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Technical Memorandum

To: Daniel B. Fishman, Technology Manager, Bioenergy Technologies Office

Title: Cross-flow Filtration of Multiple Algal Strains and Mixed Populations using Embedded Membranes

Authors: Daniel M. Stevens, Mark L. Stone, Eric S. Peterson, Deborah T. Newby

Platform: Algal Biofuels

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EXECUTIVE SUMMARY

Purpose and Scope

The objective of this research is to analytically assess cross-flow membrane filtration (CFF) technology as an algal harvesting approach that will debottleneck the water recovery/nutrient recovery/recycling processes. Specifically, the focus of this investigation will be INL-developed, ceramic-embedded, erosion-resistant membrane technology, comprising stainless steel micro- and ultra-filters with controlled pore sizes to reduce membrane fouling and enhance filtration permeation properties. Parameters such as shear/face velocity and transmembrane pressure will be varied to assess impact on filtration efficiency. Detrimental effects such as cell lysis must also be considered. The project is an opportunity to analytically investigate the level of shear (cross-flow face velocity level) needed to accomplish dewatering by filtration in an economic manner while gaining insight into membrane fouling mechanisms. Furthermore, testing of the membranes with different starting concentrations of algae, as well as with a variety of membranes and filtration conditions, will allow us to establish the boundary conditions where membrane technologies are appropriate for application in an overall algal harvesting strategy.

Key results

This report details studies investigating the use of embedded membrane CFF for concentration of four algal strains and two mixed populations. Strains tested include *Chaetoceros gracilis*, *Scenedesmus dimorphus*,*Chlorella* (USU80), and *Pseudochlorococcum typicum.* All mixed populations tested were predominantly *Chlorella*, which were grown in outdoor raceways at Utah State University.

Conclusions

This research is designed to identify critical improvements to dewatering and moisture management that can significantly impact the cost of harvesting and logistics for algae as a biomass feedstock. Membranes were evaluated with multiple strains and mixed populations that simulate those expected from an outdoor raceway. Impacts of face velocity and trans-membrane pressure were assessed. Data generated from these studies indicate that CFF with embedded membranes can be a viable dewatering technology and warrants additional research. Flux values with embedded membrane technology from multiple strains and two open pond configurations maintained higher flux rates than what is considered adequate for industrial standards. Embedded membranes need further testing at larger scale under real-world, open-pond configurations with environmental factors. At-scale filtration studies, where flux and membrane erosion are tracked and measured, would give a stronger determination of the effectiveness of embedded membrane technology. Membrane configurations that hold near steady-state flux rates, resist fouling, and are more corrosion-resistant to abrasive culture contaminants will perform better and offer more efficient filtration flux over extended periods of time.

Recommendations

CFF using embedded membranes shows promise as an algal dewatering technique. A large 10-disc SpinTek unit was loaned to Utah State University for testing at larger scale. If funds and algae are available for this purpose, the at-scale or near-scale testing will provide significant information as to the validity of this technology for large-scale dewatering. While parametric bench-scale testing has provided significant information regarding optimal conditions, extrapolation to a larger scale is difficult and has historically proven to be inaccurate. There is a real need to perform intermediate-scale studies that are more reflective of those required for commercial biofuel production. In addition, assessment of a variety of membranes embedded with different thicknesses of ceramic could result in improved fluxes and much lower operating costs.

Cross-Flow Filtration of Multiple Algal Strains and Mixed Populations using Embedded Membranes

Background

Algal biofuels have the potential to meet a significant portion of the U.S. renewable fuel goals. However, successful development of an algae-based biofuels and co-products industry will require the development of cost-efficient dewatering and drying methods. The objective of this project is to gain an understanding of the processes and combinations of methods that can lower the cost of dewatering algae feedstock. Algae will not succeed as a viable biomass feedstock if this R&D gap is not successfully addressed. Understanding how dewatering methods can be effectively combined to develop a more efficient harvesting system is critical to capturing the value of algal biomass.

Cross-flow filtration (CFF) shows promise as an efficient dewatering technique [1-4] and was recently down-selected as one of four technologies for further investigation by the National Alliance for Advanced Biofuels and Bioproducts (NAABB).

CFF is advantageous over standard filtration because the majority of filter cake that accumulates on the filter surface is washed away during filtration, extending the life of the filter (Figure 1). A much slower flux decline is observed for CFF and active surface filtration when compared to standard dead-end filtration. CFF may be further improved through development of a novel active surface (spinning membranes) such as is those commercialized by SpinTek. The spinning membrane technology has proven economic in other specific applications but continues to be in need of evaluation for algal dewatering.

