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Test Scoping Statement# S45

FILTRATION OF A HANFORD AW-101 WASTE SAMPLE (U)

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LIST OF ACRONYMS

CUF	Cells Unit Filter
SEM	Scanning Electron Microscope
TMP	Transmembrane pressure
WTP	Waste Treatment Plant

1.0 SUMMARY OF TESTING

1.1 OBJECTIVES

The objectives of the test that was conducted follow.

- Determine the optimum filter operating parameters (axial velocity and transmembrane pressure) to maximize filter flux.
- Determine whether the mean filter flux across the dewatering cycle matches or exceeds the plant design throughput of 0.03 gpm/ft^2. This design flux differs from the design flux listed in the test specification and can be found in reference 5.
- Dewater the feed sample to 20 wt% insoluble solids.
- Wash the sample to determine which species are removed during the washing process.
- Provide filtrate to the ion exchange test program.
- The project flowsheet for the separation of LAW entrained solids assumes the entrained solids slurry from ultrafiltration contains 20 wt % insoluble solids by weight. These tests must therefore confirm that the slurry rheology is compatible with this requirement. There is probably insufficient sample volume to achieve 20 wt % insoluble solids but this test will yield indicative data which it may be possibly extrapolated.
- No solids must pass into the ultrafiltration permeate.
- After the filtration stage is complete, the rig will be chemically cleaned to determine if the clean water flux can be returned to pre-operation (clean) levels.

1.2 CONDUCT OF TESTING

Filtration tests were conducted with the Cells Unit Filter (CUF) currently installed in Cell 16 of SRTC High Activity Caves. The unit has a 2 ft long stainless steel Mott crossflow filter of 3/8" ID and 0.1 micron nominal pore size. The system can provide up to 16.5 ft/s crossflow velocity, along with up to 80 psi transmembrane pressure (TMP). Feed from the feed reservoir passes through a progressive cavity pump. The pump is operated at variable speed by controlling the air pressure supplied to the motor that drives it. The slurry is pumped through a magnetic flow meter and heat exchanger that removes heat. Ice water, contained in a 3-gallon Igloo cooler, supplies cooling to the system. The slurry then passes through the crossflow filter. A throttle valve downstream of the filter is used to adjust the filter TMP. The filtrate flow rate is measured with a calibrated sight glass and stopwatch. The system is equipped with a manual backpulse system. The feed, concentrate, and filtrate pressures are measured with standard Bourdon-type pressure gauges. A thermocouple mounted near the bottom of the feed reservoir measures the slurry temperature.

The feed sample for the tests was an AW-101 actual waste sample previously diluted to 5 M sodium.

During the testing, personnel set the feed slurry temperature to 25° C, the axial velocity and transmembrane pressure to WTP-specified values, and collected filtrate flux data periodically.

1.3 RESULTS AND PERFORMANCE AGAINST OBJECTIVES

The key test results follow.

- The testing found an axial velocity of 11 ft/s and a transmembrane pressure of 60 psi produced the highest filter flux (0.58 gpm/ft^2) at low solids loadings (< 0.1 wt %). This result met one test objective.
- The filtration process produced an average flux of 0.05 gpm/ft2 during dewatering. This filter flux was greater than the design flux of 0.03 gpm/ft2, but the concentrated slurry contained much less than 20 wt% insoluble solids.
- Because of the lack of solids in the feed sample, it could not be dewatered to 20 wt% insoluble solids, which was one of the test objectives.
- Because of the lack of solids in the feed sample, washing was not performed (see test exception).[1,2]
- The testing produced over 20 liters of filtrate for the ion exchange program.
- The feed contained insufficient solids to measure slurry rheology.
- No solids were observed in filtrate samples.
- Because of equipment problems, chemical cleaning of the filter was not performed.

1.4 QUALITY REQUIREMENTS

This work was conducted in accordance with the RPP-WTP QA requirements specified for work conducted by SRTC as identified in DOE IWO MOSRLE60. SRTC has provided matrices to WTP demonstrating compliance of the SRTC QA program with the requirements specified by WTP. Specific information regarding the compliance of the SRTC QA program with RW-0333P, Revision 10, NQA-1 1989, Part 1, Basic and Supplementary Requirements and NQA-2a 1990, Subpart 2.7 is contained in these matrices.

The specific quality requirements for this task are described in the task technical and quality assurance plan.[4]

The measuring and test equipment used in the testing is in compliance with the SRS QA Program.

The data collected and reported was verified by independent checking (procedure E7, 2.31).

1.5 ISSUES

The following issues were raised during this test:

- The feed sample contained insufficient solids to produce a 20 wt% slurry following the dewatering step. The project needs to try to ensure future samples contain sufficient solids to perform the tests requested by the project.
- The low concentration filtration matrix tests showed the highest filter flux was obtained at 60 psi transmembrane pressure. This pressure was applied during the dewatering step, and likely contributed to the large reduction in filter flux observed. In future filter testing

and plant operation, WTP should limit the maximum transmembrane pressure during dewatering to attempt to reduce filter fouling.

2.0 CD-ROM ENCLOSURES

None

3.0 DISCUSSION

3.1 INTRODUCTION

Hanford Site personnel obtained approximately 15-liters of waste supernate from tank 241-AW-101 for shipment to the SRTC. SRTC personnel composited, characterized, and diluted the AW-101 sample (to 5 M sodium) to provide material for filtration testing. The characterization work showed the sample contained < 0.1 wt% insoluble solids.

SRTC personnel performed filtration testing. The objectives of the test follow.

- Determine the optimum filter operating parameters (axial velocity and transmembrane pressure) to maximize filter flux.
- Determine whether the filtration process can achieve the design flux of 0.03 gpm/ft2 during the dewatering process.
- Dewater the feed sample to 20 wt% insoluble solids.
- Wash the sample to determine which species are removed during the washing process.
- Provide filtrate to the ion exchange test program

The task was requested through a Test Specification (TSP-24590-01-00001, Rev.0, June 13, 2001) from the River Protection Project personnel.[3] The work is also described in R&T scoping statement S45.

3.2 EXPERIMENTS

3.2.1 Equipment

Filtration tests were conducted with the Cells Unit Filter (CUF) currently installed in Cell 16 of SRTC High Activity Caves (see Figure 1). The unit has a 2 ft long stainless steel Mott crossflow filter of 3/8" ID and 0.1 micron nominal pore size. The system can provide up to 16.5 ft/s crossflow velocity, along with up to 80 psi transmembrane pressure (TMP). Feed from the feed reservoir passes through a progressive cavity pump. The pump is operated at variable speed by controlling the air pressure supplied to the motor that drives it. The slurry is pumped through a magnetic flow meter and heat exchanger that removes heat. Ice water, contained in a 3-gallon Igloo cooler, supplies cooling to the system. The slurry then passes through the crossflow filter. A throttle valve downstream of the filter is used to adjust the filter pressure. The filtrate flow rate is measured with a sight glass and calibrated stopwatch. The system is equipped with a manual backpulse system. The feed, concentrate, and filtrate pressures are measured with standard Bourdon-type pressure gauges. A thermocouple mounted near the bottom of the feed reservoir measures the slurry temperature.

