry to 1200 grams by adding deionized water, then stir for 3 hours.

Appendix C

Data

Rows	Time Since Back Pulse	Flowrate (ft/s)	Pressure (psig)	Filtrate Flux (gpm/ft ²)	Temp (C)	Run Order
1	0	5.9	21	0.0702	30.7	1
2	5	6	20	0.0549	30.8	1
3	10	6	20	0.05	30.8	1
4	15	6	20	0.0447	30.6	1
5	20	6	21	0.0464	30.6	1
6	25	6.1	20	0.0392	30.6	1
7	30	6.1	20	0.0409	30.7	1
8	0	6.1	20	0.0664	30.7	1
9	5	6.1	20	0.054	30.7	1
10	10	6	19.5	0.0499	30.6	1
11	15	5.9	20	0.048	30.6	1
12	20	6	20	0.0423	30.7	1
13	25	6	20	0.0424	30.8	1
14	30	6	20	0.0423	30.9	1
15	0	7.3	28	0.0971	35.2	2
16	5	7.3	28	0.0676	36.4	2
17	10	7.2	28	0.0722	36.8	2
18	15	7.5	27	0.0666	36.9	2
19	20	7.5	27	0.0628	36.7	2
20	25	7.5	27	0.0605	36.7	2
21	30	7.5	27	0.0583	36.5	2
22	0	7.5	29	0.0799	34.9	2
23	5	7.5	28	0.0602	35.2	2
24	10	7.8	28	0.0572	35.6	2
25	15	7.4	28	0.0536	35.6	2
26	20	7.4	29	0.0533	35.7	2
27	25	7.7	27	0.0485	35.5	2
28	30	7.7	27	0.0473	35.5	2
29	0	?	?	?	?	3
30	5	2.9	20	0.0661	32.6	3
31	10	2.9	21	0.0352	32	3
32	15	3	20	0.0283	32.4	3
33	20	3	20	0.0284	32.9	3
34	25	3	20	0.0274	33.3	3
35	30	3	20	0.0265	33.6	3
36	0	2.9	20	0.0588	34.3	3
37	5	2.9	20	0.0344	34.5	3
38	10	2.9	20	0.0275	34.7	3
39	15	3.1	20	0.0276	34.8	3
40	20	3	20	0.0262	35	3
41	25	3	20	0.027	33.2	3
42	30	3	20	0.0272	31.8	3
43	0	6	5	0.0269	27.9	4

H1_8WT_JMP

Rows	Time Since Back Pulse	Flowrate (ft/s)	Pressure (psig)	Filtrate Flux (gpm/ft2)	Temp (C)	Run Order
44	5	6	5	0.0302	27.8	4
45	10	6	5	0.0303	27.7	4
46	15	6	5	0.0313	27.7	4
47	20	6	5	0.0303	27.7	4
48	25	6	5	0.0296	27.7	4
49	30	6	5	0.0299	27.7	4
50	0	6	5	0.0427	27.7	4
51	5	6	5	0.0344	27.8	4
52	10	6	5	0.0319	27.8	4
53	15	6	5	0.0323	27.8	4
54	20	6	5	0.0315	27.8	4
55	25	6	5	0.032	27.8	4
56	30	6	5	0.0318	27.8	4
57	0	7.4	13	0.0714	29.4	5
58	5	7.5	12.5	0.053	29.9	5
59	10	7.5	12	0.0515	30.2	5
60	15	7.4	12.5	0.0545	30.2	5
61	20	7.5	12.5	0.0523	30.3	5
62	25	7.5	12.5	0.0514	30.4	5
63	30	7.5	12.5	0.0507	30.6	5
64	0	7.3	12.5	0.0655	30.6	5
65	5	7.5	13	0.0545	30.8	5
66	10	7.5	12.5	0.0512	30.9	5
67	15	7.6	12.5	0.0535	31.1	5
68	20	7.5	13	0.0563	31.1	5
69	25	7.5	12.5	0.0534	31.1	5
70	30	7.5	12.5	0.0523	31	5
71	0	6	20	0.0939	31.4	6
72	5	6	20	0.0536	31.4	6
73	10	6	20.5	0.051	31.5	6
74	15	6	20	0.049	31.5	6
75	20	6	20	0.0499	31.5	6
76	25	6	20	0.0502	31.5	6
77	30	6	20	0.0525	31.5	6
78	0	6	20	0.0846	31.9	6
79	5	6	20	0.0512	32	6
80	10	6	20	0.0504	32.2	6
81	15	6	20	0.0484	32.3	6
82	20	6	20	0.0487	32.4	6
83	25	6	20	0.0488	32.2	6
84	30	6	20	0.0488	32.3	6
85	0	4.4	28	0.0752	32.3	7
86	5	4.4	28	0.0417	32.5	7

C2

Rows	Time Since Back Pulse	Flowrate (ft/s)	Pressure (psig)	Filtrate Flux (gpm/ft2)	Temp (C)	Run Order
87	10	4.6	27	0.037	32.7	7
88	15	4.3	28	0.039	32.6	7
89	20	4.4	28	0.0384	32.6	7
90	25	4.5	27.5	0.0379	32.5	7
91	30	4.4	28	0.0394	32.5	7
92	0	4.5	28	0.0825	32.5	7
93	5	4.5	27.5	0.0405	32.8	7
94	10	4.6	27.3	0.0385	32.8	7
95	15	4.6	27.5	0.0388	32.7	7
96	20	4.6	27.5	0.0392	32.6	7
97	25	4.4	27.3	0.038	32.6	7
98	30	4.5	27.5	0.0377	32.6	7
99	0	6	35	0.0919	34.5	8
100	5	5.9	36	0.0485	35.8	8
101	10	6	35	0.0469	36.3	8
102	15	6	35	0.045	36.8	8
103	20	6	35	0.0457	36.9	8
104	25	5.9	35	0.043	37.1	8
105	30	6	35	0.0436	37.3	8
106	0	6.1	35	0.0712	37.9	8
107	5	6	35	0.0495	38.1	8
108	10	6	35	0.047	38.2	8
109	15	6	35	0.044	38.6	8
110	20	6	35	0.0413	38.6	8
111	25	6	36	0.0421	38.6	8
112	30	6	35	0.0419	38.8	8
113	0	4.3	12.5	0.0193	30.5	9
114	5	4.5	12.5	0.0177	30.3	9
115	10	4.5	12.5	0.0179	30.2	9
116	15	4.5	12.5	0.0182	30.1	9
117	20	4.5	12.5	0.0182	30	9
118	25	4.5	12.5	0.0182	30	9
119	30	4.5	12.5	0.0184	30	9
120	0	4.5	12.5	0.0216	30.1	9
121	5	4.5	12.5	0.0192	30.1	9
122	10	4.5	12.5	0.0192	30.1	9
123	15	4.5	12.5	0.0195	30.1	9
124	20	4.5	12.5	0.0198	30.1	9
125	25	4.5	12.5	0.0199	30.1	9
126	30	4.5	12.5	0.0199	30.1	9
127	0	9	20	0.0269	34.9	10
128	5	9.2	20	0.0235	36.2	10
129	10	9.1	20	0.0293	36.6	10