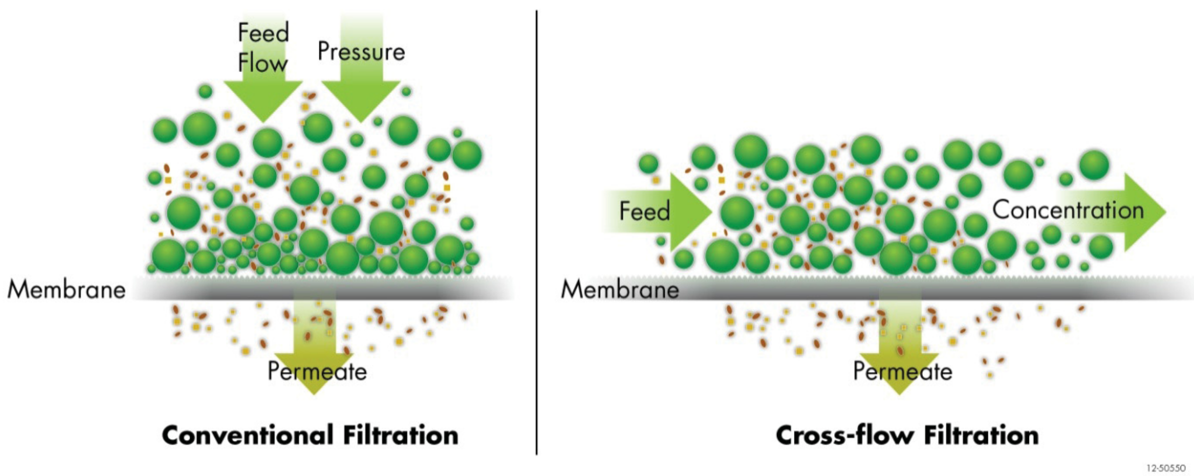

Figure 1. Schematic comparing conventional and CFF.

Preliminary technoeconomic evaluations suggest that tangential-flow filtration can concentrate feedstock up to 148 times by consuming 2.06 kWh m^{-3}, and that despite higher capital costs as compared with chemical flocculation/flotation, the payback period is only about half as long—roughly 1.5 years [5]. Research has and is being conducted to determine what combinations of parameters give the best results. Some improvements have been made by adjusting face velocity and transmembrane pressures. Other researchers have coated the surface of the filters with antifouling coatings such as porous ceramics. Such surface-coated membranes are being tested at PNNL [6]. Unfortunately, surface coatings tend to wear off by the constant bombardment of feed and particles in the feed. A significant improvement would be to embed the ceramic inside the porous metallic membrane structures to allow it to function, but also to protect it from erosion, thus making it more durable. INL has developed such embedded membranes and has proven them to be very effective in other high fouling-prone applications, such as sugar beet juice clarification [7, 8]. INL is investigating the use of these membranes for algal harvesting. The ultimate goal is to minimize penetration of the algae and associated cellular debris into the pores, increasing media permeability, while maintaining the integrity and longevity of the membranes.

Experimental Background

The SpinTek static test cell CFF unit uses flat sheet, open structured stainless steel (SS) membranes, which are rugged and commercially available. Figure 2 provides an overview of the SpinTek system used to assess performance of SS membranes and ceramic-embedded SS membranes for filtration of the algal strains and mixed populations. The SpinTek system consists of a reservoir that feeds into a pump. The liquid is pumped past a pressure gauge and throttling valve; through the membrane cell; past another gauge, throttling valve, and a heat exchanger; through a flow meter; and back to the reservoir. The pump motor is AC frequency-controlled and has a maximum speed of 1750 rpm at 60 hertz. The pump motor is connected through a gear box to the pump and has a maximum output of 4 liters per minute (Figures 2 and 3). On the left is the reservoir tank. The pump is physically situated below and behind the tank. The pump circulates the algae across the flat sheet membrane (circled in red, Figure 2) and then through a flow meter and back to the tank. The maximum pumping speed is 1 gal/min or 4 liters/min. The flow is directed through a serpentine path as shown in Figure 4, assuring turbulent flow for the system. The effective area of the membrane is 0.00465 m^2. Using the maximum flow rate of 4 LPM, it takes only 0.186 seconds to traverse the cell. This gives a face velocity of about 308 cm/sec.

Permeate is directed to a container sitting on a balance that is interfaced to a computer so that the mass of permeate with respect to time is collected (see Figure 3).

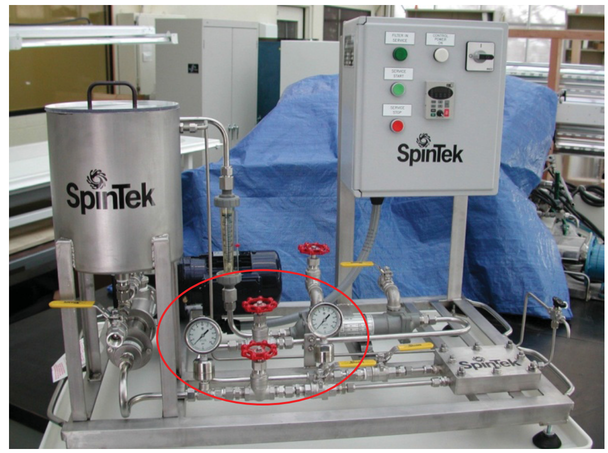

Figure 2. SpinTek static cell flat sheet cross-flow system.

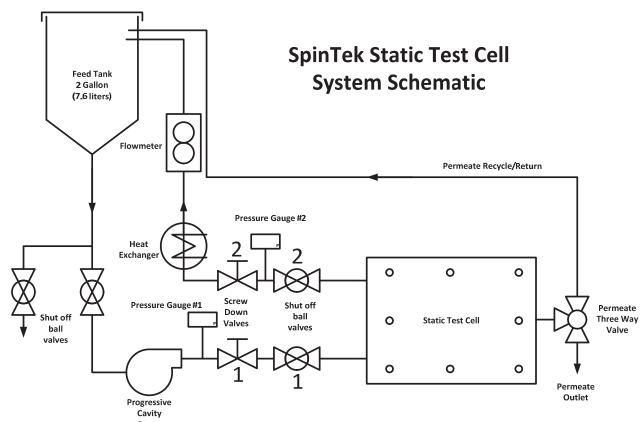

Figure 3. Schematic of SpinTek Static Test Cell System.

