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**RESULTS FROM TESTS OF DU PONT CROSSFLOW FILTER
(U)**

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RESULTS FROM TESTS OF DU PONT CROSSFLOW FILTER
(U)

by

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ISSUED: October 1994

SRTC

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ABSTRACT

In support of the Late Wash Process a 10 foot long, four tube Du Pont crossflow filter was tested with simulated waste slurry in a well-instrumented flow loop at the Thermal Fluids Laboratory (TFL). During testing, the axial velocity, transmembrane pressure, temperature and filtration time were varied. Some of the expected trends were observed. For a constant transmembrane pressure, increasing the axial velocity from 4 to 14 ft/s increased the flux of filtrate through the membrane, sometimes dramatically. Increasing the transmembrane pressure increased the flux, however, there was a diminishing return. For higher transmembrane pressures, further increases in transmembrane pressure gave little or no increase in flux. Filtration runs up to 24 hours long were made. Flux decreased with time, but the rate of decrease depended on the axial velocity. Flux decreased much faster for 6 ft/s than for 14 ft/s.

The loop contained a backpulse system which allowed filtrate to be forced periodically through the membrane in the reverse direction, from shell side to tube side. Backpulsing was provided by a piston and cylinder apparatus that allowed instantaneous measurement of filtrate flow. Backpulsing served two purposes. First, it removed filter cake from the tube walls, temporarily increasing filtrate flux. The effect lasted roughly 30 minutes when the axial velocity was 6 ft/s and was an effective expenditure of filtrate. The effect lasted only about a minute when the axial velocity was 14 ft/s and was not an effective expenditure of filtrate. Second, backpulsing effectively cleared partial plugs in the filter. A partial plug was characterized by a significantly increased resistance to filtration and also axial flow. The volume of filtrate required to accomplish backpulsing was less than expected. Backpulsing was expected to require 0.13 gal/ft². However, testing showed that all of the benefit was realized with the first 0.02 gal/ft².

The small 0.07 μm pores of the Du Pont filter are resistant to fouling by slurry particles (1.5 μm). As a result the filter was operated with slurry for five weeks or 200 hours without chemical cleaning. During that time the flux decreased only by about 10%.

EXECUTIVE SUMMARY

Crossflow filtration will be used to filter radioactive waste slurry as part of the Late Wash Process. In support of this process a 10 foot long Du Pont crossflow filter was tested with simulated waste slurry in a well-instrumented flow loop at the Thermal Fluids Laboratory (TFL). The Du Pont filter contains four porous tubes in a shell. Slurry is pumped under pressure through the tubes. Filtrate flows through the porous walls and is collected on the shell side of the filter.

During testing, the axial velocity, transmembrane pressure, temperature and filtration time were varied. For a constant transmembrane pressure, increasing the axial velocity from 4 to 14 ft/s increased the flux of filtrate through the membrane, sometimes dramatically. Increasing the transmembrane pressure increased the flux, however, there was a diminishing return. Filtration runs up to 24 hours long were made. Flux decreased with time, with the rate of decrease depending on the axial velocity. Flux decreased much faster for 6 ft/s than for 14 ft/s.

The loop contained a backpulse system that allowed filtrate to be forced periodically through the membrane in the reverse direction, from shell side to tube side. Backpulsing was provided by a piston and cylinder apparatus that allowed instantaneous measurement of filtrate flow. Backpulsing served two purposes. First, it removed filter cake from the tube walls, temporarily increasing filtrate flux. The effect lasted roughly 30 minutes when the axial velocity was 6 ft/s and was an effective expenditure of filtrate. The effect lasted only about a minute when the axial velocity was 14 ft/s and was not an effective expenditure of filtrate. Second, backpulsing effectively cleared partial plugs in the filter. A partial plug was characterized by a significantly increased resistance to filtration and also axial flow. The volume of filtrate required to accomplish backpulsing was less than expected. Using the Technical Basis for Late Wash (Landon) backpulsing was expected to require 0.13 gal/ft². However, testing showed that all of the benefit was realized with the first 0.02 gal/ft².

The small 0.07 mm pores of the Du Pont filter are resistant to fouling by tetraphenylborate slurry particles (1.5 mm). As a result the filter was operated with slurry for five weeks or 200 hours without chemical cleaning. During that time the flux decreased only by about 10%. At the end of testing the filter was chemically cleaned. The cleaning process dissolved solids that

had been trapped in the filter including cesium. In actual plant operation some of the cesium dissolved in the cleaning solutions would be radioactive Cs-137. Cleaning solutions from the present test were analyzed for cesium as well as other elements. The maximum concentration of cesium in the cleaning solutions was 2 ppm.

There was concern that the high shear centrifugal pumps used in the present test decreased the size of the particles which degraded the performance of the filter. Particle size analyses before and after the test showed a 15% reduction in median particle size. However, the Du Pont Co. at Seneca SC tested the same model filter and the same slurry before it was shipped to SRS using a low shear pump. For the limited set of data for which a comparison was appropriate there was no significant difference in fluxes.

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1. INTRODUCTION

1.1 Background

In preparation for delivery to the Defense Waste Processing Facility, slurry from Tank 49H will be washed in a process that uses a cross-flow filter [Landon, 1994, also Fink, 1994]. It had been planned to mount the filter in a vertical orientation. Recently the plan has been changed to make the orientation horizontal. Most of the flow passes through the porous tubes of the filter in the axial direction. A small part of the flow is driven through the porous walls of the tubes by a pressure difference. Filtrate collects in the shell around the porous tubes and flows out. Brief flow in the reverse direction, backpulsing, is useful for dislodging filter cake, which increases production of filtrate, at least temporarily. To provide technical support, the Thermal Fluids Laboratory (TFL) tested a ten foot long, four tube vertical Du Pont cross-flow filter in a flow loop that allowed flow in either the forward direction (i.e., tube side to shell side) or backpulse direction.

1.2 Literature Survey

Bhave [1991] gave a good review of cross-flow filtration and states definitions, Table 1, that are used in this report. This paragraph summarizes part of his textbook. Filtration flux, J , is related to transmembrane (TM) pressure drop, ΔP , and resistances.

$$J = \frac{\Delta P}{R_m + R_a + R_c + R_p} \quad (1)$$

where,

R_m = membrane resistance

R_a = adsorption resistance

R_c = cake resistance

R_p = polarization resistance

Membrane resistance is the resistance of the filter membrane with no solids or solutes present. It is measured by passing ultrafiltered water through the membrane. Adsorption resistance is caused by the adsorption of large molecules or small particles inside the pores of the filter. They progressively degrade the performance of the filter by reducing the effective area of the pores. Cake resistance is the resistance of the layer of solids on top of the filter membrane. It depends on the thickness and porosity of the cake layer. Polarization resistance occurs because the concentration of particles and solutes can be greater near the membrane surface than in the bulk liquid. Back diffusion of solute and particles from the wall to the bulk liquid reduces the net filtration flux and act as a resistance. Increasing the filtrate flux increases the concentration of solute and particles at the membrane. Since there is an upper limit to the concentration of solute and particles at the surface, there is an upper limit to filtrate flux, irrespective of TM pressure. Filtrate flux increases in proportion to TM pressure up to the "threshold pressure", termed the pressure controlled regime. Above the threshold pressure and as the result of concentration polarization, increases in TM pressure cause only small increases or no increase in flux, termed the mass-transfer-controlled regime.

Lu, et al. [1993] concluded that axial velocity affects the rate of diffusion of particles and also what fraction of particles adhere when they touch the filter cake at the wall. Stamatakis and Tien [1993] considered the lateral force on a particle because it is in a shear field. Murkes and Carlsson [1988] gave expressions for filtration flux for the cases of low and high axial velocities.

$$J = \text{const. } v^{3/2} \quad \text{for } v \rightarrow 0 \quad (2)$$

$$J = \frac{B \Delta P}{\mu L} \quad \text{for } v \rightarrow \infty \quad (3)$$

where B is Darcy's permeability constant, L is the thickness of the filter medium and μ is viscosity of the filtrate.

1.3 Previous SRS and SRS Sponsored Work for Late Wash Filtering

A number of tests of crossflow filters have been performed at SRS. Some of the more recent tests in support of Late Wash are listed below. Morissey [1992] tested a 0.5 μm cross-flow filter with 9.5 wt % solids Late Wash slurries. The filter had one 17 inch long tube and was oriented horizontally. The report does not contain much information about the hydraulic performance of the filter when used with slurry. Baich [1993] investigated the plugging of a Mott filter containing three 6 inch long parallel tubes. He intentionally plugged one of the filter tubes by stopping the axial flow until the tube was packed with an estimated concentration of 50 wt %. Flow was then restored. Repeated attempts to dislodge the plug using backpulsing were unsuccessful. Monson and Baich [1992a] tested a 24 inch long 0.5 μm Mott filter with a TM pressure of 13 psid and backpulsing every five minutes. Despite the backpulsing the flux decreased by half over a period of about nine hours. The rate of decrease increased when the concentration of the slurry was allowed to increase to 12 wt %. Monson and Baich [1992b] also tested Vacco cross-flow filters having pore sizes of 1 μm and 3 μm . The flux of the 3 μm Vacco filter decreased faster than the 0.5 μm Mott filter, but the flux of the 1 μm Vacco decreased more slowly. All of the above work was done with filters that were 24 inch long or shorter. Short filters are expected to give higher filtrate fluxes because the wall shear is relatively high for the first 20 diameters down a pipe. During October 1993 the Du Pont Company located at Seneca SC also tested a ten foot long four tube Du Pont filter but in a horizontal orientation [Garner and Brandon, 1993 or Nash, 1993]. The Seneca test was scoping in nature and inexpensive and the data from it gave helpful guidance for the present test.

