Crossflow Ultrafilter Module Draining and Flush Testing for the Hanford Tank Waste Treatment and Immobilization Plant - Lessons Learned in Declogging Crossflow Filters – 9511

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ABSTRACT

This paper describes testwork conducted in order to study crossflow ultrafilter module draining and flushing for the Hanford Tank Waste Treatment and Immobilization Plant. The objective of the testing was to demonstrate that the current design, with a flush tank at elevation 29.9 m (98'-00") has enough pressure head to drain (to a minimum elevation ~1.5 m [~5'-00"]) and clean out the ultrafilter tube side. Without demonstrating this, a potential failure of the flush system could cause immoveable solids to plug the tubular membranes of the filters causing serious adverse impacts to plant availability and/or throughput, and could permit deleterious flammable gas accumulations. In conjunction with the water flush, the plant also utilizes air purging to prevent build up of flammable gases.

Two filter configurations were investigated, one being the baseline horizontal layout and one being an alternative vertical layout. The slurry used in the tests was a non radioactive simulant (kaolin-bentonite clay), and it mimicked the rheological properties of the real waste slurry. The filter modules were full scale items, being 2.44 m (8') in length and containing 241 by 1.3cm (½") id sintered stainless steel filter tubes.

INTRODUCTION

In 1943 the US Army Corps of Engineers selected an area of about 1550 square kilometers (600 square miles) in southeastern Washington State, the Hanford Site, for producing nuclear materials in support of the United States' war effort. Today the Hanford site is operated by two Department of Energy (DOE) field offices - the Richland Operations Office (RL) and the Office of River Protection (ORP). ORP retains the responsibility for remediating the waste stored there that resulted from over forty years of reactor operations and production. Hanford is considered the DOE's largest and most complex environmental cleanup effort, a national priority.

Hanford cleanup involves the retrieval, treatment, and disposal of millions of gallons of liquid and semi-liquid waste. The material consists of approximately 208,000 cubic meters (55 million gallons [US]) of highly radioactive and mixed hazardous waste stored in large underground storage tanks, some of which have leaked into the soil and threaten the nearby Columbia River. To accomplish the ORP mission DOE established the River Protection Project (RPP) to ensure the protection of the river from the leaked tank contents. ORP-RPP has contracted with a team consisting of Bechtel National, Inc. (BNI) and Washington Group International, a subsidiary of the Washington Division of URS Corporation, to design, build and commission a facility to immobilize the most mobile contents of these tank wastes in glass.

The facility is called the Hanford Tank Waste Treatment and Immobilization Plant Project (WTP), and is currently under construction at the approximate center of the Hanford site adjacent to the feed source tanks.

The WTP is comprised of four major elements: pretreatment, low activity waste (LAW) vitrification, high level waste (HLW) vitrification, and a large sophisticated chemical laboratory. The Pretreatment Facility (PTF) is designed to treat and separate the waste feed delivered from the Hanford tanks into a low-activity waste stream by removing most of the solids and radioisotopes, diverting the solids and radioisotopes to a high-level waste stream. The two independent waste streams are then sent to the LAW and HLW vitrification facilities to produce immobilized (vitrified) low-activity waste (ILAW) and immobilized high-level waste (IHLW) forms.

The PTF contains inaccessible "black" cells, and a "canyon"-type radioactive process cell (hot cell). The canyon houses the majority of the special processing equipment, including ultrafilters, ion exchange columns, recirculation and transfer pumps. The equipment in the hot cell is interconnected by remotely removable piping which can be accessed by an overhead crane. Operations and maintenance within the hot cell is controlled remotely, observed by television and manipulated by the crane for all equipment operation, maintenance, removal, or replacement.

