Full-Scale Cross-Flow Filter Testing in Support of the Salt Waste Processing Facility Design - 8430

A.B. Stephens, R.M. Gallego
General Atomics
3550 General Atomics Ct, San Diego, CA 92121
USA

S.A. Singer, B.L. Swanson
Energy Solutions
1080 Silver Bluff Rd., Aiken, SC 29803
USA

K. Bartling
Parsons
1080 Silver Bluff Rd., Aiken, SC 29803
USA

ABSTRACT

Parsons and its team members General Atomics and Energy Solutions conducted a series of tests to assess the constructability and performance of the Cross-Flow Filter (CFF) system specified for the Department of Energy (DOE) Salt Waste Processing Facility (SWPF). The testing determined the optimum flow rates, operating pressures, filtrate-flow control techniques, and cycle timing for filter back pulse and chemical cleaning. Results have verified the design assumptions made and have confirmed the suitability of cross-flow filtration for use in the SWPF.

INTRODUCTION

The SWPF, to be located at the Savannah River Site (SRS) in Aiken, South Carolina, will remove highly radioactive waste constituents, principally actinides, strontium (Sr), and cesium (Cs) from salt waste solutions currently stored in SRS liquid waste tanks. The SWPF design uses monosodium titanate (MST) to adsorb the actinides and Sr from the salt waste feed. Cross-flow filters are used to concentrate the MST and other solids while producing a filtrate (clarified salt solution) suitable for further treatment for Cs removal and subsequent disposal in grout vaults. After rinsing (using a separate cross-flow filter) the concentrated MST/sludge is sent to the Defense Waste Processing Facility (DWPF) for vitrification.

A total of three large CFF units will be used to separate solids from liquid waste. An additional CFF unit is dedicated to rinsing the separated solids prior to transfer to DWPF. Previously, DOE directed initial development of the CFF process for salt solution processing [1,2,3]. To reduce programmatic risk associated with scale-up of the technology, DOE funded the fabrication and construction and operation of a full-scale CFF test system. A highly-structured test plan and matching operating procedures were developed and executed. The data gathered from the operation of the system were used to verify key assumptions made during the design of the SWPF filter systems. Operational expertise gained during the program is being used to develop operating and maintenance procedures for the SWPF.

TEST OBJECTIVES

Multiple individual test objectives were established for the CFF test program. These objectives included establishing operating parameters for the back-pulse system, evaluation of a number of control modes for the filtration system, evaluation of the behavior and properties of the concentrated sludge solution at the end of a run, establishing the effectiveness of chemical cleaning of the filter bundle, evaluating the influence of key process variables on filter performance, evaluating filter performance during simulated sludge-washing operation, evaluating system performance at or close to maximum solids concentrations, confirming overall performance of the air-pulse agitation system, observing effects from erosion in the system and feed tank, and observing the effect of the system on the solids themselves. Of the 21 individual objectives established, 19 were considered to be fully met by the test, one objective (determination of air-pulse agitator nozzle wear) was partially met, and one objective (demonstration of effective mixing at low tank levels by recirculation flow) was not met.

DESCRIPTION OF THE CFF TEST SYSTEM

The test system comprised one filter vessel, one filter bundle, one spare filter bundle, four 38 m^3 (10,000-gallon) tanks, one 3.8 m^3 (1,000-gallon) tank, seven air-pulse agitators, piping, valves, sampling equipment, utility supply systems, and controls. The filter housing, filter bundle, pumps and recirculation line sizes mimicked the SWPF full-scale design. The air-pulse agitators were 63% full-scale. The filter feed tank and salt-solution feed tank were sized at about 33% and 200% of full-scale volume. Figure 1 shows an orthographic projection of the test system along with a photograph showing a similar view that includes the filter housing, recirculation pump and filter feed tank.

Fig. 1. Overall layout of CFF test system

Planning for the CFF Test Program began in September 2004. System fabrication was completed in the summer of 2006. Execution of the test program occurred from August 2006 through August 2007.

Cross-Flow Filter

The cross-flow filter used for the test was purchased from Pall Corporation. The filter bundle had a filtering surface area of 20 m^2 (216 ft^2) consisting of 220 filter tubes (see Fig. 2). Each tube was 3 m (10 ft) long with a 1.2 cm (0.46 in) outer diameter and a 1.0 cm (0.39 in) inner diameter. The effective pore size was 0.1 micron (μm), created by a zirconia coating on the inside surface of the sintered-metal tubes. The filter vessel, which housed the bundle, had a 66cm (26in) diameter and was 4.6 m (15 ft) long.

