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EM Task 9 - Centrifugal Membrane Filtration

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1.0 BACKGROUND

This project is designed to establish the utility of a novel centrifugal membrane filtration technology for the remediation of liquid mixed waste streams at U.S. Department of Energy (DOE) facilities in support of the DOE Environmental Management (EM) program. The Energy & Environmental Research Center (EERC) has teamed with SpinTek Membrane Systems, Inc., a small business and owner of the novel centrifugal membrane filtration technology, to establish the applicability of the technology to DOE site remediation and the commercial viability of the technology for liquid mixed waste stream remediation.

The technology is a uniquely configured process that makes use of ultrafiltration and centrifugal force to separate suspended and dissolved solids from liquid waste streams, producing a filtered water stream and a low-volume contaminated concentrate stream. This technology has the potential for effective and efficient waste volume minimization, the treatment of liquid tank wastes, the remediation of contaminated groundwater plumes, and the treatment of secondary liquid waste streams from other remediation processes, as well as the liquid waste stream generated during decontamination and decommissioning activities.

2.0 OBJECTIVES

The overall project consists of several integrated research phases related to the applicability, continued development, demonstration, and commercialization of the SpinTek centrifugal membrane filtration process. Work performed during this reporting period continued the Phase 2 evaluation of the SpinTek centrifugal membrane filtration technology and initiated Phase 3 efforts, Technology Partnering. During Phase 1 testing conducted at the EERC using the SpinTek ST-IIL unit operating on a surrogate tank waste, a solids cake developed on the membrane surface. The solids cake was observed where linear membrane velocities were less than 17.5 ft/s and reduced the unobstructed membrane surface area up to 25%, reducing overall filtration performance.

The primary goal of the Phase 2 research effort was to enhance filtration performance through the development and testing of alternative turbulence promoter designs. The turbulence promoters were designed to generate a shear force across the entire membrane surface sufficient to maintain a self-cleaning membrane capability and improve filtration efficiency and long-term performance. Specific Phase 2 research activities include the following:

- System modifications to accommodate an 11-in.-diameter, two-disk rotating membrane assembly

- Development and fabrication of alternative turbulence promoter designs

- Testing and evaluation of the existing and alternative turbulence promoters under selected operating conditions using a statistically designed test matrix
- Data reduction and analysis

The objective of Phase 3 research, Technology Partnering, was to demonstrate the effectiveness of SpinTek's centrifugal membrane filtration as a pretreatment to remove suspended solids from a liquid waste upstream of 3M's WWL cartridge technology for the selective removal of technetium (Tc).

3.0 ACCOMPLISHMENTS

During this reporting period, the work performed emphasized testing and evaluation of the existing and alternative turbulence promoters using a statistically designed experimental matrix. In addition, testing activities were performed to evaluate the effectiveness of the SpinTek system in a prefiltration application.

3.1 Turbulence Promoter Testing and Evaluation

3.1.1 Test Procedure

Testing of the turbulence promoters was performed using the statistical test matrix design shown in Table 1. Six different promoter configurations were tested. These included modifications to the original design in two different thicknesses (0.120 and 0.1875 in.), a new design in the forward position (0.120 and 0.1875 in.), and the new design in the reverse position (0.120 and 0.1875 in.). The modifications were bevels machined on the leading edge of the previously evaluated turbulence promoter designs (Stepan and others, 1998). Beveling of the leading edge was considered in attempt to change the flow around the turbulence promoter vanes and alter the boundary layer flow conditions at the membrane surface.

Each design was tested at two pressures (40 and 60 psig) and two rotor speeds (900 and 1200 rpm). Thus each turbulence promoter was tested a total of four times throughout the experiment. Feed temperature was maintained at 90°F, and the solids concentration of a kaolin clay test slurry was held constant at 20 wt % (specific gravity 1.17), although a slight increase in the solids concentration occurred because of evaporation. The tests were randomized to account for any irreversible fouling of the membrane that might occur with operating time. The first and last tests of the matrix used the original promoter operating at 60 psig and 1200 rpm. These tests were used as the baseline data for the experiment.