The key unit operation of the pretreatment process is the ultrafiltration (UF) process step. The WTP production rate and the quality of the downstream operations of both the LAW and HLW are directly related to the successful performance of this step. The equipment in the UF process step consists of two trains of ultrafilters each with multiple units connected in series. Each UF train is located in the canyon. Each UF train is served by an ultrafilter feed preparation vessel, UFP-1A/B (located in black cells), an ultrafiltration feed vessel, UFP-2A/B (located in black cells), recirculation pumps and heat exchangers. UFP-1 vessels receive, stage, and (in some cases) pretreat feed prior to feeding the UFP-2A/B vessels. (Either UFP-1 vessel can feed either UFP-2 vessel).

The two main steps for processing solids through ultrafiltration are solids concentration and solids treatment. Concentration is the step that accumulates solids in the UFP-2A/B vessels, and treatment includes leaching the solids, re-concentrating the solids, washing the solids, transferring the solids and cleaning the ultrafilters. The latter combination of steps is referred to as a campaign. UFP-2A/B are each connected to a filter train. Their contents are pumped through the ultrafilters where permeated is drawn off and the steam exiting the filters, which is now more concentrated in solids, is returned to the connected UFP-2 vessel. Additional feed is added to the UFP-2 vessels as necessary. This cycle is continued until the solids concentration reaches its target weight % solids. During concentration an in-line heat exchanger is utilized to control the temperature. Collected permeate is routed to ion exchange for additional treatment.

The ultrafilters consist of tubular mircoporous membranes manufactured from sintered 316L metallic powder. The UF system removes entrained solids from material fed from the Hanford waste tanks, which is a combined HLW and LAW feed. Solids are removed from material pumped from the UFP vessels in order to protect downstream ion exchange resin beds and to meet certain specifications for the vitrified waste products. The UFP material is concentrated via recirculation thru the ultrafiltration system to a dense slurry with an end point of ~20 weight % prior to being sent on to additional treatment, lag storage and ultimate vitrification.

In a normal shutdown, when the UF recirculation loop flow is stopped due to a planned or unplanned shutdown, the recirculation loop including the ultrafiltration modules, will be drained and flushed to ensure that residual solids remaining in the UF trains are minimized. The primary objective of doing this is to prevent plugging of the UF tubular membranes by settled material and to prevent the accumulation of hydrogen gas. Intractable plugging of the tubular membranes becomes more probable the longer the material remains in the bore of the tubular membranes.

In the normal WTP flush, flow through the recirculation loop is reversed. The loop is filled with flush solution (dilute caustic in the plant, water for the subject tests) supplied from a flush tank, which is elevated in the plant. Solution from this tank feeds into the outlet side of the ultrafilter "trains" until the recirculation loop overflows to the UFP feed vessel. Approximately one loop volume is returned to the affected UFP in an effort to preserve as much of the filtered (densified) feed lot as possible. After this initial flush to UFP the drain valve to a second plant vessel is opened and a second loop volume is displaced through the train. At this point the drain valve is closed leaving the loop filled with dilute caustic. Air is available assist the removal of solids during these cycles. A UF shell-side back pulse system is also available to assist if necessary.

In an emergency, to manage the accumulation of hydrogen gas post design basis accident (DBA), the WTP ultrafiltration loop, including filters, is cleared of sludge first by flushing via the elevated head tank then a low volume of compressed air purge is maintained. There is no important to safety (ITS) requirement to remove all or even most of the solids from the ultrafilter tubes, but only to open a flow passage to provide sweep air for removal of accumulated hydrogen, which is ITS.

Limited experimental data was available early in the project to show that high rheology material accumulated within the UFP system could be drained from the UF units, or a vent pathway opened, in the event of a shutdown. In addition to maintaining viable UF equipment after such an outage, a vent path needed to be shown to exist through the filter trains to conduct potentially explosive gases back to the UFP vessels for management by the vessel offgas system.

The testing reported herein was necessary to demonstrate the effectiveness of draining the UF modules by a gravity flush system, supplemented by air purging if needed. Tests were performed with full-scale UF modules oriented both vertically, and at a slope of 1:25 from horizontal, prototypic of the actual plant installation. Full-scale UF modules approximately 2.44 m (8') long and 0.41 m (16") in diameter containing 241 half-inch I.D. tubular membranes were provided from plant inventory for the tests. The filters and piping system were filled with a 20 weight percent (wt %) non-radioactive clay-based simulant and then flushed and drained using a mock-up of a proposed gravity plant wash system.