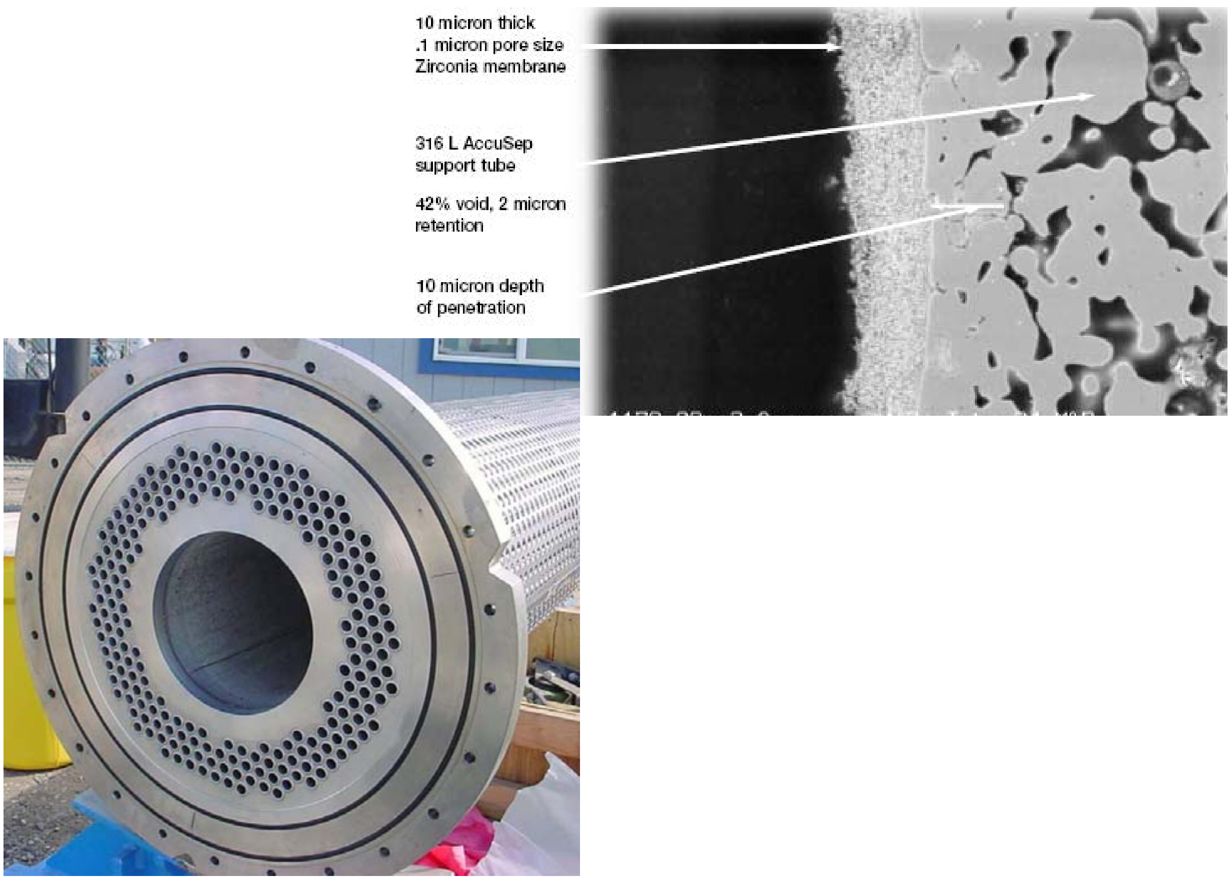

Fig. 2. Upper end of filter tube bundle showing open tube ends (left) and photomicrograph of tube cross-section (right).

DESCRIPTION OF THE CFF TEST SOLUTIONS

Feed solutions were prepared from MST and simulated sludge in an aqueous solution of 2.8 molar (M) sodium hydroxide (NaOH) and 2.8M Sodium nitrate ($NaNO_3$). The solution chemistry was chosen to mimic the overall sodium concentration (5.6M) and density (1.2-1.3 g/l) of the SWPF feed. Simulated sludge for the test included aluminum, iron, manganese, sodium and potassium solids. Tests generally began with low solids concentrations (400mg/l MST plus

600 mg/l simulated sludge) as will be typical for SWPF operation. For most tests, the solution was filtered until the concentration of solids had increased to ~7 wt%.

The recirculating concentrate was kept at 23 +/- 1°C (73 +/- 2°F), using an in-line heat exchanger in the recirculation loop. The heat exchanger used chilled water at a nominal temperature of 7°C (45°F) to cool the process fluid.

CFF CHARACTERISTICS

Conventional filtration is limited by the buildup of solids (filter cake) on the surface of the filter. As solids build up, the trans-membrane pressure (TMP) required to maintain any given filtrate flow increases (or for any given TMP the filtrate flow decreases). The filter cake generally serves to decrease the average pore size of the filter; in essence, the filter cake becomes the finest portion of the filter while the filter element becomes a support for the finer filter cake. Cross-flow filters utilize the axial velocity of the feed to limit the deposition of solids (filter cake) on the filter surface. The velocity of feed across the filter cake erodes the filter cake surface, providing a mechanism for material removal. As the cake builds, the inside diameter of the filter becomes smaller, increasing the fluid velocity for any given flow rate. Higher velocities result in more aggressive material removal, as a result an equilibrium is reached between feed flow rate and the depth of the filter cake. As feed flow increases, the equilibrium depth of the filter cake would be expected to decrease. This potentially increases filtrate flow for any given TMP but potentially increases the effective pore size of the filter at the same time. Higher axial flow rates also require more power from the recirculation pumps. Thus there are trade offs – high feed flow rates promote higher filtrate rates and potentially longer operational periods between back-pulsing or conventional cleaning while increasing power requirements for the recirculation pumps.