Once started, the testing was performed around the clock until all tests were completed. Data for each test were logged for approximately 4 hr, giving ample time for the system to reach steady-state operation. At the end of each test, the outer surfaces of each disk were rinsed free of filter cake by water collected near the end of the trial run from the permeate line. This was done

TABLE 1

Beveled-Edge Turbulence Promoter Evaluation Test Matrix

Run Number	Promoter Design	Pressure, psig	Rotor Speed, rpm
1	Original (baseline)	60	1200
2	New design, forward (0.1875 in.)	60	1200
3	New design, forward (0.120 in.)	60	900
4	New design, forward (0.120 in.)	40	1200
5	New design, forward (0.1875 in.)	40	900
6	New design, reverse (0.120 in.)	40	900
7	New design, reverse (0.120 in.)	40	1200
8	Original (baseline)	40	900
9	New design, reverse (0.1875 in.)	40	900
10	New design, forward (0.120 in.)	60	1200
11	New design, reverse (0.1875 in.)	60	1200
12	Original design (0.1875 in.)	60	1200
13	Original design (0.1875 in.)	40	1200
14	Original (baseline)	40	1200
15	New design, forward (0.120 in.)	40	900
16	New design, reverse (0.1875 in.)	40	1200
17	Original design (0.1875 in.)	60	900
18	Original design (0.1875 in.)	40	900
19	New design, reverse (0.120 in.)	60	900
20	New design, reverse (0.120 in.)	60	1200
21	New design, forward (0.1875 in.)	60	900
22	Original (baseline)	60	900
23	New design, forward (0.1875 in.)	40	1200
24	New design, reverse (0.1875 in.)	40	900
25	Original (baseline)	60	1200

to maintain a constant solids concentration within the feed tank. The inner surfaces of each disk (i.e., the bottom of the top disk and the top of the bottom disk) were examined for filter cake development. The inner surfaces were deemed the most important since in a full-scale unit the disks are stacked on top of one another. The fluid movement between the membrane disks on these units accounts for most of the filtration, with the contribution of the outer surfaces of the top and bottom disks being relatively small by comparison.

3.1.2 Power Consumption Measurement

Efficiency of the turbulence promoters was determined by measuring power consumption of the motor rotating the filtration disks while measuring the permeate flux. A power analyzer was attached to the wires conveying power directly to the motor. This allowed measurement of power directed to the rotor motor only and decreased the possibility of measuring power fluctuations from other parts of the system. To measure the power of the three-phase motor, the analyzer measured current in one phase and measured the voltage between the other two. Current was measured intermittently throughout the test runs in each of the other phases to ensure that all phases were drawing the same amount. Power consumption was logged to a computer. Although power was the only parameter that had to be logged, other parameters (including voltage, amperage, power factors, and total power usage) were logged to ensure that proper data were obtained for the power consumption calculations.

3.1.3 Data Collection

A link between the test unit and a computer allowed data collected from each test to be automatically logged on the computer. Test parameters such as feed pressure, temperature, and flow, as well as membrane rotational speed and permeate flow, were all measured and recorded along with the time of day and elapsed time from the start of the test. Permeate flux was determined from the measured flow rate and membrane area. Data were collected at 5-min intervals. The computer data log does not show the average value of the test parameters over the 5-min period, but rather the value of the parameters at the time the data were recorded.

3.1.4 Test Results

The average steady-state data collected while the test matrix was performed are presented in Table 2. The table shows the feed pressure, permeate flow rate, rotor speed, and power consumption, as well as the time of day and run time for each particular test. Data from the first hour of each test were not used in determining the averages since, in some cases, large performance fluctuations occurred in the beginning of the test.

Previous testing conducted using the test unit showed that membrane performance tends to degrade with operating time. This degradation results from irreversible fouling that happens when particles plug the pores within the membrane. Washing the membranes between test runs removes almost all of the filter cake, but cannot remove particles that are trapped deep within the membrane pores. The statistical matrix run order was randomized to take the irreversible membrane fouling into consideration. The randomization also helped to eliminate any bias that could occur while the tests were performed.