2. TEST DESCRIPTION

2.1 Test Loop Hardware

This test was performed as part of Task 93-032-1 [Steinke, 1993] and run according to Procedure 93-021, Revision 2 [Steinke, 1994]. The Du Pont cross-flow filter tested contained four ten foot long tubes with 5/8" inside diameter inside a shell. The tubes were made from sintered stainless steel with an average pore size of about 100 μm , with the exception of the ends of the tubes which were solid metal. The Du Pont filter is designed to be a surface filter rather than filtering inside the pores of the filter. To minimize particle passage into the pores there is a layer of sintered titanium dioxide with a thickness of 30 μm and an average pore size of 0.06 μm on the inside surface of the stainless steel tubes. All of the filtering action is by the porous layer of titanium dioxide. The effective filtering area is 6.34 ft^2 . The Mott cross-flow filter, which will be tested next, does not have the titanium dioxide layer and therefore the filtering is done by the pores of the sintered stainless steel. Because of the larger pores, the Mott clean water resistance is lower than for the Du Pont filter. However, Du Pont claims that the filter stays cleaner when filtering and has improved performance. At the conclusion of the upcoming Mott filter tests the two filters will be compared.

The Du Pont cross-flow filter was mounted in the test loop shown in Figure 1, which was designed by T. J. Steeper and J. W. Corbett and documented in prints ST-MDX5-10210, ST-MDX5-10212 and ST-MDX5-10213. There are actually two linked flow loops, one for slurry and one for cleaning solution. The cross-flow filter and the backpulse mechanism are common to both loops. One pump is dedicated to the cleaning loop. Two other pumps are dedicated to the slurry loop. Having two largely separate loops reduced contamination of the slurry and loss of slurry during the cleaning operation. During normal operation slurry was pumped out of the slurry reservoir, through a flowmeter, axially through the tubes of the filter and back to the reservoir.

The pressure inside the tubes of the filter is higher than in the space outside the tubes, which forces filtrate through the porous tube wall. The TFL loop allows the experimenter to either mix the filtrate back into the slurry or collect the filtrate and concentrate the slurry. When the slurry loop was used the loop was referenced to atmospheric pressure at the free surface in the slurry reservoir, about four feet off the floor. The reservoir was located low to allow slurry to drain to the reservoir. However, this placement had a disadvantage. The loop extended about 20 feet off the floor so that parts of the loop were at a sub-atmospheric pressure. Leaks in the piping had to be avoided because significant volumes of air would have been sucked into loop and mixed with the slurry.

The cross-flow filter can be backpulsed. Normally, filtrate collected on the shell side of the filter flowed through a cylinder, out a hole near the top of the cylinder, through a flowmeter and back into the slurry loop piping where it remixed with the slurry. When the filter was to be backpulsed pressurized air drove down a piston in the cylinder. After the piston had traveled an inch it covered the hole in the side of the cylinder blocking filtrate flow to the flowmeter. All filtrate was forced back through the porous tubes of the filter, dislodging filter cake.

Backpulsing was not always successful for restoring filter performance and chemical filter cleaning was necessary. Before cleaning the loop, slurry was drained from it. The loop was flushed and backpulsed with ultrafiltered, deionized water that contained a trace (0.006 wt %) of sodium hydroxide to allow the flowmeters to operate. The water was drained and stored. Then a 1 wt % solution of oxalic acid was placed in the cleaning loop and circulated around the cleaning loop accompanied with some backpulsing. Then there was another clean water flush. Then, a 1 wt % sodium hydroxide solution was circulated. Finally there was another clean flush before returning to operation with slurry. Cleaning solutions were labeled and stored. The most successful cleaning was done somewhat differently. A 1 wt % solution of hydrogen peroxide was used instead of oxalic acid. Also the sodium hydroxide solution that followed it was allowed to remain in the loop overnight.

2.2 Procedure

The testing followed a written procedure [Steimke, 1994]. At the start of each day of testing the pressure lines were purged with clean filtrate to remove air or solids. Then the zero pressure reading on the differential pressure gages was recorded. One or both slurry pumps were turned on depending on the required flowrate for the test. Valves V3 and V11 were iteratively adjusted to achieve both the desired axial flow and TM pressure. To backpulse, the position of V11 was marked. Then V11 was opened fully to reduce the tube side pressure and the valve supplying pressurized air to backpulse piston was opened. The position of the backpulse piston was monitored as it was driven downward. When it had reached the desired travel the driving air pressure was relieved and the previous valve positions were restored. For runs after February 17, 1993, valve V11 was not opened, but kept it in the same position. This was operationally simpler and no less effective. Data were logged during backpulse and also during steady state. At the end of nearly all days of testing the loop was kept full of slurry.

In shakedown tests both the slurry loop and the cleaning loop were tested using a dilute (0.006 wt %) solution of sodium hydroxide in ultra-filtered, deionized water. The resulting pH of 11 gave enough ions to allow the magnetic flowmeters to operate. In steady state tests, both the axial pressure drop and the TM pressure drop were measured. The performance of the backpulse system was tested with transient tests.

At various times samples were taken of slurry, filtrate and cleaning solutions. Table 2 is a list of the samples. Tables 3, 4 and 5 contain the results of analyses of the samples.

The temperature of the slurry was controlled to ± 2 °C using tubing coils that could be supplied with either chilled cooling water or steam.

2.3. Instrumentation

Figure 1 shows the location of three pressure measurements, three differential pressure measurements, five temperature measurements, the flow of slurry or cleaning solution to the tube side of the filter and the flow of filtrate. Pressure transducers DP1, DP2, and P1 were located 6 inches below the pressure tap at the slurry inlet to the filter. Pressure transducers P2, P3, and DP3 were located 38 inches below the pressure tap at the slurry outlet from the filter. The distance between those two pressure taps was 143 inches. The position of the backpulse cylinder was measured using a linear displacement device. A triple beam balance or an electronic scale was used to measure mass. The identification numbers of the instruments are listed in Table 6 as well as the instrument calibrations and the data acquisition system (DAS) calibrations. DAS calibrations were necessary for instruments that had a milliamp output. The milliamp output was passed through calibrated 500 ohm resistors that produced the voltages that were read by the DAS. Data were recorded using a Macintosh® based data acquisition system (DAS) using Workbench® software. Steady state conditions were generally logged at a rate of once per second. Backpulses were logged at a rate of five per second.

2.4. Data Reduction

A Trapeze® spreadsheet was written that plotted the instantaneous values of flows, gage pressures, differential pressures, temperatures and the position of the backpulse piston. Average values were computed. For the cases of data logs for steady state conditions the averages were copied and pasted into a data summary. For the cases of logs made during transient conditions, such as backpulses, graphs of the transient measurements were plotted. TM pressure was computed as the average of the difference between the slurry and filtrate pressures at the top (DP3) and the difference at the bottom (DP2). Axial pressure drop, DP1, and axial flow, Q1, were also plotted. Net forward filtrate flow was computed as the reading on magnetic flowmeter 2 (Q2) minus the flow driven by the moving piston, which was the area of the piston multiplied by its velocity. Instantaneous piston velocity was computed as the difference in two successive positions divided by the time increment. The DAS reads a minimum incremental size in the voltage output of the displacement gage. The effect of the minimum increment is to generate noise in the computation of piston velocity. Therefore, smoothing was performed by computing a running average over five consecutive piston velocities. Flux was computed as TM flow in gpm divided by the membrane area, 6.34 ft². Flux is controlled by Darcy's law in which flux is inversely proportional to viscosity. Following the recommendation of Du Pont engineers at Seneca all fluxes were referenced to 37°C using the following equation.

$$F(37^{\circ}) = F(T) \frac{\mu(T)}{\mu(37^{\circ})} \quad (4)$$

Total resistance was computed as the average TM pressure divided by the net forward flux. During a backpulse both the net flux and TM pressure were negative, so that the resistance was still positive.

2.5. Slurry Description

The recipe for slurry is listed in Table 7. The same slurry was previously used in Du Pont tests at Seneca, SC then shipped to SRS. The TFL received 11.2 gallons of slurry weighing 94.8 pounds or a density of 63.3 lb/ft³. The slurry was analyzed by TNX after its receipt at the TFL and found to contain 8.21 wt % of insoluble solids. It was desired to run most of the tests with 10 wt % inside the tubes of the filter. The filtrate part of the loop requires 3.72 gallons to fill. The removal of 3.72 gallons of filtrate would have increased the concentration in the tubes to more than 10 wt %. Therefore, 0.87 gallons (7.36 lb) of slurry were removed and 1.87 gallons of simulated filtrate

were added. This achieved a 10 wt % in the filter tubes during operation without overfilling the loop. The simulated filtrate that was added consisted of 7.08 L of filtered water, 10.6 g of NaTPB and 0.71 g of NaOH.