H1_8WT_JMP

Rows	Time Since Back Pulse	Flowrate (ft/s)	Pressure (psig)	Filtrate Flux (gpm/ft2)	Temp (C)	Run Order
130	15	8.9	20	0.0207	36.4	10
131	20	9	20	0.0216	36.2	10
132	25	8.9	20	0.0182	35.9	10
133	30	8.9	20	0.0191	35.9	10
134	0	9	20	0.0269	36.4	10
135	5	8.9	20	0.0236	37	10
136	10	9	20	0.0208	38	10
137	15	9.1	20	0.0211	38.5	10
138	20	9	20	0.0207	38.5	10
139	25	9	20	0.0184	38.4	10
140	30	8.9	20	0.0195	37.7	10
141	0	6	20	0.026	35.2	11
142	5	6	20	0.0193	34	11
143	10	6	20.5	0.0175	33.6	11
144	15	6	20	0.0159	33	11
145	20	6	20	0.0155	32.7	11
146	25	6.1	20	0.0146	32.5	11
147	30	6	20	0.0148	32.4	11
148	0	6.1	20	0.0246	32.1	11
149	5	6.1	20	0.0176	32.1	11
150	10	6	20	0.0169	32.2	11
151	15	6	20	0.0164	32.2	11
152	20	6	20	0.0161	32.4	11
153	25	6	20	0.0149	32.4	11
154	30	5.9	20	0.0146	32.3	11

Rows	Time Since Back Pulse	Flowrate (ft/s)	Pressure (psig)	Filtrate Flux (gpm/ft2)	Temp (C)	Run Order
1	0	6.1	20	0.1255	30.1	1
2	5	6	20.5	0.076	30.1	1
3	10	6	20.5	0.0708	30.1	1
4	15	6	20.5	0.0685	30.1	1
5	20	6	20.5	0.0671	30.1	1
6	25	6	20.5	0.0647	30.1	1
7	30	6	20	0.0618	30	1
8	0	6	20	0.0884	30	1
9	5	6	20	0.0603	30	1
10	10	6	20	0.0528	30	1
11	15	6	20	0.0534	30.1	1
12	20	6	20.5	0.0521	30.2	1
13	25	6	20	0.0526	30	1
14	30	6	20	0.053	30	1
15	0	7.4	33	0.1124	33.4	2
16	5	7.6	33	0.0925	34.3	2
17	10	7.4	33	0.0912	34.9	2
18	15	7.4	32.5	0.0896	35.2	2
19	20	7.4	32.5	0.0884	35.4	2
20	25	7.4	32	0.0869	35.4	2
21	30	7.4	32.5	0.0872	35.4	2
22	0	7.4	33	0.0603	36.8	2
23	5	7.3	32	0.0505	37.5	2
24	10	7.5	32.5	0.0515	37.8	2
25	15	7.4	33	0.0536	38	2
26	20	7.6	32	0.0549	38.5	2
27	25	7.5	32	0.0598	38.9	2
28	30	7.6	32.5	0.0661	39.2	2
29	0	3	25.5	0.0849	31.3	3
30	5	3	25	0.0555	31	3
31	10	3.1	25	0.0484	30.9	3
32	15	3	25	0.0456	30.8	3
33	20	3	25	0.0419	30.7	3
34	25	2.9	25.5	0.0407	30.7	3
35	30	3.1	25	0.0412	30.6	3
36	0	3.1	25	0.0774	30.4	3
37	5	3	25	0.0575	30.4	3
38	10	3	25	0.0507	30.4	3
39	15	3	25	0.045	30.6	3
40	20	3	25	0.0422	30.7	3
41	25	3	25	0.0394	30.6	3
42	30	3	25.5	0.038	30.7	3
43	0	6	10	0.055	30	4

Rows	Time Since Back Pulse	Flowrate (ft/s)	Pressure (psig)	Filtrate Flux (gpm/ft2)	Temp (C)	Run Order
44	5	6	10	0.0394	29.5	4
45	10	6	10	0.0382	29.4	4
46	15	6	10	0.038	29.3	4
47	20	6	10	0.0395	29.3	4
48	25	6	10	0.0394	29.4	4
49	30	5.9	10	0.0442	29.4	4
50	0	6	10	0.0166	29.2	4
51	5	6	10	0.0275	29.7	4
52	10	5.9	10.5	0.0276	29.8	4
53	15	6.1	10	0.0263	29.8	4
54	20	6.1	10	0.0279	29.7	4
55	25	6	10	0.0285	29.7	4
56	30	6	10.5	0.03	29.8	4
57	0	7.5	18	0.0284	31.8	5
58	5	7.5	17.5	0.0437	32.1	5
59	10	7.6	17.5	0.0417	32.2	5
60	15	7.7	17.5	0.042	32.2	5
61	20	7.5	17.5	0.0429	32.2	5
62	25	7.4	17.5	0.0451	32.2	5
63	30	7.6	17.5	0.045	32.3	5
64	0	7.5	17.5	0.0331	32.3	5
65	5	7.4	17.5	0.0404	32	5
66	10	7.4	18	0.0401	32.3	5
67	15	7.6	18	0.0424	32.4	5
68	20	7.5	18	0.0442	32.4	5
69	25	7.5	18	0.0458	32.5	5
70	30	7.5	18	0.0492	32.5	5
71	0	6	25	0.0707	33.5	6
72	5	6	25	0.0527	33.6	6
73	10	6	25	0.0488	33.6	6
74	15	6	25	0.0499	33.6	6
75	20	5.9	25	0.052	33.7	6
76	25	6	25.5	0.0556	33.7	6
77	30	6	26	0.0575	33.8	6
78	0	6.1	25	0.0651	34.1	6
79	5	6	24.5	0.0477	34.2	6
80	10	6	25	0.0472	34.2	6
81	15	6	25	0.0434	34.2	6
82	20	6	25	0.0417	34.2	6
83	25	6	25	0.0414	34.2	6
84	30	6	25	0.0404	34.1	6
85	0	4.5	32.5	0.0741	33.3	7
86	5	4.6	32.5	0.0572	33.8	7

