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Michael Christopher Malak
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**Full-Scale Operation of a Tubular Ultrafiltration
System in the Treatment of Oily Waste**

Michael C. Malak

Thesis submitted to the
College of Engineering and Mineral Resources
at West Virginia University
in partial fulfillment of the requirements
for the degree of

Master of Science
in
Civil Engineering

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Morgantown, West Virginia
1999

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ABSTRACT

An aluminum company in West Virginia uses an oil-water (metal working fluid) in their rolling mill process for lubrication. In the past, the company collected the oily-waste into two lined waste ponds with a combined holding capacity of 5 million gallons. Separation of the oil-water mixture occurred as emulsifiers in the metal working fluid broke down. Free oil was skimmed resulting in a pond effluent, which contained 0.2 to 1.0-% oil. Pond effluent was sprayed on a treatment field and the remaining oil was degraded naturally. The daily flow to the spray fields averaged 80,000 gallons. In 1993, concerns about direct land treatment of the waste surfaced, due to new groundwater regulations issued by the West Virginia Department of Environmental Protection. As a result, the company investigated alternatives for oily-waste treatment. The technologies studied were as follows: chemical addition dissolved air flotation (CA-DAF), biological aerated filter, tubular and rotary ultrafiltration (UF), land application, and constructed wetlands. The primary pollutant of concern was oil/grease (O/G).

Separation of the free oil in a single three million-gallon pond was selected as primary treatment. Tubular ultrafiltration was chosen as the secondary treatment process. Tubular UF was selected to treat the remaining water phase or pond effluent. Permeate from the tubular UF is sent to a hybrid constructed wetlands for polishing. Residual from the tubular UF is treated using high-shear rotary Ultrafiltration (HSR-UF). HSR-UF is able to concentrate oily-waste to ~ 70% oil. The residual from the HSR-UF was to be disposed of off site.

CHAPTER 1

INTRODUCTION

An aluminum company in West Virginia uses an oil-water mixture (metal working fluid) in their rolling mill process for lubrication. In the past, the company collected the oily-waste into two lined waste ponds with a combined holding capacity of 5 million gallons. Separation of the oil-water mixture occurred as emulsifiers in the metal working fluid broke down. Free oil was skimmed resulting in a pond effluent, which contained 0.2 to 1.0% oil. Pond effluent was sprayed on a treatment field and the remaining oil was degraded naturally. The daily flow to the spray fields averaged 80,000 gallons. In 1993, concerns about direct land treatment of the waste surfaced, due to new groundwater regulations issued by the West Virginia Department of Environmental Protection. As a result, the company investigated alternatives for oily-waste treatment. The technologies studied were as follows: chemical addition dissolved air flotation (CA-DAF), biological aerated filter, tubular and rotary ultrafiltration (UF), land application, and constructed wetlands. The primary pollutant of concern was oil/grease (O/G). Separation of the free oil in a single three million gallon pond was selected as primary treatment. Tubular ultrafiltration was chosen as the secondary treatment process. Tubular UF was selected to treat the remaining water phase or pond effluent. Permeate from the tubular UF was to be sent to a hybrid constructed wetlands for polishing. Residual from the tubular UF was to be treated using high-shear rotary Ultrafiltration (HSR-UF). HSR-UF is able to concentrate oily-waste to ~ 70 % oil. The residual from the HSR-UF was to be disposed of off site.

Following full-scale system construction, West Virginia University's Department of Civil and Environmental Engineering (WVU-CEE) was asked to startup the system and optimize performance.

OBJECTIVE AND GOALS

The objective of the entire study was to develop a standard operating plan for the entire oily-waste system. In partial fulfillment of this objective, the following goals were developed:

1. Develop operating plan for tubular UF system that optimizes system performance.
2. Determine free oil production rates.
3. Develop a mass balance model on oil for tubular UF system.
4. Investigate the role of concentration polarization on permeate flux.

Chapter 2

BACKGROUND

In this section membrane filtration; types of membrane separation processes; configuration of membrane geometries are discussed. In addition membrane limitations and factors controlling membrane performance and membrane fouling models will be discussed.

Membrane Separation

Membrane filtration is pressure driven separation process designed to separate fluid/fluid and particle/fluid mixtures using porous membranes. The membrane allows the fluid to pass and retains the particles and other dissolved substances. The membrane acts as a barrier that separates the material according to their physical and molecular size. Particles smaller than the pores on the membranes are allowed to pass while particles of larger size are retained or rejected. Material that pass through the membrane is known as permeate, while the retained material is returned to the feed tank to be concentrated further. Permeate flux is the term used to describe the rate at which the fluid is passing through the membrane. Flux is measured as volume/membrane area-time.

GENERAL TYPES OF MEMBRANE PROCESSES

The diameter of the particle or molecular weight of the molecule that is rejected in the separation process is one way to characterize membranes, known as the molecular weight cutoff or MWCO. There are several types of membrane filtration processes including Reverse Osmosis (RO), Nanofiltration (NF), Ultrafiltration (UF), and

Microfiltration (MF). In Figure 2.1, the usable range of each membrane processes are presented (Perry and Green, 1997).

REVERSE OSMOSIS

Reverse osmosis (RO) is a membrane separation technology that separates materials with diameters from $\sim 10^{-4}$ to 10^{-3} μm . The common particles that RO generally separates are metal ions and salts. As a result RO is mainly used for purifying brackish and sea waters.[Belfort, 1998] Osmosis is the diffusion of water through a semi-permeable barrier from an area of low concentration to an area of higher concentration. RO on the other hand, is the exact opposite of osmosis. In RO, the pressure in the concentrated side of the membrane is increase above the osmotic pressure so that the water diffuses from the more concentrated side to the pure waterside of the membrane.

NANOFILTRATION

Nanofiltration (NF) is generally the same type technology as reverse osmosis. The difference is that Nanofiltration separates particles from solution that range from $\sim 10^{-3}$ to 10^{-2} μm . NF is often used to soften water. Dewatering of pesticides and herbicides solutions is also another common use of Nanofiltration.[Perry and Green 1997]

ULTRAFILTRATION

Ultrafiltration (UF) is the separation process at which, hydrostatic pressure is applied to the feed solution. Water and dissolved materials, which have low molecular weights, are allowed to pass through the membranes. Larger particles such as emulsified oils and other suspended materials are rejected [Goldsmith, 1974]. UF is used to separate particle sizes that range from $\sim 10^{-3}$ to 1 μm . Use of ultrafiltration has been successful in

Figure 2.1 Usable Ranges of Membrane Process (Perry and Green, 1997)

metalworking processes such as rolling mills that use emulsified oil solution for lubrication. Some other applications for Ultrafiltration are presented in Table 2.1 [Toyomoto 1992].

MICROFILTRATION

Microfiltration (MF) is similar to UF. Microfiltration like UF uses an applied pressure to drive water through a porous membrane. The difference is MF has larger pore sizes than UF. MF is used to separate materials that range in size from $\sim 10^{-1}$ to $10\ \mu\text{m}$. Microfiltration is often used in industries such as fermentation, medical, food and beverage and electronic. Applications of MF are presented in Table 2.2. [Toyomoto and Higuchi, 1992]

MEMBRANES

Membranes used in separation processes are classified by the molecular weight or the diameter of the particle retained by the membrane. In theory, compounds having greater molecular weight than the molecule weight cutoff (MWCO) will be retained by the membrane. Compounds with less molecular weight than the MWCO will pass through the membrane as permeate. MWCO can be misleading, in that compounds with less molecular weights than the MWCO may still be retained by the membrane because of the compounds unique shape.

Membranes must be able to withstand the mechanical, chemical and biological stresses imposed during operation. Membranes are generally made from durable polymers that are able to withstand periodic cleanings to remove foulants and other debris from the

Table 2.1 Applications for Ultrafiltration

Industry	Applications
Fermentation	Sterilization and removal of micro-particles in liquid or gas
Medical	Transfusion filter set: hemocyte/serum separation: purification of surgical water
Electronic	Removal of microparticles from the ultrapure water; purification of chemicals and solvents
Food and Beverage	Purification of edible oils, beverages, draft beer and draft wine
Others	Removal of micro-particles from solvents and oils; water purifiers for home use; purification of condensed water at nuclear plants

Table 2.2 Applications for Microfiltration

Industry	Applications
Fermentation	Production of sterilized or pyrogen-free water; concentration/purification of enzymes; production of vaccines; purification of fermented liquors
Medical	Filter-type artificial kidney
Electronic	Purification of ultrapure water
Automobile	Recovery of electrodeposition paints
Chemical	Purification of colloid and emulsion
Food and beverage	Clarification of fruit juices; production of unrefined spirits; removal of dregs from soy sauce.

membrane's surface. The membranes are chosen by their compatibility with the waste stream, ability to retain particles and maintain performance over a long period of time.

Membrane manufacturing is important in understanding the separation and permeation mechanism of small molecules passing through a membrane. As stated before, membranes are generally made of durable natural polymers, such as cellulose or synthetic polymers such as, polycarbonate or polysulfone. In Figure 2.2, a schematic of general manufacturing of polymer membranes is presented [Cheryan, 1986]. The polymer is first mixed with suitable solvent and swelling agents. The mixture is known as cast dope. The next phase of the process is to test a small sample of the casting dope under controlled conditions to assure the casting dope makes a satisfactory membrane. The controlled test is usually performed in a glass plate. If the cast dope passes the quality control test, the entire batch is placed into the casting machine. The casting machine is the critical process in the production of membranes. Casting equipment is designed specifically for each type of membrane or module configuration. Therefore, the casting machines are usually designed and constructed by the manufacturers themselves. In general, membranes are manufactured in flat sheets. However, membranes can be cast directly onto the module they are made for (e.g. tubular modules). The membranes then undergo an annealing or drying process and are checked for performance characteristics before being constructed into the final form [Cheryan, 1986]. During the drying process, solvents in the casting evaporate forming the pores of the membrane. The membranes are then preserved in a wet storage.

Figure 2.2 A Schematic of the general Manufacturing Process of Membranes(Cheryan, 1986)

Cellulose Acetate Membranes

One common type of membrane used in UF applications is cellulose acetate membranes. The raw material for cellulose acetate membranes is cellulose. The major source of cellulose is wood pulp. Cellulose and its derivatives are linear, rod-like and rather inflexible molecules. These characteristics are important for RO and UF application in that these membrane processes are operated at high pressures. Therefore, the cellulose membrane material is excellent for withstanding these pressures. In Table 2.3, advantages and disadvantages of cellulose acetate membranes are presented [Cheryan, 1986].

Ceramic Membranes

Ceramic membranes are membranes that are made from inorganic mineral materials. In theory, ceramic membranes are extremely versatile, since these membranes are made of inorganic components. Unlike cellulose acetate membranes, both membrane and support structures are able to withstand wide ranges in temperature and pH. In addition ceramic membranes are very resist to chemical and abrasion degradation. Ceramic membrane durability have been tested using strong caustic soda solutions at temperatures approaching the boiling point and no apparent damage to the membranes were observed [Cheryan, 1986]. One disadvantage of ceramic membranes is that these membranes tend to be expensive, because of their durable qualities.

Table 2.3, Advantages and Disadvantages of Cellulose Acetate Membranes

Advantages	Disadvantages
Cellulose acetate strong molecular structure is ideal for pressure driven membrane processes.	Have fairly narrow temperature and pH ranges. (recommended max. temperature of 30°C, and pH range of 2-8 preferable 3-6)
High permeate flux and salt rejection properties.	Cellulose acetate membranes have been reported to undergo a compaction phenomena. (results in permeate flux decline)
Cellulose acetate membranes are easily manufactured.	Highly susceptible to biodegradation due to the natural cellulose material.
The raw material (cellulose) is a renewable resource.	Sanitizers such as chlorine, will oxidize cellulose acetate, thus damaging the membrane

CONFIGURATION OF MEMBRANE MODULES

There are many different module configurations for UF and MF used in commercial applications. The most common are tubular, spiral wound , hollow fiber and plate and frame [Belfort 1988].

Tubular

In Figure 2.3, a schematic of a tubular module is presented [MacNeil and McCoy, 1989]. A tubular membrane consists of a porous membrane that is cast as a tube on the inside of a support tube, which is in turn placed into a another tube usually made of PVC. The feed flows through the tube at a high velocity. The feed velocity has to be high enough to cause turbulence at the membrane surface. Reynolds numbers up to 130,000 have been used in tubular systems [Belfort, 1988]. The permeate is forced radially through the membrane and is collected through a port located at the end of the tube. Tubular membranes are usually between 5 and 10 feet in length and 0.5 to 1 inch in diameter. Operating pressures usually are about 90 psi for commercial units [MacNeil and McCoy, 1989]. Tubular units are easily cleaned. Large flow channels make it easier to remove accumulated material on the membranes surface [MacNeil and McCoy, 1989]. Disadvantages of tubular membranes are a low packing density.

Spiral Wound

In Figure 2.4, a schematic of the spiral wound module is presented [MacNeil and McCoy, 1989]. In the spiral wound module, several flat membranes are layered tightly together between a two plastic screen supports and then rolled. The membranes are then seal together at the edges and placed into permeate collection tube. [Belfort, 1988] The feed solution flow through the wound membrane. As it does, permeate is forced through

Figure 2.3 A Schematic of a Tubular Membrane Module (Perry and Green, 1997)

Figure 2.4. A Schematic of a Spiral Wound Membrane Module(MacNeil and McCoy, 1989)

the porous membrane and is collected. The feed material that is rejected flows to the end of the modules and exits. Spiral wound membranes can be operated at pressure up to ~ 150 psig. The diameters of these modules usually range from ~ 5 - 20 cm. A disadvantage to the spiral wound modules is that fouling occurs more readily than of the tubular membranes due to smaller flow channels [MacNeil and McCoy, 1989]. Spiral wound modules have been successful in some areas. Recently the spiral wound design was found to be one of the leading contenders for large scale commercial applications in the biotechnology field.[Belfort, 1988]

Hollow Fiber

In Figure 2.5, a schematic of a hollow fiber module is presented [MacNeil and McCoy, 1989]. Hollow fibers are bundled into a U-shaped arrangement for feed flow on the outside or in a straight pattern for feed flow on the inside. Opposite to tubular modules, hollow fiber membranes do not have an underlying support. For the U-shaped configuration, feed flows at high pressure across the outside of the hollow fibers. Permeate is forced radially inward through the unsupported fibers. The permeate collects in the center and flows to a collection chamber. For the straight pattern, the feed solution travels through the center bore. Permeate from the feed solution travels radially outward through the fibers. Hollow fiber membranes, similar to other membrane modules, have advantages and disadvantages. The U-shaped design is low in cost, compact and has a low water hold up. Disadvantages to the U-shaped design is that shell-side feed hollow fiber tend to plug easily and are relatively difficult to clean. The inside feed or straight configured hollow fiber design improves the possibility for cleanings, by reversing the

Figure 2.5. A Schematic of a Hollow Fiber Membrane Module (MacNeil and McCoy, 1989)

flow of permeate clogged pores of the membranes are cleaned. This design is increasingly being used in the biomedical and biochemical fields.[Belfort, 1988]

Plate and Frame

In Figure 2.6, a schematic of a plate and frame module is presented [MacNeil and McCoy, 1989]. Plate and frame systems have porous membranes with disc-shape spacers between them. The spacers are used to direct feed solution along the membrane's surface radially. The membranes can be placed in series or parallel inside the housing. Permeate is collected at the outer edges of the membrane discs. The concentrate or rejected material flows to the top of the housing and returns to the feed tank. An advantages to the design is a low volume hold-up per unit membrane area. The low volume hold up per membrane area makes this design an excellent system for recovering valuable biologicals. Another advantage with the design is that replacement of membranes are quick and easy. Disadvantages include, high probability for channel clogging and difficulties in cleaning effectively. [Belfort, 1988]

Membrane Operation Modes

There are three primary separation modes used in filtration. These separation modes are (1)semi-batch or modified batch mode, (2) batch mode and (3) recycle mode. Since membrane separation technologies are volume reduction processes, the concentration factor(CF) is an important system parameter. CF is defined as the ratio of feed concentration at a given time over the initial feed concentration. Concentration factors are generally expressed as 1X, 2X, etc, and increase as the separation system treats waste.

Figure 2.6 A Schematic of a Plate and Frame Membrane Module (MacNeil and McCoy, 1989)

Recycle Mode

In the recycle mode, feed solution is pumped to the membranes from a feed tank. As the feed travels along the membrane permeate is forced through the membrane and returned back to the feed tank. The reject solution also returns to the feed tank. Thus, the solution in the feed tank remains at a constant concentration. Pilot scale laboratory studies are often operated in recycle mode to test membrane performance at constant concentrations.

Semi-Batch Mode

In Figure 2.7, a schematic of the semi-batch operation mode is presented [Koch Membrane System, 1993]. In the semi-batch mode, fresh feed solution (1X) is continuously being supplied to the feed tank and the same rate permeate is leaving the system. As a result the concentration in the feed tank increases with time. It is possible to dewater large volumes of waste, thus, reducing the amount that needs to be disposed.