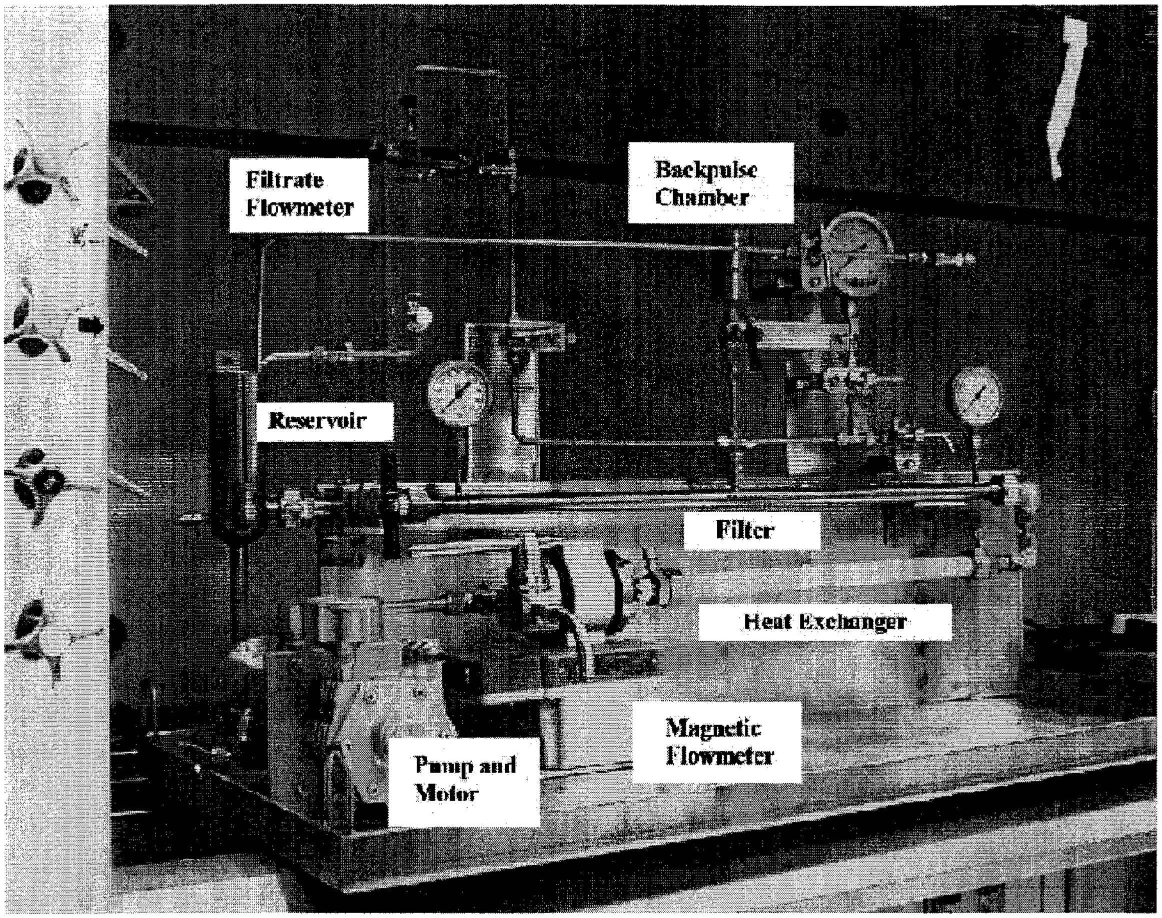

Figure 3.1 Cells Unit Filter (CUF)

3.2.2 Test Preparation

The filter rig was flushed with 0.01 M sodium hydroxide and cleaned with 1M nitric acid before testing. The three (see Table 1.1) clean water flux tests were performed at 5, 10, and 20 psi. One of the tests was performed at 5 psi rather than 30 psi, because the clean water flux at 30 psi was too fast to measure accurately. The 'water' used for the clean water flux tests was 0.01M NaOH pre-filtered through a 0.1 micron absolute rated filter to ensure consistent quality.

The authors obtained a single composite of the AW-101 from the characterization task. The sample was previously diluted so that its sodium level was 5 ± 0.5 M.

3.2.3 Solubility Tests

Before filtration testing started, personnel collected samples to determine the solubility of species as a function of temperature. Personnel placed 800 ml of the 5 M sodium feed sample into the CUF feed tank. They recirculated the sample with the feed pump and adjusted the temperature to 15° C, 50° C, and 25° C, using the recirculation pump for heating and ice water for cooling. Each temperature was maintained for one hour before collecting two samples from the feed tank. The samples were filtered through a 0.45 µ syringe filter, diluted approximately 30X with 0.01 M sodium hydroxide, and submitted for analysis.

3.2.4 Filtration Tests

Following the collection of sample for solubility measurements, personnel began the actual waste filtration tests. The temperature of liquids flowing in the CUF was controlled to 25 ± 5 °C. The temperature was controlled by recirculating water from an ice bath through the shell side of the heat exchanger (Figure 3.1). The recirculation pump was turned on and off to control the temperature. Each set of conditions was run for one hour, and each set of conditions was run after at least one backpulse of the filter.

Table 3.1 shows the test conditions. Each test condition (except 1.14) was maintained for a period of one hour with operating parameters recorded every ten minutes. Permeate flux was corrected to 25°C by the use of the following equation[3]:

$$Flux = \frac{P}{A} * C$$

where Flux = permeate flux at 25°C (gpm/ft^2)
P = permeate flow rate (gpm)
A = filter surface area (ft^2)
C = temperature correction factor = $e^{(2500*((1/(273+T))-(1/298)))}$

The temperature correction factor corrects flux back to an equivalent flux at 25°C and accounts for changes in fluid viscosity and surface tension.

The next thirteen tests (1.1 to 1.13) empirically determined the optimum de-watering conditions (subject to the caveat that this is only a reduced length, single tube rig) for the dilute feed slurry. The filtrate was recycled, so that entrained solids levels close to that of the input feed were seen by the filter.

Small samples of concentrate slurry and of filtrate were collected for analysis of elemental metals and isotopic activity during runs 1.1, 1.7, and 1.13. Because of the lack of insoluble solids in the feed sample, the concentrate samples were not analyzed (see Text Exception[2]). The filtrate was diluted approximately 30X in 0.01 M NaOH prior to analysis. The purpose of the analyses is to monitor any changes in composition or any changes in separations provided by the filter.