Rows	Time Since Back Pulse	Flowrate (ft/s)	Pressure (psig)	Filtrate Flux (gpm/ft2)	Temp (C)	Run Order
87	10	4.5	32.5	0.0554	34	7
88	15	4.4	32.5	0.0537	34.1	7
89	20	4.5	33	0.0557	34.2	7
90	25	4.5	32.5	0.0532	34.1	7
91	30	4.5	32.5	0.0515	34.1	7
92	0	4.5	32	0.1245	34.1	7
93	5	4.4	32.5	0.0685	33.9	7
94	10	4.5	33	0.0565	33.8	7
95	15	4.5	32.5	0.0506	33.7	7
96	20	4.5	32.5	0.0495	33.6	7
97	25	4.5	32.5	0.0485	33.5	7
98	30	4.5	32.5	0.0484	33.6	7
99	0	5.9	40.5	0.0806	36.3	8
100	5	6	40	0.055	37.8	8
101	10	6	41	0.0583	38.1	8
102	15	6	40	0.0478	38.1	8
103	20	5.9	40	0.042	37.7	8
104	25	5.8	40	0.0454	37.8	8
105	30	5.6	40	0.0394	37.8	8
106	0	6	40.5	0.0503	38.5	8
107	5	6	41	0.0466	38.8	8
108	10	5.9	41	0.0459	38.9	8
109	15	5.9	40.5	0.0466	38.8	8
110	20	6	40.5	0.0463	38.9	8
111	25	6	40.5	0.044	38.8	8
112	30	5.9	40	0.0407	38.7	8
113	0	8.8	27	0.0193	37.3	9
114	5	8.9	26.5	0.0207	38.6	9
115	10	9	25.5	0.0187	39.6	9
116	15	8.9	25	0.0207	40.6	9
117	20	8.8	25.5	0.0194	39.5	9
118	25	8.8	26	0.0193	39.7	9
119	30	8.9	25	0.0182	40	9
120	0	8.8	25	0.0249	40.1	9
121	5	8.4	25	0.0216	39.1	9
122	10	?	?	?	?	9
123	15	?	?	?	?	9
124	20	?	?	?	?	9
125	25	?	?	?	?	9
126	30	?	?	?	?	9
127	0	4.6	18	0.0207	33.2	10
128	5	4.5	17.5	0.0185	32.1	10
129	10	4.5	18	0.019	31.9	10

C.7

H1_1_5WT.JMP

Rows	Time Since Back Pulse	Flowrate (ft/s)	Pressure (psig)	Filtrate Flux (gpm/ft2)	Temp (C)	Run Order
130	15	4.5	18	0.0194	31.8	10
131	20	4.5	18.5	0.0201	31.8	10
132	25	4.5	17.5	0.0201	31.8	10
133	30	4.6	17.5	0.021	31.9	10
134	0	4.4	17.5	0.0283	32.5	10
135	5	4.5	17.5	0.0218	32.2	10
136	10	4.5	18	0.0247	32.2	10
137	15	4.4	18	0.0256	32.3	10
138	20	4.6	17.5	0.0263	32.3	10
139	25	4.5	17.5	0.027	32.4	10
140	30	4.5	17.5	0.0296	32.5	10
141	0	5.9	25	0.0334	33.7	11
142	5	6	25	0.0299	34	11
143	10	5.9	25	0.0313	34.3	11
144	15	5.9	25	0.0326	34.4	11
145	20	6	25	0.0353	34.9	11
146	25	6	25	0.0335	34.7	11
147	30	6	25	0.0293	34.3	11
148	0	6	25	0.0246	34.1	11
149	5	6	25	0.0236	33.9	11
150	10	6	25	0.0225	33.4	11
151	15	6	25	0.0207	33.3	11
152	20	5.9	25	0.0214	33.2	11
153	25	5.9	25	0.0205	33	11
154	30	6	25	0.021	32.9	11

Rows	Time Since Back Pulse	Flowrate (ft/s)	Pressure (psig)	Filtrate Flux (gpm/ft ²)	Temp (C)	Run Order
1	0	6	25	0.0893	31.8	1
2	5	6	25	0.0674	31.9	1
3	10	5.9	25	0.0651	31.8	1
4	15	5.9	25	0.0628	31.8	1
5	20	6	25	0.06	31.8	1
6	25	6	25	0.0571	31.7	1
7	30	5.9	25	0.0575	31.6	1
8	0	5.9	25	0.0725	31.7	1
9	5	6	25.5	0.0597	31.6	1
10	10	6	25	0.0567	31.6	1
11	15	6	25	0.0549	31.7	1
12	20	6	25	0.0524	31.7	1
13	25	6	25	0.0527	31.7	1
14	30	6	25	0.0509	31.6	1
15	0	7.5	32.5	0.0884	33.6	2
16	5	7.5	32.5	0.073	34.8	2
17	10	7.5	33	0.0708	35.4	2
18	15	7.5	33	0.0712	35.9	2
19	20	7.5	32.5	0.0673	36.2	2
20	25	7.6	32	0.0657	36.4	2
21	30	7.4	32.5	0.0669	36.6	2
22	0	7.6	32	0.0781	36.9	2
23	5	7.5	33	0.0716	37	2
24	10	7.5	33	0.0693	37.1	2
25	15	7.5	32.5	0.0657	37	2
26	20	7.5	32.5	0.0646	36.9	2
27	25	7.4	32.5	0.0639	36.9	2
28	30	7.5	32	0.0619	36.9	2
29	0	3	25	0.0544	29.5	3
30	5	3	25	0.0465	29.3	3
31	10	2.9	25	0.0443	29	3
32	15	2.9	25	0.043	28.9	3
33	20	3	25	0.0429	29	3
34	25	3	25	0.0424	29	3
35	30	3	25	0.0419	28.9	3
36	0	3	25	0.0525	29	3
37	5	3	25	0.0432	29	3
38	10	3	25	0.0413	28.9	3
39	15	2.9	25	0.0407	28.9	3
40	20	3	25	0.0404	28.9	3
41	25	3	25	0.0401	28.9	3
42	30	3	25.5	0.04	29	3
43	0	6	10.5	0.0279	28.9	4