The effectiveness of draining was determined by visual examination of the tubes to estimate the distribution of residual waste across the face of the tube sheets. In addition, a method was devised to supplement visual inspection by conducting low pressure air flow measurements, comparing these results with pristine conditions. For flushing via the gravity system, testing was performed at conditions comparable to those of the full-scale plant configuration. Modifications to the modules were made as required to perform testing.

EXPERIMENTAL

The test program was broken up into three phases:

- Test Phase 1: Basic Drain (Scoping) Tests – This phase established the drain behavior of a single Ultrafilter assembly (after filling with simulant), with no assist from air or water flushes.

- Test Phase 2: Double Filter Head Tank Drain Tests – This phase established the drain behavior of a pair of Ultrafilter assemblies, connected in series, with the assist of water flushes and air purges as necessary.

- Test Phase 3: Double Filter Head Tank Pumped Flush and Drain Test – This phase determined the effectiveness of the full flow circulation of simulant in clearing the filter tubes.

Each of these phases, except phase 3, was conducted with the filter in both vertical and horizontal configurations.

Phase 1A – single filter, vertical orientation

Phase 1A simulant gravity draining was performed on September 27, 2007. As expected, essentially all of the simulant drained within the first minute. Prior to the initiation of testing Phase 1A, the tubes were inspected for the ability to visibly determine whether they were open or not. In the clean filter, 191 tubes could be verified as clear. The rest of the tubes were either warped to the extent that it was not possible to see through them, or were at locations (near the sides) where a straight view path was not possible. After the gravity drain, essentially all of the 191 tubes were open.

Fig. 1. Phase 1A test setup

Phase 1B – single filter, horizontal orientation

Gravity draining of simulant for Phase 1B was performed on October 2, 2007. The initial drain was performed with the valves leading to the shell side of the filter set in the closed position (no venting of shell side). Essentially no drainage was observed and all 241 tubes remained blocked.

After visual examination, the flange was replaced, and valves for venting of the flange area and also for venting the tube side were opened. Draining commenced almost immediately after opening the shell side vent. Draining was observed to occur in most of the tubes in the lower 1/3 of the filter, while essentially no draining occurred in the upper portions of the filter. Figure 2 shows the tube side after removing the flange to inspect for blockage after the venting.

Each tube was then inspected both visually and with a pneumatic tube testing device custom built for this testwork. The pneumatic device indicated that forty-one tubes were open. Most of these tubes also were visually open, although some appeared blocked before testing with the pneumatic device. (Note that the tube measurement device allowed determination of blockage in individual tubes, but required physical access to each of the tubes which was only feasible for Phase 1. Such access was not possible in Phases 2A, 2B, and 3B, which used an alternative method for blockage measurements.)

Fig. 2. Partial opening of tubes after venting of shell side of filter during Phase 1B

A general observation was that draining of the tubes appeared to be assisted by water from the shell side during the drain, which could explain the pattern of open and closed tubes. The water level in the shell side could have dropped below the upper level of tubes before they had a chance to clear. It should be noted that this condition is not likely to occur during plant conditions, where the shell side would be expected to remain full throughout the drain.

Phase 2A – Two filters in series, vertical orientation

The gravity drain with simulant for Phase 2A was performed on December 14, 2007. The drain was started with no venting of the shell side. Approximately 148 gallons of simulant were drained over the first 13 minutes of the drain, most of this during the first few minutes. After 13 minutes, the shell side vents were opened and additional drainage occurred over the next 10 minutes. Total drainage was 791 liters (209 gals [US]), as compared to a total inventory, including the volume of water in the shell side, of 939 liters (248 gals). It should be noted that during the gravity drain with water, only 825 liters (218 gals) were recovered, with the difference attributed to some portions being trapped in some locations and/or incomplete filling (entrapment of air bubbles during the filling operations).