The fourteenth feed test, 1.14, was designed to evaluate filter performance during dewatering and to produce filtrate for ion exchange testing. The dewatering produced approximately 22 liters of filtrate. The dewatering was performed by pumping feed from the composite carboys to the CUF feed tank, running the crossflow filter at the optimum conditions found in tests 1.1 to 1.13, and collecting filtrate into containers for further program use.

Filtrate was recycled back to the concentrate reservoir so that the total filter runtime was 48 hours. The dewatering was conducted in four stages. After approximately one-fourth of the feed volume was filtered, the unit was run in recycle mode for 10-12 hours. Flux, axial velocity, and transmembrane pressure measurements were recorded hourly. This process was repeated for the other three fourths of the composite batch so that the total runtime is 48 hours.

A slurry sample was collected for particle size analysis by scanning electron microscope (SEM). Particle size was performed by SEM rather than Microtrac, because the feed slurry did not contain sufficient solids to perform the Microtrac analysis.

Because of the lack of solids in the feed and equipment problems, the high solids loading filtration matrix and slurry washing were not performed.[2]

Table 3.1 Filtration Test Conditions

Test no.	Sample	Transmembrane pressure (psi)	Crossflow Velocity (ft/s)
1.0	water	5, 10, 20	11
1.1	Feed	40	11
1.2	Feed	40	11
1.3	Feed	40	11
1.4	Feed	30	9
1.5	Feed	30	13
1.6	Feed	50	13
1.7	Feed	50	9
1.8	Feed	40	11
1.9	Feed	40	7
1.10	Feed	40	15
1.11	Feed	20	11
1.12	Feed	60	11
1.13	Feed	40	11
1.14	De-watering	60	11

During the testing, the filter unit was observed leaking. Personnel attempted repeatedly to fix the leaks, but were unsuccessful. After 43 hours of dewatering (test 1.14), the leaks became so severe that the test needed to be terminated. SRTC discussed this problem with WTP and obtained a test exception to terminate the test.[2]

3.3 RESULTS

3.3.1 Clean Water Flux

The authors cleaned the filter with nitric acid. The cleaning was conducted by filling the feed tank with 500 ml of 1 M nitric acid, and recirculating the cleaning solution for one hour. The CUF was drained and an additional 500 ml of 1 M nitric acid was added to the feed tank and recirculated for one hour. Following cleaning, two 500 ml batches of 0.01 M sodium hydroxide were added to the feed tank and recirculated for one hour.

Personnel added 0.01 M sodium hydroxide (clean water) to the feed tank and measured the clean water flux at 5, 10, and 20 psi. Figure 3.2 shows the clean water flux results. The clean water flux measurements are consistent with previous clean water flux measurements, and indicate the filter has been sufficiently cleaned.

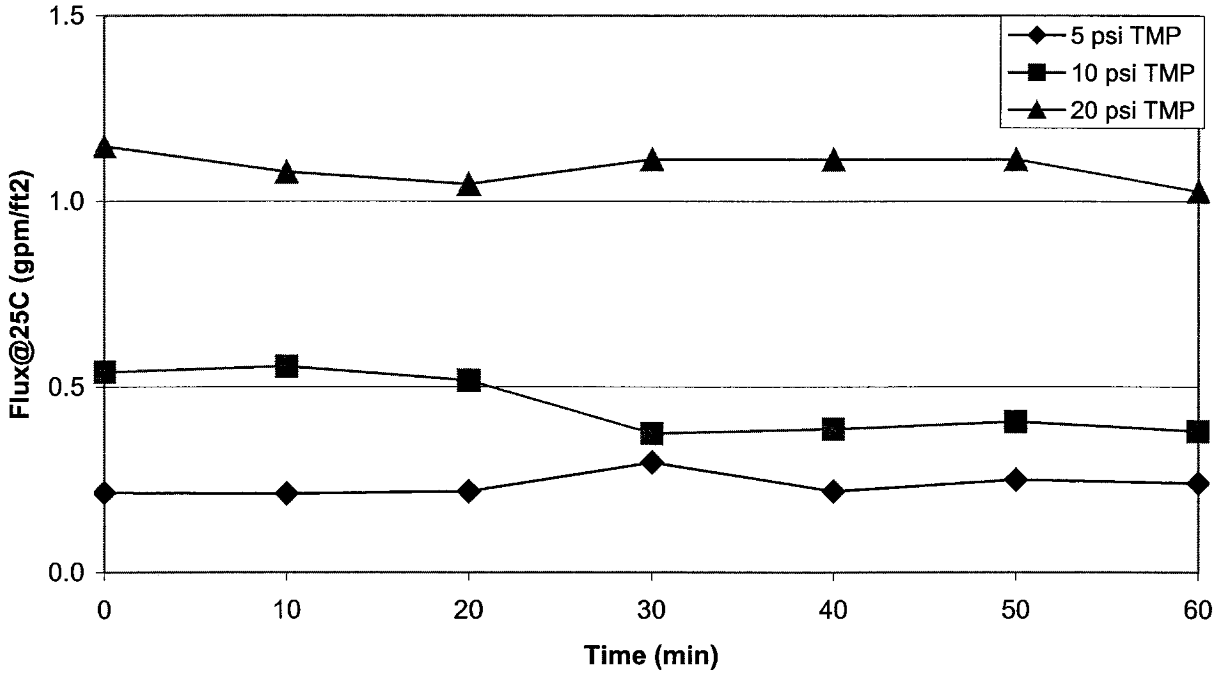

Figure 3.2 Clean Water Flux

3.3.2 Soluble Species in Sample

Personnel placed 800 ml of the feed sample into the CUF feed tank. They recirculated the sample with the feed pump and adjusted the temperature to 15° C, 50° C, and 25° C, using the recirculation pump for heating and ice water for cooling. Each temperature was maintained for one hour before collecting two samples from the feed tank. The samples were filtered through a 0.45 μ syringe filter, diluted approximately 30X with 0.01 M sodium hydroxide, and submitted for analysis. Table 3.2 shows the analyses. The table shows the concentration of each analyte that is soluble at the target temperature.