H1_05WT_JMP

Rows	Time Since Back Pulse	Flowrate (ft/s)	Pressure (psig)	Filtrate Flux (gpm/ft2)	Temp (C)	Run Order
44	5	6	10	0.021	28.7	4
45	10	6	10	0.023	28.7	4
46	15	6	10.5	0.0226	28.6	4
47	20	6	11	0.023	28.6	4
48	25	6	10	0.0216	28.7	4
49	30	6	10	0.0209	28.6	4
50	0	6	10	0.0257	28.8	4
51	5	6	10.5	0.0233	28.6	4
52	10	6	10	0.0216	28.5	4
53	15	5.9	10	0.0178	28.4	4
54	20	6	10	0.022	28.5	4
55	25	6	10	0.0216	28.5	4
56	30	6	10	0.0216	28.5	4
57	0	7.5	18	0.0387	30.1	5
58	5	7.5	18	0.0341	30.3	5
59	10	7.5	18	0.0334	30.5	5
60	15	7.6	17.5	0.0324	30.7	5
61	20	7.6	17.5	0.0324	30.7	5
62	25	7.5	17.5	0.0335	30.8	5
63	30	7.6	17.5	0.0327	30.9	5
64	0	7.5	17.5	0.0226	31.1	5
65	5	7.5	17.5	0.0324	31	5
66	10	7.5	17.5	0.0316	31	5
67	15	7.5	18	0.0289	31	5
68	20	7.5	17.5	0.0314	30.9	5
69	25	7.5	17.5	0.0269	30.9	5
70	30	7.5	17.5	0.0318	30.9	5
71	0	6	25	0.0475	30.6	6
72	5	6	25	0.0423	30.7	6
73	10	5.9	25	0.0408	30.7	6
74	15	6	25	0.0402	30.7	6
75	20	6	25	0.039	30.7	6
76	25	6	25	0.0382	30.7	6
77	30	6	25	0.0407	30.7	6
78	0	6	25	0.0453	30.8	6
79	5	6	25	0.0406	30.8	6
80	10	6	25	0.0411	30.8	6
81	15	6	24.5	0.0394	30.8	6
82	20	6	25	0.0409	30.8	6
83	25	6	25	0.0383	30.9	6
84	30	6	25	0.0388	30.5	6
85	0	4.5	32.5	0.0581	29.3	7
86	5	4.5	32.5	0.0524	29.6	7

Rows	Time Since Back Pulse	Flowrate (ft/s)	Pressure (psig)	Filtrate Flux (gpm/ft2)	Temp (C)	Run Order
87	10	4.5	32.5	0.0496	29.8	7
88	15	4.5	32.5	0.0476	29.7	7
89	20	4.5	32.5	0.0469	29.8	7
90	25	4.5	32.5	0.0447	29.8	7
91	30	4.5	32.5	0.0464	29.7	7
92	0	4.4	33	0.0575	30	7
93	5	4.5	32	0.0485	30	7
94	10	4.5	32.5	0.0464	30.1	7
95	15	4.5	32.5	0.0457	30.1	7
96	20	4.6	32.5	0.0445	30.1	7
97	25	4.5	32.5	0.043	30.1	7
98	30	4.5	32.5	0.0422	30.1	7
99	0	6	40	0.0681	32.5	8
100	5	6	40	0.06	33.7	8
101	10	6.1	40	0.0573	34.4	8
102	15	6.1	40	0.0555	34.8	8
103	20	6	40	0.0549	35.1	8
104	25	6	40	0.0535	35.3	8
105	30	6	40	0.0536	35.4	8
106	0	6	40	0.071	35.8	8
107	5	6	40	0.0583	35.8	8
108	10	6	40	0.0565	35.9	8
109	15	6	40	0.0536	35.9	8
110	20	6	40	0.0531	35.9	8
111	25	6	40	0.0519	35.9	8
112	30	6	40	0.051	35.9	8
113	0	9	25	0.0491	34.3	9
114	5	9.1	25.5	0.0429	35.5	9
115	10	9	25	0.0408	35.8	9
116	15	9	25	0.0386	36.2	9
117	20	9	25	0.0373	36.3	9
118	25	8.9	25.5	0.0371	36.1	9
119	30	9	25	0.038	36.3	9
120	0	9	25.5	0.0408	36.8	9
121	5	8.9	25	0.0329	36.6	9
122	10	9	24.5	0.028	36.6	9
123	15	9	25	0.0297	36.8	9
124	20	9.2	24.5	0.0284	37.1	9
125	25	9.1	25	0.0284	37.2	9
126	30	9.1	25	0.0302	37.3	9
127	0	4.6	17.5	0.0243	31.7	10
128	5	4.5	17.5	0.0218	31.1	10
129	10	4.6	17.5	0.0209	30.4	10

C.11

H1_05WT_JMP

Rows	Time Since Back Pulse	Flowrate (ft/s)	Pressure (psig)	Filtrate Flux (gpm/ft2)	Temp (C)	Run Order
130	15	4.5	17.5	0.021	30.2	10
131	20	4.5	17.5	0.0213	30	10
132	25	4.5	18	0.0214	29.9	10
133	30	4.5	17.5	0.021	29.7	10
134	0	4.4	17.5	0.0251	29.6	10
135	5	4.5	18	0.0234	29.6	10
136	10	4.4	17.5	0.0227	29.4	10
137	15	4.5	17.5	0.0221	29.5	10
138	20	4.5	17.5	0.0217	29.4	10
139	25	4.5	18	0.0229	29.4	10
140	30	4.5	18	0.0226	28.7	10
141	0	6.1	24.5	0.0342	31.4	11
142	5	6.1	25	0.0357	31.5	11
143	10	6	25	0.0302	31.6	11
144	15	6	25	0.0293	31.8	11
145	20	6	25	0.0291	31.9	11
146	25	5.9	25	0.0291	31.8	11
147	30	6	25	0.0291	31.9	11
148	0	6.1	24.5	0.0337	32	11
149	5	6	25	0.0304	32	11
150	10	6	25	0.0294	31.9	11
151	15	5.9	25	0.0297	31.9	11
152	20	6	25	0.0299	32	11
153	25	6	25	0.0287	32	11
154	30	6	25	0.0289	32.1	11