Batch Mode

In Figure 2.8, a schematic of the batch mode is presented [Koch Membrane System, 1993]. In the batch mode, the feed solution is pumped to the membranes from the feed tank. Unlike the semi-batch mode, fresh 1X feed solution is not continuously pumped into the feed tank while permeate is removed. The concentration in the feed tank increases as the volume decreases. Batch mode is often applied after the semi-batch mode to further reduce the volume of waste that needs to be disposed of.

Figure 2.7 A Schematic of Semi-batch Operation Mode (Koch Membrane Systems, 1993)

Figure 2.8 A Schematic of Batch Operation Mode(Koch Membrane Systems, 1993)

Particle Filtration

Ultrafiltration has proven effective in many different applications, such as waste rolling mill coolant and in the recovery of electrodeposition paints. Although, commercially successful, the mechanisms of the ultrafiltration process are not fully understood. The ultrafiltration of macromolecules causes a decline in the flux passing through the membrane. Concentration polarization and the formation of a gel layer are the main causes attributed to the decline in flux. [Jonsson and Tragardh, 1990] The gel layer is part of the concentration polarization layer. The gel layer is composed of macromolecules that have presumably reached the maximum concentration [Toyomoto and Higuchi, 1992]. Concentration polarization is defined as the accumulation of rejected solutes at the membrane's surface. A schematic of the concentration polarization phenomena is presented in Figure 2.9 (Cheryan, 1986). Solute is brought to the membrane surface by convective transport. As water permeates through the membrane solute molecules cumulate at the membranes surface. Flux decline occurs due to an increased resistance in the concentration boundary layer. Operating parameters such as, transmembrane pressure, temperature, cross-flow velocity and feed concentration influence the effects of concentration polarization. However, concentration polarization effects should be reversible since its effected by changing operating parameters (Cheryan, 1986). A drawing of these operation parameters effecting concentration polarization is presented in Figure 2.10. As transmembrane pressure is increased, feed concentration is increased, or hydraulic turbulence is decreased, the permeate flux becomes independent of pressure.

Figure 2.9 Concentration Polarization Phenomena(Cheryan, 1986)

Figure 2.10 Operation Parameters Effecting Concentration Polarization(Cheryan 1986)

Polarization Theory

There are three widely accepted models that are used to explain the relationship between permeate flux and operating parameters. They are 1) the osmotic pressure model, 2) the gel layer model, 3) the resistance in series model [Jonsson and Tragardh, 1990]. Before explaining these models a discussion of how fluid flows through membrane pores will be introduced. Fluid flow through porous membranes can be described by the Darcy equation.

(1)

$$J = K\Delta P / \mu \Delta L$$

where:

J = permeate flux, L/m^2h

K = specific permeability, m^2

ΔP = transmembrane pressure, Pa

μ = viscosity, Pa s

ΔL = membrane thickness, m

The membrane thickness, ΔL is difficult to measure in an asymmetric membrane. The reason being the pores of the membranes have increasing diameters. As a result the thickness is not constant. A solution to this problem, is to combine the thickness and the specific permeability to form the hydraulic resistance of the membrane, $R_m = \Delta L / K$.

Ultrafiltration is a separation process, therefore solutes and other particles are retained on one side of the membrane. Thus, the Darcy equation does not fully describe the flow through the membrane [Jonsson and Tragardh, 1990]

Osmotic Pressure Model

For typical Ultrafiltration applications of low concentration macromolecular solutions, the osmotic pressure is too small to be compared with the supplied pressure and for this reason can be neglected. For solutions with high macromolecule concentrations the osmotic pressure is also high and cannot be neglected [Toyomoto and Higuchi, 1992]. When the osmotic pressure due to solute accumulation at the membrane surface is not negligible, the Hagen-Poiseuille model often used to describe fluid flow through a membrane: (2)

$$J = \epsilon r^2 (\Delta P_T - \Delta \pi) / 8 \mu \Delta x$$

Where J = permeate flux, ϵ = membrane surface porosity, r = mean pore radius, ΔP_T = hydraulic pressure difference between the feed and the permeate, $\Delta \pi$ = osmotic pressure difference between the feed and permeate, μ = viscosity of the fluid permeating the membrane, Δx = membrane thickness. The osmotic pressure is generally small compared to the applied pressure in ultrafiltration applications such as oil in water emulsions [Cheryan, 1986]. In this case Hagen-Poiseuille Model is simplified:

(3)

$$J = \epsilon r^2 (\Delta P_T) / 8 \mu \Delta x$$

When using Hagen-Poiseuille Model several assumptions have to be made: (1) The fluid flow through the membrane pores is fully developed laminar flow. (2) The permeate is incompressible. (3) The permeate is Newtonian, meaning viscosity of the permeate is dependent on shear stress and shear rate. (4) Permeate flow is independent of time (steady-state conditions). [Cheryan, 1986]

Gel Layer Model

The gel layer model was the first model to explain the decrease in flux in UF applications. As stated previous, part of the concentration polarization layer is a nonfluid gel-like layer that forms at the surface of the membrane, when the solute concentration reaches the limiting value, c_g (the concentration of gel layer). Equation (4) is derived from equation (3) by replacing c_w with c_g , which is the concentration of the solute in the gel layer [Toyomoto and Higuchi, 1990]

(4)

$$J = K \ln(c_g - c_p)/(c_b - c_p)$$

Usually the concentration of the gel layer (c_g) is extremely high compared to concentration of the permeate (c_p). As a result c_p can be neglected and the equation is present as:

(5)

$$J = k \ln(c_g/c_b)$$

Equation (5) predicts a linear relationship between J and c_g with $-k$ being the slope of the line. Flow velocity, channel height, feed viscosity and the diffusion coefficient of the solute are all considered when determining the value of k .

Resistance in Series Model

The resistance in series models assumes permeate flux is determined by the membrane resistance (R_m), the concentration polarization boundary layer resistance (R_{bl}), and any layer of adsorbed solute resistance (R_a). With these assumptions, the resistance in series models is described by the following equation [Jonsson and Tragardh, 1990]:

(6)

$$J = \Delta P / \mu (R_m + R_a + R_{bl})$$

The concept of adsorptive layer resistance can be explained by realizing that some membranes might have the capacity to adsorb solutes from feed solutions. Adsorption onto the membrane walls might also occur when particles small enough to flow through the membrane pores adsorb to the membrane wall and as a result resist flow.

Membrane Fouling

Membrane fouling, similar to concentration polarization, can result in a decrease in permeate flux over time. However, membrane fouling is different from concentration polarization. For example, when the flow rate in a cross-flow membrane separation system is reduced, permeate flux will decrease. If the decrease in permeate flux is due to concentration polarization (i.e., the accumulation of solute molecules at the membrane's surface), the permeate flux should return to the initial value when the flow rate is raised. However, if the permeate flux does not increase to the initial value when the flow rate is increased, the membrane has experienced fouling.

Fouling is the term used to describe the loss of throughput of the membrane as it becomes physically and/or chemically changed by the feed solution. Membrane fouling is primarily due to pore plugging and/or solute adsorption. Fouling can be caused by a variety of compounds. Some of these foulants are 1) dissolved organics (humic substances, biological slimes and macromolecules), 2) dissolved inorganics (CaSO_4 , CaCO_3 , Mg(OH)_2 and Fe(OH)_3) and 3) particulate matter [Jonsson and Boesen, 1984]

In the case of pore plugging, solute molecules from the feed solution are forced into the membrane pores, causing a decrease in permeate flux. In Figure 2.11, a schematic of membrane fouling due to pore plugging is presented. Pore plugging is more prevalent in a situation where the membrane is subject to low hydraulic turbulence and high transmembrane pressure. At high transmembrane pressure and low hydraulic turbulence, the solute molecules have an increased chance of being forced into the membrane pores. Some solute particles, if small enough, enter the membrane pores and adsorb onto the pore walls. The adsorbed molecules cause a decrease in effective pore diameter. The decrease in effective pore diameter causes an increase in membrane resistance, thus decreasing the permeate flux. [Jonsson and Tragardh, 1990]

Lee *et al.* (1984) studied the effects on operating pressure on membrane fouling using 3% and 5% oil/water emulsions. In Figure, 2.12 the effects of operating pressure on permeate flux are presented (Lee *et al.*, 1984). At lower operating pressures, membrane fouling(loss of permeate) was negligible. However, permeate flux decline becomes more prevalent when the operating pressure was increased to 4 bars. Lee *et al.* (1984) concluded that as the pressure increased, the probability of oil droplets coming in contact with the membrane's pores increased. Additionally, some of the pores the operating pressure exceeded the capillary pressure. As a result the oil droplets were deformed and entered the membranes structure decreasing the permeate flux.

Membrane fouling is not an uncontrollable problem. The proper selection of operating conditions, membrane chemistry and cleaning methods are important factors that

Figure 2.11, A Schematic of Membrane Fouling Due to Pore Plugging (Cheryan, 1986)

Figure, 2.12 The Effects of Operating Pressure on Permeate Flux (Lee *et al.* 1984)

can minimizing permeate flux loss due to membrane fouling. For example, the operating pressure (transmembrane pressure) should be balanced to provide maximum permeate flux at minimum transmembrane pressure. An excess of pressure could cause solute molecules to deform and enter membrane pores as presented earlier in study performed by Lee *et al.* (1984).

Reed *et al.* (1997) reported that membrane fouling can be reduced by using hydrophilic and negatively charged membranes. A membrane with a negative charge may be chosen for a contaminant that is also negatively charged. The repulsive force between the contaminant and the membrane will act to decrease the amount of fouling that occurs. In addition, using a hydrophilic (water-attracting) membrane allows water to pass through the membrane's pores more readily.

The primary method of restoring permeate flux lost due to membrane fouling is membrane cleanings. Fouling which is removed through membrane cleanings is called "reversible fouling" and fouling that cannot be removed by cleanings is called "irreversible fouling." Although cleanings are used to restore permeate flux, the use of aggressive chemicals such as concentrated acidic and caustic solutions often result in shortened membrane life [Perry and Green, 1997].

Mathematical Models of Fouling

The simplest type of model relates flux to the time and/or volume permeated. In Table 2.4 a list of mathematical fouling models are presented [Cheryan, 1986/Mallevalle, 1996]. Most of the models assume that the build up of the fouling layer is a first order reaction. Additionally, the model are semi-empirical in that, the models do not help explain

Table 2.4 Mathematical Fouling Models(Cheryan, 1986/Mallevalle, 1996)

Model	Reference
$J = J_o t^{-b}$	Sheppard and Thomas(1970) Kuo and Cheryan (1983)
$J = J_o e^{-bt}$	Sheppard and Thomas(1970)
$J = J_o V^{-b}$	Merin and Cheryan (1980)
$J = e^a V^{-b}$	Matthews <i>et al.</i> (1978)
$J = J_{ss} + B e^{-bt}$	Concentration Polarization/Adsorption Model
$J = J_o / (1 + J_o k t)$	Cake Formation Model

or understand the phenomenon itself. Also, some of the models predict that permeate flux will be zero at infinite time, which may not actually occur in practice. These models are useful in that the parameters (b , fouling index, and J_0 , initial permeate flux at time zero) correlated with operating parameters can help give some understanding of the fouling phenomenon. [Cheryan, 1986]

Cheryan and Merin studied the fouling phenomenon during ultrafiltration of cottage cheese whey. In Table 2.5, the composition of cheese whey is presented [Cheryan and Merin, 1983]. To study the effects of individual proteins in the overall fouling process, each of the major protein fractions in cheese whey were made up in the proper concentrations presented in Table 2.5. The proteins that are present in cheese whey are α -lactalbumin, β -lactoglobulin and bovine serum albumin. Additionally, the role of salt in the fouling process was studied. Two different aqueous environments were studied; a whey dialysate (WD) buffer and a salt free system (SF). The WD system mimicked the original environment of the cheese whey. The model that best fit the data was based on the assumption that the amount of flux is a function of the cumulative volume permeated. The equation is as follows:

$$J = J_0 V^{-b}$$

Where J is instantaneous flux at any time t , J_0 is the initial flux at $t = 0$, V is the volume permeated, and b is the fouling index. [Cheryan and Merin, 1983]

During the experiment a total of eight different feeds were studied. Whey, α -lactalbumin, β -lactoglobulin and bovine serum albumin (BSA) were dissolved in SF and WD environments and processed in the UF system. In Figure 2.13, the results of SF system are presented.

Table 2.5. Composition of Cheese Whey. [Cheryan and Merin, 1983]

Composition	Concentration, %
Total Solids	6.0 – 6.5
Lactose	4.5 – 5.0
Salts	0.5 – 0.9
Fat	0.1 – 0.5
α -lactalbumin (Protein)	0.16
β -lactoglobulin (Protein)	0.4
Bovine serum albumin (Protein)	0.04

Figure 2.13. Result of the Salt Free System. [Cheryan and Merin, 1983]

A similar set of curves were obtained in the WD system [Cheryan and Merin, 1983]. Since fouling seemed to occur immediate after UF started up, the experiments were held at 10 minutes of operational time. Fouling was found to occur in two stages: an initial rapid decline in flux followed by a more gradual decline in flux. In Table 2.6 a list of J_0 and b values for WD and SF system are presented [Cheryan and Merin, 1983]. In general, J_0 and b presented in Table 2.6, implies that the presence of salts have significant effects on the rate of flux decline. Additionally, α -lactalbumin had the strongest gel-forming tendencies (lowest J_0), and β -lactoglobulin had the worst long-term fouling effects (highest b values). The original whey, had the worst overall fouling due to the combined effects of the individual proteins and salts.

Kuo and Cheryan (1983) conducted a fouling study of an acid whey in a spiral wound unit. The study focused on the effects of pressure and flowrate on the fouling index, b . The experiments were conducted at pressures of 240, 310 and 485 kPa. The flow rates were 3 and 10 L/min at 240 kPa, 3 and 8 L/min at 310 kPa, and 3 and 10 L/min at 485 kPa. To keep feed concentration constant, a total recycle mode was used. The fouling model that was used during the study is as follows:

$$J=J_0t^{-b}$$

Where J is the permeate flux an any time t , t is the operation time, J_0 is the instantaneous flux at $t = 0$ and b is the fouling index. [Kuo and Cheryan, 1983]

A summary of the results of the experiment are presented in Table 2.7. In general, higher flow rate and intermediate transmembrane pressure of 310 kPa, reduced the rate of

Table 2.6. Value of J_0 and b from Cheryan and Merin experiments

Protein	System	J_0	b
Whey	Native	1.369	0.297
	SF	1.905	0.163
α -lactalbumin	WD	1.722	0.123
	SF	1.549	0.160
β -lactoglobulin	WD	2.694	0.214
	SF	3.163	0.136
Bovine serum albumin	WD	2.777	0.147
	SF	1.853	0.069

WD = whey dialystate environment, SF = salt free environment

Table 2.7, Results of Pressure and Flow Rate on the Fouling Index, b (Kuo & Cheryan, 1983)

ΔP_T (kPa)	Q (L/min)	Jo (L/min)	B
240	3	1.1234	0.179
	10	1.2687	0.089
310	3	1.1595	0.191
	8	1.4067	0.126
	10	1.4579	0.076
485	3	1.2790	0.208
	10	2.3446	0.384

fouling at least in the initial stages. However, at the highest transmembrane pressure studied, high flow rate did not benefit permeate flux. In addition, b values decreased in general, with increasing flow rates at the low and intermediate pressure (indicating a lower fouling rate with higher flow rate). However, a sharp increase in b was observed at the highest pressure. The phenomena stated above can be explained by Kuo and Cheryan fouling theory. The theory states: “The rate at which membranes foul by particulate deposition is controlled by the rate of deposition (V_d) and the rate of removal of the deposited material (V_r), e.g., by shear forces. If $V_d > V_r$, fouling will occur and a decline in flux will be observed. At higher flow rate, the rate at which solutes are brought in contact with the membrane is high, but the removal by shear forces is also high. The resulting effect is that the net rate of deposit ($V_d - V_r$) is lower at low flow rates.” [Kuo and Cheryan, 1983] Such a phenomenon was observed in the first 90 to 120 minutes of Kuo and Cheryan’s experiments. However, after that period of time, a sudden change in the fouling rate occurred. The change in fouling rate that was observed in the experiment is presented in Figure 2.14.

The reason for the change in fouling rate was complicated. Although a total recycle of rejected material and permeate was maintained, it was theorized that small solutes, e.g. lactose and salts, which pass through the membrane, could get “trapped” in the pores. The solutes became trapped either by adsorption or “crowding”. As more permeate passed through the membrane, the trapped solutes would further concentrate and would eventually crystalline and precipitate in the pores. Kuo and Cheryan observed that fouling occurred in three stages in their experiments. The three stages are as

Figure 2.14 Three Stage Change in Fouling Rate, (Kuo and Cheryan, 1983)

a relatively rapid flux decline, 2) after most of the adsorptive site are saturated, $V_d - V_r$ approached zero, thus a constant flux would be observed, 3) as the membrane continues to produced permeate, solutes trapped in the pores would become crowded, and eventually precipitate in the pores further reducing flux.