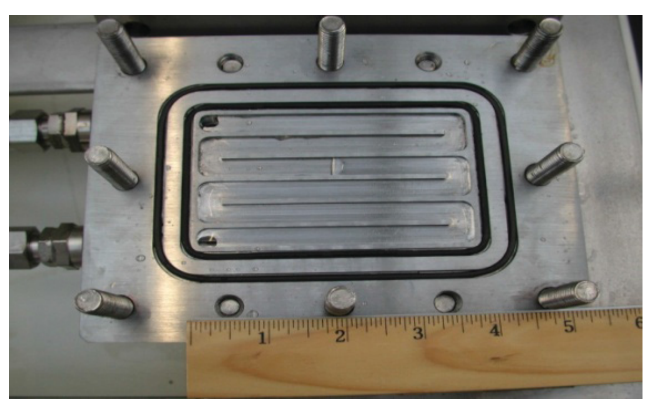

Figure 4. SpinTek membrane cell.

The Embedding Process

In previous work involving the clarification of beet juice, a significant improvement in the longevity of the porous stainless steel tubular membranes was realized by embedding the porous structure with fused ceramic particles [7, 8]. The particles were ‘filtered’ into the membrane tubes and calcined. By embedding the active filtration element inside the membranes and not on the surface, the ceramic was protected inside the matrix of the membrane and allowed the filter to maintain flux longer. The surface-applied ceramic in contact with feed is less resilient than ceramic embedded directly into the membrane.

In most industrial processes using membrane filtration, accessory material (debris, sand, dirt) suspended in the feed can damage the membrane and render it less effective. This foreign material can damage the membrane directly or slowly damage the membrane so it fouls at a higher rate. These suspended materials make it necessary to physically or chemically clean a membrane. As a cake builds upon the matrix of the membrane and does not get thoroughly cleaned (depth fouled), that membrane will ultimately have to be pulled out of production for deep cleaning or replacement [7]. In an effort to reduce membrane damage and maintain permeation flux rates, membrane embedding techniques were researched at INL. Embedding the membrane with substrate material like TiO_2 or ZrO_2 causes the fluid’s harsh bulk flow to interact directly with the substrate material and not the active filtration element (ceramic layer in this case), thus prolonging the membrane’s life while maintaining a lower initial permeation rate, but a much longer-lived filtration membrane.

Methods and Results

Embedding Method

INL initially developed the embedded membrane concept using internal laboratory-directed research and development (LDRD) funding. The same embedding methodology was applied to this work with the exception that the ceramic was embedded into flat sheet membranes. Work was initiated with 10, 20, and 30 wt% ceramic loadings as described below.

A sheet (28 cm × 53 cm) of porous stainless steel (SS) with a nominal pore size of 0.5 micron was used as the starting substrate.

A commercially available, surface-modified titania (titanium dioxide) with a diameter of 0.35 micron was added to nanopure water and a surfactant at 10, 20, 30, and 40 wt%. Initially, stainless steel disks with a diameter of 47 mm were infused with the slurry of titania then heated under nitrogen in a tube furnace at 900 degrees Celsius. These disks were tested for permeation before and after modification. At 300 torr, 100 mL of nanopure water was timed as it passed through the disks.

In membranes without modification, 100 mLs of nanopure water passed in approximately 10 seconds, whereas, the modified (embedded) disks took anywhere between 1.5 to 8 minutes. After various tests defining the embedding, larger square membranes to fit the SpinTek STC unit were designed and cut. The filtration rates correspond to 7.25 l/M^2-sec, 0.81l/M^2-sec, and 0.015l/M^2-sec, respectively, showing a significant decrease in membrane permeability and significant size exclusion properties for the filtration process as well.

SS square membranes measuring 11.5 cm × 7.5 cm were then cut from identical sheets as described above. These membranes were embedded as described above with 10-, 20-, and 30-wt% ceramic. Briefly, the pores of the SS filters were partially filled with very fine ceramic powder and then heated to cause the ceramic powder to sinter. This process results in pore size reduction while the embedded ceramic is protected from the flowing feed stream, as opposed to other approaches were ceramic is applied to only the surface of the membranes.

Determination Ceramic Loadings for Filtration Testing

As described above, to determine the most ideal wt% ceramic to embed into the membranes, three concentrations were selected at 10, 20, and 30 wt%. A *Chlorella* (USU80) culture at pond concentrations (0.1–0.5% solids) was used as the substrate for initial filtration tests with newly embedded 0.5-µm filters with various ceramic loadings.

The profiles of the runs are shown in Figure 5. The non-embedded filter shows a slow continuous drop in performance during the 8+ hour run. The 10- and 30-wt% embedded filters have a much flatter profile with very little drop in performance after 9 hours of running.