Rows	Time Since Back Pulse	Flowrate (ft/s)	Pressure (psig)	Filtrate Flux (gpm/ft ²)	Temp (C)	Run Order
1	0	6	25.5	0.2938	31.9	1
2	5	6	25	0.1602	32.4	1
3	10	6	25.5	0.1612	32.4	1
4	15	6.1	25	0.1535	32.3	1
5	20	?	?	?	?	1
6	25	6	25	0.1544	32.2	1
7	30	6	25	0.1632	32.1	1
8	0	5.9	25	0.3004	32.1	1
9	5	5.9	25	0.1744	32.1	1
10	10	6	25	0.1618	32.1	1
11	15	6.1	25	0.1681	32	1
12	20	6	25	0.1632	32	1
13	25	6	25	0.1697	31.9	1
14	30	6	25	0.1664	31.9	1
15	0	7.4	33	0.3097	34.2	2
16	5	7.5	32.5	0.1792	34.9	2
17	10	7.4	32.5	0.1709	35.4	2
18	15	7.4	33	0.1654	35.6	2
19	20	7.5	32.5	0.1612	35.5	2
20	25	7.5	32.5	0.1664	35.8	2
21	30	7.5	33	0.1643	35.8	2
22	0	7.5	32.5	0.2727	34.1	2
23	5	7.5	32.5	0.1686	35.5	2
24	10	7.4	32.5	0.1572	35.9	2
25	15	7.5	32.5	0.1602	36.1	2
26	20	7.5	32.5	0.1592	36.4	2
27	25	7.5	32.5	0.1582	36.4	2
28	30	7.5	32.5	0.1582	36.5	2
29	0	3.1	25	0.1844	29.7	3
30	5	3.1	24.5	0.1393	29.5	3
31	10	3	25	0.1473	29.4	3
32	15	2.9	25	0.149	29.2	3
33	20	2.9	25	0.1544	29.2	3
34	25	3.1	25	0.1535	29.2	3
35	30	3	25	0.1602	29.3	3
36	0	3	25	0.2209	29.4	3
37	5	3	25	0.1709	29.3	3
38	10	3	25	0.1732	29.3	3
39	15	3	25	0.1694	29.2	3
40	20	3	25	0.1709	29.3	3
41	25	3	25	0.1664	29.3	3
42	30	3	25	0.1697	29.3	3
43	0	5.9	10.5	0.125	29.4	4

H2_C107.JMP

Rows	Time Since Back Pulse	Flowrate (ft/s)	Pressure (psig)	Filtrate Flux (gpm/ft2)	Temp (C)	Run Order
44	5	6	10.5	0.0854	29.3	4
45	10	6	10	0.0806	29.3	4
46	15	6	10.5	0.0806	29.4	4
47	20	6	10.5	0.0806	29.4	4
48	25	6	10	0.0777	29.4	4
49	30	6	10.5	0.0796	29.5	4
50	0	6	10	0.1098	29.6	4
51	5	6	10	0.0835	29.3	4
52	10	6	10	0.0811	29.2	4
53	15	6	10	0.0789	29.2	4
54	20	6	10	0.0777	29.2	4
55	25	6	10	0.0779	29.2	4
56	30	6	10	0.0772	29.2	4
57	0	7.5	18	0.1805	31	5
58	5	7.5	17.5	0.1226	31.5	5
59	10	7.5	17.5	0.1215	31.6	5
60	15	7.5	17.5	0.1144	31.7	5
61	20	7.5	17.5	0.1141	31.8	5
62	25	7.5	17.5	0.1146	31.8	5
63	30	7.6	17.5	0.1119	31.8	5
64	0	7.5	17.5	0.1282	31.9	5
65	5	7.5	17.5	0.1032	31.9	5
66	10	7.5	17.5	0.1095	31.9	5
67	15	7.6	17	0.1059	31.9	5
68	20	7.4	18	0.1063	31.9	5
69	25	7.5	17.5	0.1025	31.8	5
70	30	7.5	17.5	0.1021	31.8	5
71	0	5.9	24.5	0.2101	31.9	6
72	5	6	25	0.1452	32	6
73	10	6	25	0.144	32	6
74	15	5.9	25	0.1393	32	6
75	20	6.2	25	0.1314	32.1	6
76	25	6	25	0.1288	32	6
77	30	6	25	0.1321	32.1	6
78	0	5.9	25.5	0.1871	32.1	6
79	5	5.9	25.5	0.1448	32	6
80	10	6	25	0.1408	32.1	6
81	15	6	25	0.1432	32.1	6
82	20	5.9	25.5	0.15	32	6
83	25	5.8	26	0.1363	32	6
84	30	5.9	25	0.1342	32	6
85	0	4.5	33	0.2288	31.8	7
86	5	4.6	32	0.1871	32.5	7

C.14

Rows	Time Since Back Pulse	Flowrate (ft/s)	Pressure (psig)	Filtrate Flux (gpm/ft ²)	Temp (C)	Run Order
87	10	4.6	32.5	0.1899	32.8	7
88	15	4.4	33	0.1805	33.1	7
89	20	4.5	32.5	0.1709	33.6	7
90	25	4.5	32.5	0.1831	33.1	7
91	30	4.5	32.5	0.1987	32.9	7
92	0	4.6	32	0.2309	32.9	7
93	5	4.5	33	0.178	32.8	7
94	10	4.5	32.5	0.1942	32.7	7
95	15	4.5	32.5	0.2136	32.7	7
96	20	4.5	32.5	0.2248	32.6	7
97	25	4.5	32.5	0.2209	32.7	7
98	30	4.5	32.5	0.2288	32.7	7
99	0	6	40	0.2727	34.3	8
100	5	6	40.5	0.1961	35.4	8
101	10	6	40	0.1942	35.9	8
102	15	6	40	0.1788	36.3	8
103	20	6.1	40	0.1813	36.6	8
104	25	6	40	0.1839	36.7	8
105	30	6	40	0.1857	36.8	8
106	0	5.9	40	0.2418	36.8	8
107	5	6	40	0.1922	36.8	8
108	10	6	40	0.1913	36.8	8
109	15	6	40	0.1885	37	8
110	20	6	40	0.1848	37.1	8
111	25	6.1	40	0.1772	37.1	8
112	30	6.1	40	0.1788	37	8
113	0	8.8	25	0.1232	34.9	9
114	5	9.1	25	0.1124	36.8	9
115	10	9.1	24.5	0.1086	37.4	9
116	15	9	26	0.117	37.4	9
117	20	9	25	0.1038	37.4	9
118	25	9	25	0.105	37.5	9
119	30	9	25	0.1063	37.4	9
120	0	9.1	24.5	0.1294	37.7	9
121	5	9.1	25	0.1114	38	9
122	10	9.1	25	0.1081	38.3	9
123	15	9	25	0.1068	38.2	9
124	20	9	25	0.1068	38.2	9
125	25	9	25	0.0993	38.2	9
126	30	9	25	0.0956	37.7	9
127	0	4.6	17	0.1021	30.2	10
128	5	4.5	17.5	0.077	29.9	10
129	10	4.5	17.5	0.0779	29.8	10