TABLE 2

Data Collected During Beveled-Edge Turbulence Promoter Evaluation Tests

Randomized Test Run Number	Feed Pressure, psi	Rotor Speed, rpm	Promoter Design[a]	Permeate Flux, gfd	Power Consumption, kW	Test Duration, hr:min	Cumulative Membrane Run Time at Start of Test, hr:min
1	59.41	1189.27	Orig	216.40	1.17	4:01	0:00
2	59.59	1192.96	NF+	201.97	1.14	4:09	4:01
3	59.47	908.42	NF−	123.63	0.57	3:50	8:10
4	39.55	1191.39	NF−	180.89	1.05	4:01	12:00
5	39.41	894.57	NF+	128.55	0.70	4:01	16:01
6	39.53	894.06	NR−	120.93	0.56	4:01	20:02
7	39.53	1198.59	NR−	190.17	1.09	3:58	24:03
8	39.49	896.64	Orig	151.29	0.57	3:51	28:01
9	39.50	904.68	NR+	148.32	0.59	4:05	31:52
10	59.52	1189.02	NF−	200.45	1.07	4:06	35:57
11	59.43	1208.29	NR+	222.26	1.20	4:01	40:03
12	59.68	1193.87	Orig+	239.12	1.26	3:50	44:04
13	39.49	1210.72	Orig+	224.12	1.26	3:51	47:54
14	39.65	1192.61	Orig	213.07	1.16	4:01	51:45
15	39.43	893.65	NF−	125.07	0.55	4:01	55:46
16	39.55	1187.31	NR+	209.78	1.15	4:01	59:47
17	59.29	903.73	Orig+	159.86	0.65	4:01	63:48
18	39.47	894.49	Orig+	159.30	0.63	4:06	67:49
19	59.45	896.61	NR−	130.36	0.54	4:01	71:55
20	59.36	1189.12	NR−	202.65	1.04	4:05	75:56
21	59.47	905.92	NF+	139.63	0.59	4:01	80:01
22	59.45	891.96	Orig	144.38	0.59	4:01	84:02
23	39.54	1190.33	NF+	191.20	1.19	4:13	88:03
24	39.40	888.50	NR+	130.62	0.16	3:56	92:16
25	59.37	1187.41	Orig	217.07	1.16	4:01	96:12

[a] Orig = original design; NF = new design, forward position; NR = new design, reverse position; − = 0.120-in. thickness; + = 0.1875-in. thickness.

The results of matrix testing are shown in Table 2. Statistical analyses of the steady-state, averaged values contained in Table 2 will be performed to create statistical models that will account for membrane degradation with time and more accurately predict the results by which to compare turbulence promoter efficiency. The validity of these models will be checked by inputting operating variables (time, rotor speed, promoter thickness and position) and comparing the resulting predicted values for permeate flux and rotor power consumption to those obtained during the test. Additional test conditions, if appropriate, will be identified based on the results of statistical analyses.

3.2 Technology Partnering – SpinTek and 3M

SpinTek's centrifugal membrane filtration is a crosscutting technology with a number of applications for cleanup of DOE weapons complex liquid wastes. One of these applications is the enhancement of downstream unit operations, such as adsorption or ion exchange processes where even low levels of suspended solids create operational problems.

3M has developed technologies that are capable of selectively removing dissolved radionuclides from liquid wastes. A limiting factor in the effectiveness of the 3M technology is the accumulation of suspended materials that decrease throughput, creating plugging well before the cartridges are completely utilized with respect to removal capability. Testing was conducted to evaluate improvements to the 3M WWL Tc removal cartridges using SpinTek's centrifugal membrane filtration as a pretreatment to removal suspended material.

3.2.1 Test Procedures

Testing was conducted to evaluate 3M WWL Tc cartridge performance under three different conditions: 1) without prefiltration, 2) with prefiltration using conventional cartridge-style paper prefilters, and 3) with prefiltration using the SpinTek centrifugal membrane filtration technology.

Water used in the tests was collected from the English Coulee, a tributary of the Red River of the North that flows through the campus of the University of North Dakota. The water was intended to represent an impounded water at DOE facilities and had a relatively low suspended solids concentration. Total suspended solids during test trials without prefiltration were measured to be 11 mg/L. During trials with conventional prefiltration and SpinTek prefiltration, the total suspended solids concentration was 35 mg/L.

All test trials were conducted at a constant flow rate of 10 gallons per hour. English Coulee water was pumped from a 1500-gallon polyethylene storage tank that served as a feed storage reservoir. During trials conducted without prefiltration, the water was pumped through the 3M WWL Tc removal cartridge and recirculated back to the storage tank. Inlet pressure was monitored throughout the duration of the test trial.