3. DISCUSSION OF RESULTS

3.1. Functional Dependence of Filtrate Flux and Resistance

Figures 2 and 3 and also Table 8 show the results of pressure scans logged from 2 to 5 minutes after the test conditions had been set and a backpulse had been performed to eliminate the effect of previous conditions. Figure 2 plots actual fluxes, while Figure 3 plots fluxes normalized to 37°C using equation 4. This normalization was done to allow a more meaningful comparison of fluxes at different filtrate temperatures. The effect of time will be discussed in Section 3.2. While the fluxes decrease with time the difference between logging 2 minutes after a backpulse and 5 minutes after a backpulse is not significant. For a pressure scan the axial velocity and filtrate temperature were held constant and the TM pressure was changed. The test sequence was randomized to allow the detection of slow changes in intrinsic filter performance. The instantaneous resistance through the filter was computed as the TM pressure divided by the TM flux. Analysis of the data showed that the resistance was still changing significantly for some of the runs. Therefore, runs for which the average change in resistance was greater than an acceptance criterion of 3 psid ft²/gpm per second were not plotted. Other values of the acceptance criterion were examined. Lower values of the acceptance criterion decreased the number of data points but did not change the shape of the curves. Higher values of the acceptance criterion allowed some data points that were significantly higher than the curves. The shapes of the curves for the scans are similar and agree with Bhavde description in Section 1.2. For pressures less than the threshold pressure the flux is proportional to the TM pressure. For higher TM pressures the flux increases more slowly. It is convenient to define the threshold pressure as the intersection of the line through the pressure controlled regime data and the line through the mass-transfer-controlled regime data. The threshold pressures for the TFL scans at 6, 10 and 14 ft/s were about 5, 16 and 26 psid, respectively. For the TFL data, velocity seems to make no difference for TM pressures less than about 6 psid and TM pressure is the controlling variable. For TM pressures higher than 26 psid the TM pressure has less effect and velocity is the controlling variable. Note that flux is a strong function of axial flow. For a TM pressure of 20 psid and a temperature of 30°C increasing the axial velocity from 6 ft/s to 14 ft/s increases the flux by a factor of 3.8. Also shown in Figure 3 are typical clean water fluxes for the filter. Naturally, they are higher than fluxes with slurry because there is no filter cake resistance or polarization resistance, only membrane and adsorption resistance, probably due to bacteria.

Figure 2 shows that the fluxes for 50°C and 6 ft/s were about twice as large as for 30°C and 6 ft/s. Figure 3 shows that the normalization process which compensates for filtrate viscosity removed most of that difference but did not make the data coincide. The reason for this is that the normalization is correct for membrane resistance and filter cake resistance, but not polarization resistance. At the higher TM pressures the ratio between the normalized fluxes at 50°C and 30°C was about 1.2. However, the unnormalized ratio was 1.76. Therefore, the temperature normalization captured most of the difference.

Seneca [Garner and Brandon, 1993 or Nash, 1993] test data are also shown. The pressure listed in the Seneca report was tube-side pressure. The Seneca estimate of shell-side pressure, 1.2 psig, was subtracted to give TM pressure. It is more difficult to estimate a threshold pressure for the Seneca data because the axial velocity was decreased from 13.4 ft/s to 10.7 ft/s as the TM pressure was increased from 20 to 50 psid. However the Seneca data fall between the TFL data for 10 and 14 ft/s as was expected.

Figure 4 shows the same data as in Figure 3 but expressed as total resistance. This resistance and all others in this report were referenced to 37°C using Darcy's Law, Equation 4. Temperatures

were measured at five locations in and around the loop. The temperature in the filtrate line was used for the referencing process. Bhavé suggested that the total resistance to filtration is the sum of the membrane resistance of the filter, adsorption resistance, the resistance of the filter cake on the surface of the membrane and the polarization resistance in the flowing fluid as shown in Equation 1. The total resistance measured for the Du Pont crossflow filter varied from 300 psid ft²/gpm to 2000 psid ft²/gpm, both normalized to 37°C. The trends for the total resistance will be discussed below. Membrane resistance for the Du Pont crossflow filter with 0.07 µm pores was 80 psid ft²/gpm. (For comparison, the Mott Company claims a membrane resistance of about 2.5 psid ft²/gpm for their 0.5 µm cross-flow filter.) Adsorption resistance was measured during nominally clean water runs and varied from zero to 240 psid ft²/gpm. Adsorption resistance seems to be due to both accumulation of solids in the pores of the filter and blockage of flow by bacteria. Adsorption resistance was greatly reduced by chemical cleaning, then it slowly increased. By difference, the sum of filter cake resistance, and polarization resistance varied from about 150 to 1900 psid ft²/gpm and was function of axial velocity, TM pressure and to a smaller extent filtrate temperature. More discussion of the types of resistance follows.

Membrane resistance for the Du Pont crossflow filter was measured by pumping deionized ultrafiltered water through it. It was expected that the membrane resistance would be independent of TM pressure and time invariant. It was also expected that the forward and backpulse would be equal. Figure 5 shows the history of the nominally clean resistance of the Du Pont filter. Ultrafiltered, deionized water was first placed in the loop on October 21, ten days before day #1 on the graph. On day #1 the forward and backpulse resistances were 195 and 95 psid ft²/gpm, respectively. Both resistances increased with time, but decreased after each chemical cleaning. Chemical cleaning will be discussed more in Section 3.8. The forward and backward resistances were both equal to 80 psid ft²/gpm, the minimum value, after an aggressive chemical cleaning on December 15-16, 1993. It was concluded that the membrane resistance was 80 psid ft²/gpm and that any additional resistance measured for nominally clean water was adsorption resistance. Since no sludge or chemicals other than very dilute sodium hydroxide were present the adsorption resistance was tentatively attributed to the presence of bacteria.

Bacteria were found during a microscopic examination of a sample of nominally clean and originally deionized and ultrafiltered water from the loop at a concentration of $1.44 \times 10^5/\text{mL}$ [Fliermans, 1993]. When the water was allowed to remain in the loop for a period of days the TM resistance increased. When cleaning steps were performed that were expected to kill bacteria and dissolve their cells the resistance decreased. The postulated reason follows. Fliermans [1993] measured the length of the bacteria to be about one micrometer. Therefore, the bacteria can not pass through the small pores of the filter so that the filtrate is free of bacteria when it passes through the pores. (More details on bacteria given in Section 3.8 on Filter Cleaning.) Given time, bacteria can migrate through the test loop and colonize the filtrate side of the loop. Forward flow tends to push bacteria over the tube-side pore openings, increasing resistance. Backpulse flow tends to push bacteria away from the tube-side pore openings, decreasing resistance. However, it must be acknowledged that there is an alternate explanation. Particles could have been continuously dislodged from the inside surfaces of the flow loop and mixed with the water. These particles could have been destroyed by the chemical treatments. The resistance from bacteria or dislodged particles varied from zero to 240 psid ft²/gpm. Ionizing radiation from actual high level waste might prevent the growth of bacteria, in which case the adsorption resistance would be less and filtration fluxes would be somewhat higher than listed in this report.

The remainder of the resistance, the sum of filter cake resistance and polarization resistance, varied over a range of roughly 150 to 2000 psid ft²/gpm. Filter cake resistance depends on the thickness of the filter cake. Higher axial velocities, 12 or 14 ft/s, tend to shear off filter cake or reduce the rate at which it forms, resulting in lower filter cake resistances, than for 6 or 8 ft/s. (The DWPF

Late Wash Technical Bases [Fink, 1994] call for axial velocities in the range from 4 to 8 ft/s.) Higher filtration fluxes or higher TM pressures can cause a thicker filter cake and higher filter cake resistances.

Polarization resistance is the result of filtrate flux dragging particles to the surface of the filter and increasing the local concentration of solids there. It is balanced by the process of turbulent diffusion which transports particles from the region of high concentration near the surface to the middle of the tubes of the filter. The rate of turbulent diffusion increases with increasing axial velocity so that polarization resistance decreases. Polarization resistance increases with increasing TM pressure and filtrate flux. Polarization resistance is a small effect for TM pressures less than the threshold pressure, which appears as a "knee" in a plot of flux vs. TM pressure. For TM pressures less than the threshold pressure, flux is proportional to TM pressure. For TM pressures greater than the threshold pressure, polarization resistance is important and increases in TM pressure result in relatively small increases in flux.

3.2. Time Dependence of Filtrate Flux

For most of the individual runs, data were logged when the conditions had been maintained for less than ten minutes. However, three runs at constant 10 wt % slurry concentration inside the tubes of the filter were significantly longer, one 22 hour run and two 7 hour runs. There was no indication of plugging of the pores of the filter during those runs. While there was accumulation of filter cake on the membrane of the filter, a backpulse was just as effective for restoring filtrate flux at the seventh hour and the twentieth hour as at the first hour. For comparison, one Late Wash filtering session would be 20 hours long. High velocities, 12 or 14 feet per second, resulted in total resistances that increased to relatively low steady state values in about five minutes. Low velocities, 6 or 8 feet per second, resulted in higher total resistances that slowly increased over an hour or longer to relatively high values. Details of the longer runs follow.

The 20 hour run, shown in Figures 6 through 10, was performed at an axial velocity of 6 ft/s, the current design basis for Late Wash. The abscissa for the figures referred to in this section is clock time. Ordinarily the abscissa is elapsed time from the start of logging. Figure 8 shows that the first 13 hours of the run were at a TM pressure of 7 psid, the threshold pressure for that axial velocity. Figure 8 also shows the axial pressure drop for the 22 hours, which was somewhat noisy but constant at 0.3 psid with time. Because the average flux was low, 0.01 gpm/ft², the TM pressure was increased to 40 psid for the remaining ten hours. This increased the average flux to 0.014 gpm/ft². Figure 6 shows the filtrate flow in gpm. Dividing that flow by 6.34 ft² gives the flux. The saw tooth appearance of the flux is the result of decrease in filtration rate over the period of 30 minutes followed by a backpulse which removed filter cake. Correspondingly the filter cake resistance increased with time. After each hour of operation the resistance had increased by about 100% and a backpulse was performed to restore the flux. The actual backpulses were removed from the plots for clarity. The amount backpulsed each time was about 0.04 gal/ft². Backpulsing always restored the previous performance. More discussion of backpulsing appears in Section 3.5. Therefore, there was no sign that membrane resistance plus bacterial resistance was increasing during the run or that the pores of the filter were plugging. Figure 6 also shows the axial flow which was constant at 23 gpm or 6 ft/s. Temperature was measured at five locations, but the most important location was the filtrate loop where the temperature was 30°C. Figure 9 shows the gage pressures at three locations in the loop. The increase in the slurry pressure at 14 hours was accomplished by increasing the flow restriction at the valve downstream of the filter and decreasing the resistance at the upstream valve.