C.15

H2_C107.JMP

Rows	Time Since Back Pulse	Flowrate (ft/s)	Pressure (psig)	Filtrate Flux (gpm/ft ²)	Temp (C)	Run Order
130	15	4.5	17.5	0.0796	29.7	10
131	20	4.5	17.5	0.0827	29.6	10
132	25	4.5	17.5	0.0902	29.5	10
133	30	4.5	17.5	0.0929	29.5	10
134	0	4.4	17.5	0.1342	29.6	10
135	5	4.5	17.5	0.0975	29.5	10
136	10	4.4	17.5	0.1001	29.5	10
137	15	4.5	18	0.1038	29.5	10
138	20	4.5	17.5	0.1017	29.5	10
139	25	4.5	17.5	0.1046	29.5	10
140	30	4.5	17.5	0.1081	29.5	10
141	0	5.9	25	0.1465	30.7	11
142	5	6	25.5	0.1124	31.3	11
143	10	6	25	0.1059	31.8	11
144	15	6	25	0.1029	31.9	11
145	20	6	25	0.1055	32	11
146	25	6	25	0.0986	32	11
147	30	6	24.5	0.0949	32	11
148	0	6.1	25	0.1119	32.2	11
149	5	6	25	0.111	32.2	11
150	10	5.9	25	0.11	32.4	11
151	15	6	25	0.1021	32.4	11
152	20	6	25	0.1025	32.4	11
153	25	5.9	25.5	0.1055	32.5	11
154	30	6.1	25	0.0997	32.4	11

Appendix D
Data Regression

Response: mean(Filtrate Flux (gpm/ft2))

Summary of Fit

RSquare	0.727274
RSquare Adj	0.685316
Root Mean Square Error	0.006057
Mean of Response	0.047951
Observations (or Sum Wgts)	16

8WT90 5-107

Lack of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack of Fit	4	0.00032082	0.000080	4.6253
Pure Error	9	0.00015606	0.000017	Prob>F
Total Error	13	0.00047688		0.0264
			Max RSq	0.9107

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	0.002954	0.007794	0.38	0.7108
Flowrate (ft/s)	0.0055906	0.001095	5.11	0.0002
Pressure (psig)	0.0005971	0.000174	3.43	0.0045

Effect Test

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
Flowrate (ft/s)	1	1	0.00095704	26.0893	0.0002
Pressure (psig)	1	1	0.00043172	11.7690	0.0045

Response Surface

Coef	Flowrate (ft/s)	Pressure (psig)	Mean(Filtrate Flux (gpm/ft2))
Flowrate (ft/s)	0	0	0.0055906
Pressure (psig)	?	0	0.0005971

Couldn't Solve Critical Values. Singular.

EigenStructure

Contour Plot Specification

Check two factors, edit grid/scale values.

Variable	From	To	By
☒ Flowrate (ft/s)	2	8	1
☒ Pressure (psig)	0	40	5
Mean(Filtrate Flux (gpm/ft2))	0.002	0.07	0.01

Go

Contour Plots

Whole-Model Test

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	0.00127169	0.000636	17.3335
Error	13	0.00047688	0.000037	Prob>F
C Total	15	0.00174857		0.0002

Flowrate (ft/s)

Effect Test

Sum of Squares	F Ratio	DF	Prob>F
0.00095704	26.0893	1	0.0002

Pressure (psig)

Effect Test

Sum of Squares	F Ratio	DF	Prob>F
0.00043172	11.7690	1	0.0045

Response: Mean(Filtrate Flux (gpm/ft²))

Summary of Fit

RSquare	0.767303
RSquare Adj	0.728521
Root Mean Square Error	0.00984
Mean of Response	0.045542
Observations (or Sum Wgts)	22

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	0.0504022	0.010889	4.63	0.0002
Run Order	-0.004538	0.000669	-6.78	<.0001
Flowrate (ft/s)	-0.000921	0.001341	-0.69	0.5009
Pressure (psig)	0.0011826	0.000266	4.44	0.0003

1.5 wt% S-107

Effect Test

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
Run Order	1	1	0.00445000	45.9577	<.0001
Flowrate (ft/s)	1	1	0.00004569	0.4718	0.5009
Pressure (psig)	1	1	0.00191102	19.7362	0.0003

Response Surface

Coef	Run Order	Flowrate (ft/s)	Pressure (psig)	Mean(Filtrate Flux (gpm/ft ²))
Run Order	0	0	0	-0.004538
Flowrate (ft/s)	?	0	0	-0.000921
Pressure (psig)	?	?	0	0.0011826

Couldn't Solve Critical Values. Singular.

EigenStructure

Contour Plot Specification

Check two factors, edit grid/scale values.