An air-flow measurement method was used to evaluate blockage. Blockages of 45% for Filter A and 55% for Filter B were obtained. Visual examination was performed with a borescope and although images typical of the examination showed tubes appearing to be open there was no way to determine if they were clear all the way through to the other end of the filter. Many of the tubes showed blockage with simulant in these examinations.

After the gravity drain, the Ultrafilter Module was refilled and a water flush was performed. The catch tank contained 1590 liters (420 gals) of liquid following this step. The liquid trapped in the upstream portion of the second filter in series (filter B) was then drained into the catch tank by opening a drain valve. This action produced an additional 379 liters (100 gals) of liquid. The total of 1968 liters (520 gals) compared well with a total inventory of 2377 liters (628 gals) of simulant and water. The inventory included the system volume of simulant plus two shell sides of water that were in the piping and module, and the two system volumes in the flush. Much of the difference between the amount in the inventory and the amount recovered could be attributed to water remaining in the shell sides of the Ultrafilters and some simulant remaining in portions of the piping upstream (with respect to the flush) of the Ultrafilter Module. The flush was followed by a 3 minute low-flow (30 scfm) air purge. Air-flow blockage measurements were then performed, which indicated blockages of 82% for Filter A and 27% for Filter B.

A 2 minute high-flow (1500 scfm) air purge followed by a 3 minute low-flow air purge was then performed. Air temperatures below freezing (29^{o}F) were noted just upstream of Filter B during the last half-minute of the high flow air purge. The blockage was re-measured and found to be 72% for Filter A and 27% for Filter B. Borescope examination showed a spectrum of blockages from essentially open to some individual tubes with significant blockage and apparently congealed simulant.

A portion of the top tube sheet in Filter A appeared to be covered by a mass of thickened simulant that was likely blown over from Filter B during the purges and/or air flow measurements, and this could account for much of the observed blockage. It was also noted while removing the inspection plates for the examination, the simulant appeared to be more congealed (similar to cottage cheese) than observed in the other test phases, although this had not been specifically looked for before. It is not known whether this may have been due to some changes in the simulant, or the low air temperatures experienced during the purge, or some combination of both.

Phase 2B – Two filters in series, horizontal orientation

The simulant portion of Phase 2B was conducted on December 5, 2007. The gravity drain was initiated by venting both the tube side and the shell side of the module during the drain. No significant drainage (a total of approximately 19 liters [5 gals]) was observed for approximately 9 minutes, after which draining began, starting at a rate of a few liters per minute and tapering off until draining was essentially complete after a total of 35 minutes (including the initial 9 minutes) and a total of 197 liters (52 gals) drained. Blockages of 85% were determined for Filter A and 75% for Filter B.

The system was refilled with simulant and water and a water flush was performed. 1703 liters (450 gals) of simulant plus water were recovered in the catch tank (tank T2), as compared with a total inventory of 2037 liters (538 gals) (1 system volume of simulant and 2 system volumes of flush water plus 272 liters (72 gals) of water in the shell side portions of the two filters). The flush was followed by a 3 minute, low-flow (30 scfm) air purge after which the blockage was measured and found to be 34% blocked for Filter A and 25% blocked for Filter B.