Back-pulsing, i.e., forcing filtrate back from the clean side to the dirty side of the filter provides an alternate or supplementary approach to controlling filter cake. Back-pulsing can clear some or all of the filter cake from the surface of the filter, potentially increasing filtrate flow during subsequent operation. By using periodic back-pulsing, it should be possible to limit the thickness of the filter cake without resorting to high axial velocities. A disadvantage of back-pulsing is that the filter cake is violently disturbed, potentially exposing the raw filter element, possibly increasing the effective pore size of the filter until the cake depth increases, with a resultant degradation of filtrate quality due to the presence of larger particulates in the filtrate.

STRUCTURE OF TESTS

Operational Variables

As noted above, many process variables interact to affect the performance of cross-flow filters. These variables include feed characteristics (solids content, solids size distribution and fluid viscosity), TMP, axial velocity in the filter, initial condition of the filter, and back-pulsing. The system was configured to provide independent control of viscosity (maintained constant via temperature), TMP and axial velocity.

In the SWPF, filtration occurs as a batch process. Since CFF operation is affected by a number of variables that change over the course of processing a normal batch (solids content, pressures and flows), and since the intent of this testing was to examine the performance of the CFF in conditions relevant to SWPF operation, the basic unit-of-comparison for evaluating changes in operating conditions was chosen to be the processing of a single batch. In practice, this meant that a single "run" required the filtration of approximately 50 m^3 (13,000 gal) of feed. Each such run required approximately 5, 8-hour shifts to complete. During testing, the unit was operated on a 3-shift-per-day basis.

Typical system operation included "re-doping" and chemical cleaning, described below.

Re-doping

The maximum solids concentration in the CFF after a processing a single tank full of fluid was limited by the initial feed concentration, the starting volume of the feed and ending volume of feed once the system reached the minimum operational level in the feed tank. The ending volume of the feed included the volume of the dirty, or feed-side of the filter loop plus the volume of liquid remaining in the feed tank at the minimum operational level. The feed-side of the filter loop included the lines between the feed tank and the recirculation loop, the recirculation loop volume (including the volume of pumps and other equipment in the loop, and the feed-side volume of the filter. For the CFFS, the feed tank volume was 38 m^3 (10,000 gal), while the feed-side of the recirculation loop was 1.1 m^3 (284 gal). The residual volume in the feed tank at the minimum operational level was 0.2m^3 (41 gal). Thus the minimum ending volume of feed in the system was 1.2 m^3 (325 gal). Note that at the minimum residual volume, the air-pulse agitators were no longer active; mixing was limited to that provided by the recirculation flow. The SWPF is not expected to operate in this manner.

The maximum feed concentration factor that could be attained by the system for prototypical starting feed concentrations was ~31. CFF test starting solids concentrations were generally ~0.08 wt% solids. Thus the first cycle of the system was expected to reach a solids concentration of ~2.5 wt%. To reach higher concentrations a second cycle, starting at the ending concentration of the first cycle was run. Sufficient additional material (at the ending concentration of the first cycle) was added to the feed tank to allow the second cycle to reach the target concentration. This addition of material is referred to as "re-doping".

Re-doping allowed a 38 m^3 (10,000 gal) feed tank to simulate the operation expected using the larger tanks included in the SWPF design.

Chemical Cleaning

A chemical cleaning system was provided to restore filter performance between tests when specified. Primary cleaning of the filter tubes and system piping was performed by introducing and circulating a solution of half molar (0.5M) oxalic acid ($H_2C_2O_4$). Cleaning effectiveness was determined by comparing the permeation of 0.02M caustic solution during final rinse of each cleaning cycle throughout the test series. Chemical cleaning was used to ensure that comparative tests started out on equal footing with respect to the initial condition of the CFF.

Work-up Tests

Work-up (WR) Tests were used to pre-select the back-pulse technique (as noted in Table I) and to allow operators to become familiar with the system performance, prior to conducting the actual tests. The previously described feed solution was used.

Table I. Work-up Matrix

Item	Work-up Test 1	Work-up Test 2	Work-up Test 3
Back-pulse Method	Short pulse	Series of short pulses	Various
Back-pulse Interval	Fouling Criteria	Fouling Criteria	Fouling Criteria
PSD and wt%	Measured	Measured	Measured
Cleaning Solution[3]	0.5M $H_2C_2O_4$	0.5M $H_2C_2O_4$	0.5M $H_2C_2O_4$