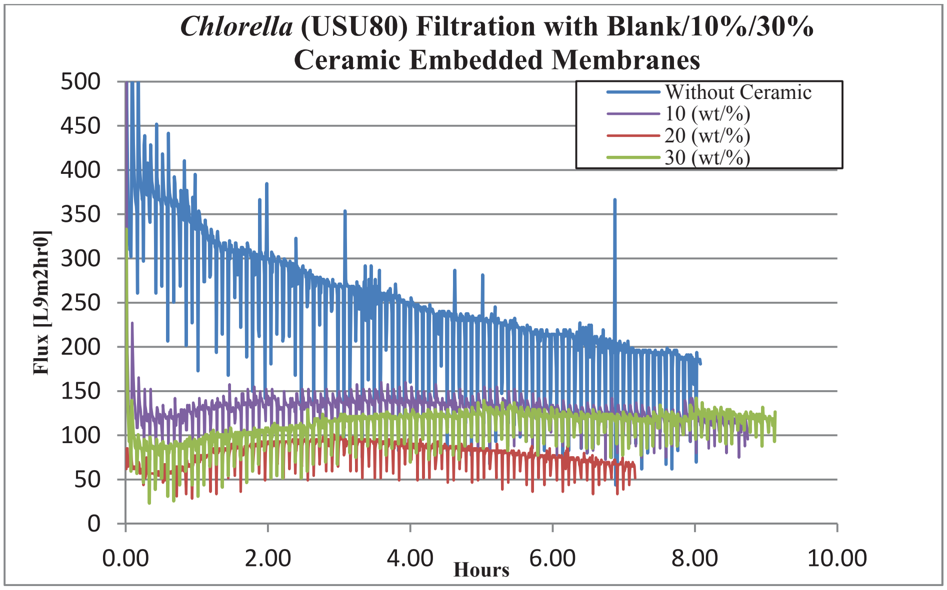

Figure 5. *Chlorella* (USU80) pond concentration 0.1–0.5% solids run against a native membrane and 10, 20, and 30% ceramic-embedded membranes.

While the native membrane's flux rate decreased to nearly linear fashion, the embedded membranes provided constant flux (albeit reduced flux initially) over the course of the test period.

Moderate initial flux and the ability of the membrane to maintain flux over extended periods of time were the largest contributing variables in choosing the embedding concentration of 10% ceramic by weight in each subsequent dewatering experiment. Algal pond characteristics vary by species and can change with daily external inputs throughout their growth cycles. To understand CFF more effectively, four algal species were tested using the SpinTek STC unit using the predetermined 10-wt% embedded technology.

This information expands our understanding of where filtration can be used within the harvesting/ dewatering supply chain. In order to effectively evaluate permeation flux from four different algal cultures, baseline cross-flow unit parameters still needed to be determined.

Establishing baseline parameters for filtration studies

In order to establish baseline parameters using the CFF unit, three parameters were tested in order to have optimal performance with the embedded membranes. These parameters included transmembrane pressure (TMP), flow rate, and backflush pressure.

Figures 6 and 7 show the effects of two important parameters: TMP and the feed flow rate in liters per minute (LPM). In this series of experiments both the feed flow rate and the transmembrane pressures were varied. When the membrane cell output valve is completely open, the reading on the input gauge is 11–12 psi corresponding to a TMP of 6 psi. At a TMP of 6 psi, the feed flow rate was tested at 4 LPM for one run and 2 LPM for the other. Under these conditions the higher flow rate gave significantly better fluxes over the entire run, demonstrating that a high surface shear reduces fouling. When the output valve was partially closed to produce a TMP of 36 psi, the benefit of having a higher flow rate decreased due to higher fouling.

When the TMP was set at 66 psi, the flow rates of the two runs (4 LPM and 2 LPM) were essentially indentical. This set of results suggests that the best run conditions for algae processes in this system were 4 LPM at a TMP of 36 psi or lower.

Membrane Backflushing

One of the most common techniques used to improve filter performance is membrane backflushing (Figure 8). The procedure simply forces a flow of liquid or gas from the membrane's permeate side to the membrane's feed side. This helps to knock loose any foulant build up on the membrane and improves performance, which increases the time between more aggressive surface cleanings.

In the INL system, a three-way valve was installed on the permeate transport tube. Under normal conditions, the permeate flows through the valve and into the collection vessel.

When the valve actuates, it closes the permeate flow tube and directs a flow of nitrogen gas into the permeate tube. This forces the liquid permeate and some of the gas back through the membrane. Overall, backflushing yields higher fluxes and longer run times (Figure 7). When the backflush occurs, it empties the liquid in the permeate volume, so some time is required to reestablish the permeate flow. Because the flow is improved after the flush, the flow is higher than just before the backflush. The peaks that look like "noise" peaks indicate the pressure pulses that result from the backflushing process.

In order to best approach CFF the transmembrane pressure was fixed below 36 psi with a flow of 4 LPM while backflushing was selected to flush at 10 minute intervals, which includes a pulse for approximately 4–5 seconds.

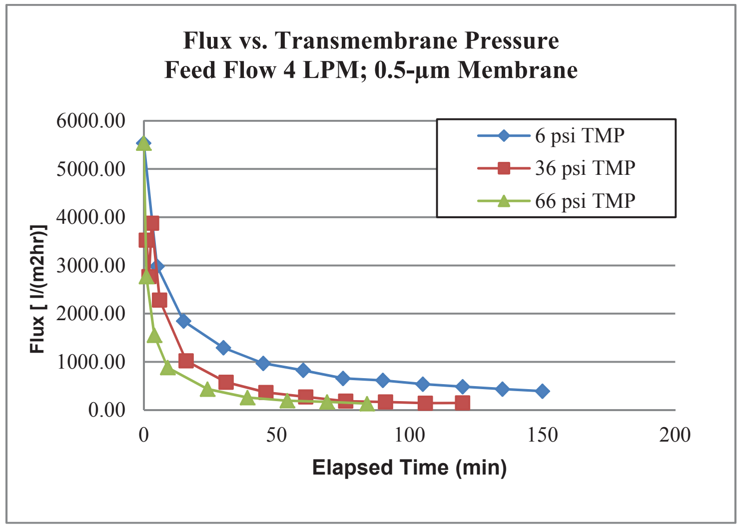

Figure 6. The various transmembrane pressures at 4 LPM using the *Chlorella sp.* (USU80).