Seven hour runs were made at axial velocities of 10 and 14 ft/s as shown in Figures 11 through 14. In both cases the TM pressure was 38 psid and the filtrate temperature was 30°C. An initial backpulse was made as soon as the operating conditions had been established to rule out the possibility of a filter cake plug. After that no backpulsing was done. At 10 ft/s the resistance

started at 700 psid ft²/gpm and increased to 1000 over seven hours. At 14 ft/s filter performance was nearly steady throughout the seven hour period with little sign of degradation of performance and a resistance of 450 psid ft²/gpm.

3.3. Effect of Solids Concentration of Slurry

Filtering performance depends on the solids concentration of the slurry. Surprisingly, higher solids concentrations led to lower total resistances and higher filtrate production rates for runs at an axial velocity of 6 ft/s. Apparently, higher concentrations of slurry are more effective for preventing the formation of filter cake or shearing off existing filter cake. The base case run of 10 wt % and 6 ft/s had an initial total resistance of about 400 psid ft²/gpm which increased to 800 psid ft²/gpm in an hour, at which time backpulsing was required.

The base case run was followed by two concentration runs, each having a duration of 7 hours. In both cases the axial velocity was 6 ft/s, the filtrate temperature was 30°C and the TM pressure was equal to the threshold pressure for that velocity, 7 psid. In the first run, shown in Figures 15 and 16, the tube-side insoluble solids concentration was increased from 10 wt % to 12 wt % by removing filtrate from the loop over the span of one hour. The filtrate was stored so that it could be added back to the loop later. There was a backpulse immediately following concentration, then the loop was run in filtrate recycle mode for an additional six hours. With the exception of the period of filtrate withdrawal the TM pressure held constant, while the flux decreased from 0.016 gpm/ft² to 0.008 gpm/ft² and the resistance doubled. It should be noted that while the resistance doubled, it did so more slowly than for Section 3.2 above in which the resistance doubled in about one hour for the same velocity and TM pressure but a constant 10 wt % insoluble solids concentration inside the tubes of the filter.

In the second concentration run, shown in Figures 17 and 18, the initial tube-side concentration was increased from 12 wt % to 15 wt % over the span of one hour. Then the loop was run in recycle mode for an additional six hours. As before, the pressure held constant for the last six hours. However, the resistance actually decreased from 700 psid ft²/gpm to 300. Because of this unexpected result the differential pressure gages were checked at the end of the run with no flow in the loop. The differential pressure gages used to measure TM pressure, #2 and #3, read zero for zero flow as they should. The following is a possible explanation for the unexpected result. Increasing solids concentration in the loop may cause two competing effects. The larger solids concentration moving toward the membrane increases filter cake resistance. The larger solids concentration moving axially may be more effective at shearing filter cake from the surface.

3.4. Clearing Filter Cake Plugs with Backpulsing

Backpulsing (briefly reversing the direction of filtrate flow) has two functions, cleaning off filter cake and clearing plugs. A plug is an accumulation of filter cake that partially or completely blocks axial flow through one or more of the tubes of the filter. Partial plugs sometimes formed during testing when pressure and flow were adjusted to give the desired operating conditions. Backpulsing was very effective for clearing partial plugs from the Du Pont crossflow filter. As an example, Table 8 shows that on January 17 from time 1430 to time 1525 runs were made at 14 ft/s (54 gpm), a TM pressure of 20 psid and 30°C. The axial pressure drop was about 7.8 psid and the total resistance was 300 psid ft²/gpm. Valves V11 and V3 were then adjusted to achieve a TM pressure of 35 psid, also for 14 ft/s. Figures 19 through 21 show data logged just seconds prior to a backpulse. After the adjustment of valves, but before the backpulse, the axial pressure drop and TM resistance had increased to 10.6 psid and 2000 psid ft²/gpm, respectively. The significant increase in both is considered to be a signature of partial plugging. At time 2 seconds in Figures 19 through 21, V11 was opened to decrease the tube side pressure and facilitate a backpulse. From time 15 seconds to 54 seconds air pressure was applied to the backpulse piston driving it down 18 inches and forcing filtrate through the filter membrane. During the backpulse the

backward resistance through the membrane was 170 psid ft²/gpm. At time 74 seconds V11 was restored to its original position. After a lapse of 80 seconds, data logging was restored. The TM resistance was about 390 and the axial pressure drop was 7.9 psid. Therefore, the backpulse restored the previous value of axial pressure drop and greatly reduced TM resistance.

3.5. Removing Filter Cake from Membrane with Backpulsing

Backpulsing also removed filter cake from the membrane of the filter. For operation at a low axial velocity (6 ft/s), periodically backpulsing the filter was essential to prevent serious degradation of net filtrate production. Net production is the filtrate flow minus the amount of filtrate consumed during backpulsing. For runs at 6 ft/s backpulsing consumed about 7% of filtrate production. Figures 22 through 24 show part of the data from a 24 hour run at 6 ft/s, TM pressure of 40 psid and 30°C on February 11. There was a backpulse once an hour. Following the backpulse the resistance doubled over the period of an hour and the flux halved. The biggest increase in resistance was just after the backpulse and the subsequent rate of increase slowed. There are periods of noisy signals just before and just after a backpulse. For clarity, the noisy periods were deleted from the graphs. The filtrate flows varied between 0.13 and 0.06 gpm, giving fluxes between 0.02 and 0.01 gpm/ft². The average filtrate flow was 5 gph and the amount backpulsed was 0.17 gph so that backpulsing was an effective way to increase average filtrate flow when the axial velocity was 6 ft/s.

At an axial velocity of 14 ft/s the total resistances were low even without backpulsing. Also the filter cake reformed in about a minute so that the effect was short-lived. Figures 25 through 27 show the backpulse at the beginning of the seven hour run at 14 ft/s, TM pressure of 38 psid and 30°C. The backpulse was done in the event that the adjustment of valves required to establish the operating conditions had created a partial pluggage. The rest of the run is shown in Figures 13 and 14. Before the backpulse the resistance was 400 psid ft²/gpm and the flux was 0.08 gpm/ft². Just after the backpulse the resistance was 370 psid ft²/gpm. After 30 minutes the resistance was back to 400 psid ft²/gpm again and slowly increased to 460 psid ft²/gpm over the course of 6.5 hours. Backpulsing at 14 ft/s is probably not worth the effort and consumption of filtrate. The Du Pont Company recommends operating their filter at relatively high velocities so that backpulsing is seldom necessary.

3.6. Required Volume of Backpulse

The volume of backpulse liquid necessary to remove filter cake from the Du Pont cross-flow filter was less than expected. The capacity of the backpulse system was designed using the Technical Basis for the Late Wash Facility [Landon, 1993] which states that the total backpulse volume for a Mott cross-flow filter should be equal to three times the filter medium wall volume. Using the same criterion for the Du Pont filter indicates a backpulse requirement of 0.13 gal/ft² of filter membrane. Because the membrane area is 6.34 ft², the backpulse piston and cylinder were designed to deliver as much as one gallon of filtrate to the shell side of the filter. For the initial runs the full gallon was used.

However, inspection of the data showed that a smaller volume, about 0.1 gallon or 0.02 gal/ft², was necessary to backpulse the Du Pont filter. Figures 28 through 30 show a one gallon backpulse. In preparation for the backpulse valve V11 was opened which reduced the slurry pressure, Figure 30, from 25 to 19 psig. At 17 seconds, the air pressure above the piston was increased to 70 psig. The piston immediately began moving downward, Figure 29, driving out filtrate. The piston moved faster for the first second because initially there was a low resistance flow path through the filtrate flowmeter. After the piston moved an inch, it covered the hole in the cylinder leading to the filtrate flowmeter and the piston speed slowed somewhat to a constant speed at 19 seconds. Both the net filtrate flow and the TM pressure became negative so that the

resistance is still positive. Prior to the backpulse the resistance, Figure 29, was 300 psid ft²/gpm. At 19 seconds, when the piston had reached constant speed, the resistance reached a constant value of 140 psid ft²/gpm, where it remained for the rest of the backpulse. At the end of the backpulse, the air pressure on the piston was relieved and the piston moved upward under the pressure in the filtrate line, but slowly. Resistance continued to be computed during this period, but was noisy because there are finite increments of motion that can be measured for the piston. Note that the resistance has reached its final value by 20 seconds when the volume displaced was 2.5 inches or 0.14 gallon or 0.022 gal / ft². This is less than the 0.14 gal / ft² in the Late Wash Technical Basis [Landon, 1993]. A low volume requirement for backpulsing is desirable because backpulsing reverses the filtering process. The volume requirement may pertain only to the Du Pont filter because it is a surface filter. Mott cross flow filters and other depth filters may require more backpulse volume because they may trap fine particles inside the filter medium.

3.7. Separation Effectiveness of Filter

The primary objective of cross-flow filtration process for Late Wash is to retain the radionuclide Cs-137 in slurry and to pass filtrate that is nearly free of Cs-137. One of the measures of filter performance was to analyze the concentrations of cesium in the original slurry and in the filtrate. Samples of the slurry and filtrate were collected and analyzed for various ions, including cesium and potassium. A description of the dates and circumstances of the samples is listed in Table 2. Slurry samples JS-TFL02, JS-TFL10, JS-TFL11 and JS-TFL14 were collected at the same times as filtrate samples JS-TFL03, JS-TFL09, JS-TFL12 and JS-TFL13, respectively. The results of the analyses are listed in Table 3. The ratios of the cesium concentrations in the four slurry samples to the concentrations in the corresponding filtrate samples, called DF, were 3800, 5800, 5400 and 5900, respectively. Potassium TPB is more soluble than cesium TPB. The DF ratios for potassium were 15500, 7500, 7800 and 3000, respectively. The DF values for potassium were expected to be less than those for cesium. T. A. Policke at TNX estimates the uncertainty of a concentration measurement to be less than 5% of the reported value. Therefore, the uncertainty in DF is less than 10% of the computed value. By way of comparison, cesium DF's for short Du Pont, Mott and Vacco filters have been measured to be >4900 [Nash, 1993], 2000 [Landon, 1993] and >6000 [Monson and Hansen, 1993], respectively.