Table 3.2 Concentration of Analytes in Filtered Supernate Samples

	15° C	15° C	25° C	25° C	50° C	50° C
Species	d/m/ml	d/m/ml	d/m/ml	d/m/ml	d/m/ml	D/m/ml
Cesium-137	1.81E+08	1.87E+08	1.88E+08	1.89E+08	1.77E+08	1.88E+08
Strontium-90	4.43E+04	3.17E+04	4.63E+04	2.91E+04	3.53E+04	3.89E+04
Technetium-99	8.57E+04	8.59E+04	8.42E+04	7.84E+04	7.32E+04	7.59E+04
Americium-241	1.03E+03	2.35E+03	1.89E+04	9.02E+02	3.40E+05	< 1.28E+03
Europium-154	<6.72e5	< 1.76e6	< 1.75e6	< 1.91e6	< 1.34e6	< 1.86e6
Europium-155	< 2.43e6	< 2.58e6	< 2.79e6	< 2.69e6	< 2.65e6	< 2.74e6
Pu-239/240	58	228	70	171	177	154
Total Alpha	< 1643	< 1659	1932	< 1595	< 1984	< 1781
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Al	6194	6197	5808	5840	5784	5793
Ba	<6.2	< 6.2	< 6.2	< 6.2	< 6.2	< 6.2
Ca	< 7.5	< 7.5	< 7.5	< 7.5	< 7.5	< 7.5
Cd	< 1.4	< 1.4	< 1.4	< 1.4	< 1.4	< 1.4
Co	95	95	101	97	105	98
Cr	20	20	20	20	20	19
Cu	16	16	18	18	18	18
Fe	4.8	< 1.2	< 1.2	< 1.2	< 1.2	< 1.2
K	9095	8427	8353	8334	8203	8248
La	< 2.3	< 2.4	< 2.3	< 2.4	< 2.4	< 2.4
Mg	< 1.7	< 1.7	< 1.7	< 1.7	< 1.7	< 1.7
Mn	< 0.26	< 0.26	< 0.26	< 0.26	< 0.26	< 0.26
Mo	< 17.3	20.9	< 17.3	< 17.4	< 17.3	< 17.3
Na	59658	59678	56124	56761	55883	55641
Ni	4.4	4.8	4.8	4.6	< 4.4	< 4.4
Pb	< 10.4	< 22.6	< 10.4	< 10.5	< 10.4	< 10.4
Si	14.3	12.6	11.4	9.9	10.0	10.9
Ti	< 2.5	< 2.5	< 2.5	< 2.5	< 2.5	< 2.5
U	< 163	< 164	< 163	< 164	< 163	< 164
Zn	< 1.0	< 7.2	1.4	1.2	< 1.0	< 1.0
TOC	906	974	927	1073	859	1031
TIC	482	515	656	637	529	514
Cl	1011	1016	1012	1083	1046	1047
F	163	164	163	164	163	164
NO3	38794	39020	38830	39044	38562	38621
SO4	65	66	65	66	65	65
PO4	163	164	196	164	196	164
oxalate	228	230	261	262	261	262
nitrite	19495	19772	19382	19588	19052	19311
formate	456	459	457	492	458	491

3.3.3 Filtration Test Results

Figure 3.3 shows the results of the low concentration matrix tests. The filter flux is well above the design flux of 0.03 gpm/ft2. The filter flux shows good correlation with transmembrane pressure. A similar plot of flux against axial velocity did not show any correlation (see Figure 3.4).

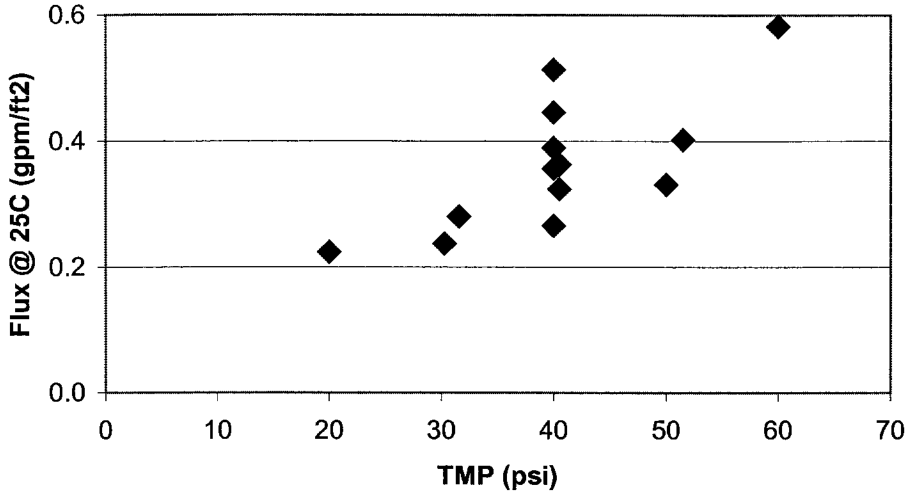

Figure 3.3 Low Concentration Filtration Matrix Test

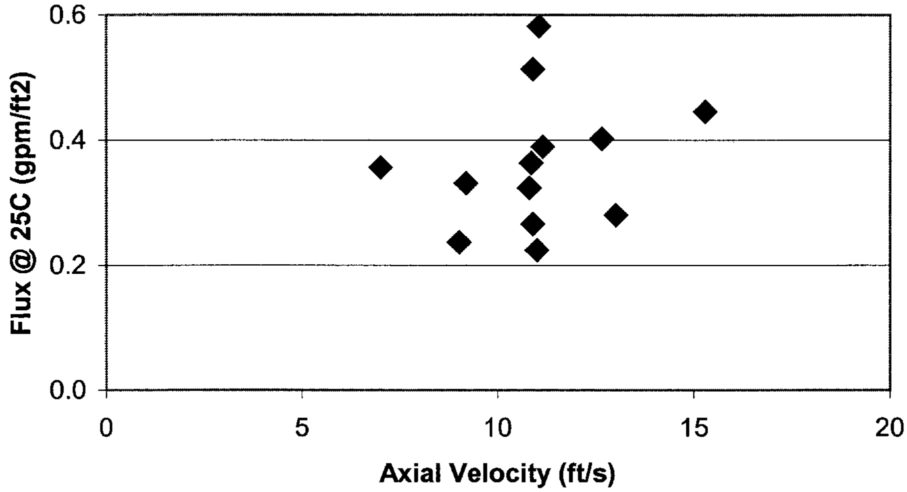

Figure 3.4 Low Concentration Filtration Matrix Test

One plausible reason for the strong correlation with TMP is the low insoluble solids loading in the feed slurry (< 0.1 wt%). Because the feed contained very few solids, little or no filter cake formed. Increasing the axial velocity (and corresponding wall shear stress) would not be able to reduce the filter cake thickness when no significant filter cake existed. In addition, since little or no filter cake formed, increasing the transmembrane pressure would not cause filter cake compression, which decreases filter flux.

At 20 psi transmembrane pressure, the filter flux is ~ 0.2 gpm/ft2 compared to ~ 1 gpm/ft2 with clean water. This small change in filter flux with the actual feed might indicate that it contains insufficient solid particles to completely cover the filter surface and form much of a filter cake.

The WTP should note that the feed did not blind the filter. Previous filter tests with actual Hanford Tank waste containing very few insoluble solids have blinded filters very rapidly (AN-102, prior to precipitation).

Following the matrix tests, the authors performed dewatering of the feed slurry using the optimum conditions from the matrix tests (60 psi, 11 ft/s). Figure 3.5 shows the filter flux as a function of time. Initially, the filter flux was greater than 0.15 gpm/ft2. After a few hours, it decreased to 0.1 gpm/ft2. By the end of the dewatering, the filter flux decreased to 0.01 gpm/ft2. The average flux during the dewatering process was 0.05 gpm/ft2, which is greater than the design flux of 0.03 gpm/ft2.