Tests using conventional prefiltration and SpinTek centrifugal membrane filtration were then conducted in a parallel mode. A block flow diagram is shown in Figure 1. English Coulee

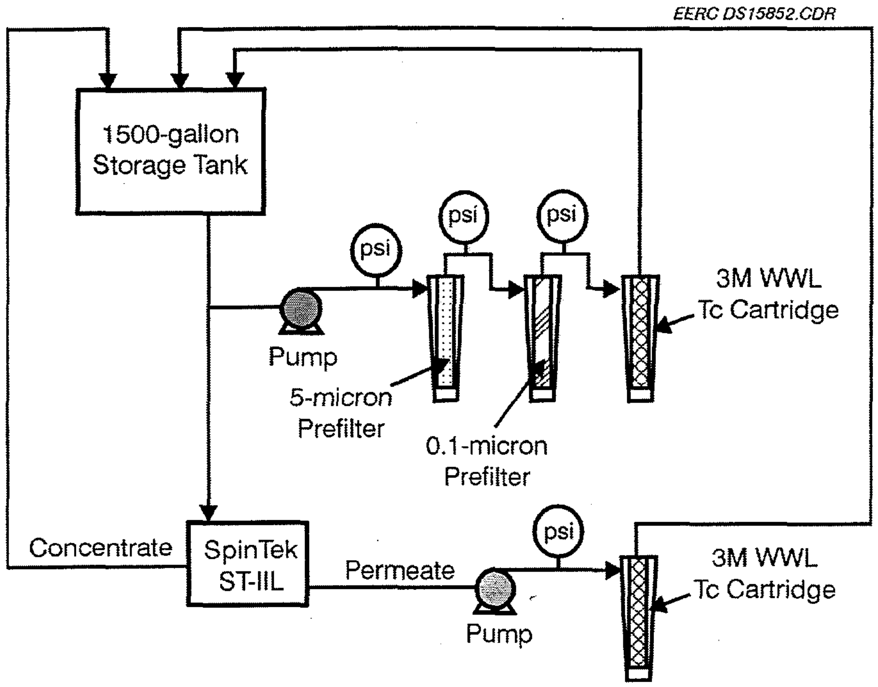

Figure 1. Prefiltration test block flow diagram

water was pumped directly from the feed water storage tank through two conventional filters prior to the 3M WWL cartridges. These filters had nominal pore sizes of 5 and 0.1 µm, respectively. Filtered water was then passed through the 3M WWL cartridge and recirculated back to the feed storage tank. Pressure indicators were placed at the inlet side of each of the filter cartridges to monitor pressure increases in each filter because of accumulation of suspended solids. Filter inlet pressure readings were data-logged to a computer at 30-minute intervals throughout the duration of the test runs.

Parallel test trails using SpinTek prefiltration also used English Coulee water pumped directly from the feed storage tank. Permeate from the SpinTek ST-IIL unit was directed to a 30-gallon surge tank before being pumped through a 3M WWL cartridge. Concentrate from the ST-IIL unit was directed back to the feed storage tank. As with the conventional prefiltration system, inlet pressure was monitored throughout the test run and data-logged at 30-minute intervals. The SpinTek ST-IIL unit was operated at ambient temperatures at a feed rate of 600 L/hr, a pressure of 60 psig, and a rotor speed of 1200 rpm.

3.2.2 Test Results

3.2.2.1 No Prefiltration

The test with no prefiltration was run for approximately 1 hour, shut down, and restarted approximately 5 days later. The test run was operated for a total of approximately 4.5 hours, at which time the inlet pressure reached 70 psig. Total throughput at test termination was approximately 38 gallons. Figure 2 shows the inlet pressure versus total throughput without prefiltration. As shown in Figure 2, the inlet pressure diminished to less than 5 psig upon test continuation.

3.2.2.2 Conventional Prefiltration

The conventional prefiltration test run was operated for approximately 102 hours, during which time the 5-µm filter had to be replaced three times because of filter plugging. Although inlet pressure of the 5-µm filter reached a maximum allowable value of approximately 70 psig three times, no significant pressure increase was observed at either of the other filters.

At test conclusion, approximately 748 gallons of total throughput had been achieved with an average throughput for each 5-µm filter of approximately 250 gallons. The observed inlet pressure versus total throughput volume is presented in Figure 3.