Sheppard and Thomas (1970), studied the effects of circulation velocity a commercial cellulose acetate membrane to determine performance. To model the fouling the following equation was used:

$$J = J_o(e^{-bt})$$

Where: J = Flux at time t
T = time of operation
 J_o = initial flux at $t = 0$
b = fouling index

The average flux over a 1-yr period of operation is only 24.4% of the initial flux, when the value of b is 0.3 and the average flux over a 1-yr period of operation exceeds 90% of the initial flux only when the value of b is less than 0.02.

From the study, the mean value of the exponent, b, decreased from 0.09 to 0.026 as the axial velocity increased from 1.64 to 24 ft/s. Increasing the axial velocity from 1.64 to 24 ft/s would on the average increase the average flux during the first years of the operation from 64.5 to 88% of the initial value.

Operating Parameters

The following operating parameters are important for UF systems. These operating parameters are: (1) feed cross-flowrate, (2) transmembrane pressure, (3) temperature/viscosity, (4) cleaning procedure.

Flowrate

Volumetric flowrate is defined as the volume of wastewater pumped through the membrane unit. In a crossflow filtration system, high feed flowrates will create turbulence, which in turn reduces the influence of concentration polarization at the membrane surface. Turbulence in a membrane system is one of the simplest methods of controlling the effects of concentration polarization.

Reed et al. (1997) looked at the effects of crossflow velocity on the treatment of an oily wastewater using a tubular UF system. By increasing the crossflow velocity from 9 to 21 ft/s, increased the P(negative charged) and M(non-charged) membranes fluxes from 33 to 38 gal/ft²-d and from 20.5 to 24 gal/ft²-d, respectively. The cross-flow velocity was increased by increasing the applied pressure in the system.

Transmembrane Pressure

The transmembrane pressure is the driving force in UF systems. The average transmembrane pressure is calculated by the following equation:

(7)

$$P_{tm} = [(P_{in} + P_{out})/2] - P_{perm}$$

where; P_{tm} is the average transmembrane pressure

P_{in} is the pressure at the entrance of the membrane

P_{out} is the pressure at the exit of the membrane

P_{perm} is the pressure exerted on the permeate (usually zero)

Mahdi and Skold (1991) conducted UF experiments on synthetic metal working fluids to determine the effects of temperature and inlet pressure on flux. At 25 °C, inlet pressure was increased from 0.2 to 0.3 kPa and an increase in the initial flux was from ~

25 to 25 L/m²-h. At a temperature of 30 °C, an increase in inlet pressure from 0.2 to 0.3 kPa caused an increase in initial flux from ~ 21 to 30 L/m²-h. Studies by Applegate (1984) using a UF system, proved that higher transmembrane pressures increase productivity of membranes. Increasing the pressure from 0.5 to 33 psig, increased the permeate flow from ~ 1.51 to 2.27 m³/d at a crossflow velocity of ~ 3.35 m/s.

Reed *et al.* (1997) performed pressure excursion experiments using a tubular UF system treating an oily waste. The transmembrane pressure was increased from 27.5 to 43.5 psi. The resulting permeate fluxes of the P(negative charged) and M(non-charged) increased from 34 to 43 gal/ft²-d and from 16 to 26 gal/ft²-d, respectively.

Temperature/Viscosity

Temperature control in UF systems is important due to some membranes being sensitive to high temperatures. Temperature also influences viscosity. As temperature of the feed is increased, feed viscosity decreases resulting in a higher permeate flux. The decrease in viscosity results in an increase in fluid flow through the membrane (Jonsson *et al.*). Increasing temperature can proven to be beneficial in UF system, however, some membranes cannot tolerate high temperature. As a result these membrane systems are operated at lower feed temperatures. An increase in viscosity occurs with lower feed temperatures, therefore, an increase in power may be necessary to pump the fluid. Wahl *et al.* (1979) interviewed 21 full-scale tubular UF operators and determined that wastewater temperature ranged from 50 to 100 °F and averaged 92 °F.

Yuksel et al. (1991) reported that treatment of an aqueous phase of a demulsified mixture was sensitive to temperature changes. The critical temperature was approximately 35 °C. Operation below this temperature resulted in treatment of waste with a lower oil viscosity. The low oil viscosity resulted in increased fouling because the oil was able to pass into the filter and lower the efficiency of the filter. This effect was reversed if the temperature was increased.

Mahdi and Skold (1991) conducted a field study on a waterbased metalworking fluid using a UF system. At a constant pressure of 0.2 kPa, an increase in feed temperature from 25 to 30 °C increased permeate flux from approximately 12 to 22 L/m²h. At a constant pressure of 0.3 kPa, an increase in temperature from 25 to 30 °C, increased permeate flux from ~ 22 to 31 L/m²h.

pH

The pH of a feed solution is an important operating parameter because some membranes may be degraded at extreme pH levels, depending on their material composition. Feed pH can also effect solute-membrane and solute-solute relationships. The pH of membrane cleaning solutions vary in pH, from very acidic to very basic. Therefore, degradation of the membrane should be considered before deciding on the type of cleaner for the membrane.

Cleaning Process

After the membranes have become fouled and permeate flux decreases to unacceptable levels the membranes are cleaned. There are several methods used for cleaning membrane systems. One method commonly used is washing the membrane with a base solution followed by an acid solution. There are 6 steps in base/acid cleaning method. These are cleaning steps are (Blank and Brady, 1993):

1. Flush system of wastewater with clean water
2. Clean system with a caustic/surfactant solution for roughly one hour. Typically the cleaning solution is a 0.1% solution, pH ~ 10, 100-110°F.
3. Flush system with warm water to remove cleaning solution.
4. Clean system with an acid solution, to remove salt deposits (at 100-120°F for one hour).
5. Flush the system to remove acid with warm water.
6. Perform a clean water flux to confirm cleanness of membrane

For large tubular membranes, spongeballs are sometimes used. The spongeball are sent through the membranes tubular to remove fouling. The spongeballs are effective at removing particles on the membranes surface. This type of mechanical cleaning is often used in membrane systems that treat oil and water wastes [Blank and Brady, 1993]. The spongeballs increases the contact between the oil on the membrane surface and the soap. [Pinto, 1978].

Another method of cleaning is backwashing. Hollow fiber membranes are capable of being backwashed. In this case, the particles that are lodged in the membrane pores and dislodged by the reversed flow through the membranes.

Zaidi et al. (1992) conducted field scale experiments using ceramic tubular filtration units to remove oil from oilfield brines. A three step process was used to clean the membranes. The three step process included: 1) a hot caustic wash, 2) a fresh water rinse, and 3) acid wash. Investigators concluded that cleaning with detergents and mechanical means did not always restore the filters original flux. Thus some fouling was considered to be irreversible.

CHARACTERISTICS OF OIL-IN-WATER EMULSIONS

The metal-working industry produces large amounts of oily wastewaters. Some the metal working processes that use large volumes of emulsified oils for lubrication and cooling include, metal rolling, forming, grinding and cutting operations. These metal working lubricants provide 1) control friction, 2) reduced tool wear and 3) improve surface quality of the workpiece. Metal working lubricants commonly consist of petroleum oil compounds, water and various additives. Petroleum oils occur naturally. These petroleum oils are refined by means of distillation, solvent extraction or molecular sieving. There are two commonly used types of metalworking lubricants. These lubricants are straight oils and emulsions [Laemmle, 1991].

Straight oils are generally made up of petroleum oil derivatives, which provide excellent friction reduction and good corrosion protection. Disadvantages of using straight oils are their poor capability to remove heat and are potential fire hazards due to

the low flash points. Straight oils are generally used when lubrication is the major factor and cooling is the minor factor [Laemmle, 1991].

Emulsions are mixtures that consists of either simple or compound oils added to water. Two major advantages to using emulsions is the oil phase portion capability to lubricate and the water phase to cool industrial equipment. A schematic of an emulsified oil droplet is present in Figure 2.15. [Burke, 1991] In a oil-water emulsion, oil is said to be the “dispersed phase” and water is the “continuous phase.” Typical oil globule sizes from ~ 0.2 to $10\ \mu\text{m}$. Since the typical size of the emulsified oil droplets are similar in size to, or larger than, the wavelength of visible light, emulsions appear milky white. [Laemmle, 1991].

Emulsions have to be stabilized with emulsifiers because oil-in water mixtures are not thermodynamically stable. In other words, the state of lowest free energy is total separation. As a result, emulsifiers have to be added to stabilize the mixture and prevent the oil and water from separating. Emulsifiers concentrate at the oil-water interface and prevent oil globule coalescence. Emulsions can vary in stability, depending on the characteristics of the oil and the concentration and nature of the emulsifiers. Since the hydrophilic end of the oil-water emulsion is negatively charged, the net surface charge of the emulsified oil droplet is negative. The emulsified oil droplets tend to stay dispersed due to electrostatic repulsion between the emulsified oil droplets. The emulsion is then said to be kinetically stable because the state of lowest free energy if the emulsion is still total separation [Laemmle, 1991].

The ability of the oil-water emulsion to provide adequate lubrication is tied into the availability of the oil phase to lubricate. Two factors controlling availability of the oil

Figure 2.15, A Schematic of an Emulsified Oil Droplet (Burke, 1991)

phase is emulsion stability and concentration of oil in the emulsion (percent oil). In general, the higher the percent oil, the greater is the availability of oil or lubrication.

Also,

the higher the percent oil, the less stable an emulsion is. Additionally, as the oil content increases cooling capability decreases because there is less water for cooling.

Unfortunately, the less stable the emulsion is, the greater the chance of rapid, often unpredictable declines in stability. The unpredictable behavior can lead to operating problems in metalworking processes. Therefore, the stability and percent oil of an emulsion must be balanced to meet the lubrication and cooling needs of the metalworking operation.

Since oil-water emulsions are kinetically stable, rather than thermodynamically stable, the “batch life” of the emulsion has to be taken into consideration. New emulsions are generally the most stable and have the least oil available for lubrication. Over time the maximum performance of the emulsion is reached as emulsifiers are depleted through biological degradation and as debris generated in the emulsion provides nucleation sites for globule coalescence. Yet, as the emulsion degrades further, the emulsion becomes very unstable and has to be disposed of. New emulsion has to be introduced into the process. Emulsion that are initially less stable have a shorter batch life than emulsions which are more stable initially [Laemmle, 1991].

Typical oil-water emulsions used in rolling mill process contain petroleum oils, emulsifiers, biocides and antifoaming agents. In general, emulsion solutions used in metalworking operations contain approximately 5 to 10 % oil and approximately 90 to 95 % water [Laemmle, 1991].

CHAPTER 3

MATERIAL AND METHODS

During the fabrication process, metal working fluid mixtures are used for lubrication. The metal working fluid or coolant consisted of a 5 percent mineral oil and 95 percent de-mineralized water. The coolant is monitored over this period and when the coolant fails to meet certain process specifications, it is pumped out of the hot line mill to a 600,000 gallon storage tank. While in the storage tank pH of the waste is checked to prevent treatment problems down stream of the tank. In Figure 3.1, a schematic of the treatment process is presented. If the pH is in the range of 4 to 8 the coolant is either pumped or gravity drained to pond #2. Pond #2 is a fully designed RCRA facility with double liner and leak detection. The capacity of pond #2 is roughly 3 million gallons. While residing in pond #2 for roughly 28 days, emulsifiers in the waste coolant breakdown. The oil that separates is skimmed off the top of the pond. The resulting water phase or pond effluent had a remaining oil content of 0.2 to 1.0 %. The oily waste is then pumped by 25 horsepower Goulds pumps, to two identical concentration tanks located adjacent to the tubular ultrafiltration building. Each concentration tank is capable of holding 20,000 gallons of raw waste and is ~ 18 feet tall in height. The concentration tanks supply oily waste to the two tubular Ultrafiltration unit located inside the adjacent building.

Two tubular crossflow ultrafiltration skids were used in this study. In Figure 3.2, a profile on one UF skid is presented. In each skid, 736 Koch membranes were arranged into 23 rows. In each row, two banks exist, containing 16 membranes that are connected

Figure 3.1 Proposed Treatment Process

A. Figure 3.2 Profile of the Tubular UF System

in series. The individual membranes are 9.0 feet long, with a membrane surface area of 2.2 ft². The tubular membranes are negatively charged and rated for a MWCO of 120,000. The molecular weight rating of these membranes allows water to pass through the pores on the membrane, while retarding or resisting the larger oil molecules.

System Overview

During the initial pre-start up, oily waste or pond effluent from pond #2, is pumped to the 20,000 gallon concentration tank until the tank is filled to a level of ~ 15 feet. The waste is supplied to the system by a 25 horsepower Goulds open impeller centrifugal pump located on the UF skid. A larger 125 horsepower Goulds open impeller centrifugal pump receives the waste and sends the waste to two identical manifolds. From each manifold the oily waste is sent to 23 membrane banks. In Figure 3.2, a schematic of the top view membrane configuration in each UF unit is presented. Each of the 23 membrane banks has 16 tubes or membranes connected in series. The water that passes through the membranes are channeled through permeate collection tubes. The collection tubes direct all permeate into permeate manifolds. The permeate flowrate is constantly monitored by a Bailey Fischer and Porter magnetic flowmeter. The permeate leaves the system and is discarded in to pond #1. Pond #1 similar to pond #2, is a fully designed RCRA facility with double liners and leak detection.

The rejected oil that did not pass through the membrane is collected into two concentrate manifolds. From these manifolds a portion of the concentrate is directed back to the 125 horsepower pump where it is recirculated to maintain the necessary cross-flow velocity. The cross flow velocity for the systems averages ~12 ft/s and

B. Figure 3.3 Top View Membrane Configuration

Reynolds numbers $> 100,000$. The portion of the concentrate that was not redirect back for recirculation, is returned to the 20,000 gallon concentration tank. In the concentration tank, the fluid returning from the system is mixed with the waste and eventually undergoes the same process described above.

The process explained above is a semi-batch process. As permeate is removed the level in the concentration tank drops. The level of the oily waste inside the concentration tank is monitored by Milltronic electric level indicators. When the level inside the tank drops to the specified point of 11.0 ft, the feed pump at the pump house sends more pond effluent into the tank and fills the tank up to its initial level of ~ 15.0 ft.

As the UF system concentrates the oily waste, an amount of free oil separates out of the solution and rises to the top of the tank forming a layer. As the process continues more and more oil accumulates at the top of the feed tank. Skim-Pak oil skimmers located in the concentration tanks skim off this layer and send it to an oil sump located at the base of the tank. From this sump, the oil is pump to storage tanks and then sold for other purposes or disposed of. Without these skimmers to extract the free oil, the sonic level indicators would start to malfunction. The oil can absorb or distort the signal being sent by the meter, resulting in inaccurate level readings.

While the system is operating, certain system parameters are observed on a PLC to monitor system performance. Recycle and concentrate pressures are monitored to assure a proper transmembrane pressure of 54 to 58 psi are maintained. The maximum pressure allowed to be exerted by the recirculation pump is 92 psi, in order to protect the membrane from being damaged. The recirculation pressure could be controlled by a butterfly valve located on the discharged side on the pump. Concentrate pressure was

controlled on the PLC by using Bettis pressure control valve. Recycle, concentrate and permeate flowrates were also monitored on the PLC. Concentrate temperature was measured on inline temperature probe located in the recycle stream of the system. Maximum concentrate temperature was set at 120 °F to protect against membrane and system damage.

System Operation

An experiment or run started by filling one of the 20,000 gallon tanks with fresh 1X pond effluent from pond #2. A run was defined as the semi-batch of the waste in the concentrate tank. A run ended when the contents in the tank were purged to storage tanks for disposal. Runs are subdivided into subruns. Subruns are defined as the interval of time the system was in operation (concentration mode) between system cleanings. Over the course of these subruns, permeate flux was monitored. The system was developed to operate at a average permeate flow of 29 gal/min or average flux of 25.8 gal/ft²-d each. This set point enables the systems to produce roughly 80,000 gallons of permeate per day. To assure that the demands on the system are being met, a running permeate average was updated daily. If the average permeate flow dropped below the 29 gal/min the system was shutdown and cleaned. Another parameter that was used to determine the length of a subrun was the instantaneous permeate flow. A operating set point of 18 gal/min or 16 gal/ft²-d was used, because a low flow such as this is not recommended by the producer of the membranes.

Other parameters that were monitored throughout a subrun included permeate turbidity, and pH and conductivity of both the concentrate and the permeate.

Sampling Procedure

While the system operated samples of the concentrate, permeate, pond effluent and skimmed oil from tanks were taken. The frequency and method of analysis for each sample taken, will be discussed in following section.