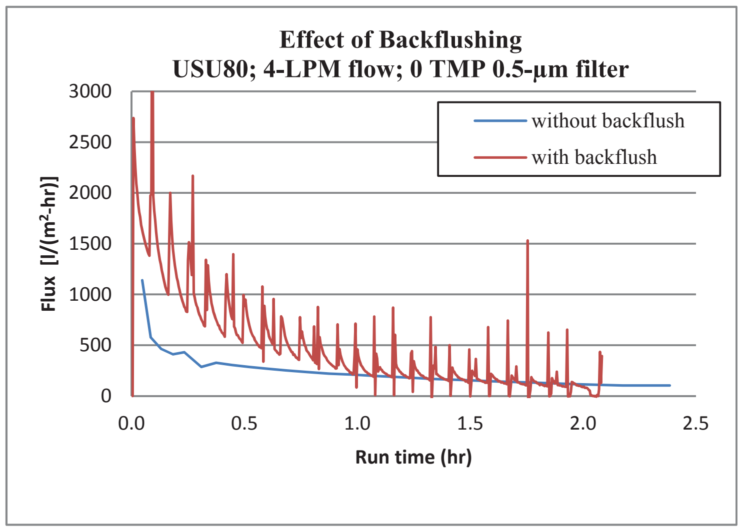

Figure 7. Effect of nitrogen back flushing on *Chlorella* (USU80) culture.

Figure 8. Nitrogen backflow before (left) and after (right) backflush.

Algae feed properties and microalgal strains

The four algae cultures described below were grown in closed photobioreactors in a greenhouse at INL. A *Chlorella* sp. (USU80) obtained from Utah State University (USU), and *Scenedesmus dimporphus* and *P. typcium* obtained from UTEX, were all grown in Modified Bold 3N media [9]. *C. gracilis* obtained from UTEX was grown in #25 media developed by USU. Each of these batch cultures were grown in 20-L clear carboys with appropriate lighting.

Each reactor was supplied with instrument air supplemented with 1% CO_2 throughout the entire growth period. Each culture was illuminated with full-spectrum bulbs with a schedule of 14 hours ON and 10 hours OFF to simulate the light and dark phases of algal growth.

Key results for four algal species using the SpinTek Static Test Cell (STC)

Each algal species behaves differently under similar filtration conditions. In each of the experiments performed, the STC unit was selected to run at 60 Hz, which maintains roughly 4 LPM throughout the system. The transmembrane pressure was set at ~11 psi while backflush pressure was maintained at 50 psi with nitrogen. Backflush intervals were set at 10 minutes with the duration of the backpulse set at 4–5 seconds. The cultures were maintained at a constant concentration throughout the test by recycling the filtrate back into the culture feed. The flux rate was monitored over prolonged periods of filtration (>180 minutes) with a feed that maintained constant % solids. This simulated a one-pass modular filtration system that could be partitioned in the algae supply chain and more specifically in dewatering. Maintaining constant feed allowed us to more specifically understand the permeation ability of the embedded filter over time.

Figure 9 shows the use of a *Chlorella* (USU80) strain using an embedded and non-embedded filter. As shown in the graph, the non-embedded membrane has a greater flux initially when compared to the embedded membrane. The flux of the non-embedded membrane, however, continues to decline with time as the membrane fouls. The embedded membrane's flux is initially significantly lower but continues to maintain a near steady state permeate flux for the duration of the experiment. Longer run times would be necessary to fully assess embedded versus nonembedded membranes. Membrane configurations that show permeation consistency in operation, suggest promise for long-term use of embedded membranes in a field application.

The four algal species in these studies included three green algae and one diatom. Figure 10 shows that in all four culture filtration runs, flux decreased slightly from the start of the test but was maintained for a substantial amount of time during the filtration run. Each upward pulse/spike in the graph indicates the nitrogen backflush pressure pulse.

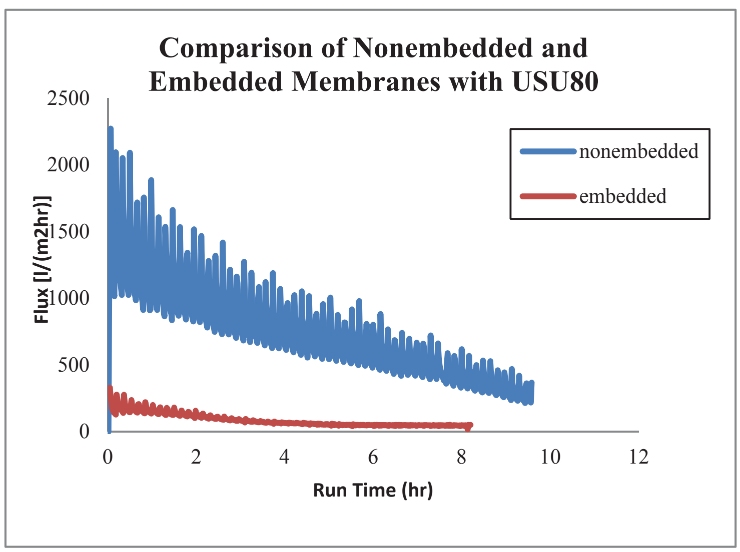

Figure 9. Comparison of a non-embedded and embedded membrane using a *Chlorella* sp. with a 0.5-µm membrane.