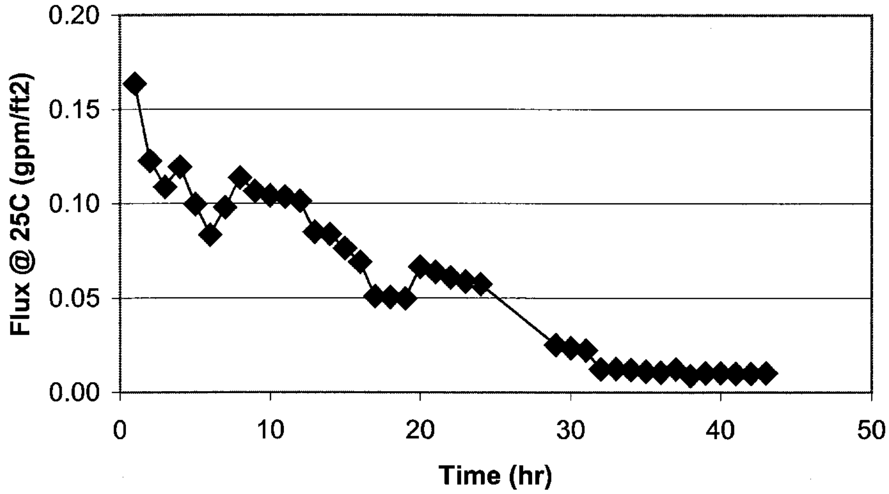

Figure 3.5 Filter Dewatering Test

One plausible reason for the large reduction in filter flux could be the operating parameters. The dewatering was conducted at 11 ft/s axial velocity and 60 psi transmembrane pressure. The high pressure could have cause cake compression as the feed was concentrated and solids accumulated in the filter cake. This phenomenon has been documented in the technical literature.[6] In future testing, as well as plant operation, WTP should consider limiting the maximum transmembrane pressure used to reduce filter cake compression.

Another plausible explanation is that the initial feed solution contained insufficient solid particles to challenge the filter. As the filter saw additional fresh feed, it became fouled and the filter flux declined significantly.

3.3.4 Sample Analyses

During the filtration tests, SRTC collected filtrate samples during tests 1.1, 1.7, and 1.13, and submitted them for analysis. Table 3.4 shows the results.

Table 3.3 Filtrate Sample Analysis

Component	Test 1.1 Filtrate	Test 1.7 Filtrate	Test 1.13 Filtrate
	d/m/ml	d/m/ml	d/m/ml
Cesium-137	1.71E+08	1.78E+08	1.95E+08
Strontium-90	2.62E+04	6.23E+04	2.12E+04
Technetium-99	6.79E+04	7.40E+04	8.37E+04
Europium-154	< 3.43E+04	< 4.30E+04	< 4.98E+04
Europium-155	< 3.13E+05	< 3.19E+05	< 3.36E+05
Am-241	< 682	< 1293	< 1157
Pu-239/240	218	148	42
Total Alpha	< 1188	1422	< 2924
	mg/l	mg/l	mg/l
Al	6114	6354	7040
Ba	< 6.1	< 6.0	< 6.0
Ca	< 7.4	< 7.3	< 7.3
Cd	< 1.3	< 1.3	< 1.3
Co	96	95	120
Cr	24	27	29
Cu	13	13	13
Fe	1.9	< 1.1	1.3
K	8195	8345	9132
La	< 2.3	< 2.3	< 2.3
Mg	< 1.7	< 1.7	< 1.7
Mn	< 0.26	< 0.25	< 0.25
Mo	18.2	< 16.8	19.4
Na	78425	84399	95447
Ni	< 4.3	5.2	5.6
Pb	< 10.2	< 10.1	< 10.1
Si	23.8	27.9	< 2.4
Ti	< 2.5	< 2.4	< 2.4
U	< 160	< 158	< 159
Zn	< 1.0	2.4	2.9
TOC	947	964	923
TIC	541	958	1151
Cl	1088	1170	1142
F	96	95	95
NO3	39372	40777	44077
SO4	64	95	63
PO4	160	126	127
oxalate	672	632	349
nitrite	18726	19725	21721
formate	448	379	349

Because of the lack of solids in the feed sample, the solids samples were not analyzed for chemical constituents.

One concentrated feed sample was collected and analyzed for insoluble solids. The insoluble solids concentration was < 0.1 wt%.

Because of the lack of solids in the feed sample, it could not be analyzed for particle size distribution by Microtrac. Instead the particle size distribution was analyzed by scanning electron microscope (SEM)[2]. SEM sample platforms were dipped in the feed slurry. The platforms were removed and placed in a shielded sample bottle. The bottle was removed from the shielded cells and transported to the SEM laboratory. The sample platform was analyzed with the SEM. The instrument produced "pictures" of the particles from the feed slurry. The size of a large number of particles were measured. The average particle size was $1.3 \pm 0.8\ \mu$.

4.0 FUTURE WORK

The actual waste sample from AW-101 did not contain sufficient solids and therefore an adequate simulant cannot be formulated and validated.

Scoping statements 46 and 47 cover Envelope A waste (AW-101) only. This waste is not currently planned to be processed on plant without blending with HLW and thus the data is not required. Deleting the workscope allows for the work associated with SS 48 and 148 to be replanned to better balance resource utilization. Process verification will be demonstrated using a blend of AP-104, AN-105 or appropriate available Envelope A entrained solids and SY-102 HLW waste, which is more representative of plant processing.

The actual waste operation will process AW-101 blended with HLW feed that is delivered post phase 1 (currently projected to be C-107/AW-103). The scoping statements 46 and 47 specify testing AW-101 without blending, this does not adequately represent future operations.

The objective can be accomplished through testing with waste samples that have greater certainty in their initial composition and projected HLW feed delivery sequence ultimately providing a more representative blend. In addition, availability of envelope A samples and SY-102 sample, early next year, provides a viable choice for selecting test materials.

5.0 REFERENCES

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4. C. A. Nash and M. R. Poirier, Task Technical and Quality Assurance Plan for 241-AW-101 LAW Entrained Solids Ultrafiltration", WSRC-TR-2001-00430, Rev. 0, October 8, 2001.