Concentrate Samples:

Concentrate samples were taken 2X/week while the system processed waste, to be analyzed for oil content. The sample port was located on the bottom half of the concentrate tanks. Triplicate samples were taken at the beginning and end of a subrun for QA/QC. If a subrun last for a long period of time, concentrate samples were then triplicated every 10%. To determine the oil content of the concentrate samples, the analytical lab located on site, utilized an acid split solution, and consisted of saturated sodium bisulfate with 20 percent sulfuric acid. Equipment needed to perform the analysis consisted of an 8 % graduate babcock bottle, 20 mL pipette and centrifuge. Once the samples were mixed thoroughly, 20 mL were extracted and placed into each of the 8 % babcock bottle. Then approximately 20 mL of acid solution are added to each and then mixed. The babcock bottles were then placed into a heated water bath and boiled (100 °C) for a minimum of 30 minutes. After 30 minutes, the babcock bottles were filled up to the bottle neck with more acid solution and placed in the centrifuge in balanced positions. The samples were then centrifuged for a minimum of 20 minutes, refilled with acid to top of graduated neck and centrifuge for an additional 20 minutes. The percent oil content

was read directly from the bottle graduation to the nearest 0.1 percent. [Century Aluminum Corporation Technical Dept.]

Permeate Samples:

Permeate samples were taken roughly every twenty four hours and analyzed for turbidity, pH, conductivity and temperature. Samples were taken from a permeate drain line that was connected into the permeate to pond #1 manifold. Every other sample that was taken during operation, was analyzed for oil and grease. Triplicate samples were taken every 10% for QA/QC. To determine the oil and grease of the permeate samples a Freon extract test was used. The reagents and working solutions needed for the analysis was Trichlorotrifluoroethane Optima Grade Freon and De-ionized water. The equipment consisted of a Horiba Oil Content Analyzer Model OCMA-220, two graduated cylinders and a waste beaker. After the analyzer readings have stabilized, 15 mL of the permeate sample was measured out and poured into the sample inlet located on the analyzer. The same amount of freon was measured out and poured into the same inlet. The system then automatically analyzed the amount of oil concentration present in the sample. After the instrument stabilizes the reading can be read directly from the display. The measurement range for this analysis was 0 to 200 ppm.

[Century Aluminum Corporation Technical Dept.]

Pond Effluent Samples:

Pond effluent samples were taken roughly every other day and analyzed for oil content, using the method described earlier. Samples were taken from sampling port located on a six inch feed line to the concentrate tanks.

Concentrate Tank Skimmings:

Oil that was skimmed from the top of each concentrate tank was sampled regularly for oil content. A sample was taken from the oil sump where the skimmings collected before being sent to the storage tank area. Due to the high oil content of the skimmings acid split solutions could not be used for this analysis. A procedure utilizing a centrifuge and 15 mL graduated pear shaped bottle was implemented. After the skimming sample was mixed vigorously, 10 mL of the sample were poured into the pear shape bottle. The sample was then placed into a centrifuge in a balanced position, using a water filled blank if necessary. The samples were centrifuged for a minimum of 30 minutes. The result could be read directly on the graduated bottle. The measurement range for this analysis was from 0 to 100 ± 0.05 percent.

Flushing the System

After the system was shutdown a flush sequence ensued. During the flush, a 4000 gallon flush tank was used. The tank was either filled with permeate from the two UF systems or with softened water. The flush lasted for a total of 4 minutes. The purpose of the flush was to remove the majority of oily-water from the system before the cleaning solution is utilized.

Cleaning

Once the system was flushed, the membranes were cleaned before the wastewater can be processed again. Cleaning removes the build-up of oil and other material from the membranes surface. Removing oil and other debris from the membranes allows for higher fluxes.

The first stage in the preparation of cleaning was to make up the cleaning solution. Koch recommended a 0.5 - 1.0 % KLD or "Koch Liquid Detergent" cleaning solution for the membranes. To reduce cleaning costs a 0.5% solution was used for the cleaning. To achieve the mixture, 6 gallons of KLD was added to ~ 600 gallons of softened water. Softened water was used during the cleaning for two reasons. The EDTA in the KLD soap will react with the ions the produce hard water. Thus reducing the KLD's cleaning effectiveness. Additionally, using hard water at high temperatures can cause scaling at the membranes surface. The cleaning tank used in these experiments was a 1000 gallon CIP or "Cleaning in Place" tank. Once the solution was made, the contents were mixed and heated for approximately 3 hours or until the cleaning solution reached a temperature of 130 °F. While the cleaning solution was heated, it was pH adjusted to ~ 10 using Kochkleen 120.

Once the cleaning solution was heated and pH adjusted, the chemical clean mode is initiated. The cleaning solution had to be reheated and pH adjusted to ~ 10 again once the solution was circulated through the system. The actual cleaning was started when the concentrate temperature reached 120 °F. The system was allowed to circulate and clean for a period of 40 minutes. Over the course of the 40 minute cleaning, temperature, turbidity, pH, conductivity and permeate flux were monitored. Permeate flux was monitored every 10 minutes. Permeate temperature, pH, turbidity, and conductivity were monitored every 15 minutes. Cleaning feed temperature, pH and conductivity were monitored every 30 minutes.

After 40 minutes elapsed, the system was shutdown and prepared for a spongeball cleaning. Spongeball cleaning were instituted in order to scour and clean the pores of the

membranes. The spongeballs, were supplied by Koch and were 0.5 inches in diameter. Once the valves were adjusted on the system for spongeball retrieval, the system underwent two spongeball passes. During each pass, fifty spongeballs were allowed to travel through the system once. During the spongeball sequence, the PLC was monitored closely to note the maximum permeate flow achieved. After the spongeball sequence was performed, the valves were readjusted to the normal mode setting. The system was then cleaned for an additional 40 minutes with the same cleaning solution.

Acid Cleaning

Acid cleanings were initiated when system performance was below average. Over time metals ions clog the membrane pores and spongeballing doesn't remove them totally. As the metals ions build up, the permeate flux decline directly affecting the treatment rate. As a result, acid cleanings are instituted to remove the metals from the pores of the membranes. Acid cleanings were also implemented before starting a new run, insure that the membranes were as clean as possible to start the new run.

The acid cleanings were performed after the system was cleaned with KLD and flushed with 4000-gallons of water. The CIP tank was drained, cleaned with hot water and refilled with 600 gallons of softened water. The water was then pH adjusted to ~2.2 as it heated to 120 °F. The pH adjustment was performed using a mixing tank located adjacent to the cleaning tank. The pH adjusting solution consisted of one box of the proprietary carboxylic acid to 55 gallons of softened water. When the desired temperature was reached, the acid mixture was allowed to circulate through the system for one hour. Similar to the KLD cleaning, temperature, turbidity, pH, conductivity and permeate flux

were monitored during the acid cleaning. After one hour elapsed on the acid cleaning the system was flushed with water. The CIP tank was drained, cleaned out and refilled with softened water. A 0.3% KLD solution was made by adding ~ 3 gallons of KLD to 600 gallons of water. The cleaning solution was then heated to 120 °F and allowed to circulate for one hour. The same parameters were monitored for this cleaning as well.

CHAPTER 4

RESULTS

In the following section, the results that were obtained at the facility are presented. Information that will be presented in this section is as follows: characteristics of influent, permeate and concentrate, cleanings, and flux characteristics.

UF1-R7

UF1-R7 started on January 16, 1998 at 09:40 and ended on February 7, 1998 at 00:50. The run lasted for 21.2 days. The objectives of the run were: 1) monitor system performance, 2) estimate the volume of free oil that forms at the top of the concentrate tanks and 3) conduct an oil mass balance on the system in order to note the change occurring in the system. UF1-R7 had 4 subruns. Each subrun and cleaning is discussed separately in the following sections.

In Figure 4.1, permeate flux versus time for UF1-R7 is presented. In Figure 4.2, permeate turbidity versus time for UF1-R7 is presented. In Table 4.1, a summary of permeate operating parameters for UF1-R7 is presented. In Table 4.2, a summary of concentrate operating parameters for UF1-R7 is presented. In Table 4.3, a summary of permeate cleaning parameters for UF1-R7 is presented. In Table 4.4, a summary of concentrate cleaning parameters for UF1-R7 is presented. In Table 4.5, a summary of permeate O/G samples analyzed for UF1-R7, is presented. In Table 4.6, a summary of concentrate oil content samples analyzed for UF1-R7, is presented. In Table 4.7, a summary of free oil skimming samples analyzed for UF1-R7, is presented. In Table 4.8, a summary of free oil production for UF1-R7 is presented.

Figure 4.1 Permeate Flux versus Time for UF1-R7

Figure 4.2 Permeate Turbidity versus Time for UF1-R7

Table 4.1. Summary of Permeate Parameters for UF1-R7

Subrun ID	Flux (gal/ft²-d) [min – max] Avg ±std	Temperature (°F) [min – max] Avg ±std	Turbidity (NTU) [min – max] Avg ±std	pH [min – max] Avg ±std	Conductivity(μS/cm) [min – max] Avg ±std	O/G (mg/L) [min – max] Avg ±std
1	[13.3 – 56.9] 23.2±11.8	[69.2 – 79.1] 75.9±3.1	[6.9 – 14.7] 10.7±2.6	[6.1 – 6.6] 6.3±0.14	[406 – 685] 558±65	[2 – 8] 4.1±2.4
2	[19.6 – 96.9] 43.5±22.4	[71.7 – 76.8] 74.4±2.2	[4.5 – 7.0] 5.8±0.96	[5.4 – 6.0] 5.8±0.24	[66.4 – 704] 453±247	[4 – 6.7] 5.4±1.2
3	[16 – 99.6] 31.2±17.8	[73.1 – 80.0] 76.5±2.5	[0.84 – 11.1] 2.8±2.8	[5.4 – 5.7] 5.7±0.25	[82 – 759] 528±186	[2 – 5] 4.3±1.1
4	[17.8 – 34.7] 22.9±2.9	[73.2 – 78.2] 76±1.4	[0.84 – 3.7] 1.9±1.0	[4.5 – 6.3] 5.6±0.44	[165 – 601] 465±139	[2 – 6] 4.4±1.5

Table 4.2. Summary of Concentrate and Pond Effluent Parameters for UF1-R7

Subrun ID	Temperature (°F) [min – max] Avg ±std	pH [min – max] Avg ±std	Conductivity(μS/cm) [min – max] Avg ±std	Oil Content (%) [min – max] Avg ±std	Pond Effluent O/G (mg/L) [min – max] Avg ±std
1	[72.8 – 84.7] 80.5±3.8	[6.4 – 7.1] 6.7±0.34	[531 – 646] 585±47	[0.65 – 1.45] 1.1±0.4	[0.4 – 0.6] 0.5±0.1
2	[76.0 – 82.0] 78.9±2.7	[6.1 – 6.4] 6.2±0.19	[177 – 440] 308±186	[1.45 – 5.0] 3.2±2.5	[0.5]
3	[76.5 – 86.0] 81.2±3.1	[5.7 – 6.1] 5.9±0.24	[18 – 615] 404±336	[5.0 – 7.4] 6.2±1.7	[0.5 – 1.6] 1.0±0.5
4	[78.9 – 82.1] 80.5±1.1	[4.9 – 6.1] 5.5±0.44	[261 – 429] 364±77	[7.4 – 9.1] 8.2±0.9	[0.46 – 1.2] 0.7±0.3

Table 4.3. Summary of Permeate Cleaning Parameters for UF1-R7

Subrun ID	Flux (gal/ft²-d) [min – max] Avg ±std	Temperature (°F) [min – max] Avg ±std	Turbidity (NTU) [min – max] Avg ±std	pH [min – max] Avg ±std	Conductivity(μS/cm) [min – max] Avg ±std
1	[33.5 – 86.3] 62.3±8.9	[89.2 – 98.0] 93.3±3.9	[43.8 – 108.9] 68.8±29.6	[6.7 – 6.8] 6.8±0.03	[628 – 742] 688±52
2	[36.5 – 68.5] 54.8±4.8	[89.2 – 102] 95±5.2	[5.6 – 40] 17.8±14	[5.7 – 6.5] 6.3±0.33	[687 – 919] 823±100
3	[21.3 – 26.7] 26.1±1.2	[87.7 – 98.0] 92.8±3.0	[3.9 – 10.7] 6.6±2.1	[4.9 – 6.5] 5.7±0.64	[449 – 617] 562±59
4	[28.5 – 37.4] 32.9±1.9	[88 – 98.7] 93.6±3.7	[7.3 – 15.0] 10.4±2.2	[6.5 – 7.0] 6.7±0.12	[589 – 718] 644±39

Table 4.4. Summary of Concentrate Cleaning Parameters for UF1-R7

Subrun ID	Temperature (°F) [min – max] Avg ±std	pH [min – max] Avg ±std	Conductivity(μS/cm) [min – max] Avg ±std
1	[95 – 110] 103.5±5.5	[6.7 – 6.8] 6.8±0.03	[1342 – 1420] 1383±37
2	[95 – 110] 102.5±5.8	[5.7 – 6.5] 6.3±0.33	[1482 – 1850] 1656±156
3	[95 – 106.4] 101.5±4.8	[4.9 – 6.5] 5.7±0.64	[520 – 944] 761±135
4	[95 – 107.5] 102.2	[6.5 – 7.0] 6.7±0.12	[968 – 1109] 1058±51

Table 4.5 Summary of Permeate O/G Samples for UF1-R7

Subrun ID	Date/Time	Sample Results (mg/L)		
		#1	#2	#3
1	1/16/98 (17:20)	2		
1	1/17/98 (04:35)	4	3	5
1	1/18/98 (02:08)	6		
1	1/18/98 (15:02)	3		
1	1/19/98 (04:45)	2		
1	1/19/98 (15:36)	2		
1	1/20/98 (05:45)	8		
2	1/20/98 (23:15)	4		
2	1/21/98 (11:32)	6		
2	1/22/98 (13:27)	5		
2	1/23/98 (00:32)	7	7	6
3	1/24/98 (01:12)	2		
3	1/25/98 (02:02)	4		
3	1/26/98 (01:30)	5		
3	1/26/98 (12:46)	4		
3	1/27/98 (10:00)	5		
3	1/28/98 (02:57)	5		
3	1/29/98 (02:37)	4	5	6
4	1/30/98 (04:21)	5		
4	1/31/98 (01:08)	3		
4	2/1/98 (02:07)	4		
4	2/2/98 (00:39)	6		
4	2/2/98 (23:37)	6	5	6
4	2/3/98 (22:25)	5		
4	2/4/98 (22:37)	6		
4	2/6/98 (03:39)	5		
4	2/6/98 (23:38)	1	3	4

Table 4.6 Summary of Concentrate Oil Content Samples for UF1-R7

Subrun ID	Date/Time	Sample Results (%)		
		#1	#2	#3
1	1/15/98 (14:20)	0.6	0.7	
1	1/16/98 (10:30)	0.6	0.6	0.6
1	1/16/98 (16:32)	1.2	1.0	0.9
1	1/17/98 (11:45)	0.8	1.0	0.6
1	1/18/98 (19:40)	1.6	1.9	1.4
2	1/20/98 (17:16)	2.2	1.4	1.5
2	1/22/98 (00:29)	3.9		
3	1/23/98 (19:10)	3.4	5.0	
3	1/26/98 (16:58)	7.6	7.6	7.4
3	1/29/98 (07:55)	7.4	7.6	7.6
4	2/2/98 (13:10)	7.8	8.0	8.2
4	2/6/98 (16:07)	5.0		
4	2/7/98 (00:16)	6.2	9.6	8.6

Table 4.7 Summary of Skimming Samples for UF1-R7

Subrun ID	Date/Time	Sample Results (mg/L)		
		#1	#2	#3
1	1/16/98 (11:00)	4,000		
1	1/17/98 (11:05)	6,000		
1	1/19/98 (15:18)	5,000		
2	1/21/98 (13:25)	5,000		
3	1/23/98 (19:35)	5,000		
3	1/25/98 (11:25)	16,000		
3	1/27/98 (10:00)	14,000		
3	1/28/98 (21:46)	6,000	6,000	7,000
4	2/1/98 (13:20)	8,000		
4	2/2/98 (12:15)	12,000		
4	2/3/98 (10:50)	6,000		
4	2/4/98 (14:20)	6,000		
4	2/5/98 (23:39)	5,000		
4	2/6/98 (23:16)	5,000	4,000	5,000

Table 4.8 Summary of Free Oil Productions for UF1-R7

Subrun ID	Subrun Length, d	Total Free Oil, gal	Free Oil Production, gal/d
1	4.1	0.0	0.0
2	2.9	258	88.9
3	5.9	1,464	248.1
4	8.3	1,752	211.1

In Table 4.9, a summary of pond effluent samples analyzed for UF1-R7, is presented.