Significance

The principal defining characteristic of the effectiveness of membrane filtration is permeation flux. Permeation flux values define a membrane's ability to be useful for filtration because they can indicate how well membranes filter and retain solids. Although membranes can show promise at first, the fouling process can be slow but continuous. Traditional membranes used for filtration tend to foul and become damaged due to accumulation of small particles and colloidal material suspended within the feed upon the membrane surfaces.

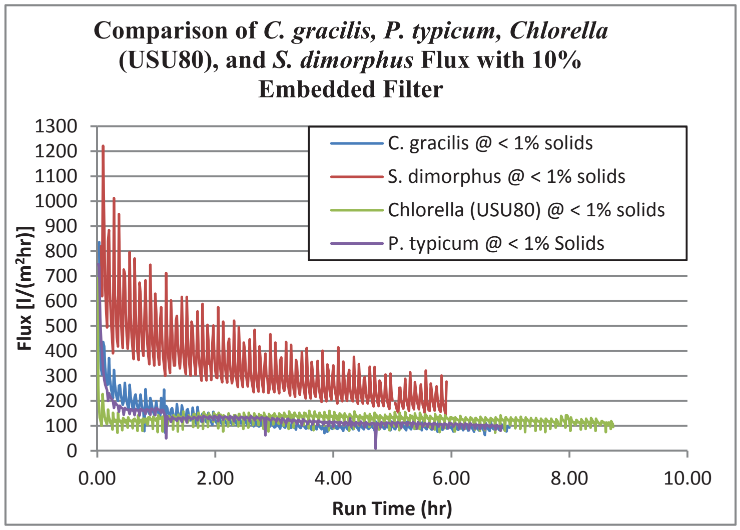

Figure 10. Filtration run on 4 algal species; *C. gracilis*, *P. typicum*, *S. dimorphus*, and a *Chlorella* (USU80) using 10% ceramic embedded filters.

As seen in Figure 10 and Table 1, the *Chlorella* sp. (USU80) and *P. typicum* parallel each other with relatively similar flux throughout the test runs. These two cultures have similar cell diameters from all of the species tested. These cells are generally smaller than *S. dimorphus* and *C. gracilis* and have more opportunity to clog the membrane and cause it to foul. The larger algae like *S. dimorphus* has overall higher flux when compared to other green algae like USU80 and *P. typicum* and could be less likely to foul the membrane. The diatom, *C. gracilis*, shows higher flux in the first couple of hours when compared to USU80 and *P. typicum* but then declines. This could be due to the fact that a number of the more fragile cells lyse and their contents slowly permeate into the membrane substructure causing fouling.

Furthermore, this could also be due to the fact that the diatom cells do not hold up to the vigor of culture recycling to maintain constant concentration (Table 1). This could be an indication as to the ability of different algal species to maintain viability during filtration and where boundaries can be established for these variations.

Table 1. Flux rates of multiple species of algae at different concentrations over 2-hour run time.

Algal Species	Flux Rate [L/(m^2-h)]			
Hours	0.5 (hr)	1 (hr)	2 (hr)	5 (hr)
C. gracilis	216	162	124	94
S. dimorphus	590	436	356	208
***Chlorella* (USU80)**	114	119	143	134
P. typicum	164	163	132	110

In all of the conditions tested in these studies, permeation flux values are over 90 L/(m^2-h). For industrial processes using CFF, it has been suggested that 30–40 L/(m^2-h) are considered acceptable [10].

In addition to the four algal mono-cultures individually run, three mixed cultures were also filtered using this technology. USU has been a partner in the dewatering work and supplied INL with two different open-pond raceway cultures from their outdoor facility in 20-L carboys. They were designated USU *Chlorella sp.* Mix Population #1 and *Chlorella sp.* Mix Population #2, as per location. These cultures were both initially a chlorella strain but had a variety of algae and debris. Three runs were performed using the *Chlorella* sp. Mixed Population #1 sample at 4-LPM flow rate with 0.2-µm and 0.5-µm filters at two transmembrane pressures (Figure 12).

After about an hour, the runs with the lower TMP and nominal pore size yielded the highest fluxes. The smallest pore membrane had the highest flux for the first 2 hours, which gradually came into line with the 0.5-µm membrane with a flux rate of ~150-L/(m^2-h).

Although the flux values differed from each filtration run, flux values for each of the runs after 2 hours were above 100 L/(m^2-h).

The *Chlorella* sp. Mix Population #2 culture was filtered using a lower TMP (~5 psi) with two filter pore sizes at 4-LPM flow rate (Figure 13). This culture had visually higher amounts of containments (leaves, dirt, dead insects) than the two outdoor ponds filtered, which could explain the lower flux values from these two runs. The 0.2-µm membrane had a flux rate of 53 L/(m^2-h), and the 0.5-µm membrane had a flux rate of 32 L/(m^2-h)after 2 hours of filtration.

In order to assess boundary conditions of filtration for algae, additional experiments using concentrated streams need to be performed (Figure 14). The use of these data in determining where filtration will fit in the dewatering steps is important and valuable in order to understand the true value of CFF. Boundary conditions have been established for pond concentrations from these experiments and are positive in the fact that they identify consistent filtration is achievable.