5. 24590-PTF-MVC-10-00001, Rev. B, *Ultrafiltration System (10-UFP) Vessel Batch Volume Sizing Calculation*, July 17, 2002

6. Mark C. Porter, Ed., Handbook of Industrial Membrane Technology, Noyes, Park Ridge, 1990.

APPENDIX A. FILTRATION DATA

Test	**1.01**	**Water**								
Time (min)	Temp (F)	P1 (psi)	P2 (psi)	F1 (gpm)	F2 (ml/min)	Temp (C)	TMP (psi)	Vel (ft/s)	Flux (gpm/ft2)	Flux-25C (gpm/ft2)
0	78.9	20	10	3.80	400	26.1	10	11.0	0.556	0.540
10	73	20	10	3.82	375	22.8	10	11.1	0.521	0.555
20	70	20	10	3.85	333	21.1	10	11.2	0.463	0.517
30	84	20	10	3.80	300	28.9	10	11.0	0.417	0.374
40	82	20	10	3.86	300	27.8	10	11.2	0.417	0.386
50	78.8	20	10	3.78	300	26.0	10	11.0	0.417	0.406
60	83.1	20	10	3.78	300	28.4	10	11.0	0.417	0.380
	78.5	20	10	3.81	300	25.9	10	11.1	0.458	**0.451**

Test	**1.02**	**Water**								
Time (min)	Temp (F)	P1 (psi)	P2 (psi)	F1 (gpm)	F2 (ml/min)	Temp (C)	TMP (psi)	Vel (ft/s)	Flux (gpm/ft2)	Flux-25C (gpm/ft2)
0	75.0	30	10	3.58	800	23.9	20	10.4	1.112	1.148
10	79.0	30	10	3.84	800	26.1	20	11.1	1.112	1.078
20	81.0	30	10	3.86	800	27.2	20	11.2	1.112	1.045
30	77.0	30	10	3.86	800	25.0	20	11.2	1.112	1.112
40	77.0	30	10	3.70	800	25.0	20	10.7	1.112	1.112
50	77.0	30	10	3.68	800	25.0	20	10.7	1.112	1.112
60	78.0	30	10	3.88	750	25.6	20	11.3	1.043	1.027
	77.7	30	10	3.77	793	25.4	20.0	10.9	1.102	**1.091**

Test	**1.03**	**Water**								
Time (min)	Temp (F)	P1 (psi)	P2 (psi)	F1 (gpm)	F2 (ml/min)	Temp (C)	TMP (psi)	Vel (ft/s)	Flux (gpm/ft2)	Flux-25C (gpm/ft2)
0	69.5	15	10	3.70	137	20.8	5	10.7	0.191	0.215
10	75.0	15	10	3.77	148	23.9	5	10.9	0.206	0.212
20	75.0	15	10	3.78	152	23.9	5	11.0	0.211	0.218
30	73.0	15	10	4.01	200	22.8	5	11.6	0.278	0.296
40	76.5	15	10	4.02	156	24.7	5	11.7	0.217	0.219
50	77.0	15	10	3.85	179	25.0	5	11.2	0.249	0.249
60	76.0	15	10	3.85	170	24.4	5	11.2	0.236	0.240
	74.6	15	10	3.85	163	23.7	5	11.2	0.227	**0.236**

Test	**1.1**										
Time (min)	Temp (F)	P1 (psi)	P2 (psi)	F1 (gpm)	F2 (ml/min)	P3 (psi)	Temp (C)	TMP (psi)	Vel (ft/s)	Flux (gpm/ft2)	Flux-25C (gpm/ft2)
0	80	50	10	3.83	462	50	26.7	40	11.1	0.642	0.613
10	73	50	10	3.72	375	50	22.8	40	10.8	0.521	0.555
20	76.7	50	10	3.73	375	50	24.8	40	10.8	0.521	0.524
30	77	50	10	3.73	353	50	25.0	40	10.8	0.491	0.491
40	77.7	50	10	3.75	353	50	25.4	40	10.9	0.491	0.486
50	77.2	50	10	3.77	353	50	25.1	40	10.9	0.491	0.489
60	77.5	50	10	3.74	316	50	25.3	40	10.9	0.439	0.436
	77.0	50	10	3.75	370	50.0	25.0	40	10.9	0.514	**0.513**

Test	**1.2**										
Time (min)	Temp (F)	P1 (psi)	P2 (psi)	F1 (gpm)	F2 (ml/min)	P3 (psi)	Temp (C)	TMP (psi)	Vel (ft/s)	Flux (gpm/ft2)	Flux-25C (gpm/ft2)
0	77.3	50	10	3.78	375	50	25.2	40	11.0	0.521	0.519
10	78.5	50	10	3.80	267	50	25.8	40	11.0	0.371	0.363
20	77.7	50	10	3.83	267	50	25.4	40	11.1	0.371	0.367
30	77.2	50	10	3.87	261	50	25.1	40	11.2	0.363	0.362
40	75.7	50	10	3.88	250	50	24.3	40	11.3	0.348	0.355
50	78.3	50	10	3.87	267	50	25.7	40	11.2	0.371	0.364
60	77.2	50	10	3.85	286	50	25.1	40	11.2	0.398	0.396
	77.4	50	10	3.84	282	50.0	25.2	40.0	11.1	0.392	**0.389**

Test	**1.3**										
Time (min)	Temp (F)	P1 (psi)	P2 (psi)	F1 (gpm)	F2 (ml/min)	P3 (psi)	Temp (C)	TMP (psi)	Vel (ft/s)	Flux (gpm/ft2)	Flux-25C (gpm/ft2)
0	76.0	50	10	3.78	300	51	24.4	40.5	11.0	0.417	0.424
10	79.1	50	10	3.91	250	51	26.2	40.5	11.4	0.348	0.336
20	75.6	50	10	3.66	250	51	24.2	40.5	10.6	0.348	0.355
30	77.4	50	10	3.72	261	51	25.2	40.5	10.8	0.363	0.361
40	74.0	50	10	3.69	250	51	23.3	40.5	10.7	0.348	0.364
50	75.0	50	10	3.69	250	51	23.9	40.5	10.7	0.348	0.359
60	78.0	50	10	3.72	250	51	25.6	40.5	10.8	0.348	0.342
	76.4	50	10	3.74	259	51	24.7	40.5	10.9	0.360	**0.363**

Test	**1.4**										
Time (min)	Temp (F)	P1 (psi)	P2 (psi)	F1 (gpm)	F2 (ml/min)	P3 (psi)	Temp (C)	TMP (psi)	Vel (ft/s)	Flux (gpm/ft2)	Flux-25C (gpm/ft2)
0	75.6	40	10	3.05	171	41	24.2	30.5	8.9	0.238	0.243
10	76.7	40	10	3.05	171	41	24.8	30.5	8.9	0.238	0.239
20	76.2	40	10	3.14	171	41	24.6	30.5	9.1	0.238	0.241
30	78.4	40	10	3.11	169	41	25.8	30.5	9.0	0.235	0.230
40	77.4	40	10	3.12	162	40	25.2	30	9.1	0.225	0.224
50	79.9	40	10	3.13	185	40	26.6	30	9.1	0.257	0.246
60	82.6	40	10	3.15	185	40	28.1	30	9.1	0.257	0.236
	78.1	40	10	3.11	173	40.6	25.6	30.3	9.0	0.241	**0.237**