UF1-R7-SR1

UF1-R7-SR1 was started on January 16, 1998 at 09:40 and ended on January 20, 1998 at 12:07. The length of the subrun lasted 4.06 days. The total permeate volume produced was 134,050 gal.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 13.3 to 56.9 gal/ft²-d. Permeate temperature ranged from 69.2 to 79.1 °F with an average of 75.9 °F. Concentrate temperatures ranged from 72.8 to 84.7 °F with an average of 80.5 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content started out at around 0.65% and increased to 1.45 % by the end of the experiment. The total volume of free oil that was produced during subrun #1 was 0 gallons. The average daily free oil production was 0.0 gallons/day.

Oil/Grease (O/G), Turbidity and Pond Effluent

Permeate O/G remained low, averaging 4.1 mg/L and ranging from 2.0 to 8.0 mg/L. Permeate turbidity ranged from 6.9 to 14.7 NTU with an average of 10.7 NTU. Pond effluent ranged from 4000 to 6000 mg/L and averaged 5000 mg/L during subrun #1.

Conductivity and pH

Permeate pH ranged from 6.1 to 6.6 with an average of 6.3. Concentrate pH

Table 4.9 Summary of Pond Effluent O/G Samples for UF1-R7

Subrun ID	Date/Time	Sample Results (mg/L)		
		#1	#2	#3
1	1/16/98 (11:00)	4,000		
1	1/17/98 (11:05)	6,000		
1	1/19/98 (15:18)	5,000		
2	1/21/98 (13:25)	5,000		
3	1/23/98 (19:35)	5,000		
3	1/25/98 (11:25)	16,000		
3	1/27/98 (10:00)	14,000		
3	1/28/98 (21:46)	6,000	6,000	7,000
4	2/1/98 (13:20)	8,000		
4	2/2/98 (12:15)	12,000		
4	2/3/98 (10:50)	6,000		
4	2/4/98 (14:20)	6,000		
4	2/5/98 (23:39)	5,000		
4	2/6/98 (23:16)	5,000	4,000	5,000

ranged from 6.4 to 7.1 with an average of 6.7. Permeate conductivity ranged from 531 to 646 $\mu\text{S}/\text{cm}$ and averaged 585 $\mu\text{S}/\text{cm}$. Concentrate conductivity's ranged from 406 to 685 $\mu\text{S}/\text{cm}$ and averaged 558 $\mu\text{S}/\text{cm}$.

UF1-R7-SR1 Cleaning

After UF1-R7-SR1 was shutdown on January 20, 1998 at 12:07, it was cleaned at 13:00 using a 0.5 % KLD cleaning solution. The cleaning solution was recycled for total of two hours. Cleaning was started at a temperature of $\sim 100^\circ\text{F}$. The system temperature was not allowed to increase above 110°F due to a pipe rupturing in previous experiments. If the system temperature reaches 110°F , it is shutdown and allowed to cool, to approximately 100°F . After which it is started again to finish the rest of the two-hour cleaning. Total downtime for this cleaning was 300 minutes. Over the course of the cleaning, temperature, turbidity, pH, conductivity and permeate flux were monitored. Permeate flux was monitored every 10 minutes. Permeate temperature, pH, turbidity, and conductivity were monitored every 15 minutes. Concentrate temperature, pH and conductivity were monitored every 30 minutes. The same procedure for data collection was carried out in future cleanings.

Permeate Flux and Temperature

During the first hour and 15 minutes of the cleaning, the permeate flux ranged from 33.5 to 60.5 $\text{gal}/\text{ft}^2\text{-d}$ and averaged 45.9 $\text{gal}/\text{ft}^2\text{-d}$. Permeate temperature ranged from 89.2 to 98.0°F and averaged 93.3°F . Concentrate temperature ranged from 95 to 110°F and averaged 103.5°F .

The system was shutdown 75 minutes into the cleaning because the concentrate temperature reached 110°F . The system was allowed to cool for 105 minutes and then restarted to complete the two-hour cleaning. During the second half of cleaning, the permeate flux ranged from 61.4 to 86.3 $\text{gal}/\text{ft}^2\text{-d}$ and averaged 78.8 $\text{gal}/\text{ft}^2\text{-d}$. Concentrate

temperatures ranged from 101 to 110 °F and averaged 105.0 °F. Permeate temperature were not taken during the second hour of cleaning due to human error.

pH, Conductivity and Turbidity

Permeate pH ranged from 6.7 to 6.8 with an average of 6.8. Concentrate pH ranged from 6.8 to 6.9 with an average of 6.9. Permeate conductivity ranged from 628 to 742 $\mu\text{S}/\text{cm}$ and averaged 688 $\mu\text{S}/\text{cm}$. Concentrate conductivity ranged from 1342 to 1420 $\mu\text{S}/\text{cm}$ and averaged 1383 $\mu\text{S}/\text{cm}$. Permeate turbidity ranged from 43.8 to 108.9 NTU and averaged 68.8 NTU. Turbidity of only the permeate was monitored. Concentrate turbidity was over the range of the turbidity meter.

UF1-R7-SR2

UF1-R7-SR2 was started on January 20, 1998 at 17:06 and ended on January 23, 1998 at 15:07. The length of the subrun lasted 2.88 days. Subrun #2 was shutdown because the running permeate average was reached. The total permeate volume produced was 157,440 gal.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 19.6 to 96.9 gal/ft²-d. Permeate temperature ranged from 71.7 to 76.8 °F with an average of 74.4 °F. Concentrate temperatures ranged from 76.0 to 82.0 °F with an average of 78.9 °F.

Concentrate Oil Content and Free Oil Production

During subrun #2, concentrate oil content started out at 1.45 % and increased to 5.0 %. The total volume of free oil that was produced during subrun #2 was 258 gallons. The average daily free oil production was 88.9 gallons/day.

Oil/Grease, Turbidity and Pond Effluent

Permeate O/G remained low, averaging 5.4 mg/L and ranging from 4.0 to 6.7 mg/L. Turbidity was also low, averaging 5.8 NTU and ranging from 4.5 to 7.0 NTU. Pond effluent was constant around 5000 mg/L.

Conductivity and pH

Permeate pH ranged from 5.4 to 6.0 with an average of 5.8. Concentrate pH ranged from 6.1 to 6.4 with an average of 6.2. Permeate conductivity ranged from 66.4 to 704 $\mu\text{S}/\text{cm}$ and averaged 453 $\mu\text{S}/\text{cm}$. Concentrate conductivity's ranged from 177 to 440 $\mu\text{S}/\text{cm}$ and averaged 308 $\mu\text{S}/\text{cm}$.

UF1-R7-SR2 Cleaning

After UF1-R7-SR2 was shutdown on January 23, 1998 at 15:07, it was cleaned at 15:37 using a 0.5 % KLD cleaning solution. The cleaning solution was recycled for total of two hours running time. Cleaning was started at a temperature of $\sim 100^\circ\text{F}$. If the system temperature reaches 110°F , it is shutdown and allowed to cool, to approximately 100°F . After which it is started again to finish the rest of the two-hour cleaning. Total downtime for this cleaning was 233 minutes.

Permeate Flux and Temperature

During the first hour of the cleaning, the permeate flux ranged from 36.5 to 54.2 gal/ft²-d and averaged 46.1 gal/ft²-d. Permeate temperature ranged from 89.2 to 102°F and averaged 95°F . Concentrate temperature ranged from 95 to 110°F and averaged 102°F over the course of the first hour.

The system was shutdown 66 minutes into the cleaning because the concentrate temperature reached 110°F . The system was allowed to cool for 71 minutes and then

restarted to complete the two-hour cleaning. During the second hour of cleaning, the permeate flux ranged from 60.0 to 68.5 gal/ft²-d and averaged 63.4 gal/ft²-d. Concentrate temperatures ranged from 103 to 111 °F and averaged 107 °F. Permeate temperature were not taken during the second hour of cleaning due to human error.

pH, Conductivity and Turbidity

Permeate pH ranged from 5.7 to 6.5 with an average of 6.3. Concentrate pH ranged from 6.5 to 6.6 with an average of 6.5. Permeate conductivity ranged from 687 to 919 µS/cm and averaged 823 µS/cm. Concentrate conductivity ranged from 1482 to 1850 µS/cm and averaged 1656 µS/cm. Permeate turbidity ranged from 5.6 to 40.0 NTU and averaged 17.8 NTU. Turbidity of only the permeate was monitored.

UF1-R7-SR3

UF1-R7-SR3 was started on January 23, 1998 at 19:00 and ended on January 29, 1998 at 17:05. The length of the subrun lasted 5.86 days. Subrun #3 was shutdown because the running permeate average of 29 gpm was reached. The total permeate volume produced was 234,960 gal.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 16.0 to 99.6 gal/ft²-d. Permeate temperature ranged from 73.1 to 80.0 °F with an average of 76.5 °F. Concentrate temperatures ranged from 76.5 to 86.0 °F with an average of 81.2 °F.

Concentrate Oil Content and Free Oil Production

During subrun #3, concentrate oil content started out at 5.0 % and increased to 7.4 %. The total volume of free oil that was produced during subrun #3 was 1,464 gallons. The average daily free oil production was 248.1 gallons/day.

Oil/Grease, Turbidity and Pond Effluent

Permeate O/G remained low, averaging 4.3 mg/L and ranging from 2.0 to 5.0 mg/L. Turbidity was also low, averaging 2.8 NTU and ranging from 0.84 to 11.1 NTU. Pond Effluent ranged from 5000 to 16,000 mg/L and averaged 10,250 mg/L.

Conductivity and pH

Permeate pH ranged from 5.4 to 5.7 with an average of 5.7. Concentrate pH ranged from 5.7 to 6.1 with an average of 5.9. Permeate conductivity ranged from 82 to 759 $\mu\text{S}/\text{cm}$ and averaged 528 $\mu\text{S}/\text{cm}$. Concentrate conductivity's ranged from 18 to 615 $\mu\text{S}/\text{cm}$ and averaged 404 $\mu\text{S}/\text{cm}$.

UF1-R7-SR3 Cleaning

After UF1-R7-SR3 was shutdown on January 29, 1998 at 17:05, it was cleaned at 17:05 using a 0.5 % KLD cleaning solution. The cleaning solution was recycled for total of two hours running time. Cleaning was started at a temperature of $\sim 100^\circ\text{F}$. If the system temperature reaches 110°F , it is shutdown and allowed to cool down, to approximately 100°F . After which it is started again to finish the rest of the two-hour cleaning. Total downtime for this cleaning was 475 minutes.

Permeate Flux and Temperature

During the first hour, the permeate flux ranged from 21.3 to 25 gal/ft²-d and averaged 23.2 gal/ft²-d. Permeate temperature ranged from 87.7 to 94.3 $^\circ\text{F}$ and averaged 90.1 $^\circ\text{F}$. Concentrate temperature ranged from 95 to 110 $^\circ\text{F}$ and averaged 102.3 $^\circ\text{F}$ over the course of the first hour.

The system was shutdown 60 minutes into the cleaning because the concentrate temperature reached 110°F . The system was allowed to cool for 73 minutes and then restarted to complete the two-hour cleaning. During the second hour of cleaning, the

permeate flux ranged from 26.7 to 30.2 gal/ft²-d and averaged 29.0 gal/ft²-d. Concentrate temperatures ranged from 94.6 to 106.4 °F and averaged 100.8 °F. Permeate temperature ranged from 90.8 to 98.0 °F with an average of 95.4 °F.

pH, Conductivity and Turbidity

Permeate pH ranged from 4.9 to 6.5 with an average of 5.7. Concentrate pH ranged from 5.3 to 6.6 with an average of 5.9. Permeate conductivity ranged from 449 to 617 µS/cm and averaged 562 µS/cm. Concentrate conductivity ranged from 520 to 944 µS/cm and averaged 761 µS/cm. Permeate turbidity ranged from 3.9 to 10.7 NTU and averaged 6.6 NTU.

UF1-R7-SR4

UF1-R7-SR4 was started on January 30, 1998 at 02:00 and ended on February 7, 1998 at 00:50. The length of the subrun lasted 8.27 days. The total permeate volume produced was 292,650 gal. Subrun #4 marked the end of UF1-R7. After the system was shutdown, the concentrate in the feed tanks was purged to the tank farm.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 17.8 to 34.7 gal/ft²-d. Permeate temperature ranged from 73.2 to 78.2 °F with an average of 76.0 °F. Concentrate temperatures ranged from 78.9 to 82.1 °F with an average of 80.5 °F.

Concentrate Oil Content and Free Oil Production

During subrun #4, concentrate oil content started out at 7.4 % and increased to 9.1 %. The total volume of free oil that was produced during subrun #4 was 1,752 gallons. The average daily free oil production was 211.1 gallons/day.

Oil/Grease, Turbidity and Pond Effluent

Permeate O/G remained low, averaging 4.4 mg/L and ranging from 2.0 to 6.0 mg/L. Turbidity was also low, averaging 1.9 NTU and ranging from 0.8 to 3.7NTU. Pond effluent O/G ranged from 6000 to 12000 mg/L and averaged 6800 mg/L.

Conductivity and pH

Permeate pH ranged from 4.5 to 6.3 with an average of 5.6. Concentrate pH ranged from 4.9 to 6.1 with an average of 5.5. Permeate conductivity ranged from 165 to 601 $\mu\text{S}/\text{cm}$ and averaged 465 $\mu\text{S}/\text{cm}$. Concentrate conductivity's ranged from 261 to 429 $\mu\text{S}/\text{cm}$ and averaged 364 $\mu\text{S}/\text{cm}$.

UF1-R7-SR4 Cleaning

After UF1-R7-SR4 was shutdown on February 7, 1998 at 00:50, it was cleaned at 02:00 using a 0.5 % KLD cleaning solution. The cleaning solution was recycled for total of two hours running time. Cleaning was started at a temperature of $\sim 100^\circ\text{F}$. If the system temperature reaches 110°F , it is shutdown and allowed to cool, to approximately 100°F . After which it is started again to finish the rest of the two-hour cleaning. Total downtime for this cleaning was 1170 minutes.

Permeate Flux and Temperature

During the first hour, the permeate flux ranged from 28.5 to 32.9 gal/ft²-d and averaged 30.6 gal/ft²-d. Permeate temperature ranged from 88.0 to 97.1 $^\circ\text{F}$ and averaged 92.8 $^\circ\text{F}$. Concentrate temperature ranged from 95 to 106.4 $^\circ\text{F}$ and averaged 100.9 $^\circ\text{F}$ over the course of the first hour.

The system was shutdown 60 minutes into the cleaning because the concentrate temperature reached 110°F . The system was allowed to cool for 60 minutes and then restarted to complete the two-hour cleaning. During the second hour of cleaning, the

permeate flux ranged from 32.9 to 37.4 gal/ft²-d and averaged 35.2 gal/ft²-d. Permeate temperatures ranged from 89.4 to 98.7 °F with an average of 94.3 °F. Concentrate temperatures ranged from 98.2 to 107.5 °F and averaged 102.8 °F.

pH, Conductivity and Turbidity

Permeate pH ranged from 6.5 to 7.0 with an average of 6.7. Concentrate pH ranged from 6.3 to 7.1 with an average of 6.8. Permeate conductivity ranged from 589 to 718 µS/cm and averaged 644 µS/cm. Concentrate conductivity ranged from 968 to 1109 µS/cm and averaged 1058 µS/cm. Permeate turbidity ranged from 7.3 to 15.0 NTU and averaged 10.4 NTU.

UF1-R7-SR4 Acid Cleaning

After a regular cleaning and flush was performed on the system, an acid cleaning was implemented for one-hour. The acid cleaning started once the 600 gallons of softened water was pH adjusted to ~ 2.2.

Permeate Flux and Temperature

During the acid cleaning, the permeate flux ranged from 33.8 to 39.1 gal/ft²-d and averaged 36.5 gal/ft²-d. Permeate temperature ranged from 75.3 to 91.0 °F and averaged 84.2 °F. Concentrate temperature ranged from 84 to 100 °F and averaged 92.8 °F.

pH, Conductivity and Turbidity

Permeate pH ranged from 2.6 to 3.6 with an average of 3.0. Concentrate pH ranged from 2.7 to 3.3 with an average of 2.9. Permeate conductivity ranged from 757 to

1201 $\mu\text{S}/\text{cm}$ and averaged 1091 $\mu\text{S}/\text{cm}$. Concentrate conductivity ranged from 1332 to 2500 $\mu\text{S}/\text{cm}$ and averaged 1616 $\mu\text{S}/\text{cm}$. Permeate turbidity ranged from 4.9 to 22.4 NTU and averaged 8.8 NTU.

UF1-R7-SR4 Cleaning After Acid

After the acid cleaning and flush, the system was then cleaned again using a 0.3 % KLD solution for one-hour.