For consistency, all work-up tests started at constant TMP of 172 kPa (25 psid). Recirculation flow was maintained at 4.5m^3/min (1,200 gpm, 14.7 ft/sec axial velocity). In order to establish a preferred method of back-pulsing, three different modes of operation were evaluated: single, short-burst pulses (pulses of one second), a series of short-burst pulses (three pulses in rapid succession, each of one-second duration), and a single, long-burst pulse (one pulse of five seconds). The decision to perform a back-pulse was based on the calculation of a fouling value. This value accounted for the interaction of TMP on flow, such that changes in flow due to TMP were ignored. Thus the decision to back-pulse was independent of TMP changes created by manipulation of system controls. The fouling value was calculated using equation 1:

$$fouling = \frac{gpm}{\sqrt{\Delta p_{filter}}} \quad \text{or} \quad fouling = \frac{filtrate\ flow(gpm)}{\sqrt{TMP}} \qquad \text{(Eq. 1)}$$

When the fouling value dropped to the pre-selected point (generally ½ the starting, or clean value) back-pulsing was performed. The control software recorded the fouling value and the frequency and duration of back-pulsing.

Main Tests

Table II presents the CFF test matrix, including test type, purpose, fluids tested, flow rates, and test duration.

Table II. Test Matrix

Test No.	Test Type	Test Operation	Value	Frequency[a]	Purpose
1	Process Control	Process feed solution at different feed pressure Hold pressure constant for entire run	TMP 80, 140, 240 kPa (12, 20, 35 psi)	3 tests	Monitor time needed to reach a concentration of 7 wt% solids Measure flux decline during run

Test No.	Test Type	Test Operation	Value	Frequency[a]	Purpose
2	Process Control	Start at low pressure and increase as needed to maintain filter flux	Filter Flux 49, 57, 64 l/min (13, 15, 17 gpm)	3 tests	Monitor time needed to reach a concentration of 7 wt% solids Measure pressure drop across filter
3	Process and Hydraulic	Process feed solution at different cross-flow rates	Axial velocity 2.8, 3.4, 4.0 m/sec (9, 11, 13 ft/sec)	3 tests	Compare filter flux at various cross-flow rates Measure change in pressure drop for the whole filter housing at varying cross-flow rates Establish a relationship between filter fouling and axial velocity, which is a function of FT-125
4	Process Control	Use preferred parameters determined from Tests 1-3 Test long-term effects of filter	Preferred TMP, filter flux, axial velocity.	4 tests	Confirmation of preferred parameters Long-term effects of filter without cleaning between runs Test higher solids wt% solids (9 wt%)
5	Process	Process with MST only	Solids concentration 0.03 wt% solids	3 tests	Monitor time needed to reach a concentration of 7 wt% solids Test second strike conditions Measure flux decline during run
6	Process	Process concentrated solution with addition of water	Observe time and volume for dilution	1 test	Evaluate length of time required to dilute to 0.5M Na^+ concentration Evaluate volume of water required in dilution
7	Test 7 was deleted				
8	Process	Operate system to maximum solids content	Solids concentration – Maximum attainable	1 test	Gather data on filter performance at high-solids and recovery from high solids condition
9	Process and Hydraulic	Evaluate APA system operation as tank level is reduced	APAs configured per previous APA testing	1 test	Check suspension of solids throughout tank as tank level is reduced
10	Laboratory	Perform elemental and morphology analysis on MST suspended in salt solution	0.4 grams per liter (g/L) MST	2 tests	Identify effects of salt solution on MST Identify shearing effects of CFFS equipment on MST

Test No.	Test Type	Test Operation	Value	Frequency[a]	Purpose
11	Process	Process at fixed values of feed concentration, TMP and AV	Various	12 tests	Gather data on filter performance with constant feed concentration

[a]Tests are labeled A, B, C, D, etc. For example, tests 1A, 1B and 1C are denoted for the three tests in test number 1.

RESULTS

Issues with the Original Filter Design

Initial operation of the filter system disclosed a flaw in the design of the seal between the filter housing and filter bundle. The initial filter bundle/housing design utilized a double o-ring seal between two horizontal, flat surfaces to seal the filter bundle to the housing. This seal required both surfaces to be closely controlled for flatness and perpendicularity. The seal also required that the filter bundle be pressed down (preloaded) to provide compression of the o-rings. Pressure differentials developed during operation of the filter acted to lift the filter bundle, reducing preload on the seal. It was determined that a combination of out-of-tolerance conditions of the sealing surfaces and an inability to maintain an adequate preload resulted in leakage of the feed material by the seal, allowing feed to enter the filtrate (clean side) of the filter housing. Once this condition was identified, the design was reviewed and modified. The horizontal flat-face seal was abandoned, and a new piston-ring-style seal was incorporated. This new seal design used a pair of o-rings in grooves in the outside diameter of a vertical cylindrical surface on the filter bundle (the piston) mating with the inside diameter of a vertical cylindrical sealing surface in the housing. The design eliminated the need for dynamic preloading of the seals and allowed better control of the geometries of the sealing surfaces during manufacture. A new housing was manufactured by Pall Corporation incorporating the new design features. The new assembly was reinstalled in the test system and testing was resumed.

Work-up Runs

The focus on the work-up tests was the selection of the back-pulse method to be used for subsequent testing. Solids were re-used for entire workup test series. In between each test, the filter loop and FFT were rinsed with filtrate to reclaim the solids. After reclaiming solids, the filter was put through a chemical cleaning cycle to ensure that each test had the same initial conditions.