3.2.2.3 SpinTek Prefiltration

The SpinTek prefiltration test run was operated for approximately 240 hours, at which time a recycle line failure prompted the end of the test. After 240 hours of operation and approximately 2400 gallons of total throughput, no significant pressure increase had been observed at the inlet of the Tc filter. Figure 4 displays the measured inlet pressure over time during the SpinTek prefiltration test run.

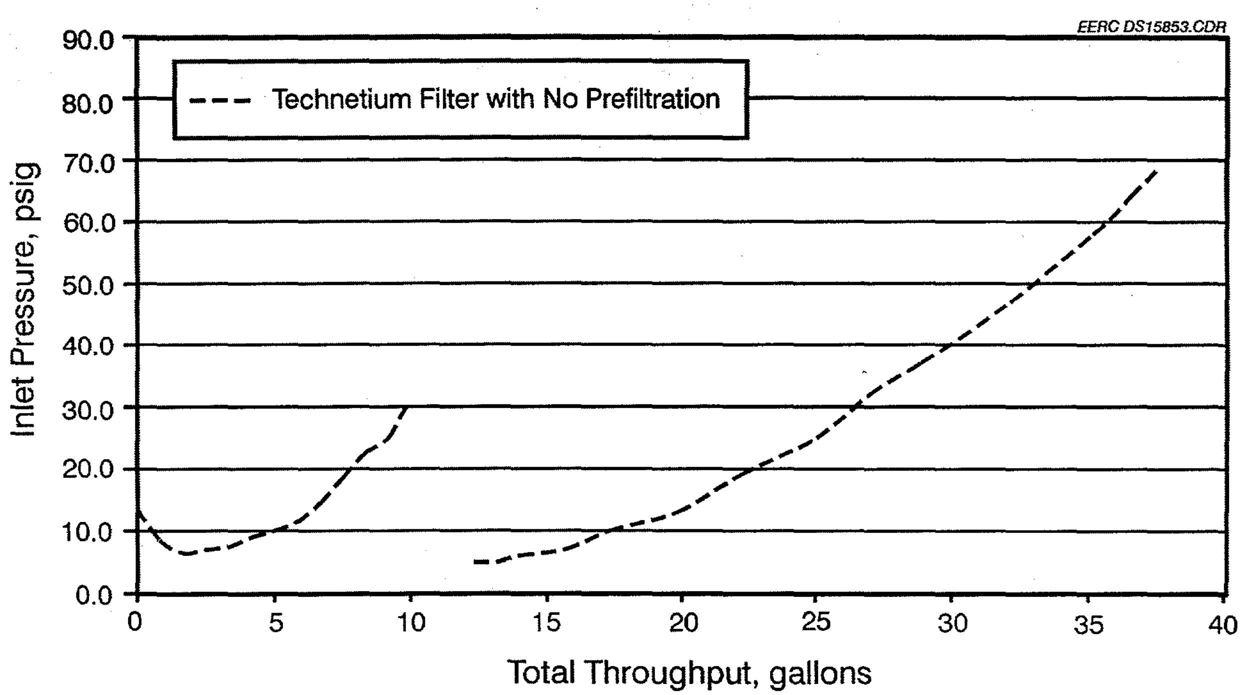

Figure 2. Pressure versus throughput – no prefiltration.