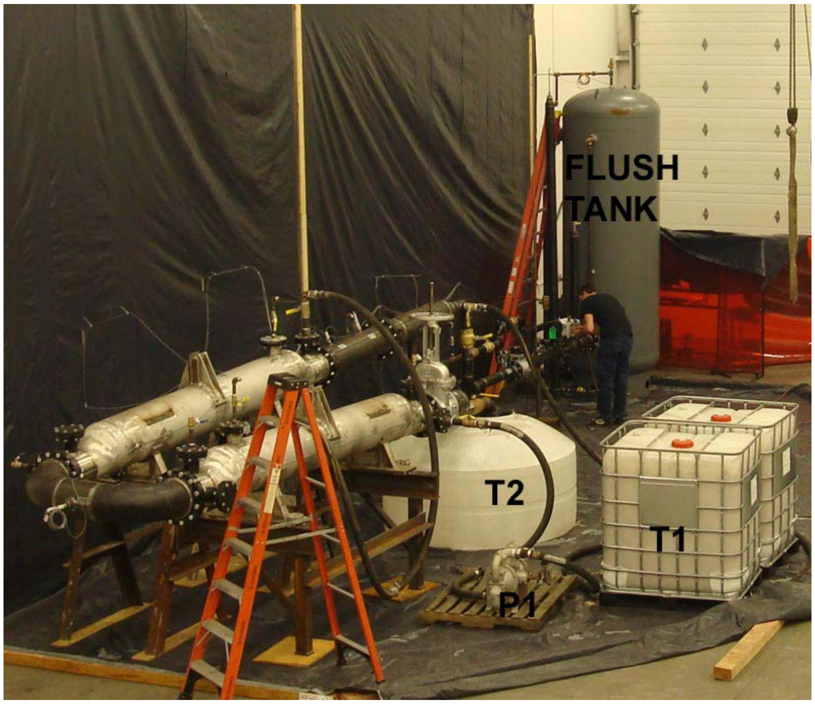

Fig. 3. Test setup for Phase 2B

A 2 minute high flow air purge followed by 3 minutes of a low flow air purge was then performed and the blockages were again measured and found to be 30% blockage for Filter A and 18% for Filter B.

Phase 3B – Two filters in series, horizontal orientation

Results of Phase 3B are summarized in Table I. Simulant testing commenced January 28, 2008. The Phase 3B test configuration was significantly different than that of Phase 2B. The primary difference was the addition of piping and pumping systems enabling the circulation of simulant at full plant-scale flow rates (nominally 500 m^3/hr [2200 gpm]). An additional difference was in the simulant path for gravity drains. The simulant path for gravity drains in Phase 3B required the simulant to pass through a portion of 10 cm (4-inch) diameter piping whereas the gravity drain path for Phase 2B was through a 25 cm (10-inch) valve directly into the spent simulant Tank. This is the likely reason that no tube cleanout was obtained during the gravity drains for Phase 3B (100% blockage in both Ultrafilters), as compared to the limited tube cleanout (85% blockage and 75% blockage) observed for gravity drains in Phase 2B.

The initial portions of Phase 3B were conducted with water. The pump outlet pressure was measured just upstream of the first Ultrafilter Module at 23.9 psi. Pressure drops across the individual Ultrafilters were 9.9 psi for Ultrafilter A (DPA) and 6.3 psi for Ultrafilter B (DPB) at the average flow rate of 502 m^3/hr (2210 gpm) for a pump speed of 1012 rpm. It is likely that at least part of the differences between the pressure drops noted for Filter A and Filter B was instrument error, as the pressures were small and represented the differences between numbers measured from sensors with a range of 0-200 psi. When increasing pump speed, the flow rate, and pressures increased at essentially the same time.

Table I. Summary of Results from Phase 3B – Head Tank Pumped Flush and Drain Test of a Double Ultrafilter Module with Near Horizontal Orientation

Stage	% Blockage* (Measured by Air Flow)		Pumping Parameters		Differential*** Pressure		Simulant Yield Stress	Simulant Temperature	Visual Observations/Comments
	Filter A	Filter B	Flow (GPM)	Pump RPM	Filter A** (psi)	Filter B (psi)	(Pa)	(F)	
Initial Full Scale Pumping	na	na	2250	1386	29.7	26.8	33.6	78.8	Yield stress reported is an average of 4 sample locations.
1st Gravity Drain	100	100							
1st Full Scale Pumping	na	na	2231	1338	23.0	25.6		79.9	
2nd Gravity Drain	100	100							
2nd Full Scale Pumping	na	na	2259	1328	22.6	24.5		81.8	
3rd Gravity Drain	100	100							
3rd Full Scale Pumping	na	na	2232	1311	21.8	24.0		83.4	
4th Gravity Drain	100	100							
After Water Flush	12	15							All tubes appeared to be clear in visual exam.
Full Scale Pumping After Water Flush	na	na	2231	1332	21.5	23.7		82.6	
After High Flow Air Purge	45	42							Bottom 1/3 of tubes appeared to be blocked in visual exam.
Full Scale Pumping After Air Purge	na	na	2250	1327	21.6	24.1		83.2	
Full Scale Pumping - Restart After 117 hours	na	na	2254	1332	21.9	23.6	23.2	79.1	Yield stress sample taken from main line during pumping.