Test	**1.5**										
Time (min)	Temp (F)	P1 (psi)	P2 (psi)	F1 (gpm)	F2 (ml/min)	P3 (psi)	Temp (C)	TMP (psi)	Vel (ft/s)	Flux (gpm/ft2)	Flux-25C (gpm/ft2)
0	78.0	40	10	4.65	267	42	25.6	31	13.5	0.371	0.366
10	78.6	40	10	4.42	240	43	25.9	31.5	12.8	0.334	0.326
20	73.6	40	10	4.43	200	43	23.1	31.5	12.9	0.278	0.293
30	79.7	40	10	4.44	176	43	26.5	31.5	12.9	0.245	0.235
40	79.2	40	10	4.47	185	43	26.2	31.5	13.0	0.257	0.249
50	75.0	40	10	4.49	171	44	23.9	32	13.0	0.238	0.245
60	77.1	40	10	4.48	179	44	25.1	32	13.0	0.249	0.249
	77.3	40	10	4.48	203	43.1	25.2	31.6	13.0	0.282	**0.280**

Test	**1.6**										
Time (min)	Temp (F)	P1 (psi)	P2 (psi)	F1 (gpm)	F2 (ml/min)	P3 (psi)	Temp (C)	TMP (psi)	Vel (ft/s)	Flux (gpm/ft2)	Flux-25C (gpm/ft2)
0	76.9	50	0	4.43	353	53	24.9	51.5	12.9	0.491	0.492
10	77.5	50	0	4.40	300	53	25.3	51.5	12.8	0.417	0.414
20	76.9	50	0	4.18	300	53	24.9	51.5	12.1	0.417	0.418
30	75.4	50	0	4.49	267	53	24.1	51.5	13.0	0.371	0.381
40	73.5	50	0	4.24	286	53	23.1	51.5	12.3	0.398	0.420
50	76.1	50	0	4.32	240	53	24.5	51.5	12.5	0.334	0.338
60	76.3	50	0	4.46	250	53	24.6	51.5	12.9	0.348	0.351
	76.1	50	0	4.36	285	53	24.5	51.5	12.7	0.396	**0.402**

Test	**1.7**										
Time (min)	Temp (F)	P1 (psi)	P2 (psi)	F1 (gpm)	F2 (ml/min)	P3 (psi)	Temp (C)	TMP (psi)	Vel (ft/s)	Flux (gpm/ft2)	Flux-25C (gpm/ft2)
0	74.3	50	0	3.17	240	50	23.5	50	9.2	0.334	0.348
10	73.0	50	0	3.34	231	50	22.8	50	9.7	0.321	0.342
20	77.0	50	0	3.03	222	50	25.0	50	8.8	0.309	0.309
30	77.3	50	0	3.11	231	50	25.2	50	9.0	0.321	0.320
40	78.0	50	0	3.33	240	50	25.6	50	9.7	0.334	0.329
50	75.2	50	0	3.06	235	50	24.0	50	8.9	0.327	0.336
60	76.9	50	0	3.12	240	50	24.9	50	9.1	0.334	0.334
	76.0	50	0	3.17	234	50	24.4	50	9.2	0.326	**0.331**

Test	**1.8**										
Time (min)	Temp (F)	P1 (psi)	P2 (psi)	F1 (gpm)	F2 (ml/min)	P3 (psi)	Temp (C)	TMP (psi)	Vel (ft/s)	Flux (gpm/ft2)	Flux-25C (gpm/ft2)
0	75.8	40	0	3.76	222	40	24.3	40	10.9	0.309	0.315
10	84.8	40	0	3.84	222	40	29.3	40	11.1	0.309	0.274
20	83.0	40	0	3.82	218	40	28.3	40	11.1	0.303	0.276
30	83.5	40	0	3.79	207	40	28.6	40	11.0	0.288	0.260
40	85.1	40	0	3.67	174	40	29.5	40	10.7	0.242	0.214
50	83.2	40	0	3.68	207	40	28.4	40	10.7	0.288	0.262
60	81.3	40	0	3.72	200	40	27.4	40	10.8	0.278	0.260
	82.4	40	0	3.75	207	40	28.0	40	10.9	0.288	**0.266**

Test	**1.9**										
Time (min)	Temp (F)	P1 (psi)	P2 (psi)	F1 (gpm)	F2 (ml/min)	P3 (psi)	Temp (C)	TMP (psi)	Vel (ft/s)	Flux (gpm/ft2)	Flux-25C (gpm/ft2)
0	74.4	40	0	2.36	176	40	23.6	40	6.9	0.245	0.255
10	78.6	40	0	2.63	185	40	25.9	40	7.6	0.257	0.251
20	83.1	40	0	2.40	250	40	28.4	40	7.0	0.348	0.316
30	78.3	40	0	2.44	300	40	25.7	40	7.1	0.417	0.409
40	83.7	40	0	2.40	353	40	28.7	40	7.0	0.491	0.443
50	79.7	40	0	2.34	300	40	26.5	40	6.8	0.417	0.400
60	76.6	40	0	2.36	300	40	24.8	40	6.9	0.417	0.420
	79.2	40	0	2.42	266	40	26.2	40	7.0	0.370	**0.356**

Test	**1.10**										
Time (min)	Temp (F)	P1 (psi)	P2 (psi)	F1 (gpm)	F2 (ml/min)	P3 (psi)	Temp (C)	TMP (psi)	Vel (ft/s)	Flux (gpm/ft2)	Flux-25C (gpm/ft2)
0	80.0	40	0	5.13	400	40	26.7	40	14.9	0.556	0.531
10	85.0	40	0	5.24	375	40	29.4	40	15.2	0.521	0.461
20	74.5	40	0	5.20	316	40	23.6	40	15.1	0.439	0.457
30	85.0	40	0	5.25	308	40	29.4	40	15.2	0.428	0.379
40	76.1	40	0	5.37	308	40	24.5	40	15.6	0.428	0.434
50	75.0	40	0	5.29	300	40	23.9	40	15.4	0.417	0.430
60	75.7	40	0	5.38	300	40	24.3	40	15.6	0.417	0.426
	78.8	40	0	5.27	330	40	26.0	40	15.3	0.458	**0.445**

Test	**1.11**										
Time (min)	Temp (F)	P1 (psi)	P2 (psi)	F1 (gpm)	F2 (ml/min)	P3 (psi)	Temp (C)	TMP (psi)	Vel (ft/s)	Flux (gpm/ft2)	Flux-25C (gpm/ft2)
0	73.4	30	10	3.74	158	30	23.0	20	10.9	0.220	0.233
10	74.5	30	10	3.72	158	30	23.6	20	10.8	0.220	0.229
20	85.0	30	10	3.76	187	30	29.4	20	10.9	0.260	0.230
30	78.9	30	10	3.76	171	30	26.1	20	10.9	0.238	0.231
40	75.5	30	10	3.85	150	30	24.2	20	11.2	0.209	0.214
50	74.0	30	10	3.83	150	30	23.3	20	11.1	0.209	0.219
60	75.8	30	10	3.88	150	30	24.3	20	11.3	0.209	0.213
	76.7	30	10	3.79	161	30	24.8	20	11.0	0.223	**0.224**