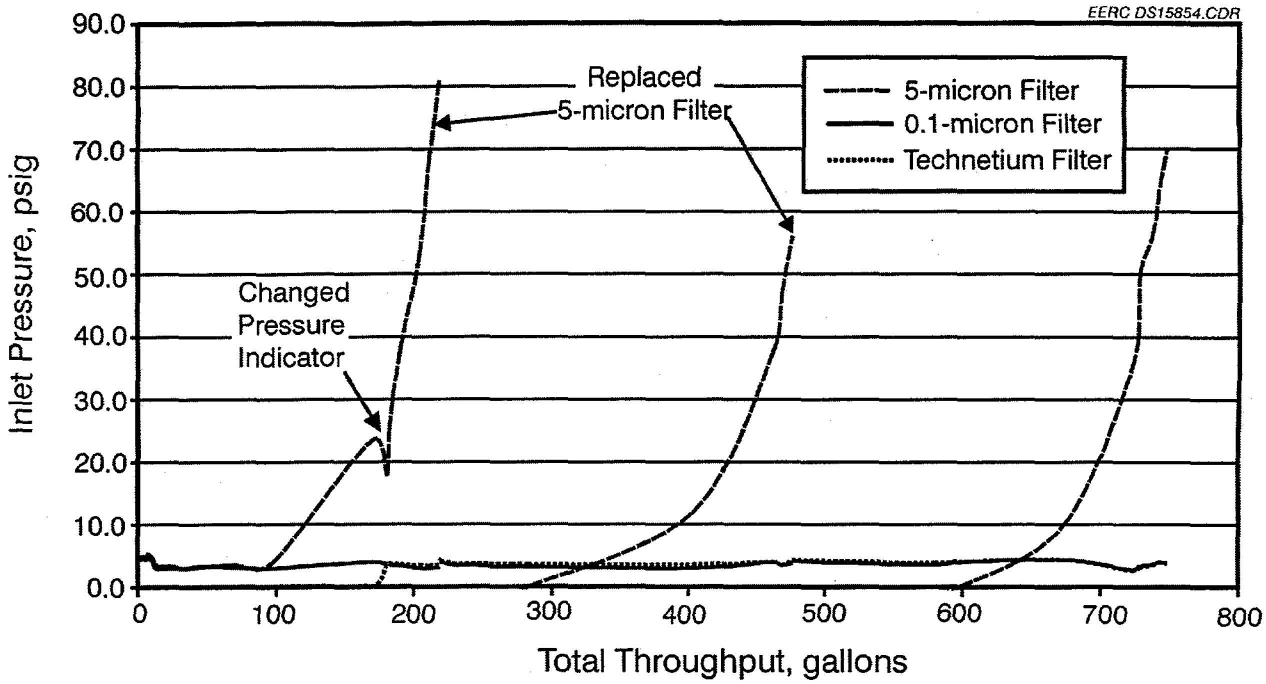

Figure 3. Pressure versus throughput – conventional prefiltration.

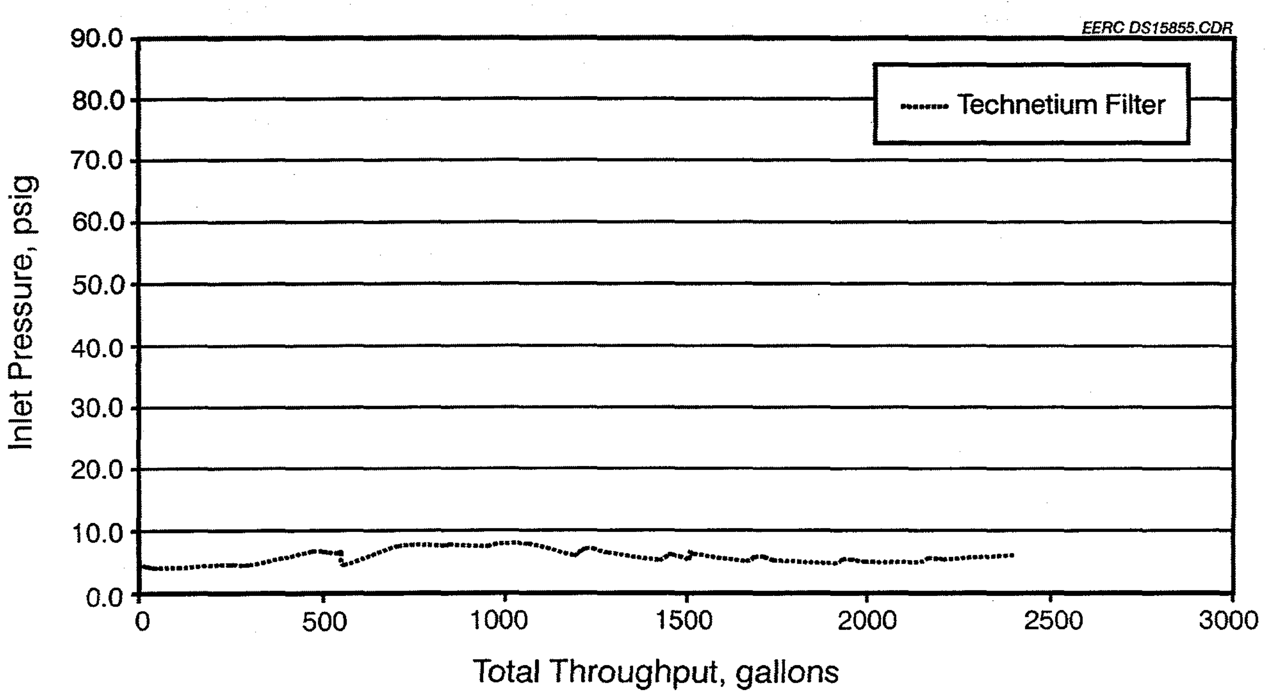

Figure 4. Pressure versus throughput – SpinTek prefiltration.