3.8. Filter Cleaning

The Du Pont filter was chemically cleaned five times. The first three times were during shakedown tests with nominally clean water because the filter resistance had increased unexpectedly, presumably due to growth of bacteria. The fourth time was because slurry was inadvertently allowed to flow to the filtrate side, fouling the shell side of the filter. The fifth time was just prior to removing the filter from the loop, rather than being required by a decrease in operating flux. Cleaning involved five steps: water rinse, 1 wt % oxalic acid solution, water rinse, 1 wt % sodium hydroxide solution and a final water rinse. The step that was most effective for decreasing the total resistance was 1 wt % sodium hydroxide.

Figure 5 plots forward and backward resistances of the filter for clean water or cleaning solutions over a period of months. With one exception the loop was always filled with freshly deionized, ultra-filtered water or a solution made with freshly deionized, ultra-filtered water. The exception was the oxalic acid cleaning of March 1 which reused the oxalic acid solution from January 21. The initial filling of the loop was on October 21. Then the loop was drained and refilled. On November 2 and 3 the first data were collected. The forward and backward resistances were about 190 psid ft²/gpm and 95 psid ft²/gpm, respectively. By November 17 the resistances had increased to 320 psid ft²/gpm and 146 psid ft²/gpm. There was suspicion that bacteria were growing in the water, so a sample was sent to C. B. Fliermans [1993], who measured a bacteria count of 1.44×10^5 /mL and found that a 1 wt % solution of oxalic acid could be expected to reduce the bacteria count by an order of magnitude over a period of sixty hours. On November 19

the loop was cleaned with 1 wt % oxalic acid, followed by cleaning with 1 wt % sodium hydroxide solution on November 23. McCabe and Hazen [1994] had previously determined that a 1 wt % solution of sodium hydroxide (0.25 M) will both kill bacteria and dissolve (lyse) their cell walls. The forward resistance decreased to as low as 155 psid ft²/gpm. The backward resistance decreased to as low as 96 psid ft²/gpm. Because the resistances increased somewhat over the next few days the loop was cleaned with 1 wt % hydrogen peroxide on December 15 followed by 1 wt % sodium hydroxide solution. This cleaning was the most successful for decreasing both resistances, both of which were measured to be about 80 psid ft²/gpm. However, within hours after refilling the loop with ultra-filtered water, the forward resistance had increased to 120 psid ft²/gpm. No measurements were made of the backward resistance during this time.

Du Pont at Seneca saw the same trends in clean water resistance. Their first measurement of clean water resistance on September 14 was 135 psid ft²/gpm. By the end of the following days the resistance had increased to 182. Following a cleaning with 60°C sodium hydroxide solution on September 28 the resistance decreased to 92 psid ft²/gpm.

The resistance of the TFL Du Pont filter increased over two intervals of time during the course of testing with slurry. The first interval was the first five days of testing. During this time a valve was inadvertently opened, allowing some slurry to flow directly to the filtrate loop. This may have allowed the slurry to clog the relatively large pores on the shell side of the filter. This caused the backpulse resistance for slurry runs to increase from 140 psid ft²/gpm to 220 psid ft²/gpm. After cleaning, the forward and backward clean water resistances decreased to 160 psid ft²/gpm and 75 psid ft²/gpm, respectively. During the following three weeks of testing with slurry the backward resistance increased from 170 psid ft²/gpm to 200 psid ft²/gpm. On March 1 the slurry was drained and replaced with clean water. The initial forward and backward resistances were 270 psid ft²/gpm and 200 psid ft²/gpm. Cleaning reduced the resistances to 180 psid ft²/gpm and 100 psid ft²/gpm.

Some observations and conclusions are made about bacteria in cross-flow filter loops.

- a. Bacteria are present and can multiply significantly within days.
- b. The bacteria can significantly increase the clean water resistance of the filter.
- c. The bacteria increase the forward resistance more than the backward resistance. This may be because the normal direction of TM flow tends to push the bacteria over the pores on the tube side, but away from the pores on the shell side of the filter.
- d. The most effective method was to circulate 1 wt % sodium hydroxide solution and leave it in the loop overnight. This type of cleaning makes the forward and backward resistances nearly equal.
- e. Simulated slurries are expected to contain bacteria which affect the resistance of the filter. Actual waste slurry may have levels of ionizing radiation that would kill bacteria. Therefore, the resistance for actual waste slurry may be lower than for simulated slurry and the filtration fluxes may be higher.

Filter cleaning is not necessary very often for the Du Pont cross-flow filter. On January 25 the flux for 37 psid and 14 ft/s was 0.092 gpm/ft² and the flux for 30 psid and 6 ft/s was 0.020 gpm/ft². On February 18 and February 24 the same two sets of conditions gave fluxes of 0.079 gpm/ft² and 0.19 gpm/ft², respectively. There were no filter cleanings during that four weeks of testing. Therefore, even with no filter cleaning the Du Pont filter performance does not degrade much.

3.9. Cesium in Filter Cleaning Solutions

The Du Pont filter was cleaned twice after slurry service, over the period January 20-24 and again on March 1. Cleaning solutions were analyzed for a number of components. The reason was that a Du Pont cross-flow filter used to filter radioactive slurry would have to be cleaned periodically. The cleaning solutions would dissolve radionuclides trapped in the filter. The most important radionuclide is Cs-137. The highest concentration of total cesium in the spent cleaning solutions was 2.1 ppm in the initial water rinse solution. The concentration of total cesium in the slurry was about 250 ppm. The highest concentrations of potassium in cleaning solution and slurry were 60 ppm and 9000 ppm, respectively. The full results of the analyses are given in Table 4. A condensed list for just cesium and the related element potassium is shown below.

Sample ID	Date	Description	Cs, ppm	K, ppm	K/Cs
JS-TFL04	01/21	initial rinse	0.105	11.7	111
JS-TFL05	01/21	1 wt % oxalic acid solution	0.92	29.9	33
JS-TFL06	01/24	intermediate rinse	0.255	11.5	45
JS-TFL07	01/24	1 wt % sodium hydroxide	0.085	3.09	36
JS-TFL08	01/24	final rinse	0.05	4.57	91
JS-TFL15	03/01	initial rinse	2.08	58.5	28
JS-TFL16	03/01	1 wt % oxalic acid solution	0.92	31.8	35
JS-TFL17	03/02	rinse	0.05	3.65	73
JS-TFL18	03/02	rinse	0.05	0.38	8

The greatest concentrations of Cs were in the initial rinse on March 1. The next highest concentrations were in the two oxalic acid cleaning solutions.

3.10. Lay-up of Filter

One concern with cross-flow filters is that the pores might clog with solids if a shutdown required that slurry be drained from the filter and the slurry residue dried and hardened in the pores. To test this concern the filter was drained of slurry without rinsing on a Friday afternoon, February 25 and the loop was vented to the roof of the laboratory through a 1.0 inch hose to allow air into the filter under non-drying or enclosed conditions. On Monday morning the loop was easily restarted and the previous hydraulic resistance was restored. The total resistance at an axial velocity of 14 ft/s and a TM pressure of 35 psid was 400 psid ft²/gpm, a typical value for those conditions. It is concluded that being drained and vented for a weekend did not hurt the performance of the filter. However, it should be noted that Kilpatrick [1994] concluded that filter drying times are greater than three days. If more time had been allotted for this test, the conclusion might have been different.

It should be noted that the loop was not normally vented when work stopped at the end of the day. If the loop was not vented it remained filled with liquid. Liquid was held up in the loop by atmospheric pressure.

3.11. Filter Cake Removal by High Axial Flows

There seems to be a difference of opinion in the technical literature on the role of axial velocity in cross-flow filtration. Some sources [Lu, et al., 1993 and Stamatakis and Tien, 1993] state that the axial velocity affects the fraction of the solid particles approaching the existing filter cake that stick to it. However, once stuck, a particle will continue to stick, unless the membrane is backpulsed or cleaned chemically. A consequence of this view is that the filter cake thickness and resistance can only increase with time, although perhaps very slowly. Other sources [Murkes and Carlsson, 1988, and Bhave, 1991] state that the axial velocity can sweep away previously deposited solid particles. It was desired to determine which explanation was true for the present application. An axial velocity of 6 ft/s, a TM pressure of 30 psid and a temperature of 30°C were established. Then a backpulse was performed to initialize the filter cake. The conditions were maintained for one

hour, after which the velocity was increased to 8 ft/s, then 10, then 12 and finally 14 ft/s as shown in Figure 31. The resistance (and filter cake thickness increased during the period that the velocity was 6 ft/s. The resistance also increased for a velocity of 8 ft/s but more slowly. The resistance held nearly constant for a velocity of 10 ft/s and decreased for velocities of 12 and 14 ft/s. It is concluded that the velocities of 12 and 14 ft/s have the capability to shear off existing filter cake. Therefore, the axial flow was shearing away solids and the second explanation is correct, at least for this situation.