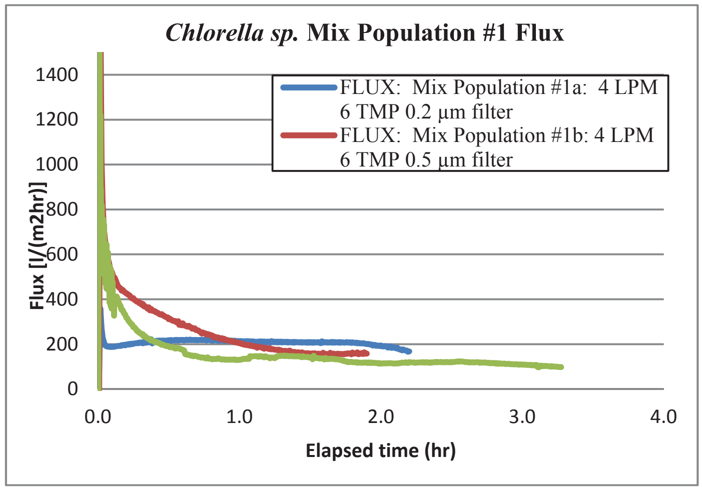

Figure 12. Flux values using *Chlorella* sp. Mixed Population #1 filtered using embedded membranes.

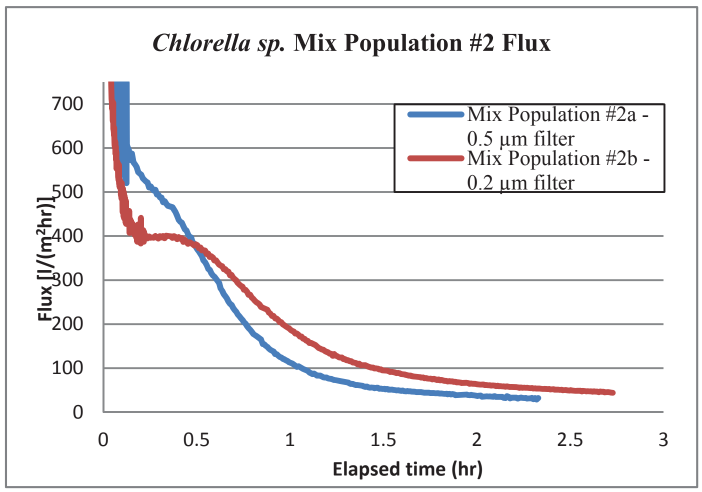

Figure 13. Flux values using Chlorella sp. mixed population #1 filtered using embedded membranes.

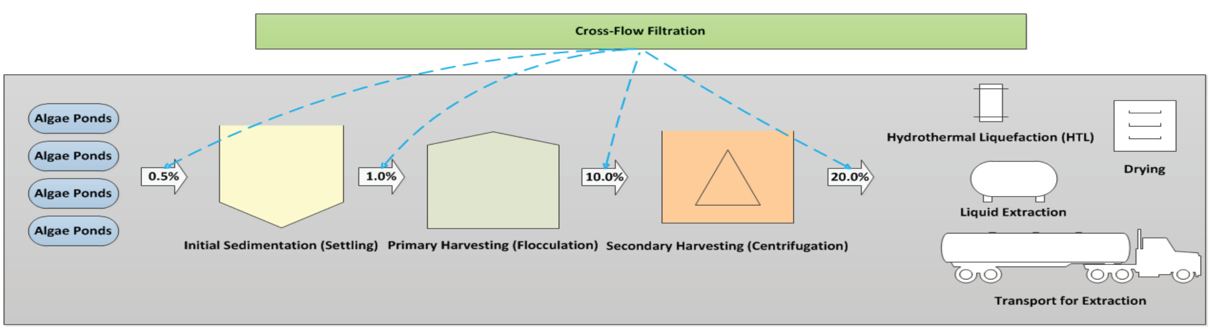

Figure 14. Biomass tracking from algal pond harvesting concentration through secondary harvesting. Dashed lines indicate potential harversting stages where CFF may be useful; a full understanding of CFF boundary conditions will allow identification of optimal utilization points for this technology.

In an effort identify insertion points for CFF in algal dewatering technology (Figure 15); a *Chlorella* culture was concentrated to 1.5 and 3% solids using INL's indoor raceway and a Sorvall/DuPont SS-34/KSB continuous centrifuge. Multiple raceways were grown for several weeks each, dewatered using the continuous centrifuge and combined to generate sufficient concentrated culture for boundary filtration experiments. These concentrated cultures were then run on the CFF system using embedded membranes.

The flux for 1.5 and 3% solids are relatively stable and consistent with each other. The flux for the 0.5% solids is approximately 3 times higher than the other concentrated cultures.