System parameters for tests WR1, WR1A and WR2 were:

- Feed pump at full speed
- Recirculation flow at 4.5 m^3/min (1200 gpm, 14.7 ft/sec axial velocity)
- TMP at 170 kPa (25 psi)
- Back-pulse air pressure at 800 kPa (100 psig)

During WR3, WR3A, and WR3B, the system parameters were actively changed in order to promote fouling.

Work-up runs WR1, WR1A (a repeat of WR1) and WR2 showed that during normal operations, back-pulsing was required only after a process upset (generally a decrease in axial flow through the filter). It was found that an entire batch could be processed at the conditions chosen prior to having the back-pulsing criteria being met. Based on these runs, no differentiation between the short-pulse and multi-pulse techniques could be made. As a result WR3, originally planned as a long-pulse run, was modified to promote fouling of the filter to allow a meaningful comparison of the three back-pulse techniques. Axial flow was decreased to create fouling conditions. Following back-pulsing, time-to-foul was monitored. This technique was repeated multiple times for each of the three back-pulse schemes. There was no significant difference in effectiveness between the back-pulse methods. As a result, the simplest (and most economical) method, a single, short back-pulse, was selected for use in subsequent testing.

Main Test Runs

Test Series 1 – Effect of TMP on Performance

Test Series 1 was intended to explore the influence of TMP on filter operation. Tests were performed with the TMP held constant at 83, 140 and 240 kPa (12, 20, and 35 psid) while feed flow and recirculation flow were kept constant. Prior to each test in this series, the filter was put through the standard chemical cleaning cycle. The initial solids concentration was 0.4 g/L MST and 0.6 g/L sludge simulant. New solids were used for each test. Additional solids and liquid were added mid-test (re-doping) to allow solids concentration to reach 7 wt% at the minimum FFT operating level. Filtration continued until the slurry was concentrated to 7 wt% solids.

The filtrate flow data taken while concentrating the slurry to 7 wt% for each test is shown graphically in Fig 3. As expected, increased TMP results in decreased processing time and increased flow. No negative characteristics were associated with increased TMP during this test series.

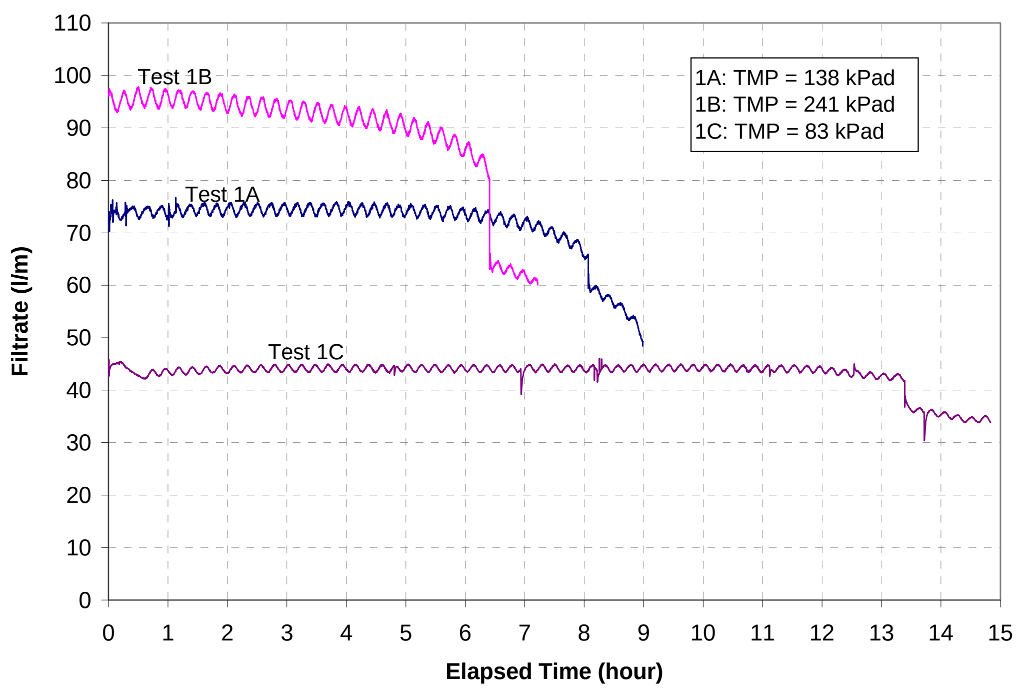

Fig. 3 Test 1 Series Filtrate vs. TMP

Test Series 2 – Effect of Filtrate Flow on Performance

Test Series 2 was intended to explore filter operation at constant filtrate flow. Tests were performed with filtrate flow held constant at 64, 57, and 49 l/min (17, 15, and 13 gpm). Feed pump speed and recirculation flow were kept constant for all three tests. TMP was varied to control filtrate flow. Prior to each test in this series, the filter was put through the standard chemical cleaning cycle. The initial solids concentration was 0.4 g/L MST and 0.6 g/L sludge simulant. Additional solids and liquids were added mid-test (re-doping) to allow solids concentration to reach 7 wt%. Filtration continued until the slurry was concentrated to 7 wt% solids.