3.12. Draining Test

A draining test, run at the request of the customer, is shown in Figure 32. Differential pressure measurements were used to track the draining of the shell-side. The test started at 0 seconds with both the shell-side and tube-side of the filter filled with water. The tube side was quickly drained. By 150 seconds the shell-side had drained down to the top pressure tap so that the TM pressure measured at the top of the filter was zero. As the shell-side of the filter continued to drain the TM pressure measured at the bottom decreased toward zero. When the test was stopped after 40 minutes the shell-side contained 4.5 feet of the original 10 feet of water.

The average driving head for flow through the membrane is the level on the shell-side of the filter. The area available for flow through the membrane is proportional to the level on the shell-side. Therefore the rate of bottom TM pressure change is proportional to the square of the bottom TM pressure. Integrating this relationship gives a linear relationship between the inverse of the bottom TM pressure and time. Figure 33 shows the actual data plotted in this way. The plot is nearly linear between 200 and 2400 seconds.

3.13. Shear Degradation of Slurry

Meyer [1992] summarized reports of crossflow filter tests at SRS during the period 1981-1985. Some of the reports stated that the use of high shear pumps gave lower filtration fluxes than low shear pumps. Therefore, there was concern that the centrifugal pumps used for this test sheared the slurry and reduced the average particle size, which could reduce the performance of the filter. A. R. Jurgensen was asked to perform a particle size analysis for two samples of archived slurry that had never been in the loop and two samples that were removed from the loop after testing of the Du Pont filter was complete. The median particle sizes for the two archived samples were 1.68 and 1.75 μm . The median particle sizes for the two used samples were 1.44 and 1.48 μm . Details size distributions are listed below. The 15% reduction in median size is an indication of shear degradation of the slurry. However, that amount of degradation may be negligible compared with the difference in particle size from one batch of Late Wash slurry to another. The TFL received another batch of slurry that was never used with the Du Pont filter. The median size was 2.26 μm .

particle size, μm	Percentage of Particles Smaller Than Stated Diameter			
	archived slurry #1	archived slurry #2	used slurry #1	used slurry #2
3.89	100.00	100.00	100.00	100.00
2.75	89.38	90.16	98.82	99.16
1.94	58.48	62.12	76.02	74.12
1.38	33.44	36.26	46.61	44.98
0.97	12.05	13.37	18.15	17.32
median diameter	1.75 μm	1.68 μm	1.44 μm	1.48 μm

The slurry tested in the TFL flow loop had previously been used by the Du Pont Company at Seneca in October 1993 in tests with the same model of filter using a low shear pump. A significant difference in results between Seneca and the TFL might be attributed to shear degradation of the slurry by the centrifugal pumps. Comparison of the results showed no

significant difference. Therefore, there is no evidence for a significant effect of shear degradation of the slurry by the TFL centrifugal pumps on the performance of a Du Pont crossflow filter. However, a filter with larger pores, such as a Mott crossflow filter with 0.5 μm pores, might be more sensitive to shear degradation of slurry.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1. The Technical Bases for the DWPF Late Wash Facility call for TM pressures in the range from 10 to 40 psid and axial velocity in the range from 4 to 8 feet per second. Consideration should be given to increasing the axial velocity, which would greatly increase the flux. Since pumping power is limited, the optimal filtering conditions might involve higher axial velocity, fewer tubes and a smaller TM pressure.

4.2. If a Du Pont cross-flow filter is used, backpulse it with 0.02 gal/ft² instead of 0.13 gal/ft².

4.3. Keep bacteria out of solutions. Avoid reusing cleaning solutions that could grow bacteria.

4.4. Consider using hydrogen peroxide as a cleaning solution.

4.5. The TFL slurry reservoir was positioned low in the loop. This made it convenient to fill and empty the reservoir but created problems. The loop was referenced to atmospheric pressure at the free surface of the reservoir. Most of the loop was higher than the free surface of the reservoir and therefore hydrostatic legs of liquid created sub-atmospheric pressures at many points in the loop. One consequence was that a partial vacuum had to be pulled over the piston to hold it up during normal operation. Another consequence was that any air leaks in the sub-atmospheric pressure part of the loop could cause bubble and foam formation in the slurry. It is easier to seal liquid leak from inside to outside than to seal an air leak in the opposite direction.

4.6. Do not reuse cleaning solutions, particularly oxalic acid, because they grow bacteria.

5. ACKNOWLEDGEMENTS

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Table 1

Definitions taken from Bhawe [1991]

Cake layer

A fouling layer resulting primarily from the physical deposition of solids on the membrane surface

Concentration polarization

Phenomenon that occurs when solutes accumulate on or near the membrane surface as the result of their exclusion from the permeate.

Internal pore fouling

The deposition of material inside the porous structure, possibly leading to a reduction in pore volume.

Membrane fouling

The manifestation of the accumulation of particulates, solutes, colloids, etc., on the membrane surface.

Permeability

Flux per unit transmembrane pressure.

Pore blockage

The reduction in the area available for permeation as a result of the actual physical external blockage of the pores by the foulant.

Retentate

The concentrate that does not cross the filtering surface.

Table 2
Samples Taken During Testing of Du Pont Cross-Flow Filter

Sample ID	Sample Type	Description	Date	Time	Comment
JS-TFL01	JS-SLURRY	slurry	12/17	0915	well mixed sample from shipping drum
JS-TFL02	JS-SLURRY	slurry	01/14	1540	drawn from loop during filtering operation
JS-TFL03	JS-FILTRATE	filtrate	01/14	1540	drawn from loop during filtering operation
JS-TFL04	JS-CAUSTIC	dilute NaOH	01/21	0850	initial cleaning rinse
JS-TFL05	JS-OXALIC ACID	oxalic acid, 1 wt %	01/21	1345	oxalic acid solution used for cleaning
JS-TFL06	JS-CAUSTIC	dilute NaOH	01/24	1108	intermediate cleaning rinse
JS-TFL07	JS-CAUSTIC	NaOH, 1 wt %	01/24	1420	caustic solution used for cleaning
JS-TFL08	JS-CAUSTIC	dilute NaOH	01/24	1500	final cleaning rinse
JS-TFL09	JS-FILTRATE	filtrate	02/09	0910	drawn during operation prior to concentration
JS-TFL10	JS-SLURRY	slurry	02/09	0910	drawn during operation prior to concentration
JS-TFL11	JS-SLURRY	slurry	02/10	0900	drawn during operation after concentration to 12 wt %
JS-TFL12	JS-FILTRATE	filtrate	02/10	0900	drawn during operation after concentration to 12 wt %
JS-TFL13	JS-FILTRATE	filtrate	02/10	1600	drawn during operation after concentration to 15 wt %
JS-TFL14	JS-SLURRY	slurry	02/10	1600	drawn during operation after concentration to 15 wt %
JS-TFL15	JS-CAUSTIC	dilute NaOH	03/01	1130	initial cleaning rinse
JS-TFL16	JS-OXALIC ACID	oxalic acid, 1 wt %	03/01	1430	oxalic acid solution used for cleaning
JS-TFL17	JS-CAUSTIC	dilute NaOH	03/02	0840	intermediate cleaning rinse
JS-TFL18	JS-CAUSTIC	deion. flush water	03/02	0945	rinse
JS-TFL19	JS-SLURRY	slurry	03/02	1400	well mixed slurry sample