Permeate Flux and Temperature

During the second regular cleaning, the permeate flux ranged from 37.4 to 44.5 gal/ft²-d and averaged 40.8 gal/ft²-d. Permeate temperature ranged from 89.2 to 98.0 °F and averaged 94.5 °F. Concentrate temperature ranged from 95 to 107 °F and averaged 101 °F.

pH, Conductivity and Turbidity

Permeate pH ranged from 4.4 to 4.6 with an average of 4.5. Concentrate pH ranged from 4.4 to 4.5 with an average of 4.5. Permeate conductivity ranged from 380 to 419 $\mu\text{S}/\text{cm}$ and averaged 399 $\mu\text{S}/\text{cm}$. Concentrate conductivity ranged from 618 to 673 $\mu\text{S}/\text{cm}$ and averaged 647 $\mu\text{S}/\text{cm}$. Permeate turbidity ranged from 5.4 to 7.2 NTU and averaged 6.0 NTU.

UF1-R8

UF1-R8 started on February 7, 1998 at 20:20 and ended on June 25, 1998 at 07:02. The run lasted for 125 days. The objectives of the run were: 1) monitor system

performance, 2) estimate the volume of free oil that forms at the top of the concentrate tanks and 3) conduct an oil mass balance on the system in order to note the change occurring in the system.

In Figure 4.3, permeate flux versus time for UF1-R8 is presented. In Figure 4.4, permeate turbidity versus time for UF1-R8 is presented. In Table 4.10, a summary of permeate operating parameters for UF1-R8 is presented. In Table 4.11, a summary of operating concentrate parameters for UF1-R8 is presented. In Table 4.12, a summary of permeate cleaning parameters for UF1-R8 is presented. In Table 4.13, a summary of concentrate cleaning parameters for UF1-R8 is presented. In Table 4.14, a summary of permeate O/G samples analyzed for UF1-R8, is presented. In Table 4.15, a summary of concentrate oil content samples analyzed for UF1-R8, is presented. In Table 4.16, a summary of free oil skimming samples analyzed for UF1-R8, is presented. In Table 4.17, a summary of free oil production for UF1-R8 is presented. In Table 4.18, a summary of pond effluent samples analyzed for UF1-R8, is presented.

UF1-R8-SR1

UF1-R8-SR1 was started on February 7, 1998 at 20:20 and ended on February 18, 1998 at 00:00. The length of the subrun lasted 10.1 days. The system allowed to operate even though the permeate flux was lower than normal. The system was operated until the spongeball cleaning system was repaired. The total permeate volume produced was 364,800 gal.

C. Figure 4.3 Permeate Flux versus Time for UF1-R8

Figure 4.4 Permeate Turbidity versus Time for UF1-R8

Table 4.10. Summary of Permeate Parameters for UF1-R8

Subrun ID	Flux (gal/ft²-d) [min – max] Avg ±std	Temperature (°F) [min – max] Avg ±std	Turbidity (NTU) [min – max] Avg ±std	pH [min – max] Avg ±std	Conductivity(μS/cm) [min – max] Avg ±std	O/G (mg/L) [min – max] Avg ±std
1	[15.1 - 44.5] 24.8±8.6	[67.5 – 79.8] 76.3±3.5	[0.69 - 4.7] 2.1±1.5	[5.2 – 5.9] 5.5±5.5	[87 – 501] 403±107	[2.3 - 5.0] 3.8±1.0
2	[18.7 - 36.5] 23.9±4.0	[75.7 – 79.6] 77.6±1.8	[1.3 - 5.5] 2.6±1.9	[4.3 – 6.4] 5.1±0.9	[467 – 637] 529±94	[4 - 5] 4.5±0.7
3	[21.3 - 33.8] 24.6±3.5	[76.0 – 76.5] 76.3±0.35	[0.79 - 4.1] 2.5±2.4	[5.7 – 5.8] 5.8±0.10	[439 – 491] 465±37	[4] 4±0.0
4	[17.8 - 91.6] 29.7±13.4	[72.9 – 76.5] 75.6±1.4	[0.85 - 7.6] 4.2±2.4	[4.1 – 5.5] 5.2±0.48	[268 – 431] 361±50	[6] 6±0.0
5	[19.6 - 88.9] 28.6±10.8	[71.8 – 78.2] 74.7±1.8	[1.1 - 17.5] 8.0±7.4	[4.5 – 6.4] 5.6±0.58	[207 – 382] 300±57	[5] 5±0.0
6	[16.0 - 82.7] 21.7±6.4	[71.8 – 81.5] 78.4±2.5	[0.98 - 14.5] 2.7±2.2	[4.4 – 6.3] 5.1±0.5	[111 – 391] 287±77	[1 - 5] 2.8±1.7
7	[20.5 - 67.6] 27.7±7.7	[73.9 – 79.6] 77.4±1.8	[0.4 - 4.5] 2.3±1.3	[4.8 – 5.7] 5.3±0.3	[236 – 604] 350±109	[3 - 4] 3.5±0.7
8	[16.9 - 88.9] 23.0±10.4	[73.7 – 82.6] 79.4±2.8	[0.8 - 5.2] 1.9±1.3	[5.1 – 6.3] 5.4±0.3	[285 – 450] 410±110	[3 - 5] 3.7±1.2
9	[21.3 - 69.4] 30.0±9.1	[75.8 – 80.9] 78.3±1.7	[0.3 - 3.2] 1.3±1.1	[5.0 – 5.4] 5.2±0.1	[138 – 464] 312±109	[1 - 3] 2.0±1.4
10	[20.5 - 86.3] 25.6±6.9	[78.3 – 89.7] 83.6±2.7	[0.11 - 5.8] 0.80±0.9	[4.8 – 6.1] 5.5±0.3	[101 – 687] 341±122	[1 - 9] 3.9±2.5
11	[24.9 -83.6] 31.9±8.9	[85.8 – 90.3] 87.6±2.3	[228 - 476] 346±82	[4.8 – 7.1] 5.4±0.4	[228 – 476] 346±116	[2 - 5] 3.2±1.1

Table 4.11. Summary of Concentrate and Pond Effluent Parameters for UF1-R8

Subrun ID	Temperature (°F) [min – max] Avg ±std	pH [min – max] Avg ±std	Conductivity(μS/cm) [min – max] Avg ±std	Oil Content (%) [min – max] Avg ±std	Pond Effluent O/G (mg/L) [min – max] Avg ±std
1	[70.8 – 84.3] 79.8±4.0	[5.2 – 5.6] 5.4±0.15	[110 – 470] 302±134	[0.67 – 2.6] 1.6±1.4	[0.6 – 0.7] 0.63
2	[79.2 – 82.6] 81.3±1.5	[4.4 – 5.3] 4.8±0.62	[104 – 373] 238±191	[2.6 – 3.6] 3.1±0.7	[0.6 – 0.7] 0.65
3	[79.8 – 81.9] 80.9±1.5	[6.1] 6.1±0.0	[292] 292±0.0	[3.6 – 4.0] 3.8±0.3	[0.6] 0.6
4	[75.7 – 80.7] 79.6±2.0	[5.2 – 5.9] 5.5±0.47	[183 – 534] 359±248	[4.0 – 5.4] 4.7±0.9	[0.6] 0.6
5	[77.9 – 80.8] 79.0±1.0	[5.3 – 6.3] 5.9±0.44	[147 – 333] 247±90	[5.4 – 6.8] 6.1±1.0	[0.7] 0.7
6	[76.0 – 85.0] 81.9±2.2	[4.6 – 6.2] 5.3±0.4	[204 – 501] 355±105	[6.8 – 11.5] 8.9±2.4	[0.6 – 0.7] 0.68
7	[78.3 – 79.6] 81.1±1.6	[5.2 – 6.0] 5.4±0.3	[170 – 486] 354±110	[11.5 – 11.0] 10.6±1.0	[0.7 – 0.8] 0.73
8	[80 – 86] 83.3±2.2	[5.3 – 5.6] 5.4±0.1	[267 – 492] 415±110	[11.0 – 10.5] 10.8±0.5	[0.7 – 0.9] 0.8
9	[78.1 – 83.6] 81.5±1.6	[5.2 – 5.4] 5.3±0.1	[212 – 431] 342±109	[8.8 – 9.8] 9.3±0.7	[0.8] 0.8
10	[80.7 – 92.4] 87.3±2.9	[4.9 – 5.9] 5.5±0.3	[220 – 523] 406±72	[10.2 – 3.0] 8.9±3.6	[0.3 – 0.8] 0.72
11	[91.2 – 92] 91.5±0.2	[5.2 – 5.5] 5.4±0.3	[441 – 555] 498±89	[3.0 – 4.5] 3.7±0.7	[0.7 – 0.9] 0.83

Table 4.12. Summary of Permeate Cleaning Parameters for UF1-R8

Subrun ID	Flux (gal/ft²-d) [min – max] Avg ±std	Temperature (°F) [min – max] Avg ±std	Turbidity (NTU) [min – max] Avg ±std	pH [min – max] Avg ±std	Conductivity(μS/cm) [min – max] Avg ±std
1	[24.0 – 43.5] 35.2±6.0	[80.4 – 97.6] 89.6±6.1	[5.6 – 44.9] 14.8±13.9	[6.0 – 6.1] 6.0±0.1	[522 – 639] 581±46
2	[32.0 – 35.6] 33.9±0.7	[91.5 – 98.4] 96.3±2.5	[3.7 – 9.7] 4.9±2.4	NA	[454 – 617] 537±58
3	[103.2 – 128.1] 115.9±1.7	[90.1 – 97.5] 93.9±1.9	[2.2 – 4.1] 3.1±0.8	[8.8 – 9.2] 9.1±0.2	[723 – 802] 770±27
4	[76.5 – 115.6] 95.1±2.0	[110 – 112.8] 111.9±1.6	[3.6 – 8.3] 4.8±2.0	[6.5 – 6.7] 6.6±0.10	[507 – 592] 560±35
5	[80 – 108.5] 92.5±2.4	[110.6 – 114.1] 111.8±1.1	[3.2 – 9.5] 6.1±2.3	[8.5 – 9.5] 9.1±0.5	[479 – 1430] 957±428
6	[65.8 – 97.8] 81.1±3.3	[109 – 112.9] 110.9±2.0	[2.9 – 6.3] 4.4±1.6	[5.4 – 5.9] 5.7±0.2	[281 – 614] 453±158
7	[57.8 – 99.6] 78.6±3.4	[114.3 – 119.2] 116.2±1.2	[2.0 – 5.6] 3.8±1.9	[8.4 – 9.2] 8.9±0.4	[353 – 714] 544±173
8	[119.2 – 140.5] 129.5±3.5	[114.1 – 119.2] 115.1±1.2	[0.6 – 6.0] 1.6±2.2	[9.3 – 9.9] 9.6±0.4	[1285 – 2260] 1773±481
9	[88.9 – 126.3] 106.5±2.6	[89.1 – 111.1] 99.8±0.9	[1.6 – 3.0] 2.2±0.6	[6.2 – 6.3] 6.3±0.04	[733 – 874] 819±60
10	[69.4 – 103.2] 86.2±1.1	[111.8 – 118.2] 114.5±4.2	[1.0 – 6.5] 2.7±2.6	[9.4 – 9.6] 9.5±0.1	[922 – 1144] 1041±94
11	[72.4 – 128.0] 88.3±2.3	[111.4 – 118.2] 115.2±2.2	[1.2 – 7.5] 2.2±1.2	[9.5 – 9.8] 9.6±0.1	[858 – 1211] 1069±56

Table 4.13. Summary of Concentrate Cleaning Parameters for UF1-R8

Subrun ID	Temperature (°F) [min – max] Avg ±std	pH [min – max] Avg ±std	Conductivity(μS/cm) [min – max] Avg ±std
1	[82.5 – 106.7] 95.7±7.7	[6.3 – 6.7] 6.4±0.2	[1345 – 1542] 1443±93
2	[98 – 107] 104±3.5	NA	[827 – 1245] 1036±173
3	[94.4 – 105.3] 100±2.2	[9.0 – 9.2] 9.1±0.1	[1798 – 1970] 1876±65
4	[117.4 – 124.3] 121±2.8	[6.7 – 6.9] 6.8±0.10	[924 – 1411] 1162±253
5	[119.7 – 124.9] 121.2±1.5	[8.5 – 9.6] 9.1±0.5	[985 – 2300] 1725±641
6	[118 – 124.9] 120±1.6	[6.0 – 6.3] 6.2±0.2	[264 – 1043] 776±348
7	[121 – 128.8] 123.2±2.2	[8.5 – 9.3] 8.9±0.4	[712 – 1425] 1113±343
8	[120.5 – 128.8] 123.4±2.4	[9.3 – 10.0] 9.7±0.4	[1973 – 2920] 2419±468
9	[96 – 122.5] 108.6±2.1	[6.4 – 6.5] 6.5±0.1	[1228 – 1433] 1358±113
10	[121 – 126] 122.8±3.3	[9.5 – 9.6] 9.5±0.1	[959 – 2230] 1615±620
11	[120 – 125] 123.3±2.6	[9.6 – 10.0] 9.7±1.2	[1025 – 2330] 1725±255

Table 4.14 Summary of Permeate O/G Samples for UF1-R8

Subrun ID	Date/Time	Sample Results (mg/L)		
		#1	#2	#3
1	2/7/98 (22:37)	2	3	2
1	2/8/98 (23:35)	3		
1	2/9/98 (22:33)	4		
1	2/11/98 (01:11)	5		
1	2/12/98 (03:03)	4		
1	2/13/98 (22:59)	3		
1	2/16/98 (00:38)	4	5	5
2	2/19/98 (02:43)	5		
2	2/23/98 (01:18)	4		
3	2/25/98 (01:56)	6		
4	3/2/98 (21:23)	6		
5	3/7/98 (02:50)	5		
5	3/11/98 (04:39)	5		
6	3/15/98 (04:00)	3	3	3
6	3/21/98 (12:23)	2		
6	3/23/98 (09:05)	1		
6	3/29/98 (18:24)	3		
6	3/30/98 (19:02)	3		
6	4/2/98 (07:02)	5		
7	4/5/98 (09:40)	4		
7	4/9/98 (13:10)	3		
8	4/11/98 (10:15)	3		
8	4/14/98 (04:21)	5	5	5
8	4/15/98 (15:32)	3		
9	4/19/98 (01:30)	3		
9	4/21/98 (19:55)	1		
10	4/23/98 (19:05)	8		
10	4/27/98 (05:16)	4		
10	4/30/98 (12:04)	1		
10	5/3/98 (01:50)	2		
10	5/6/98 (15:30)	3		
10	5/10/98 (14:16)	4	3	4
10	5/13/98 (02:02)	5		
10	5/21/98 (16:14)	9		
10	5/29/98 (09:45)	3		
10	6/5/98 (11:45)	2		
10	6/11/98 (23:01)	2		
11	6/19/98 (14:11)	5		
11	6/21/98 (03:40)	4		
11	6/24/98 (11:30)	3		

Table 4.15 Summary of Concentrate Oil Content Samples for UF1-R8

Subrun ID	Date/Time	Sample Results (%)		
		#1	#2	#3
1	2/7/98 (20:00)	0.7	0.6	0.7
1	2/10/98 (22:35)	2.4		
1	2/13/98 (23:39)	2.3		
1	2/17/98 (23:50)	2.6	2.8	2.4
2	2/18/98 (03:05)	2.7	2.4	2.6
2	2/23/98 (10:56)	3.6	3.6	3.6
3	2/25/98 (06:46)	4.1	4.0	4.1
3	2/28/98 (16:25)	4.3		
4	3/6/98 (17:30)	5.4		
5	3/12/98 (05:40)	6.8	6.8	6.6
6	3/19/98 (11:32)	9.0		
6	4/3/98 (02:03)	11.5	11.1	11.5
7	4/10/98 (10:12)	11.0		
8	4/16/98 (01:50)	10.5		
9	4/17/98 (12:20)	8.8		
9	4/23/98 (08:40)	9.8		
10	4/23/98 (18:32)	10.2	10.5	10.2
10	4/24/98 (08:23)	12.3		
10	4/29/98 (05:26)	12.8		
10	4/30/98 (12:56)	9.5		
10	5/6/98 (13:55)	9.6		
10	5/12/98 (02:01)	11.9		
10	5/13/98 (11:22)	12.0	12.1	11.8
10	5/22/98 (09:35)	4.5		
10	5/28/98 (11:01)	6.5		
10	5/30/98 (08:44)	8.8		
10	6/6/98 (12:45)	9.3		
10	6/10/98 (12:22)	2.5		
10	6/16/98 (10:30)	3.0	3.2	3.0
11	6/25/98 (06:57)	4.5		

Table 4.16 Summary of Skimming Samples for UF1-R8

Subrun ID	Date/Time	Sample Results (%)		
		#1	#2	#3
1	2/8/98 (12:04)	99		
1	2/17/98 (23:00)	100		
2	2/19/98 (03:00)	100		
2	2/21/98 (15:30)	98		
3	2/26/98 (11:01)	100	99	100
4	3/7/98 (05:30)	100		
5	3/13/98 (12:20)	99		
6	3/23/98 (11:22)	99		
6	3/28/98 (10:10)	98		
7	4/8/98 (09:30)	100		
8	4/15/98 (10:45)	100		
9	4/21/98 (08:40)	99		
10	4/25/98 (12:20)	98		
10	4/30/98 (16:20)	98		
10	5/15/98 (11:19)	100	100	98
10	5/27/98 (13:31)	100		
10	6/5/98 (09:59)	100		
11	6/19/98 (09:05)	99		