* All discussions of "blockage", "effective area" or "clean out" relate to the longitudinal paths through the tubes and do not relate to the transverse paths through the filter media (the porous tube walls), or to filter effectiveness.
** Filter A is the downstream filter during a flush or air purge. It is the upstream filter for the normal direction of flow during plant operation.
*** Differential Pressure is the pressure drop along the length of the tubing in the Ultrafilter Module.

Initial pumping of simulant through the Double Ultrafilter Modules was performed on January 28, 2007. Simulant samples were taken at 4 locations in the simulant tank shortly after the pump was turned off, and the average yield stress was determined to be 33.6 Pa. In contrast to the behavior observed for water, there was a lag between the initial increases in pressure and the flow rate, see Figure 4. The differential pressures across Ultrafilter A and Ultrafilter B and the pressure at the outlet of the pump all began to increase immediately as the pump speed was increased, but the flow rate did not increase for a short period. It is likely that the pressure must be built up to a critical level before the simulant starts to move through the tubes, which is consistent with the Bingham fluid behavior of the simulant. The rheological studies included a determination of the effect of aging on the static shear stress of the simulant. The studies determined a static shear strength of 26 Pa immediately after mixing. This increased over the next few hours to approximately 60 Pa. Note that the pressure that would be required to overcome a shear stress of 60 Pa at the circumference of a ½-inch diameter tube 2.54 m (100”) long would be about 7 psi, which is in agreement with the data measured.