Variable	From	To	By
☐ Run Order	0	12.5	1
☒ Flowrate (ft/s)	2	10	1
☒ Pressure (psig)	5	45	5
Mean(Filtrate Flux (gpm/ft ²))	0.01	0.1	0.01

Go

Contour Plots

Run Order=6

Response: Mean(Filtrate Flux (gpm/ft²))

Summary of Fit

RSquare	0.767303
RSquare Adj	0.728521
Root Mean Square Error	0.00984
Mean of Response	0.045542
Observations (or Sum Wgts)	22

Parameter Estimates

Effect Test

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
Run Order	1	1	0.00445000	45.9577	<.0001
Flowrate (ft/s)	1	1	0.00004569	0.4718	0.5009
Pressure (psig)	1	1	0.00191102	19.7362	0.0003

Response Surface

Coeff	Run Order	Flowrate (ft/s)	Pressure (psig)	Mean(Filtrate Flux (gpm/ft ²))
Run Order	0	0	0	-0.004538
Flowrate (ft/s)	?	0	0	-0.000921
Pressure (psig)	?	?	0	0.0011826

Couldn't Solve Critical Values. Singular.

EigenStructure

Contour Plot Specification

Check two factors, edit grid/scale values.

Variable	From	To	By
☐ Run Order	0	12.5	1
☒ Flowrate (ft/s)	2	10	1
☒ Pressure (psig)	5	45	5
Mean(Filtrate Flux (gpm/ft ²))	0.01	0.1	0.01

Go

Contour Plots

Run Order=6

Whole-Model Test

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	0.00574713	0.001916	19.7846
Error	18	0.00174291	0.000097	Prob>F
C Total	21	0.00749004		<.0001

Run Order

Effect Test

Sum of Squares	F Ratio	DF	Prob>F
0.00445000	45.9577	1	<.0001

Flowrate (ft/s)

Effect Test

Sum of Squares	F Ratio	DF	Prob>F
0.00004569	0.4718	1	0.5009

Pressure (psig)

Effect Test

Sum of Squares	F Ratio	DF	Prob>F
0.00191102	19.7362	1	0.0003

Response: Mean(Filtrate Flux (gpm/ft2))

Summary of Fit

RSquare	0.944831
RSquare Adj	0.935636
Root Mean Square Error	0.003932
Mean of Response	0.042169
Observations (or Sum Wgts)	22

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	0.0143143	0.004465	3.21	0.0049
Run Order	-0.002832	0.000265	-10.69	<.0001
Flowrate (ft/s)	0.0011587	0.000536	2.16	0.0443
Pressure (psig)	0.0015441	0.000107	14.41	<.0001

0.05257% S-107

Effect Test

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
Run Order	1	1	0.00176484	114.1737	<.0001
Flowrate (ft/s)	1	1	0.00007228	4.6762	0.0443
Pressure (psig)	1	1	0.00320911	207.6087	<.0001

Response Surface

Coef	Run Order	Flowrate (ft/s)	Pressure (psig)	Mean(Filtrate Flux (gpm/ft2))
Run Order	0	0	0	-0.002832
Flowrate (ft/s)	?	0	0	0.0011587
Pressure (psig)	?	?	0	0.0015441

Couldn't Solve Critical Values. Singular.

EigenStructure

Contour Plot Specification

Check two factors, edit grid/scale values.

Variable	From	To	By
☐ Run Order	1	11	1
☒ Flowrate (ft/s)	2	10	1
☒ Pressure (psig)	5	45	5
Mean(Filtrate Flux (gpm/ft2))	0.02	0.08	0.01

Go

Contour Plots

Run Order=6

Whole-Model Test

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	0.00476511	0.001588	102.7572
Error	18	0.00027823	0.000015	Prob>F
C Total	21	0.00504334		<.0001

Run Order

Effect Test

Sum of Squares	F Ratio	DF	Prob>F
0.00176484	114.1737	1	<.0001

Flowrate (ft/s)

Effect Test

Sum of Squares	F Ratio	DF	Prob>F
0.00007228	4.6762	1	0.0443

Pressure (psig)

Effect Test

Sum of Squares	F Ratio	DF	Prob>F
0.00320911	207.6087	1	<.0001

Response: Mean(Filtrate Flux (gpm/ft2))

Summary of Fit

RSquare	0.919071
RSquare Adj	0.905583
Root Mean Square Error	0.013085
Mean of Response	0.14497
Observations (or Sum Wgts)	22

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	0.1024178	0.014862	6.89	<.0001
Run Order	-0.005714	0.000882	-6.48	<.0001
Flowrate (ft/s)	-0.005657	0.001783	-3.17	0.0053
Pressure (psig)	0.0044883	0.000357	12.58	<.0001

C-107 Supernatant

Effect Test

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
Run Order	1	1	0.00718549	41.9643	<.0001
Flowrate (ft/s)	1	1	0.00172270	10.0608	0.0053
Pressure (psig)	1	1	0.02711383	158.3489	<.0001

Response Surface

Coef	Run Order	Flowrate (ft/s)	Pressure (psig)	Mean(Filtrate Flux (gpm/ft2))
Run Order	0	0	0	-0.005714
Flowrate (ft/s)	?	0	0	-0.005657
Pressure (psig)	?	?	0	0.0044883

Couldn't Solve Critical Values. Singular.

EigenStructure

Contour Plot Specification

Check two factors, edit grid/scale values.

Variable	From	To	By
☐ Run Order	1	11.5	1
☒ Flowrate (ft/s)	2	10	1
☒ Pressure (psig)	5	45	5
Mean(Filtrate Flux (gpm/ft2))	0.075	0.225	0.025

Go

Contour Plots

Run Order=1

Whole-Model Test

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	0.03500193	0.011667	68.1388
Error	18	0.00308211	0.000171	Prob>F
C Total	21	0.03808404		<.0001

Run Order

Effect Test

Sum of Squares	F Ratio	DF	Prob>F
0.00718549	41.9643	1	<.0001

Flowrate (ft/s)

Effect Test

Sum of Squares	F Ratio	DF	Prob>F
0.00172270	10.0608	1	0.0053

Pressure (psig)

Effect Test

Sum of Squares	F Ratio	DF	Prob>F
0.02711383	158.3489	1	<.0001

Response: Mean(Filtrate Flux (gpm/ft²))

Summary of Fit

RSquare	0.953287
RSquare Adj	0.94837
Root Mean Square Error	0.00491
Mean of Response	0.083599
Observations (or Sum Wgts)	22

Lack of Fit

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	-0.001981	0.00574	-0.35	0.7337
Flowrate (ft/s)	0.0012905	0.000668	1.93	0.0685
Pressure (psig)	0.0047568	0.000243	19.60	<.0001

0.05wt% S163 Simulant

Effect Test

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
Flowrate (ft/s)	1	1	0.00008993	3.7307	0.0685
Pressure (psig)	1	1	0.00925641	384.0098	<.0001

Response Surface

Coef	Flowrate (ft/s)	Pressure (psig)]	Mean(Filtrate Flux (gpm/ft ²))
Flowrate (ft/s)	0	0	0.0012905
Pressure (psig)]	?	0	0.0047568

Couldn't Solve Critical Values. Singular.