As expected, processing time was directly proportional to filtrate flow, with the highest filtrate flow rates providing the shortest batch processing times. Comparing the TMP data for each test showed that higher filtrate flow rates required higher TMP. Since there were no apparent side effect of the increased TMPs required for high filtrate flow rates, the highest filtrate flow rate was desired. These results were consistent with the results of Test Series 1.

Test Series 3 – Effect of Axial Flow on Performance

Test Series 3 was intended to explore the influence of axial velocity on filter operation. Tests were performed with axial velocities of 2.8, 3.4, and 4.0 m/sec (9, 11, and 13 ft/sec). TMP and recirculation flow were kept constant. Prior to each test in this series, the filter was put through the standard chemical cleaning cycle. The initial solids concentration was 0.4 g/L MST and 0.6 g/L sludge simulant. Additional solids and liquid were added mid-test (re-doping) to allow the slurry to reach the target solids concentration of 7 wt%.

At the two lower axial velocities the filter became fouled at ~ 6wt% solids. At the highest axial velocity, a ~7 wt% solids concentration was achieved in less time than it took for the tests at lower axial velocity to achieve a 6 wt% solids concentration. A decrease to half the original steady-state fouling number value resulted in the triggering of a back-pulse in both the 3.8 m/sec (9 ft/sec) and 3.4 m/sec (11 ft/sec) runs prior to reaching the target solids concentration of 7 wt%. Back-pulsing at these lower axial velocities was ineffective. It is concluded that higher axial velocity reduces fouling rate and increases the effectiveness of back-pulsing.

As expected, the axial pressure drop increased proportionately with axial velocity. At 4.0 m/sec (13 ft/sec) axial velocity, the slurry was concentrated to 7 wt% in under eight hours whereas at lower axial velocities solids concentration didn’t reach the target solids concentration even when testing was extended beyond eight hours. It is concluded that processing time decreases with higher axial velocities.

Test Series 4 – Long-term Filter Operation without Chemical Cleaning

The results from Test Series 1 through 3 showed that high TMP, high filtrate flow, and high recirculation flow were best for system operation. The purpose of this test series was to identify any long-term effects from processing multiple batches of slurry without chemical cleaning in between cycles using operational parameters that optimized system performance. All subsequent tests had the same set of operating parameters:

- Feed pump at 60 Hz (Full Speed)
- Axial velocity at 4.6 m/sec (15 ft/sec)
- TMP at 240 kPa (35 psi)

Prior to the start of this test series, the filter was subjected to a standard cleaning cycle. In between each test, the filter was not rinsed or cleaned. Tests 4A, 4B and 4C began with a fresh batch of initial solids at a concentration of 0.4 g/L MST and 0.6 g/L simulant sludge; Test 4D used solids from Test 4C. Solids and liquids were re-doped during tests 4A, 4B and 4C to reach the final target concentration at the minimum FFT operation level. Test 4D was started from a higher initial solids concentration (filtrate was added to the ending condition of Test 4C). Target final concentration was 7 wt% for Test 4A and 4B. Target final concentration was 9 wt% for Test 4C and 4D.

Filtrate flow rates during times of active slurry concentration are shown in Fig. 4 (periods during re-doping are omitted). During Test 4A, the filtrate flow slowly degraded for the duration of the run. Test 4B demonstrated a fairly uniform filtrate flow up to re-doping. Test 4C showed an increased filtrate flow for the initial portion (pre-re-dope) of the run, then showed the typical flow degradation following re-dope. Test 4D, showed the lowest filtrate flows of the series and continually degraded over the test.

The increase in flow for Test 4C occurred after a back-pulse. It is possible that periodic back-pulsing would be of benefit during normal operation at high axial flow, even though the filter is not fully fouled. The temporary increase in turbidity that occurs after back-pulsing would need to be considered in evaluating the efficacy of this technique.