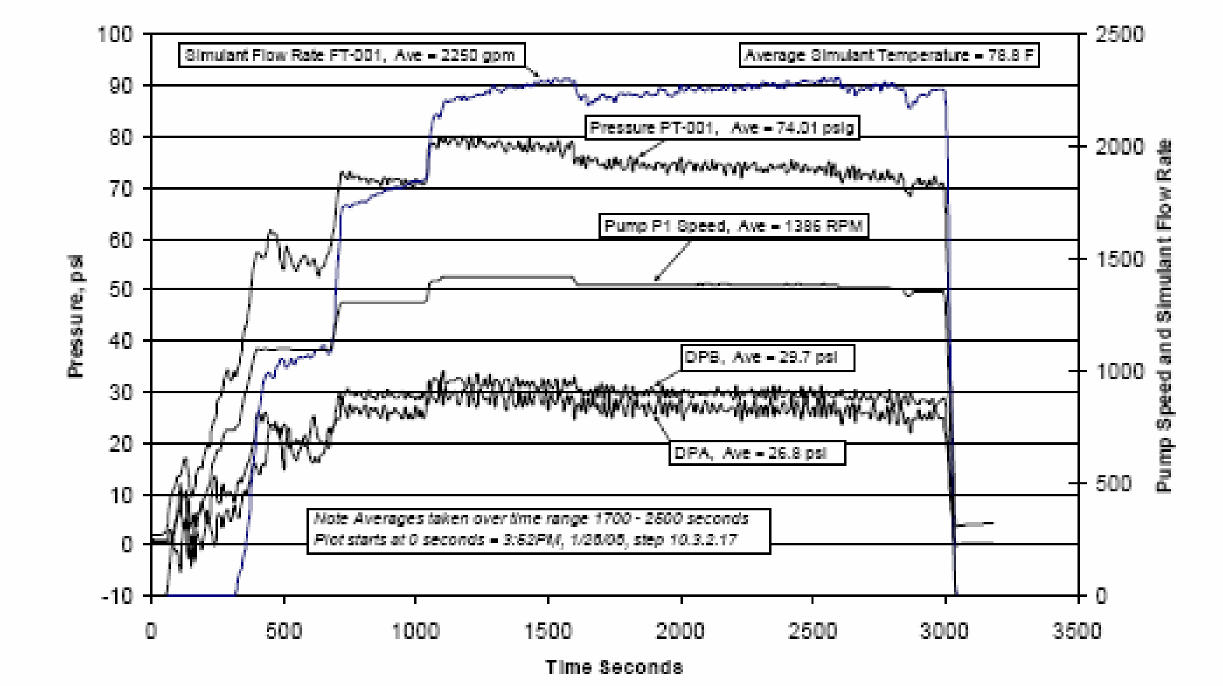

Fig. 4. Initial pumping behavior in clean double ultrafilter module

The first gravity drain was performed approximately 3 hours after the recirculation pump was turned off. The Double Ultrafilter Module was first isolated from the loop, and the drain was then initiated with the filter modules vented to atmosphere. No significant drainage was observed over a period of 25 minutes. Several additional steps were taken in an attempt to promote gravity draining:

1. It was verified that the shell sides of the Ultrafilter were completely full of water by applying city water to the shell side and testing the stream out of the vents for air bubbles. No air bubbles were observed.
2. To resolve uncertainty about any effect of the three hour period between when the initial pumping was completed and when the gravity drain was initiated, the isolation valves were reopened and the loop was circulated at 500 m^3/hr (2200 gpm) for 10 minutes. The isolation valves were then closed and the gravity drain was re-attempted approximately 2 minutes after turning the pump off. No drainage was observed.
3. City water pressure was applied to the shell side of the Ultrafilters in an attempt to create a back-pulse which could potentially be applied in the plant configuration. A total of some 7-11 liters (2-3 gals) of simulant drained from the ultrafilter modules.

No visual examination for blockage was made as it was obvious that the filters were full of simulant. As called for by the test procedure, steps had been taken to assure that the filters were completely full before performing the first full scale pumping of simulant. The recirculation pump was then restarted after the failed gravity drain. A comparison of pumping data showed that although the gravity drain was not successful in clearing the tubes, the flow behavior of the filters was essentially the same as for a clean filter. Results from the second and third gravity drains were essentially the same as for the first gravity drain. In both cases, their was no drainage and the following full scale pumping behavior was essentially the same, except for a minor reduction in differential filter pressure over the course of testing. `

A fourth gravity drain was performed, with the same result as the first three, after which a flush with two system volumes (1355 liters [358 gals]) of water was performed. To perform this flush, the flush tank was pressurized to 84 psig, the Double Ultrafilter Module was isolated from the main pump loop, and the path for the flush was opened. The flush continued until the level in the flush tank dropped below a set point, after which the flush valve automatically closed.

The flush water flow rate was approximately constant over the ~17 second duration of the flush, at 284 m^3/hr (1250 gpm). Flush water and simulant were both collected in the same vessel; therefore there was no direct way to determine if the simulant flowed as a slug during flushing. However, the shape of the curves for the pressure drops in the Ultrafilters strongly suggests that most of the simulant in the Ultrafilters was displaced by water during the initial portion of the flush. At the start of the flush, the pressure drops increased rapidly. An essentially constant flow rate was established, and the pressure drop in Ultrafilter B (the upstream filter for the flush) then began to decline (within a few seconds) as the flush water displaced the simulant in the tubes. The pressure pulse in Ultrafilter A (the downstream filter for the flush) lasted approximately twice as long. This is expected because approximately twice as much simulant passed through Ultrafilter A before the simulant in its tubes was displaced with the flush water. The maximum differential pressures achieved for the filters were less than about 20 psi. This appears to be reasonable in light of the fact that differential pressures in the mid twenties were generated with a flow rate of 2250 psi during the full scale plant pumping. During the flush, the flush vessel pressure underwent a modest decrease from 84 psig to 80 psig. The purpose of the flush vessel pressure was to simulate the combined effect of the pressure and height of the plant flush tank system and pressure drop along the flush path in the plant (this included the flush line, heat exchanger, Ultrafilters, 10-inch piping, and the pump).