Test	**1.12**										
Time (min)	Temp (F)	P1 (psi)	P2 (psi)	F1 (gpm)	F2 (ml/min)	P3 (psi)	Temp (C)	TMP (psi)	Vel (ft/s)	Flux (gpm/ft2)	Flux-25C (gpm/ft2)
0	80.1	60	0	3.74	522	60	26.7	60	10.9	0.726	0.692
10	77.5	60	0	3.82	400	60	25.3	60	11.1	0.556	0.552
20	76.6	60	0	3.82	400	60	24.8	60	11.1	0.556	0.560
30	75.8	60	0	3.86	400	60	24.3	60	11.2	0.556	0.567
40	75.1	60	0	3.86	400	60	23.9	60	11.2	0.556	0.573
50	75.9	60	0	3.78	400	60	24.4	60	11.0	0.556	0.566
60	76.2	60	0	3.77	400	60	24.6	60	10.9	0.556	0.563
	76.7	60	0	3.81	417	60	24.9	60	11.1	0.580	**0.582**

Test	**1.13**										
Time (min)	Temp (F)	P1 (psi)	P2 (psi)	F1 (gpm)	F2 (ml/min)	P3 (psi)	Temp (C)	TMP (psi)	Vel (ft/s)	Flux (gpm/ft2)	Flux-25C (gpm/ft2)
0	74.5	40	0	3.66	255	41	23.6	40.5	10.6	0.355	0.369
10	85.0	40	0	3.75	250	41	29.4	40.5	10.9	0.348	0.307
20	72.0	40	0	3.68	222	41	22.2	40.5	10.7	0.309	0.334
30	77.4	40	0	3.74	240	41	25.2	40.5	10.9	0.334	0.332
40	77.1	40	0	3.74	218	41	25.1	40.5	10.9	0.303	0.303
50	75.3	40	0	3.73	222	41	24.1	40.5	10.8	0.309	0.317
60	83.0	40	0	3.77	240	41	28.3	40.5	10.9	0.334	0.304
	77.8	40	0	3.72	235	41	25.4	40.5	10.8	0.327	**0.324**

Test	**1.14**										
Time (hr)	Temp (F)	P1 (psi)	P2 (psi)	F1 (gpm)	F2 (ml/min)	P3 (psi)	Temp (C)	TMP (psi)	Vel (ft/s)	Flux (gpm/ft2)	Flux-25C (gpm/ft2)
1	85.0	60	0	3.71	133	60	29.4	60	10.8	0.185	0.163
2	79.1	60	0	3.61	91	60	26.2	60	10.5	0.127	0.122
3	86.9	60	0	3.79	91	60	30.5	60	11.0	0.127	0.109
4	74.9	60	0	3.70	83	60	23.8	60	10.7	0.115	0.119
5	80.0	60	0	3.79	75	60	26.7	60	11.0	0.104	0.100
6	78.2	60	0	3.73	61	60	25.7	60	10.8	0.085	0.083
7	81.1	60	0	3.80	75	60	27.3	60	11.0	0.104	0.098
8	74.7	60	0	3.77	67	60	23.7	60	10.8	0.121	0.114
9	76.8	60	0	3.79	60	60	24.9	60	10.8	0.112	0.106
10	81.7	60	0	3.77	61	60	27.6	60	10.9	0.110	0.104
11	82.0	60	0	3.80	64	60	27.8	60	10.9	0.107	0.103
12	84.8	60	0	3.77	61	60	29.3	60	10.9	0.106	0.101
	80.4	60	0	3.75	76.8	60	26.9	60	10.9	0.117	**0.110**
13	81.1	60	0	3.84	65	60	27.3	60	11.1	0.090	0.085
14	82.0	60	0	3.82	65	60	27.8	60	11.1	0.090	0.084
15	80.7	60	0	3.82	58	60	27.1	60	11.1	0.081	0.076
16	77.0	60	0	3.70	49.5	60	25.0	60	10.7	0.069	0.069
17	79.1	60	0	3.74	37.7	60	26.2	60	10.9	0.052	0.051
18	79.4	60	0	3.72	37.5	60	26.3	60	10.8	0.052	0.050
19	84.9	60	0	3.71	40.3	60	29.4	60	10.8	0.056	0.050
20	76.9	60	0	3.78	44	60	24.9	60	10.9	0.070	0.066
21	80.8	60	0	3.77	43.5	60	27.1	60	10.9	0.067	0.064
22	84.4	60	0	3.74	42	60	29.1	60	10.9	0.064	0.061
23	82.2	60	0	3.71	38	60	27.9	60	10.8	0.062	0.059
24	86.0	60	0	3.80	42	60	30.0	60	10.9	0.060	0.057
	81.2	60	0	3.76	46.8	60	27.3	60	10.9	0.068	**0.064**
29	77.1	60	0	3.80	18	60	25.1	60	11.0	0.025	0.025
30	80.1	60	0	3.87	17.6	60	26.7	60	11.2	0.024	0.023
31	77.2	60	0	3.71	16	60	25.1	60	10.8	0.022	0.022
32	82.2	60	0	3.76	10	60	27.9	60	10.9	0.013	0.012
33	81.0	60	0	3.70	9.5	60	27.2	60	10.7	0.013	0.012
34	79.7	60	0	3.76	8.9	60	26.5	60	10.9	0.012	0.012
35	84.3	60	0	3.74	8.9	60	29.1	60	10.9	0.012	0.011
36	84.3	60	0	3.52	8.5	60	29.1	60	10.2	0.012	0.011
	80.7	60	0	3.73	12.1	60	27.1	60	10.8	0.017	**0.016**
37	75.7	60	0	3.59	8.6	60	24.3	60	10.4	0.012	0.012
38	82.9	60	0	3.79	6.8	60	28.3	60	11.0	0.009	0.009
39	77.0	60	0	3.85	7.3	60	25.0	60	11.2	0.010	0.010
40	80.0	60	0	3.76	7.7	60	26.7	60	10.9	0.011	0.010
41	83.4	60	0	3.75	7.8	60	28.6	60	10.9	0.011	0.010
42	84.8	60	0	2.26	8	60	29.3	60	6.6	0.011	0.010
43	78.9	60	0	3.21	7.5	60	26.1	60	9.3	0.010	0.010
	80.4	60	0	3.46	7.7	60	26.9	60	10.0	0.011	**0.010**