Based on the test run data, prefiltration was required for application with the raw water. As shown during the parallel prefiltration test run, the SpinTek prefiltration system was much more efficient at removing suspended solids prior to delivery to the Tc-specific cartridge. If the conventional prefiltration system had been operated for the 240 hours as the SpinTek prefiltration system had been operated, approximately ten 5-μm filters would have been required to achieve a throughput of 2400 gallons (one 5-μm filter per 250 gallons of throughput).

3.3 Preliminary Economic Analysis

The October 1, 1997, to March 30, 1998, semiannual report stated that an economic analysis is an integral step in the optimization of the turbulence promoter design. Choice of a design depends in part upon which of two variables most significantly affects process economics: 1) the rate of permeate production and 2) the cost of producing a given volume of permeate. An analysis was performed using the following assumptions:

- One SpinTek unit would operate 24 hr/day for each option.
- The same feed stream would be used for both options.
- Repair and maintenance would be the same for both options (in reality, operation at the less severe conditions of 40 psi and 900 rpm might require less maintenance than operation at 60 psi and 1200 rpm).
- The number of workers would be the same for both options.

The data showing the effects of rotor speed and pressure on permeate flux (i.e., the rate of permeate production) and power consumption were first presented in the October 1, 1997, to March 30, 1998, semiannual report and are presented here in Table 3. As Table 3 shows, the highest steady-state flux (200.4 gal/ft^{2}day [gfd]) was achieved using the original-design turbulence promoter operating at 1200 rpm and 60 psi. A second reading taken about 100 hr later indicated that the flux was 164.4 gfd at the same conditions. These data points were averaged to 182.4 gfd. The SpinTek unit contains two filtration membranes, each containing 1 ft^2 of surface area. Therefore, the SpinTek unit can produce 182.4 gal/ft^{2}day × 2 ft^2, or 364.8 gal/day of permeate when operated at 60 psi and 1200 rpm. For comparison purposes, a basis of 1000 gal of permeate was used. Production of 364.8 gal/day would require 2.74 days at this rate. The table shows that production of 182.4 gfd permeate required about 1.2 kW of power, or 3.29 kW to produce 1000 gal of permeate.

The lowest steady-state power usage (0.53 kW) occurred when the 0.120-in.-thick new design of turbulence promoter was used in the forward position at 900 rpm and 40 psi. Calculations analogous to those used for the higher-flux conditions show that the SpinTek unit can produce 89.6 gfd × 2 ft^2, or 179.2 gal/day at the lower-power-usage conditions. Production of 1000 gal of permeate at these conditions would require 5.58 days and, at 0.53 kW per 89.6 gfd, 2.96 kW of power.

TABLE 3

Data Showing the Effects of Rotor Speed and Pressure on Permeate Flux and Power Consumption

		Steady-State Flux, gfd		Steady-State Power Use, kW		Flux Achieved per Power Use, gfd/kW	
Pressure, psi	Promoter Design	Rotor Speed = 900 rpm	Rotor Speed = 1200 rpm	Rotor Speed = 900 rpm	Rotor Speed = 1200 rpm	Rotor Speed = 900 rpm	Rotor Speed = 1200 rpm
40	Original (0.120 in.)	124.1	176.6	0.63	1.26	197.0	140.2
40	Original (0.1875 in.)	120.9	178.1	0.63	1.26	191.9	141.3
40	New Fwd. (0.120 in.)	89.6	157.6	0.53	1.08	169.1	145.9
40	New Fwd. (0.1875 in.)	103.5	143.2	0.59	1.28	175.4	111.9
40	New Rev. (0.120 in.)	100.8	151.2	0.54	1.06	186.7	142.6
40	New Rev. (0.1875 in.)	113.7	157.0	0.61	1.26	186.4	124.6
60	Original (0.120 in.)	110.3	200.4, 164.4[a]	0.63	1.19, 1.21	175.1	168.4, 135.8
60	Original (0.1875 in.)	120.6	188.1	0.62	1.28	194.5	147.0
60	New Fwd. (0.120 in.)	98.2	143.1	0.56	1.05	175.4	136.3
60	New Fwd. (0.1875 in.)	100.6	161.9	0.60	1.23	167.7	131.6
60	New Rev. (0.120 in.)	95.8	149.2	0.58	1.1	165.2	135.6
60	New Rev. (0.1875 in.)	104.5	169.1	0.66	1.26	158.3	134.2

[a] The first value is from Test 1, while the second value is from Test 25.