Table 3
Chemical Analyses of Slurry and Filtrate Samples

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component	sample 0	JS-TFL01	JS-TFL02	JS-TFL03	JS-TFL09	JS-TFL10	JS-TFL11	JS-TFL12	JS-TFL13
potassium soluble, ppm	0.55	0.535	1.04	0.295	0.815	1.05	1.41	0.855	0.985
sodium soluble, ppm	10321	8615	717	717	692	688	703	727	698
mercury, ppm	39.78	39.7	41.7	20.5	19	37.4	42.8	18.8	18.8
mercury, vga, ppm	#NA	0.312	#NA	#NA	#NA	#NA	#NA	#NA	#NA
potassium, total, ppm	5670	7658	9672	0.624	1.14	8678	9026	1.16	2.5
cesium, soluble, ppm	0.05	0.145	0.135	0.06	0.055	0.06	0.08	0.085	0.11
cesium, total, ppm	247	287	345	0.09	0.06	347	460	0.085	0.09
total inorg carbon, ppm	3852	3225	1843	1462	1370	1652	1393	1344	1373
total org carbon, ppm	45449	44737	46593	5184	4619	48902	61933	4665	4917
total inorg+org C, ppm	49301	47962	48436	6646	5989	50554	63326	6009	6290
total carbon	60195	60818	58990	7152	6542	68788	84063	6614	6638
benzene, ppb	#NA	11539	#NA	#NA	#NA	#NA	#NA	#NA	#NA
fluoride, mg/L	#NA	100	#NA	#NA	#NA	#NA	#NA	#NA	#NA
formate, mg/L	#NA	184	#NA	#NA	#NA	#NA	#NA	#NA	#NA
chloride, mg/L	#NA	176	#NA	#NA	#NA	#NA	#NA	#NA	#NA
nitrite, mg/L	#NA	4593	#NA	#NA	#NA	#NA	#NA	#NA	#NA
nitrate, mg/L	#NA	100	#NA	#NA	#NA	#NA	#NA	#NA	#NA
sulfate, mg/L	#NA	135	#NA	#NA	#NA	#NA	#NA	#NA	#NA
oxalate, mg/L	#NA	721	#NA	#NA	#NA	#NA	#NA	#NA	#NA
phosphate, mg/L	#NA	100	#NA	#NA	#NA	#NA	#NA	#NA	#NA
ammonium, mg/L	#NA	100	#NA	#NA	#NA	#NA	#NA	#NA	#NA
boron soluble, ppm	463	471	#NA	#NA	#NA	#NA	#NA	#NA	#NA
chromium soluble, ppm	#NA	1.37	#NA	#NA	#NA	#NA	#NA	#NA	#NA
copper, ppm	0.302	0.46	#NA	#NA	#NA	#NA	#NA	#NA	#NA
manganese, ppm	0.054	0.138	#NA	#NA	#NA	#NA	#NA	#NA	#NA
iron, ppm	3.41	4.43	#NA	#NA	#NA	#NA	#NA	#NA	#NA
boron, ppm	2580	3250	#NA	#NA	#NA	#NA	#NA	#NA	#NA
titanium, ppm	266	290	#NA	#NA	#NA	#NA	#NA	#NA	#NA
sodium, ppm	10321	10200	#NA	#NA	#NA	#NA	#NA	#NA	#NA
potassium, ppm	#NA	8520	#NA	#NA	#NA	#NA	#NA	#NA	#NA
chromium, ppm	1.66	1.67	#NA	#NA	#NA	#NA	#NA	#NA	#NA
phenylboronic acid, mg/L	159	234	#NA	#NA	#NA	#NA	#NA	#NA	#NA
aniline, mg/L	1	7	#NA	#NA	#NA	#NA	#NA	#NA	#NA
phenol, mg/L	1211	2105	#NA	#NA	#NA	#NA	#NA	#NA	#NA
nitrobenzene, mg/L	1	1	#NA	#NA	#NA	#NA	#NA	#NA	#NA
nitrosobenzene, mg/L	1	1	#NA	#NA	#NA	#NA	#NA	#NA	#NA
4-phenylphenol, mg/L	1	1	#NA	#NA	#NA	#NA	#NA	#NA	#NA
2-phenylphenol, mg/L	5	1	#NA	#NA	#NA	#NA	#NA	#NA	#NA
diphenylamine, mg/L	16	7	#NA	#NA	#NA	#NA	#NA	#NA	#NA
biphenyl, mg/L	1948	1397	#NA	#NA	#NA	#NA	#NA	#NA	#NA
o-terphenyl, mg/L	32	48	#NA	#NA	#NA	#NA	#NA	#NA	#NA
m-terphenyl, mg/L	82	83	#NA	#NA	#NA	#NA	#NA	#NA	#NA
p-terphenyl, mg/L	22	18	#NA	#NA	#NA	#NA	#NA	#NA	#NA
diphenylmercury, mg/L	#NA	1	#NA	#NA	#NA	#NA	#NA	#NA	#NA
filtrate volume, mL	#NA	30	#NA	#NA	#NA	#NA	#NA	#NA	#NA
pH	8.62	10.19	10.18	10.18	10.13	10.13	10.14	10.12	10.12
% total solids	11.77	11.44	12.44	#NA	#NA	12.34	14.84	#NA	#NA
% filtrate solids	4.39	3.52	2.91	#NA	#NA	2.73	2.76	#NA	#NA
% soluble solids	4.05	3.23	2.62	#NA	#NA	2.46	2.42	#NA	#NA
% insoluble solids	7.72	8.21	9.82	#NA	#NA	9.88	12.42	#NA	#NA
tetraphenylborate, wt %	6.55	6.89	#NA	#NA	#NA	#NA	#NA	#NA	#NA
TPB, soluble, wt %	0.2	0.19	#NA	#NA	#NA	#NA	#NA	#NA	#NA

Sample 0 was taken from the slurry sent to Seneca

Table 3, continued
Chemical Analyses of Slurry and Filtrate Samples

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components	JS-TFL14	JS-TFL19	JS-TFL20	JS-TFL23
potassium soluble, ppm	1.79	1.97	2.3	2.87
sodium soluble, ppm	725	7467	6190	6510
mercury, ppm	#NA	32.6	10.5	5
mercury, vga, ppm	#NA	0.096	.1	1
potassium, total, ppm	7417	1253	5450	55.3
cesium, soluble, ppm	0.125	0.13	1.75	0.18
cesium, total, ppm	532	246	327	1.17
total inorg carbon, ppm	2419	2939	1770	1240
total org carbon, ppm	67113	35247	49700	4170
total inorg+org C, ppm	69532	38186	51400	5410
total carbon	83387	49755	67100	5870
benzene, ppb	109011	124625	156000	149
fluoride, mg/L	100	100	#NA	100
formate, mg/L	140	106	#NA	100
chloride, mg/L	140	123	#NA	111
nitrite, mg/L	4064	3478	#NA	2990
nitrate, mg/L	100	100	#NA	100
sulfate, mg/L	108	121	#NA	107
oxalate, mg/L	677	564	#NA	542
phosphate, mg/L	100	100	#NA	100
ammonium, mg/L	100	100	#NA	50
boron soluble, ppm	338	340	313	307
chromium soluble, ppm	1.18	1.34	1.25	1.19
copper, ppm	1.15	1.19	0.22	0
manganese, ppm	0.576	0.593	0.11	0
iron, ppm	12.9	9.4	12	0
boron, ppm	3010	2490	2130	0
titanium, ppm	518	245	329	0
sodium, ppm	7800	8150	7180	0
potassium, ppm	8280	6490	5550	0
chromium, ppm	1.77	1.61	0.22	0
phenylboronic acid, mg/L	316	229	184	0
aniline, mg/L	6	9	1	0
phenol, mg/L	2090	3242	2740	0
nitrobenzene, mg/L	1	1	1	0
nitrosobenzene, mg/L	1	1	1	0
4-phenylphenol, mg/L	1	1	1	0
2-phenylphenol, mg/L	2714	5396	166	0
diphenylamine, mg/L	1	7	1	0
biphenyl, mg/L	2504	2294	1790	0
o-terphenyl, mg/L	96	65	76	0
m-terphenyl, mg/L	149	135	148	0
p-terphenyl, mg/L	32	28	37	0
diphenylmercury, mg/L	1	1	1	0
filtrate volume, mL	30	30	30	0
pH	10.13	10.09	10.09	0
% total solids	16.6	9.28	12.21	0
% filtrate solids	2.75	2.82	2.66	0
% soluble solids	2.36	2.63	2.4	0
% insoluble solids	14.24	6.65	9.81	0
tetraphenylborate, wt %	11.57	5.57	7.85	0
TPB, soluble, wt %	0.15	0.16	0.16	0

Table 4
Chemical Analyses of Sodium Hydroxide Solutions

component	Sample ID										
	TFL04	TFL06	TFL07	TFL08	TFL15	TFL17	TFL18	TFL26	TFL28	TFL29	TFL30
potassium total, ppm	11.7	11.5	3.09	4.57	58.5	3.65	0.38	10.6	7.91	8.04	5.6
cesium total, ppm	0.105	0.255	0.085	0.05	2.08	0.05	0.05	1.04	0.25	0.3	0.255
benzene, ppb	176	1634	603	88	790	1290	384	275	9010	146	82
ammonium soluble, mg/L	100	100	100	100	100	100	100	50	25	25	25
phenylboronic acid, mg/L	1	1	1	1	1	1	1	1	1	1	1
aniline, mg/L	1	1	1	1	1	1	1	1	1	1	1
phenol, mg/L	45	12	1	1	1	1	1	42	1	1	1
nitrobenzene, mg/L	1	1	1	1	1	1	1	1	1	1	1
nitrosobenzene, mg/L	1	1	1	1	1	1	1	1	1	1	1
4-phenylphenol, mg/L	1	1	1	1	1	1	1	1	1	1	1
2-phenylphenol, mg/L	1	1	1	1	1	1	1	1	1	1	1
diphenylamine, mg/L	1	1	1	1	1	1	1	1	1	1	1
biphenyl, mg/L	4	1	1	1	1	1	1	10	1	1	1
o-terphenyl, mg/L	1	1	1	1	1	1	1	1	1	1	1
m-terphenyl, mg/L	1	1	1	1	1	1	1	1	1	1	1
p-terphenyl, mg/L	1	1	1	1	1	1	1	1	1	1	1
pH	10.88	2.06	12.85	11.78	11.21	3.55	3.95	10.79	2.6	12.91	12.15
TPB, wt %	0	0	0	0	0.06	0	0	0.04	0	0	0

Table 5
Chemical Analyses of Oxalic Acid Solutions

component	Sample ID		
	TFL05	TFL16	TFL27
potassium total, ppm	29.9	31.8	20.2
mercury, ppm	1.29	1	1.72
mercury, ppm	5	0.0007	1
iron, ppm	40.4	31.7	18.9
cesium, ppm	0.92	0.92	0.69
benzene, ppb	3348	3378	9910
ammonium, mg/L	100	100	25
manganese, ppm	0.72	0.623	0.11
titanium, ppm	3.3	9.02	7.8
phenylboronic acid, mg/L	1	1	1
N-phenylformamide, mg/L	1	1	1
aniline, mg/L	1	1	1
phenol, mg/L	1	18	15
nitrobenzene, mg/L	1	1	1
nitrosobenzene, mg/L	1	1	1
4-phenylphenol, mg/L	1	1	1
2-phenylphenol, mg/L	1	1	1
diphenylamine, mg/L	1	1	1
biphenyl, mg/L	1	1	1
o-terphenyl, mg/L	1	1	1
m-terphenyl, mg/L	1	1	1
p-terphenyl, mg/L	1	1	1
diphenylmercury, mg/L	1	1	1
pH	1.85	1.9	1.9
TPB, wt %	0	0	0

Table 6
Instrument Numbers and Calibration Data

Instrument Curve-Fit Data from most recent calibration:
 $Y_{out} = aX^2 + bX + c$, where X = Volts in or milliamps in:

DAS conversion:
 $Y_{out} = aX^2 + bX + c$, where X = Volts in. Y_{out} = ma.