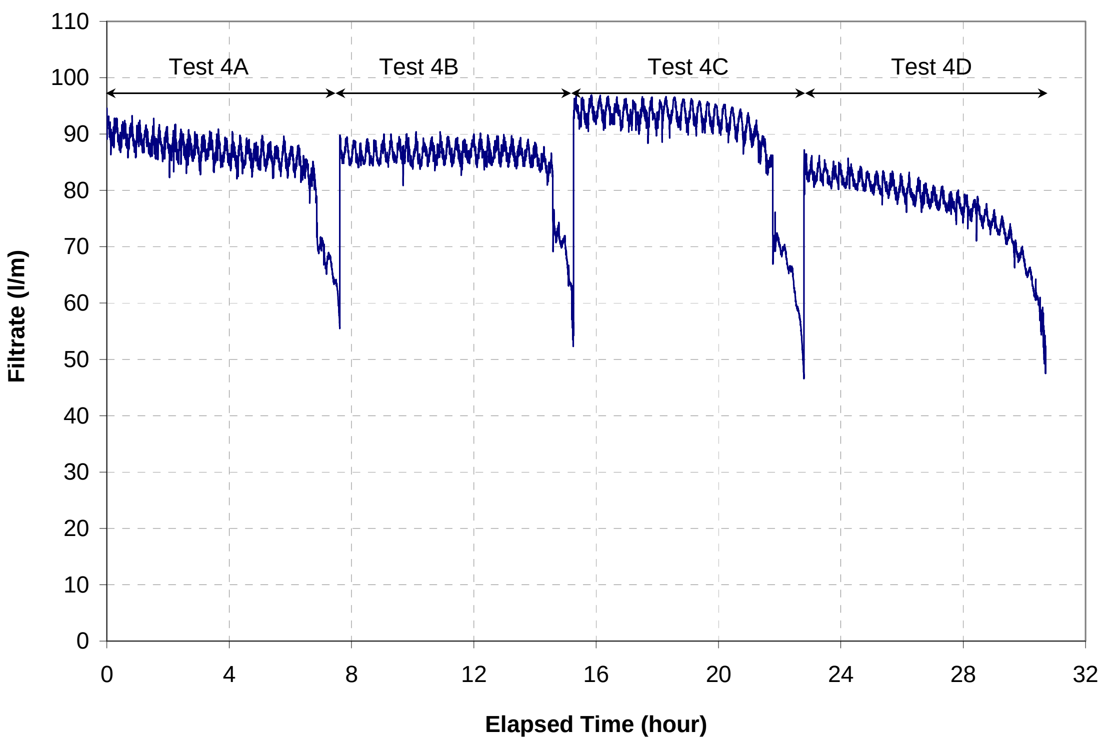

Fig. 4. Filtrate Profile without Cleaning Cycles Between Each Test

Test Series 5 – Operation Using MST Only (No Sludge Simulant)

If a second MST strike is required to process a waste batch during SWPF operations, it will occur on pre-filtered solution. Only MST will be added. No sludge solids will be present. MST will be added to the waste and the subsequently be removed via filtration. The purpose of Test Series 5 is to simulate MST-only filtration to ensure that no unforeseen difficulties are observed.

Filtrate from previous testing was re-used and populated with MST at an initial concentration of 0.4 g/L MST. The test parameters from Test Series 4 were used during this series of tests. For the first test in the series, additional MST solids were added mid-test to allow solids concentration to reach 7 wt% at the minimum FFT operating level. For the remaining two tests in the series, the solids were reused in-place in a manner identical to that used in Test 4D. In these two tests, the solids concentration was planned to begin at 0.2 wt% and end at 7 wt%. MST degradation samples (to evaluate system effects on particle size distribution) were also taken while concentrating during Test 5B.

No behavior specific to the absence of sludge was detected. System performance and processing times were similar to those seen in Test Series 4.

Test Series 6 – Solids Washing Simulation

Solids washing is used in the SWPF process to lower the sodium concentration of collected solids from 5.6M to 0.5M [Na]. During washing the concentrated solids in the Sludge Solids Receipt Tank (SSRT) are filtered through a dedicated CFF. Water is added to the SSRT at the same rate as filtrate is removed. The objective of Test 6 was to evaluate system performance during simulated solids washing operations.

Test system operation emulated that envisioned for the SWPF. The entire batch of concentrated slurry collected in the SSRT from earlier tests was transferred to the FFT. The system was operated in the same manner as in previous tests except that fresh water was used to replace the filtrate removed to continuously maintain constant level in the FFT. The total flow was monitored. The test was stopped when the total flow reached the target volume required for dilution. No adverse or unexpected behavior was noted. As expected, filtrate flow increased as sodium concentration decreased (due to the decrease in viscosity of the fluid).

Test Series 8 – Maximum Solids Test

Test 8 was conducted to see the effects of concentrating solids in the CFF system to levels higher than the normal target (7 wt%). A further goal was to evaluate methods to remove a highly-concentrated sludge from the system. A maximum target of 20 wt% was chosen for the test. Following the solids washing test, a portion of the 7 wt% slurry was transferred to the SSRT. The portion that remained in the FFT had sufficient solids to reach 20 wt% at the minimum FFT operation level. The salt solution was adjusted back to a 5.6M Na concentration by the addition of concentrated sodium hydroxide and sodium nitrate solutions. Test 8 was run with the same operating parameters as used for Test 4.

As expected the filter experienced fouling at higher solids concentrations. However, the normal fouling criteria imposed in earlier testing was ignored for this test to allow the solids to concentrate without back-pulsing. As a result filtrate flow decreased from 40 l/min (10.5 gpm) to 21 l/min (5.5 gpm) over the duration of this test. As the filter fouled, the filtrate control valve was adjusted accordingly to allow the TMP control valve to operate within its range. There were no signs of catastrophic plugging during this run. The run was eventually stopped when the minimum operating volume of the FFT was reached. The calculated solids concentration at this point was 20 wt%. The slurry was removed from the system at the end of the test using the same techniques as used for previous testing (gravity flow with air-assist at low levels). No special methods were required.