Table 4.17 Summary of Free Oil Productions for UF1-R8

Subrun ID	Subrun Length, d	Total Free Oil, gal	Free Oil Production, gal/d
1	10.1	2,056	203.6
2	5.2	1,267	243.7
3	1.5	316	210.7
4	6.1	1,679	275.2
5	5.3	2,304	434.7
6	22.4	4,936	221.3
7	6.2	2,316	373.5
8	5.4	1,589	294.3
9	5.7	2,068	362.8
10	51.3	26,823	522.8
11	6.5	4,130	635.4

Table 4.18 Summary of Pond Effluent O/G Samples for UF1-R8

Subrun ID	Date/Time	Sample Results (mg/L)		
		#1	#2	#3
1	2/7/98 (19:45)	6,000		
1	2/10/98 (14:30)	6,000		
1	2/13/98 (14:00)	7,000		
1	2/15/98 (13:45)	6,000		
2	2/20/98 (02:55)	6,000		
2	2/22/98 (04:32)	7,000		
3	2/24/98 (21:53)	6,000		
4	3/1/98 (00:15)	6,000		
4	3/2/98 (21:15)	6,000	6,000	6,000
4	3/5/98 (04:10)	6,000		
5	3/9/98 (03:25)	6,000		
6	3/13/98 (23:10)	6,000		
6	3/25/98 (15:30)	7,000		
6	3/29/98 (09:50)	6,000		
7	4/6/98 (05:30)	7,000		
7	4/9/98 (15:11)	7,000		
8	4/12/98 (08:05)	8,000		
8	4/15/98 (16:40)	7,000		
9	4/19/98 (16:50)	7,000	6,000	7,000
10	4/24/98 (01:20)	7,000		
10	4/28/98 (09:00)	9,000		
10	5/1/98 (11:13)	8,000		
10	5/6/98 (21:05)	30,000		
10	5/9/98 (12:20)	3,000		
10	5/19/98 (23:30)	8,000		
10	5/22/98 (16:00)	9,000	9,000	8,000
10	5/26/98 (09:10)	7,000		
10	6/3/98 (14:35)	8,000		
10	6/13/98 (05:10)	9,000		
11	6/19/98 (07:05)	8,000		
11	6/24/98 (07:43)	8,000		

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 15.1 to 61.4 gal/ft²-d. Permeate temperature ranged from 68.1 to 77.9°F with an average of 74.1 °F. Concentrate temperatures ranged from 72.0 to 83.4 °F with an average of 78.8 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content started out at 0.67 % and increased to 2.6% over the course of subrun #1. The total volume of free oil that was produced during subrun #1 was 2,056 gallons. The average daily free oil production was 203.6 gallons/day.

Oil/Grease, Turbidity and Pond Effluent

Permeate O/G remained low, averaging 3.8 mg/L and ranging from 2.3 to 5.0 mg/L. Turbidity was also low, averaging 2.1 NTU and ranging from 0.69 to 4.7 NTU. Pond effluent ranged from 6000 to 7000 mg/L and averaged 6300 mg/L.

Conductivity and pH

Permeate pH ranged from 5.2 to 5.9 with an average of 5.5. Concentrate pH ranged from 5.2 to 5.6 with an average of 5.4. Permeate conductivity ranged from 87.0 to 501 µS/cm and averaged 403 µS/cm. Concentrate conductivity ranged from 110 to 470 µS/cm and averaged 302 µS/cm.

UF1-R8-SR1 Cleaning

After UF1-R8-SR1 was shutdown on February 18, 1998 at 00:00, it was cleaned at 01:00 using a 0.5 % KLD cleaning solution. The cleaning solution was recycled for total of two hours running time. Cleaning was started at a temperature of ~ 80 °F. The

temperature was not to exceed 110 °F. Holes were found in the CIP tank, from the heater located at the bottom of the tank. As a result the heater was not used during this cleaning. The cleaning water was recirculated and heated by the system pumps. Total downtime for this cleaning was 180 minutes.

Permeate Flux and Temperature

During the cleaning, the permeate flux ranged from 24.0 to 43.5 gal/ft²-d and averaged 35.2 gal/ft²-d. Permeate temperature ranged from 80.4 to 97.6 °F and averaged 89.6 °F. Concentrate temperature ranged from 82.5 to 106.7 °F and averaged 95.7 °F over the course of the cleaning.

pH, Conductivity and Turbidity

Permeate pH ranged from 6.0 to 6.1 with an average of 6.0. Concentrate pH ranged from 6.3 to 6.7 with an average of 6.4. Permeate conductivity ranged from 522 to 639 µS/cm and averaged 581 µS/cm. Concentrate conductivity ranged from 1345 to 1542 µS/cm and averaged 1443 µS/cm. Permeate turbidity ranged from 5.6 to 44.9 NTU and averaged 14.8 NTU.

UF1-R8-SR2

UF1-R8-SR2 was started on February 18, 1998 at 03:00 and ended on February 23, 1998 at 10:56. The length of the subrun lasted 5.24 days. Major downtime was expected for valve replacement. As a result the system was shutdown and cleaned in order to restore a high permeate flow. The total permeate volume produced was 202,520 gal.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 18.7 to 36.5 gal/ft²-

d. Permeate temperature ranged from 75.7 to 79.6 °F with an average of 77.6 °F.

Concentrate temperatures ranged from 79.2 to 82.6 °F with an average of 81.3 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content started out at 2.6 % and increased to 3.6 % over the course of subrun #2. The total volume of free oil that was produced during subrun #2 was 1,267 gallons. The average daily free oil production was 243.7 gallons/day.

Oil/Grease, Turbidity and Pond Effluent

Permeate O/G remained low, averaging 4.5 mg/L and ranging from 4.0 to 5.0 mg/L. Turbidity was also low, averaging 2.6 NTU and ranging from 1.3 to 5.5 NTU. Pond effluent ranged from 6000 to 7000 mg/L and averaged 6500 mg/L.

Conductivity and pH

Permeate pH ranged from 4.3 to 6.4 with an average of 5.1. Concentrate pH ranged from 4.4 to 5.3 with an average of 4.8. Permeate conductivity ranged from 467 to 637 µS/cm and averaged 529 µS/cm. Concentrate conductivity's ranged from 104 to 373 µS/cm and averaged 238 µS/cm.

UF1-R8-SR2 Cleaning

After UF1-R8-SR2 was shutdown on February 23, 1998 at 10:56, it was cleaned at 15:12 using a 0.5 % KLD cleaning solution. The cleaning solution was recycled for total of two hours running time. Cleaning was started at a temperature of ~ 100 °F. If the system temperature reaches 110 °F, it is shutdown and allowed to cool down, to

approximately 100 °F. After which it is started again to finish the rest of the two-hour cleaning. The CIP tank heater was not used during the cleaning because the heating coils were melting holes in the bottom. The heater will not be used until the new tank arrives. As a result the downtime is longer than normal because the water does not heat up as fast. Total downtime for this cleaning was 440 minutes.

Permeate Flux and Temperature

During the first hour, the permeate flux ranged from 32.0 to 34.7 gal/ft²-d and averaged 33.3 gal/ft²-d. Permeate temperature ranged from 91.5 to 99.3 °F and averaged 95.6 °F. Concentrate temperature ranged from 98 to 109 °F and averaged 103 °F over the course of the first hour.

The system was shutdown 60 minutes into the cleaning because the concentrate temperature reached 110 °F. The system was allowed to cool for 62 minutes and then restarted to complete the two-hour cleaning. During the second hour of cleaning, the permeate flux ranged from 33.8 to 35.6 gal/ft²-d and averaged 34.5 gal/ft²-d. Concentrate temperatures ranged from 103 to 107°F and averaged 105 °F. Permeate temperature ranged from 95.6 to 98.4 °F with an average of 97 °F.

pH, Conductivity and Turbidity

Permeate and concentrate pH were not taken during this cleaning because the pH probe was not functioning properly. Permeate conductivity ranged from 454 to 617 µS/cm and averaged 536.5 µS/cm. Concentrate conductivity ranged from 827 to 1245 µS/cm and averaged 1036 µS/cm. Permeate turbidity ranged from 3.7 to 9.7 NTU and averaged 4.9 NTU.

UF1-R8-SR3

UF1-R8-SR3 was started on February 23, 1998 at 18:16 and ended on February 25, 1998 at 06:46. The length of the subrun lasted 1.52 days. The subrun was shut down so that a new stainless steel header could be installed and bad valves replaced. The total permeate volume produced was 58,270 gal.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 21.3 to 33.8 gal/ft²-d. Permeate temperature ranged from 76.0 to 76.5 °F with an average of 76.3 °F. Concentrate temperatures ranged from 79.8 to 81.9 °F with an average of 80.9 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content started out at 3.6 % and increased to 4.0 % over the course of subrun #3. The total volume of free oil that was produced during subrun #3 was 316 gallons. The average daily free oil production was 210.7 gallons/day.

Oil/Grease, Turbidity and Pond Effluent

Permeate O/G remained low, around 4 mg/L. Turbidity was also low, averaging 2.5 NTU and ranging from 0.79 to 4.1 NTU. Pond effluent remained constant at 6000 mg/L.

Conductivity and pH

Permeate pH ranged from 5.7 to 5.8 with an average of 5.8. Concentrate pH was constant at 6.1. Permeate conductivity ranged from 439 to 491 µS/cm and averaged 465 µS/cm. Concentrate conductivity's was constant at 292 µS/cm

UF1-R8-SR3 Cleaning

After UF1-R8-SR3 was shutdown on February 25, 1998 at 06:46, it was cleaned on February 28, 1998 at 12:00 using a 0.5 % KLD cleaning solution. There was several days of downtime due in installation of a new header. The cleaning solution was recycled for total of two hours running time. The CIP tank was cracked again so the flush tank was used for the cleaning. As a result the temperature cleaning solution could not be pre-heated before the cleaning. The solution was recycled for awhile to heat in up as much as possible. The cleaning temperature started out ~ 90 °F. Total downtime for this cleaning was 240 minutes.

Permeate Flux and Temperature

During the first hour, the permeate flux ranged from 103.2 to 109.4 gal/ft²-d and averaged 105.8 gal/ft²-d. Permeate temperature ranged from 90.1 to 94.7 °F and averaged 92.2 °F. Concentrate temperature ranged from 94.4 to 101.1 °F and averaged 97.8 °F over the course of the first hour.

The system was then shutdown and the valves were adjusted for a spongeball sequence. During the first spongeball pass the flux increased to 114.7 gal/ft²-d. The second spongeball pass yielded a flux of 114.7 gal/ft²-d.

During the second hour of cleaning, the permeate flux ranged from 124.5 to 128.1 gal/ft²-d and averaged 125.9 gal/ft²-d. Concentrate temperatures ranged from 93.9 to 97.5°F and averaged 95.5 °F. Permeate temperature ranged from 99 to 105.3 °F with an average of 102.2 °F.

pH, Conductivity and Turbidity

Permeate pH ranged from 8.8 to 9.2 with an average of 9.1. Concentrate pH ranged from 9.0 to 9.2 with an average of 9.1. Permeate conductivity ranged from 723 to 802 µS/cm and averaged 770 µS/cm. Concentrate conductivity ranged from 1798 to

1970 $\mu\text{S}/\text{cm}$ and averaged 1876 $\mu\text{S}/\text{cm}$. Permeate turbidity ranged from 2.2 to 4.1 NTU and averaged 3.1 NTU.

UF1-R8-SR4

UF1-R8-SR4 was started on February 28, 1998 at 16:00 and ended on March 6, 1998 at 17:30. The length of the subrun lasted 6.1 days. Subrun #4 was ended because the permeate running average reached 29 gal/min. The total permeate volume produced was 256,390 gal.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 17.8 to 91.6 gal/ft²-d. Permeate temperature ranged from 72.9 to 76.5 °F with an average of 75.6 °F. Concentrate temperatures ranged from 75.7 to 80.7 °F with an average of 79.6 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content started out at 4.0 % and increased to 5.4 % over the course of subrun #4. The total volume of free oil that was produced during subrun #4 was 1,679 gallons. The average daily free oil production was 275.2 gallons/day.

Oil/Grease, Turbidity and Pond Effluent

Permeate O/G remained low, around 6 mg/L. Turbidity was also low, averaging 4.2 NTU and ranging from 0.85 to 7.6 NTU. Pond effluent remained constant at 6000 mg/L.

Conductivity and pH

Permeate pH ranged from 4.1 to 5.5 with an average of 5.2. Concentrate pH ranged from 5.2 to 5.9 and averaged 5.5. Permeate conductivity ranged from 268 to 431

$\mu\text{S/cm}$ and averaged $361 \mu\text{S/cm}$. Concentrate conductivity's ranged from 183.3 to $534 \mu\text{S/cm}$ and averaged $359 \mu\text{S/cm}$.

UF1-R8-SR4 Cleaning

After UF1-R8-SR4 was shutdown on March 6, 1998 at 17:30, it was cleaned at 20:10 using a 0.5 % KLD cleaning solution. The new stainless steel CIP tank was used to clean with. Once the water was heated to $\sim 115^\circ\text{F}$, unit #1 was cleaned for 40 minutes. After 40 minutes elapsed, the system was shutdown and prepared for two spongeball passes. After the spongeball sequence the system was cleaned for an additional 40 minutes. Total downtime for this cleaning was 270 minutes.

Permeate Flux and Temperature

During the first regular cleaning, the permeate flux ranged from 76.5 to $80.0 \text{ gal/ft}^2\text{-d}$ and averaged $78.4 \text{ gal/ft}^2\text{-d}$. Permeate temperature ranged from 110 to 112.8°F and averaged 111.9°F . Concentrate temperature ranged from 117.4 to 124.3°F and averaged 121°F .

The system was then shutdown and the valves were adjusted for a spongeball sequence. During the first spongeball pass the flux increased to $115.8 \text{ gal/ft}^2\text{-d}$. The second spongeball pass yielded a flux of $126.2 \text{ gal/ft}^2\text{-d}$.

During the second 40 minutes of cleaning, the permeate flux ranged from 110.3 to $115.6 \text{ gal/ft}^2\text{-d}$ and averaged $111.7 \text{ gal/ft}^2\text{-d}$. Concentrate temperatures ranged from 117.5 to 121°F and averaged 119.3°F . Permeate temperature ranged from 108.1 to 110.9°F and averaged 109.5°F .

pH, Conductivity and Turbidity

Permeate pH ranged from 6.5 to 6.7 with an average of 6.6. Concentrate pH ranged from 6.7 to 6.9 with an average of 6.8. Permeate conductivity ranged from 507 to 592 $\mu\text{S}/\text{cm}$ and averaged 560 $\mu\text{S}/\text{cm}$. Concentrate conductivity ranged from 924 to 1411 $\mu\text{S}/\text{cm}$ and averaged 1162 $\mu\text{S}/\text{cm}$. Permeate turbidity ranged from 3.6 to 8.3 NTU and averaged 4.8 NTU.

UF1-R8-SR5

UF1-R8-SR5 was started on March 6, 1998 at 22:00 and ended on March 12, 1998 at 05:45. The length of the subrun lasted 5.30 days. Subrun #5 was ended because the permeate running average reached 29 gal/min. The total permeate volume produced was 225,490 gal.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 19.6 to 88.9 gal/ft²-d. Permeate temperature ranged from 71.8 to 78.2 °F with an average of 74.7 °F. Concentrate temperatures ranged from 77.9 to 80.8 °F with an average of 79.0 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content started out at 5.4 % and increased to 6.8 % during subrun #5. The total volume of free oil that was produced during subrun #5 was 2,304 gallons. The average daily free oil production was 434.7 gallons/day.

Oil/Grease, Turbidity and Pond Effluent

Permeate O/G remained low, around 5 mg/L. Turbidity was also low, averaging 8.0 NTU and ranging from 1.1 to 17.5 NTU. Pond effluent remained constant at 7000 mg/L.

Conductivity and pH

Permeate pH ranged from 4.5 to 6.4 with an average of 5.6. Concentrate pH ranged from 5.3 to 6.3 and averaged 5.9. Permeate conductivity ranged from 207 to 382 $\mu\text{S}/\text{cm}$ and averaged 300 $\mu\text{S}/\text{cm}$. Concentrate conductivity's ranged from 147 to 333 $\mu\text{S}/\text{cm}$ and averaged 247 $\mu\text{S}/\text{cm}$.