EigenStructure

Contour Plot Specification

Check two factors, edit grid/scale values.

Variable	From	To	By
☒ Flowrate (ft/s)	2	10	1
☒ Pressure (psig)]	7.5	27.5	5
Mean(Filtrate Flux (gpm/ft ²))	0.04	0.13	0.01

Go

Contour Plots

Whole-Model Test

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	0.00934634	0.004673	193.8703
Error	19	0.00045799	0.000024	Prob>F
C Total	21	0.00980433		<.0001

Flowrate (ft/s)

Effect Test

Sum of Squares	F Ratio	DF	Prob>F
0.00008993	3.7307	1	0.0685

Pressure (psig)

Effect Test

Sum of Squares	F Ratio	DF	Prob>F
0.00925641	384.0098	1	<.0001

Response: Mean(Filtrate Flux (gpm/ft2))

Summary of Fit

RSquare	0.975024
RSquare Adj	0.972395
Root Mean Square Error	0.004507
Mean of Response	0.152025
Observations (or Sum Wgts)	22

Lack of Fit

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	0.0607748	0.005269	11.53	<.0001
Flowrate (ft/s)	-0.001295	0.000613	-2.11	0.0483
Pressure (psig)	0.0060512	0.000223	27.15	<.0001

Effect Test

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
Flowrate (ft/s)	1	1	0.00009054	4.4562	0.0483
Pressure (psig)	1	1	0.01497949	737.2879	<.0001

0.05 wt% SS Simulant

Response Surface

Coef	Flowrate (ft/s)	Pressure (psig)]	Mean(Filtrate Flux (gpm/ft2))
Flowrate (ft/s)	0	0	-0.001295
Pressure (psig)]	?	0	0.0060512

Couldn't Solve Critical Values. Singular.

EigenStructure

Contour Plot Specification

Check two factors, edit grid/scale values.

Variable	From	To	By
☒ Flowrate (ft/s)	2	10	1
☒ Pressure (psig)]	7.5	27.5	5
Mean(Filtrate Flux (gpm/ft2))	0.1	0.22	0.02

Go

Contour Plots

Whole-Model Test

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	0.01507002	0.007535	370.8721
Error	19	0.00038602	0.000020	Prob>F
C Total	21	0.01545605		<.0001

Flowrate (ft/s)

Effect Test

Sum of Squares	F Ratio	DF	Prob>F
0.00009054	4.4562	1	0.0483

Pressure (psig)

Effect Test

Sum of Squares	F Ratio	DF	Prob>F
0.01497949	737.2879	1	<.0001

Response: Mean(Filtrate Flux (gpm/ft²))

Summary of Fit

RSquare	0.781116
RSquare Adj	0.758076
Root Mean Square Error	0.004458
Mean of Response	0.037981
Observations (or Sum Wgts)	22

Lack of Fit

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	-0.001062	0.0056	-0.19	0.8516
Flowrate (ft/s)	0.0054622	0.000674	8.11	<.0001
Pressure (psig)	0.0003528	0.00022	1.60	0.1260

8wt% S103 Simulant

Effect Test

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
Flowrate (ft/s)	1	1	0.00130680	65.7437	<.0001
Pressure (psig)	1	1	0.00005090	2.5608	0.1260

Response Surface

Coef	Flowrate (ft/s)	Pressure (psig)]	Mean(Filtrate Flux (gpm/ft ²))
Flowrate (ft/s)	0	0	0.0054622
Pressure (psig)]	?	0	0.0003528

Couldn't Solve Critical Values. Singular.

EigenStructure

Contour Plot Specification

Check two factors, edit grid/scale values.

	Variable	From	To	By
☒	Flowrate (ft/s)	3	10	1
☒	Pressure (psig)]	7.5	27.5	5
	Mean(Filtrate Flux (gpm/ft ²))	0.025	0.065	0.005

Go

Contour Plots

Whole-Model Test

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	0.00134775	0.000674	33.9020
Error	19	0.00037767	0.000020	Prob>F
C Total	21	0.00172542		<.0001

Flowrate (ft/s)

Effect Test

Sum of Squares	F Ratio	DF	Prob>F
0.00130680	65.7437	1	<.0001

Response: Mean(Filtrate Flux (gpm/ft2))

Summary of Fit	
RSquare	0.557728
RSquare Adj	0.511173
Root Mean Square Error	0.007654
Mean of Response	0.064395
Observations (or Sum Wgts)	22

Lack of Fit

Parameter Estimates					
Term	Estimate	Std Error	t Ratio	Prob> t	
Intercept	0.0225157	0.008948	2.52	0.0210	
Flowrate (ft/s)	0.0026857	0.001042	2.58	0.0184	
Pressure (psig)	0.0015746	0.000378	4.16	0.0005	

8/27/98 53 Simulink

Effect Test					
Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
Flowrate (ft/s)	1	1	0.00038951	6.6484	0.0184
Pressure (psig)	1	1	0.00101423	17.3116	0.0005

Response Surface				
Coef	Flowrate (ft/s)	Pressure (psig)]	Mean(Filtrate Flux (gpm/ft2))	
Flowrate (ft/s)	0	0	0.0026857	
Pressure (psig)]	?	0	0.0015746	

Couldn't Solve Critical Values. Singular.

EigenStructure

Contour Plot Specification

Check two factors, edit grid/scale values.

Variable	From	To	By
☒ Flowrate (ft/s)	2	10	1
☒ Pressure (psig)]	7.5	27.5	5
Mean(Filtrate Flux (gpm/ft2))	0.045	0.09	0.005

Go

Whole-Model Test

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	0.00140373	0.000702	11.9800
Error	19	0.00111315	0.000059	Prob>F
C Total	21	0.00251688		0.0004

Flowrate (ft/s)

Effect Test

Sum of Squares	F Ratio	DF	Prob>F
0.00038951	6.6484	1	0.0184

Pressure (psig)

Effect Test

Sum of Squares	F Ratio	DF	Prob>F
0.00101423	17.3116	1	0.0005

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