Assuming that electrical power for industrial customers costs approximately $0.031/kWh, the power cost to produce 1000 gal of permeate when operating at 60 psi and 1200 rpm would be $0.031/kWh × 2.74 days × 24 hr/day × 3.29 kW, or $6.71. Similarly, the power cost to produce 1000 gal of permeate when operating at 40 psi and 900 rpm would be $12.29. The costs of the production of 1000 gal of permeate at both the higher-permeate flux conditions and the lower-power-usage conditions are compared in Table 4. It is easy to see that the additional time required to process an equivalent amount of permeate more than offsets any reduction in power consumption because of changes in operating conditions.

The factor of time can be eliminated if it is assumed that the use of multiple SpinTek units allow permeate production to be accomplished in 1 day. Operation at 60 psi and 1200 rpm would require the use of three SpinTek units to meet the 1000-gal/day goal. Each unit requires 1.2 kW and produces 364.8 gal/day for a total of 1094.4 gal of permeate at an energy cost of 3 units × 1.2 kW/unit × 24 hr × \$0.031/kWh, or \$2.68. The cost per gallon would be \$0.00245.

TABLE 4

Economic Comparison of Highest Permeate Production with Lowest Power Consumption

Parameter	Highest Permeate Flux (60 psi, 1200 rpm)	Lowest Power Consumption (40 psi, 900 rpm)
Permeate Flux, gfd	200.4, 164.4 (182.4 average)	89.6
Permeate Produced, gal/day	364.8	179.2
Power Consumption, kW	1.2	0.53
Days Required to Produce 1000 gal Permeate	2.74	5.58
Power Required to Produce 1000 gal Permeate	3.29	2.96
Cost of Power, \$/kWh	0.031	0.031
Cost of Producing 1000 gal Permeate	\$6.71	\$12.29
SpinTek Units Required to Produce 1000 gal Permeate in 1 day	3	6
Permeate Produced in 1 day, gal	1094.4	1075.2
Cost of Producing 1000 gal Permeate in 1 day	\$2.68	\$2.37
Cost of Producing Permeate in 1 day	\$0.00245/gal	\$0.00220/gal

Operation at 40 psi and 900 rpm would require six SpinTek units. Each unit can produce 179.2 gal/day and requires 0.53 kW. Total production by the six units would be 1075.2 gal of permeate at an energy cost of 6 units × 0.53 kW/unit × 24 hr × \$0.031/kWh, or \$2.37. The cost per gallon in this case would be \$0.00220. Even when time is not a factor, the energy cost reductions would probably not be sufficient to offset the capital cost of additional SpinTek units and personnel to operate and maintain the equipment.

This analysis shows that maximization of permeate flux has the bigger economic impact with respect to turbulence promoter design. Therefore, from a strictly economic standpoint, optimization of the turbulence promoter design should concentrate on the original promoter with the SpinTek unit operating at 1200 rpm and 60 psi.

A more complete cost analysis of the SpinTek process as well as a comparison of the process' economics with competing technologies will be included in the final report for this project.

4.0 FUTURE WORK

Continued work on this task will involve the following:

- Phase 2
  - Complete statistical analysis of beveled-edge turbulence promoter test run data
  - Compare beveled-edge performance to previous turbulence promoter test run data
  - Complete systems analysis work
  - Complete systems integration work
  - Prepare final Phase 2 report
- Phase 3
  - Complete data reduction activities
  - Prepare final Phase 3 report

5.0 REFERENCES

Stepan, D.J., Grafsgaard, M.E., and Hetland, M.D., 1998, EM Task 9 – Centrifugal Membrane Filtration: semiannual report for the period October 1, 1997, to March 30, 1998, EERC–DOE Environmental Management Cooperative Agreement No. DE-FC21-94MC31388, EERC publication, May 1998.