Air-flow based blockage measurements of the Ultrafilters indicated residual blockages of 15% for Filter A and 12% for Filter B. Video inspection showed that, while the inlet of Filter B was completely clear, it was evident that some of the simulant was deposited near the inlet of Filter A. It is possible that this simulant had been in one of the inspection ports and deposited on the bottom of the plenum when the port was opened. All of the tubes appear to have been cleared, although close inspection of the outlet portions of both filters indicated that a small residual amount of some simulant was left in the bottom of some tubes. This relatively small amount of residual simulant could account for most of the blockage determined in the air-flow based blockage measurements.

In summary, the water flush was effective in clearing essentially all of the tubes, although a small residual was left, causing the effective area (as it relates to flow along the length of the tubes, not to be confused with the effective filtration area) to be slightly reduced. After completion of the water flush, the system was refilled and a fourth plant scale simulant pumping was performed. Pumping behavior was very similar to the earlier pumping sequences, with average differential pressures of 21.5 psi for Ultrafilter A and 23.7 psi for Ultrafilter B. The average simulant flow rate was 507 m^3/hr (2231 gpm) with a pump speed of 1332 rpm. A two minute 1500 scfm air purge followed by a three minute 30 scfm air purge was then performed. This air purge was different than the one performed in Phase 2B in that the air purge in Phase 2B followed a water flush which had already removed most of the simulant. The Double Ultrafilter Module was completely full before this purge was initiated. The differential pressures for Ultrafilters A and B were observed to rise to ~10 psig for a short period at the initiation of the purge, and then fall to a very low value for the remainder of the purge. Approximately 530 liters (140 gals) of simulant were recovered after the purge. Examination of the tube sheets after the air purge and the blockage measurements showed the bottom 30% - 40% of both ultrafilters remaining blocked. It is speculated that during the air purge, the level of simulant in the plenum in front of the Ultrafilter inlets dropped as the simulant was forced through the tubes. After a number of the tubes became exposed and cleared, the pressure differential dropped to a very low value (for a clean ultrafilter, 1100 scfm results in less than 2 cm [5”] of back pressure). This low pressure was insufficient to force the remaining simulant through the Ultrafilter tubes.
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After completion of the Air Purge Test, the Ultrafilter Module was refilled with simulant, the simulant was re-circulated at 500 m^3/hr (2200 gpm) (nominal) for 10 minutes, and the pump was turned off. The system was then left at rest for a period of 117 hours and the pump was then restarted. The flow rate, pump speed, and Ultrafilter pressures were essentially the same as observed during the earlier pumping tests, continuing the trend of slightly lower pressures for each test. The yield stress of the simulant was measured at 23.22 Pa, as compared to the average yield stress of 33.6 Pa determined from four samples taken at the start of Phase 3B. Table I lists the Phase 3B pumping parameters for each stage at which pumping was performed. There is a continuous decrease in differential pressure over the course of Phase 3B, which was attributed to a continuing decrease in simulant yield stress as the test progressed. The cause of the decrease is likely due to a combination of aging, mechanical deformation of the simulant during pumping, and the introduction of a limited quantity of water to the simulant as a result of test operations.

The full scale plant pumping behavior always returned to the pumping behavior observed at the start of the test, thus indicating that full scale plant pumping is effective in Ultrafilter tube cleanout.

A sixth phase, Phase 3A, was originally planned to determine the effectiveness of full plant-scale flow of simulant for a Double Ultrafilter Module with vertical orientation, but was not performed in this test on instruction from the customer. The current plant baseline design filter orientation is near horizontal, and these tests successfully demonstrated that the current design, with a flush tank at elevation 29.9 m (98’-00”) does have enough pressure head to drain and clean out the ultrafilter tube side.