Test Series 9 – Solids Suspension in the FFT

Previous testing [3] showed data for suspension of solids using air-pulse agitators in a flat-bottom tank at 38-m^3 (10,000-gallon) scale at two discrete levels. The tank geometries planned for the SWPF are dish-bottomed, and level will change continuously as batches are processed. Test 9 was intended to verify that the air-pulse agitation system could provide adequate solids suspension in the prototypically shaped FFT with continuously variable level. The test was run concurrently during Test 4B. Several sets of samples were collected periodically from the FFT at various radial locations and elevations.

Analytical results for the samples taken during this test show no clear localization of solids indicating that an even distribution was achieved and that mixing was adequate. Although lower than expected, the solids concentration measurements suggested that solids are uniformly suspended throughout the tank.

Test Series 10 – MST Particle Size Stability

Test 10 was performed to determine whether extended exposure of MST to the 5.6M salt solution or exposure to mechanical shearing from the CFF equipment would cause a reduction in the size of the MST particles. The samples taken during these tests were analyzed by Scanning Electron Microscopy (SEM) to obtain a particle size distribution of the MST particles (identified as titanium-containing particles).

Several feed samples were collected after adding MST solids to the FFT during preparation of the original feed batches. The samples were taken prior to the addition of sludge simulant solids and were representative of 5.6M salt solution with 0.4 g/L concentration of MST solids. Over the duration of CFF FST the samples were periodically analyzed. Results indicate that the particle size did not degrade over time.

During Test 5B, five sets of feed samples were taken periodically during the run to determine if there was any mechanical shearing of the MST particles. Reported in the data are the average particle diameters for particles identified as MST (as determined by the presence of titanium). Table III shows that the average MST particle size did not decrease over the duration of the test.

Table III. Average Particle Sizes in Feed Samples from Test 10

Sample Description	Date	MST Particle Count	MST Average Particle Diameter (µm)	Non-MST Particle Count	Non-MST Average Diameter (µm)
Feed at solids conc. ~0.2 wt%	7/5/07 13:40	946	1.3	58	1.5
Feed at solids conc. 0.4 wt%	7/5/07 19:59	952	1.3	47	1.5
Feed at solids conc. 1.3 wt%	7/5/07 23:54	968	1.5	33	1.5
Feed at solids conc. 3.1 wt%	7/6/07 1:09	849	1.3	151	1.4
Ending Feed	7/6/07 2:49	953	2.1	47	1.3

Test Series 11 – Filter Performance Under Steady-State Conditions

Test 11 was performed to provide steady-state operation data from the operation of the CFF system to allow comparison of system performance data to steady-state data obtained by others. Fourteen sets of operational parameters were demonstrated. Data were recorded for each set of steady-state conditions over two hours of operation. At the end of each two-hour period, the filter was checked against a "clean" condition by performing a flush/back-pulse sequence. This flush/back-pulse sequence consisted of reducing the TMP by closing the filtrate control valve and fully opening the TMP control valve. The recirculation pump was set to 4.5 m^3/min (1,200 gpm, 14.7 ft/sec axial velocity) and held for 15 minutes, after which a back-pulse was performed. The previous set of test parameters were established and the filtrate flow was checked. If the filtrate flow rate returned back to the "clean" condition reading observed at the start of the previous test, then the run was considered valid. If the filtrate flow rate was not within 10% then that particular set was run again until it was valid.

Test results were consistent with the results of previous testing. A summary of the average flow results for each of the tested parameter sets is shown in Table IV.

Table IV. Average Filtrate Flow from Test 11 Segments

Run Number	Solids Conc. (wt%)	TMP (kPa)	Axial Velocity (m/sec)	Average Filtrate Flow rate (l/min)
11A-1	7.0	83	4.0	21
11A-2		138		24
11A-3		241		25
11B-1		138	4.0	24
11B-2			3.4	20
11B-3			4.6	29
11B-4		310	4.6	31
11C-1	3.5	83	4.0	33
11C-2		138		39
11C-3		240		41
11D-1		138	4.0	39
11D-2			3.4	32
11D-3			4.6	39
11D-4		310	4.6	47

RESULTS BASED UPON INSPECTIONS

Removal and Installation

One of the test program objectives was to demonstrate that the filter bundle could be removed and replaced with a minimum level of operator involvement. This was done by removing the bundle for inspection and replacing it using an overhead crane. Test of the bundle-to-housing seal showed that the bundle successfully re-sealed in the housing.

Erosion and Wear

Inspection techniques employed (visual inspection, physical dimensional checks and ultrasonic thickness checks) showed no compelling evidence of wear or erosion in any of the system components as a function of operation. Separate, longer-term testing is being performed to ascertain erosion rates for the target solutions.

CONCLUSIONS

The CFF Test Program demonstrated that the SWPF CFF system could be successfully fabricated, that the SWPF CFF design assumptions were conservative with respect to filter performance and provided useful information on operational parameters and techniques. The filter system demonstrated performance in excess of expectations.

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