#	Instrument	TR-#	a	b	c	a	b	c
1	DP1	TR-1381	0	0.625	-2.5	0	2	0
2	DP2	TR-532	0	9.375	-112.5	0	2.0131	0.0047
3	DP3	TR-3115	0	9.375	-112.5	0	2.0098	0.0034
4	P1	TR-2917	0	6.25	-25	0	2.0153	0.0028
5	P2	TR-3109	0	6.25	-35	0	2.0125	0.0032
6	P3	TR-2145	0	7.8125	-41.25	0	2.0021	0.0034
7	Q1	TR-20350	0	11.28	-44.61	0	2.0148	0.0026
8	Q2	TR-20353	0	0.0746	-0.2954	0	2.0136	0.0043
9	T1	TR-2925	0	1	0			
10	T2	TR-2926	0	1	0			
11	T3	TR-2929	0	1	0			
12	T4	TR-2930	0	1	0			
13	T5	TR-2927	0	1	0			
14			0	0	0			
15			0	0	0			
16			0	0	0			
17	barometer	TR-3063	0	6.4326	-0.025			
18	BPD1		0	8.8272	-7.3487			

Table 7 Slurry Recipe

water	22272.1 g
potassium carbonate	14.6 g
potassium nitrite	1056.6 g
cesium nitrate	26.4 g
potassium nitrate	98.3 g
potassium chloride	0.9 g
potassium fluoride	0.5 g
sodium sulfate	11.3 g
sodium silicate	0.6 g
phenol	0.3 g
sodium tetraphenylborate solution, 16 wt %, with 0.1 M NaOH	23481.0 g
sodium titanate slurry, 13.13 wt %	837.9 g

The solution was irradiated to 200 megarad with a cobalt-60 source at Argonne National Laboratory.

Table 8
Data Summary for Steady State Runs, Du Pont Cross-Flow Filter

row	date	time	axial vel, fps	axial DP. psid	avg. TM press. psid	actual TM flux, gpm /ft ²	corrctd TM flux, gpm /ft ² @37°C	filtrate temp. °C	corrctd TM resistance psid ft ² / gpm @37°
1	117	1430	14.05	7.92	20.29	0.0577	0.0661	30.5	306.8
2	117	1440	14.00	7.85	20.72	0.0590	0.0673	30.7	307.6
3	117	1500	14.07	7.88	20.51	0.0587	0.0667	30.8	307.4
4	117	1525	14.01	7.84	20.56	0.0595	0.0682	30.4	301.4
5	117	1545	14.02	7.85	37.85	0.0833	0.0958	30.3	395.2
6	118	1450	13.97	7.82	29.75	0.0738	0.0861	29.7	345.6
7	118	1500	13.79	7.60	29.91	0.0798	0.0880	32.2	339.8
8	119	1340	13.80	7.67	35.56	0.0733	0.0911	26.9	390.1
9	119	1400	13.38	7.14	35.54	0.0751	0.0877	29.6	405.4
10	125	1310	13.79	7.12	10.54	0.0287	0.0327	30.7	322.0
11	125	1345	13.95	7.40	20.20	0.0532	0.0613	30.2	329.6
12	125	1355	13.50	7.04	34.92	0.0779	0.0877	31.3	398.3
13	125	1402	14.13	7.63	29.70	0.0757	0.0836	32.2	355.2
14	125	1408	13.86	7.11	8.97	0.0222	0.0256	30.4	351.1
15	125	1415	6.14	1.77	19.89	0.0144	0.0169	29.2	1174.6
16	125	1419	6.29	1.89	18.32	0.0155	0.0184	28.8	996.8
17	125	1436	6.05	1.77	30.97	0.0192	0.0212	32.3	1462.0
18	125	1443	7.94	2.74	31.11	0.0273	0.0295	33.2	1055.4
19	125	1450	5.99	1.70	9.38	0.0144	0.0160	31.8	586.4
20	125	1457	6.09	1.77	20.16	0.0170	0.0193	31.0	1044.7
21	125	1517	6.18	1.84	28.38	0.0188	0.0216	30.3	1314.9
22	125	1531	6.17	1.81	8.66	0.0153	0.0179	29.7	484.9
23	126	1108	10.11	4.39	45.52	0.0506	0.0575	30.9	792.1
24	126	1113	7.80	2.76	46.03	0.0243	0.0277	30.6	1659.5
25	128	1545	6.12	1.71	48.64	0.0311	0.0240	51.3	2026.5
26	128	1555	6.08	1.65	30.55	0.0347	0.0262	52.6	1163.9
27	128	1602	6.06	1.64	38.32	0.0336	0.0255	52.4	1503.7
28	131	947	6.12	1.67	19.20	0.0356	0.0279	50.5	688.0
29	131	1002	5.97	1.64	29.82	0.0404	0.0315	50.6	945.2
30	131	1009	7.13	2.19	31.89	0.0453	0.0355	50.3	897.6
31	131	1017	5.98	1.60	9.44	0.0311	0.0245	50.0	384.9
32	131	1305	5.86	1.66	2.95	0.0073	0.0082	31.1	359.4
33	131	1319	6.07	1.80	7.09	0.0161	0.0193	28.4	367.4
34	207	1435	6.08	1.88	6.07	0.0132	0.0180	23.2	337.2
35	207	1445	6.01	1.87	6.86	0.0148	0.0201	23.3	341.0
36	207	1515	5.98	1.74	6.79	0.0175	0.0203	29.8	333.6
37	207	1610	6.11	1.65	7.02	0.0227	0.0197	44.5	355.9
38	208	1145	6.12	1.21	6.99	0.0295	0.0200	59.7	350.2
39	208	1248	5.98	1.72	6.98	0.0117	0.0135	30.1	517.0
40	209	850	5.99	1.76	6.93	0.0170	0.0200	29.4	346.6
41	218	927	13.60	7.42	37.95	0.0847	0.0977	30.2	388.4

Table 8

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Data Summary for Steady State Runs, Du Pont Cross-Flow Filter

row	date	time	axial vel, fps	axial DP, psid	avg. TM press. psid	actual TM flux, gpm /ft ²	corrctd TM flux, gpm /ft ² @37°C	filtrate temp. °C	corrctd TM resistance psid ft ² / gpm @37°
42	218	1608	13.62	7.42	37.83	0.0763	0.0876	30.4	431.9
43	222	922	9.94	4.21	37.98	0.0532	0.0611	30.3	621.2
44	222	1620	9.92	4.21	38.00	0.0475	0.0555	29.6	684.4
45	223	1226	10.00	4.24	4.52	0.0109	0.0126	30.2	360.0
46	223	1240	9.85	4.13	7.88	0.0199	0.0230	30.1	342.9
47	223	1250	9.93	4.20	11.85	0.0293	0.0340	30.0	348.5
48	223	1302	10.01	4.27	16.06	0.0369	0.0428	30.0	375.4
49	223	1313	9.87	4.16	20.11	0.0407	0.0471	30.1	427.2
50	223	1323	10.02	4.26	26.01	0.0457	0.0522	30.6	498.0
51	223	1332	10.05	4.29	32.01	0.0475	0.0550	30.0	582.0
52	223	1342	9.90	4.17	37.96	0.0446	0.0518	29.9	732.5
53	223	1350	9.92	4.19	45.87	0.0468	0.0543	29.9	844.2

Figure 1 - Cross-Flow Filter Test Set-up

Figure 2
Du Pont Filter Pressure Scan with Slurry, Actual Fluxes

Figure 3

Du Pont Filter Pressure Scan with Slurry, Fluxes Normalized to 37°C

Figure 4

Du Pont Filter Pressure Scan with Slurry, Resistance Normalized to 37°C

Figure 5 Comparison of Forward and Backward Resistances For Du Pont Filter

Figure 6 Flows for 22 Hour Recycle Run

Figure 7 Temperatures at Five Locations for 22 Hour Recycle Run

Figure 8 Differential Pressures for 22 Hour Recycle Run

Figure 9 Gage Pressures for 22 Hour Recycle Run

CFF 0211 0053

Figure 10
Trans-Membrane Hydraulic Resistance
Normalized to 37°C for 22 Hour Recycle Run

Figure 11 Flows for Long Term Run at 10 ft/s

Figure 12 Trans-Membrane Hydraulic Resistance and Pressure Drop for 7 Hour Run at 10 ft/s

Figure 13 Flows for 7 Hour Run at 14 ft/s

Figure 14 Trans-Membrane Hydraulic Resistance and Pressure Drop for 7 Hour Run at 14 ft/s

Figure 15 Flows for Concentration Run to 12 wt %

Figure 16 Concentration Run to 12 wt %
Trans-Membrane Resistance and Pressure Drop

Figure 17 Flows for Concentration Run to 15 wt %

Figure 18 Concentration Run to 15 wt %
Trans-Membrane Hydraulic Resistance and Pressure Drop

pressures
corrected
for
offset

Figure 19 Flows for Partial Plugging Episode

Figure 20 TM Resistance and Piston Displacement for Partial Plugging Episode

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Figure 21 Differential Pressures for Partial Plugging Episode

Figure 22 Flows During Back-Pulses

Figure 23 Trans-Membrane Resistance and Piston Displacement During Back-Pulses

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Figure 24 Differential Pressures During Back-Pulses

Figure 25 Flow During Backpulse, 14 ft/s

Figure 26 Trans-Membrane Resistance and
Piston Displacement During Backpulse, 14 ft/s

Figure 27 Differential Pressures During Backpulse, 14 ft/s

Figure 28 Flows During Back-Pulse, 14 ft/s

Figure 29 Trans-Membrane Resistance and Piston Displacement During Back-Pulse, 14 ft/s

CFF 0117 1435

Figure 30 Differential Pressures During Back-Pulse, 14 1

CFF 0224 1017

Figure 31 Resistance for Changing Axial Velocity

Figure 32 Differential Pressures During Draining Test

Figure 33 Inverse Corrected Differential Pressure

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