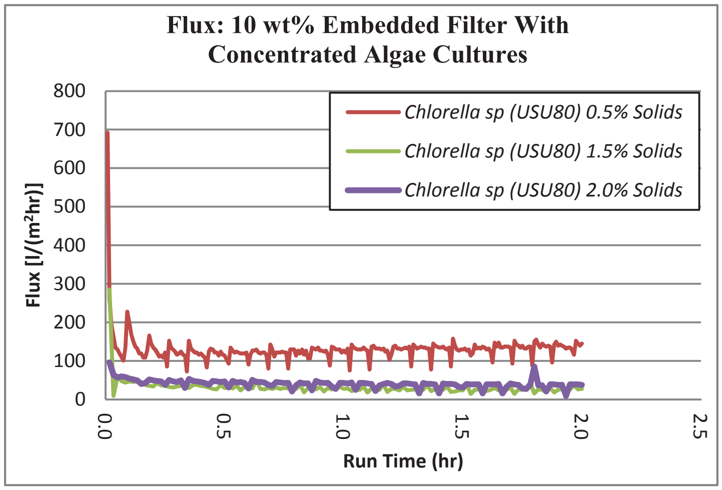

Figure 14. Flux rates for three concentrations of *Chlorella* sp. indicating the differences in flux between concentrations.

Energy Consumption

Although outside of the scope of these studies, a preliminary energy consumption study has been performed for the algal filtration process using the Static Test Cell and comparing the data with previous INL work on filtration of aqueous colloidal solutions, which showed similar behavior to algal feed streams at the STC stage of study. It is expected that moving to the small pilot scale with algae will give quite interesting and hopefully similar results. It is also expected that the economics of scale will provide a more economic process because the pump motors and thermal controls will be more carefully controlled (not over-specified by factors of 50 to 100 times, as is the case for the STC).

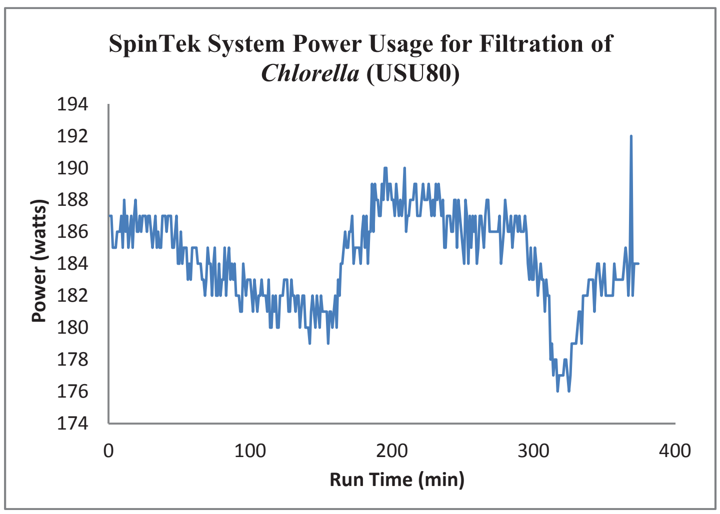

Figure 15. Average power usage for SpinTek STC using Chlorella (USU80).

STC Energy Consumption Estimate

Most power computations, however, are based on the number of kilowatts used per hour, or kwh. The average power that the SpinTek system is using is 185 watts or 0.185 kw. If the SpinTek unit is run for an hour, it would consume 0.185 kwh in most circumstances. A useful quantity to compare filtration systems would be the energy consumed to produce 1 m^3 (or 1,000 liters) of permeate. The following analysis is based upon the time it takes for our system during a run to produce an arbitrary amount. We chose 100 ml of permeate and assumed an average power consumption of 0.185 kw. Table 2 provides an example of calculations for energy consumption for the 100-ml sample.

Table 2. Example of the time and energy it takes to produce 1,000 L using the SpinTek STC.

Time to produce 100 ml	Time to produce 1000 ml or 1 L	Time to produce 1000 ml or 1 m^3	Time to produce 1000 ml or 1 m^3	Multiply by 0.185 to get:	Flux time figured for 100 ml
(min)		(hr)	(kwh)	[l/(m2-hr)]	
0.1	1	1000	17	3	12903
0.2	2	2000	33	6	6452
0.3	3	3000	50	9	4301
0.4	4	4000	67	12	3226
0.5	5	5000	83	15	2581
0.6	6	6000	100	19	2151
0.7	7	7000	117	22	1843
0.8	8	8000	133	25	1613
0.9	9	9000	150	28	1434
1	10	10000	167	31	1290

For example, with INL's current SpinTek system, if it takes 0.5 min to produce 100 ml of water, it will take 83 hours to produce 1,000 L m^3 of permeate, and would correspond to a system flux of 2581 L/(m^2-h). INL's system is significantly over-engineered and has a membrane area of only 0.00465 m^2, thus extrapolation to scale is likely to be show significant deviation from measurements performed at scale. In a recent report comparing energy costs associated with CFF and flocculation, it was noted that two runs with identical starting culture concentrations achieved a total permeation value of ~46 L h^{-1} (not flux) at 3 L min^{-1} flow rate and ~32 L h^{-1} at 5 L min^{-1} flow rate. This is a really high flow rate, but it is unsure what the membrane area was. Since this is unknown, it is hard to compare permeation flux with energy consumption. What can be calculated is the amount of energy used to permeate a cubic meter.

Conclusions

Data generated from these studies indicate that CFF with embedded membranes can be a viable dewatering technology and warrants additional research. Flux values with embedded membrane technology from multiple strains and two open-pond configurations maintain higher flux rates than what is considered adequate for industrial standards. Embedded membranes need further testing in real-world, open-pond configurations with environmental factors. At-scale filtration studies where flux and membrane erosion are tracked and measured would give a stronger determination of the effectiveness of embedded membrane technology. Membrane configurations that hold near steady-state flux rates, resist fouling, and are more corrosion resistant to abrasive culture contaminants will perform better and offer more efficient filtration flux over extended periods of time.

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