UF1-R8-SR5 Cleaning

After UF1-R8-SR5 was shutdown on March 12, 1998 at 05:45, it was cleaned at 10:10 using a 0.5 % KLD cleaning solution. Once the cleaning solution was heated to ~ 115 °F and the pH increased to ~ 10, unit #1 was cleaned for 40 minutes. After 40 minutes elapsed, the system was shutdown and prepared for two spongeball passes. After the spongeball sequence the system was cleaned for an additional 40 minutes. Total downtime for this cleaning was 435 minutes.

Permeate Flux and Temperature

During the first regular cleaning, the permeate flux ranged from 80 to 83.6 gal/ft²-d and averaged 81.8 gal/ft²-d. Permeate temperature ranged from 110.6 to 111.4 °F and averaged 111.1 °F. Concentrate temperature ranged from 119.7 to 122.5 °F and averaged 121 °F.

The system was then shutdown and the valves were adjusted for a spongeball sequence. During the first spongeball pass the flux increased to 117.4 gal/ft²-d. The second spongeball pass yielded a flux of 132.2 gal/ft²-d.

During the second 40 minutes of cleaning, the permeate flux ranged from 97.8 to 108.5 gal/ft²-d and averaged 103.2 gal/ft²-d. Concentrate temperatures ranged from 111.3 to 114.1°F and averaged 112.5 °F. Permeate temperature ranged from 117.5 to 124.9 °F and averaged 121.4 °F.

pH, Conductivity and Turbidity

Permeate pH ranged from 8.5 to 9.5 with an average of 9.1. Concentrate pH ranged from 8.5 to 9.6 with an average of 9.1. Permeate conductivity ranged from 479 to 1430 µS/cm and averaged 957 µS/cm. Concentrate conductivity ranged from 985 to 2300 µS/cm and averaged 1725 µS/cm. Permeate turbidity ranged from 3.2 to 9.5 NTU and averaged 6.1 NTU.

UF1-R8-SR6

UF1-R8-SR6 was started on March 12, 1998 at 13:00 and ended on April 4, 1998 at 01:10. The length of the subrun lasted 22.4 days. The system was allowed to run because the instantaneous permeate flow steady out into the mid to lower twenties. The total permeate volume produced was 761,940 gal.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 18 to 93 gal/ft²-d. Permeate temperature ranged from 71.8 to 81.5 °F with an average of 78.4 °F. Concentrate temperatures ranged from 76.0 to 85.0 °F with an average of 81.9 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content started out at 6.8% and increased to 11.5% during subrun #6. The total volume of free oil that was produced during subrun #6 was 4,936 gallons. The average daily free oil production was 221.3 gallons/day.

Oil/Grease, Turbidity and Pond Effluent

Permeate O/G ranged from 1 to 5 mg/L and averaged 2.8 mg/L. Permeate turbidity ranged from 0.98 to 14.5 NTU and averaged 2.7 NTU. Pond effluent oil content ranged from 6,000 to 7,000 mg/L and averaged 6800 mg/L.

Conductivity and pH

Permeate pH ranged from 4.4 to 6.3 with an average of 5.1. Concentrate pH ranged from 4.6 to 6.2 and averaged 5.3. Permeate conductivity ranged from 111 to 391 μ S/cm and averaged 287 μ S/cm. Concentrate conductivity's ranged from 204 to 501 μ S/cm and averaged 355 μ S/cm.

UF1-R8-SR6 Cleaning

After UF1-R8-SR6 was shutdown on April 4, 1998 at 01:10, it was cleaned at 02:33 using a 0.5 % KLD cleaning solution. The pH of the cleaning solution was not raised to 10 because of time and personal available at the time.

Permeate Flux and Temperature

During the first regular cleaning, the permeate flux ranged from 65.8 to 71.1 gal/ft²-d and averaged 69.0 gal/ft²-d. Permeate temperature ranged from 109 to 112.9 °F and averaged 110.9 °F. Concentrate temperature ranged from 118 to 122 °F and averaged 120 °F.

The system was then shutdown and the valves were adjusted for a spongeball sequence. During the first spongeball pass the flux increased to 92.5 gal/ft²-d. The second spongeball pass yielded a flux of 108.5 gal/ft²-d. The third spongeball pass yielded a permeate flux of 113.8 gal/ft²-d.

During the second cleaning after spongeballs, the permeate flux ranged from 90.7 to 97.8 gal/ft²-d and averaged 93.1 gal/ft²-d. Concentrate temperatures ranged from 114 to 124.9°F and averaged 116.9 °F. Permeate temperature ranged around 108.1 °F

pH, Conductivity and Turbidity

Permeate pH ranged from 5.4 to 5.9 with an average of 5.7. Concentrate pH ranged from 6.0 to 6.3 with an average of 6.2. Permeate conductivity ranged from 281 to 614 µS/cm and averaged 453 µS/cm. Concentrate conductivity ranged from 264 to 1043 µS/cm and averaged 776 µS/cm. Permeate turbidity ranged from 2.9 to 6.3 NTU and averaged 4.4 NTU.

UF1-R8-SR7

UF1-R8-SR7 was started on April 4, 1998 at 04:17 and ended on April 10, 1998 at 10:12. The length of the subrun lasted 6.2 days. The system was shutdown because the running permeate average reached 29 gpm. The total permeate volume produced was 263,600 gal.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 20.5 to 67.6 gal/ft²-d. Permeate temperature ranged from 73.9 to 79.6 °F with an average of 77.4 °F. Concentrate temperatures ranged from 78.3 to 79.6 °F with an average of 81.1 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content started out at 11.3 % and decreased to 11.0 % during subrun #7. The total volume of free oil that was produced during subrun #7 was 2,316 gallons. The average daily free oil production was 373.5 gallons/day.

Oil/Grease, Turbidity and Pond Effluent

Permeate O/G ranged from 3 to 4 mg/L and averaged 3.5 mg/L. Permeate turbidity ranged from 0.38 to 4.5 NTU and averaged 2.3 NTU. Pond effluent oil content ranged from 7000 to 8000 mg/L and averaged 7300 mg/L.

Conductivity and pH

Permeate pH ranged from 4.8 to 5.7 with an average of 5.3. Concentrate pH ranged from 5.2 to 6.0 and averaged 5.4. Permeate conductivity ranged from 236 to 425 $\mu\text{S}/\text{cm}$ and averaged 350 $\mu\text{S}/\text{cm}$. Concentrate conductivity's ranged from 170 to 486 $\mu\text{S}/\text{cm}$ and averaged 354 $\mu\text{S}/\text{cm}$.

UF1-R8-SR7 Cleaning

After UF1-R8-SR7 was shutdown on April 10, 1998 at 10:12, it was cleaned at 12:30 using a 0.5 % KLD cleaning solution. The pH of the cleaning solution was raised to ~ 9.3.

Permeate Flux and Temperature

During the first regular cleaning, the permeate flux ranged from 57.8 to 59.6 gal/ft²-d and averaged 58.7 gal/ft²-d. Permeate temperature ranged from 114.3 to 115 °F and averaged 114.6 °F. Concentrate temperature ranged from 121 to 124 °F and averaged 123 °F.

The system was then shutdown and the valves were adjusted for a spongeball sequence. During the first spongeball pass the flux increased to 177.8 gal/ft²-d. The second spongeball pass yielded the same result.

During the second cleaning after spongeballs, the permeate flux ranged from 97.8 to 99.6 gal/ft²-d and averaged 98.5 gal/ft²-d. Concentrate temperatures ranged from 114.2

to 128.8°F and averaged 123.4 °F. Permeate temperature ranged around 115.6 to 119.2 °F and averaged 117.8 °F.

pH, Conductivity and Turbidity

Permeate pH ranged from 8.4 to 9.2 with an average of 8.9. Concentrate pH ranged from 8.5 to 9.3 with an average of 8.9. Permeate conductivity ranged from 353 to 714 $\mu\text{S}/\text{cm}$ and averaged 544 $\mu\text{S}/\text{cm}$. Concentrate conductivity ranged from 712 to 1425 $\mu\text{S}/\text{cm}$ and averaged 1113 $\mu\text{S}/\text{cm}$. Permeate turbidity ranged from 2.0 to 5.6 NTU and averaged 3.8 NTU.

UF1-R8-SR8

UF1-R8-SR8 was started on April 10, 1998 at 15:30 and ended on April 16, 1998 at 02:17. The length of the subrun lasted 5.4 days. The system was shutdown because a new spongeball pipeline was going to be installed. The total permeate volume produced was 186,810 gal.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 16.9 to 88.9 gal/ft²-d. Permeate temperature ranged from 73.7 to 82.6 °F with an average of 79.4 °F. Concentrate temperatures ranged from 80.0 to 86.0 °F with an average of 83.3 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content started out at 11.2 % and decreased to 10.5 % during subrun #8. The total volume of free oil that was produced during subrun #8 was 1,589 gallons. The average daily free oil production was 294.3 gallons/day.

Permeate Oil/Grease, Turbidity and Pond Effluent

Permeate O/G ranged from 3 to 5 mg/L and averaged 3.7 mg/L. Permeate turbidity ranged from 0.8 to 5.2 NTU and averaged 1.9 NTU. Pond effluent oil content ranged from 7000 to 9000 mg/L and averaged 8000 mg/L.

Conductivity and pH

Permeate pH ranged from 5.1 to 6.3 with an average of 5.4. Concentrate pH ranged from 5.3 to 5.6 and averaged 5.4. Permeate conductivity ranged from 285 to 267 $\mu\text{S}/\text{cm}$ and averaged 410 $\mu\text{S}/\text{cm}$. Concentrate conductivity's ranged from 267 to 492 $\mu\text{S}/\text{cm}$ and averaged 415 $\mu\text{S}/\text{cm}$.

UF1-R8-SR8 Cleaning

After UF1-R8-SR8 was shutdown on April 16, 1998 at 02:17, it was cleaned at 04:40 using a 0.5 % KLD cleaning solution. The pH of the cleaning solution was raised to ~ 10.

Permeate Flux and Temperature

During the first regular cleaning, the permeate flux ranged from 119.2 to 128.1 gal/ft²-d and averaged 123.8 gal/ft²-d. Permeate temperature ranged from 114.1 to 115.5 °F and averaged 114.7 °F. Concentrate temperature ranged from 120.5 to 125 °F and averaged 123.1 °F.

The system was then shutdown and the valves were adjusted for a spongeball sequence. During the first spongeball pass the flux increased to 154.7 gal/ft²-d. The second spongeball pass yielded 165.4 gal/ft²-d. Third and fourth spongeball passes yields permeate fluxes of 181.4 and 177.9 gal/ft²-d respectively.

During the second cleaning after spongeballs, the permeate flux ranged from 133.4 to 140.5 gal/ft²-d and averaged 135.2 gal/ft²-d. Concentrate temperatures ranged

from 117.7 to 128.8 °F and averaged 123.8 °F. Permeate temperature ranged around 112.2 to 119.2 °F and averaged 115.5 °F.

pH, Conductivity and Turbidity

Permeate pH ranged from 9.3 to 9.9 with an average of 9.6. Concentrate pH ranged from 9.3 to 10.0 with an average of 9.7. Permeate conductivity ranged from 1285 to 2260 $\mu\text{S}/\text{cm}$ and averaged 1773 $\mu\text{S}/\text{cm}$. Concentrate conductivity ranged from 1973 to 2920 $\mu\text{S}/\text{cm}$ and averaged 2419 $\mu\text{S}/\text{cm}$. Permeate turbidity ranged from 0.6 to 6.0 NTU and averaged 1.6 NTU.

UF1-R8-SR9

UF1-R8-SR9 was started on April 17, 1998 at 16:20 and ended on April 23, 1998 at 08:53. The length of the subrun lasted 5.7 days. At the end of the subrun, the permeate running average was 30.9 gal/min. The total permeate volume produced was 263,620 gal. The system was shutdown because of a severe leak in an end connect.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 21.3 to 69.4 gal/ft²-d. Permeate temperature ranged from 75.8 to 80.9 °F with an average of 78.3 °F. Concentrate temperatures ranged from 78.1 to 83.6 °F with an average of 81.5 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content started out at 10.5 % and decreased to 9.8 % for subrun #9. The total volume of free oil that was produced during subrun #9 was 2,068 gallons. The average daily free oil production was 362.8 gallons/day.

Permeate Oil/Grease, Turbidity and Pond Effluent

Permeate O/G ranged from 1 to 3 mg/L and averaged 2 mg/L. Permeate turbidity ranged from 0.3 to 3.2 NTU and averaged 1.3 NTU. Pond effluent oil content ranged at 8000 mg/L.

Conductivity and pH

Permeate pH ranged from 5.0 to 5.4 with an average of 5.2. Concentrate pH ranged from 5.2 to 5.4 and averaged 5.3. Permeate conductivity ranged from 138 to 464 $\mu\text{S}/\text{cm}$ and averaged 312 $\mu\text{S}/\text{cm}$. Concentrate conductivity's ranged from 212 to 431 $\mu\text{S}/\text{cm}$ and averaged 342 $\mu\text{S}/\text{cm}$.

UF1-R8-SR9 Cleaning

After UF1-R8-SR9 was shutdown on April 23, 1998 at 08:53, it was cleaned at 14:40 using a 0.5 % KLD cleaning solution. The cleaning did not follow the same format and procedure as the cleanings performed previously. During this cleaning the system was cleaned for 20 minutes and then the new spongeball screen was tested out by adjusting the valves and performing three spongeball passes. Three spongeball passes were implemented. The spongeballs were then retrieved to see if the number put in equal the number that came out. After the small test, the system was cleaned for an addition half hour.

Permeate Flux and Temperature

During the first 20 minutes of cleaning, the permeate flux remained constant at 88.9 gal/ft²-d. Permeate temperature was only taken once during the first cleaning and ranged at 89.1 °F. Concentrate temperature ranged from 96 to 100 °F and averaged 97.9 °F.

The system was then shutdown and the valves were adjusted for a spongeball sequence. During the first spongeball pass the flux increased to 115.6 gal/ft²-d. The second spongeball pass yielded 124.5 gal/ft²-d. The third spongeball pass yielded a permeate flux of 131.6 gal/ft²-d.

During the second cleaning after spongeballs, the permeate flux ranged from 120.9 to 126.3 gal/ft²-d and averaged 124 gal/ft²-d. Concentrate temperatures ranged from 116 to 122.5 °F and averaged 119.2 °F. Permeate temperature ranged around 109.7 to 111.1 °F and averaged 110.4 °F.

pH, Conductivity and Turbidity

Permeate pH ranged from 6.2 to 6.3 with an average of 6.3. Concentrate pH ranged from 6.4 to 6.5 with an average of 6.5. Permeate conductivity ranged from 733 to 874 µS/cm and averaged 819 µS/cm. Concentrate conductivity ranged from 1228 to 1433 µS/cm and averaged 1358 µS/cm. Permeate turbidity ranged from 1.6 to 3.0 NTU and averaged 2.2 NTU.

UF1-R8-SR10

UF1-R8-SR10 was started on April 23, 1998 at 19:00 and ended on June 16, 1998 at 10:39. The length of the subrun lasted 51.3 days.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 20.5 to 86.3 gal/ft²-d. Permeate temperature ranged from 73.7 to 82.6 °F with an average of 79.4 °F. Concentrate temperatures ranged from 80.7 to 92.4 °F with an average of 87.3 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content started out at 10.2 % and decreased to 3.0 % during subrun #10. The total volume of free oil that was produced during subrun #10 was 26,823 gallons. The average daily free oil production was 522.8 gallons/day.

Permeate Oil/Grease, Turbidity and Pond Effluent

Permeate O/G ranged from 1 to 9 mg/L and averaged 3.9 mg/L. Permeate turbidity ranged from 0.11 to 5.8 NTU and averaged 0.80 NTU. Pond effluent oil content ranged from 3000 to 8000 mg/L and averaged 7200 mg/L.

Conductivity and pH

Permeate pH ranged from 4.8 to 6.1 with an average of 5.5. Concentrate pH ranged from 4.9 to 5.9 and averaged 5.5. Permeate conductivity ranged from 101 to 687 $\mu\text{S}/\text{cm}$ and averaged 341 $\mu\text{S}/\text{cm}$. Concentrate conductivity's ranged from 220 to 523 $\mu\text{S}/\text{cm}$ and averaged 406 $\mu\text{S}/\text{cm}$.

UF1-R8-SR10 Cleaning

After UF1-R8-SR10 was shutdown on June 16, 1998 at 10:39, it was cleaned at 11:00 using a 0.5 % KLD cleaning solution. The pH of the cleaning solution was raised to ~ 10.

Permeate Flux and Temperature

During the first regular cleaning, the permeate flux ranged from 69.4 to 71.1 gal/ft²-d and averaged 70.3 gal/ft²-d. Permeate temperature ranged from 111.8 to 117.2 °F and averaged 114.5 °F. Concentrate temperature ranged from 121 to 124 °F and averaged 122.5 °F.

The system was then shutdown and the valves were adjusted for a spongeball sequence. During the first spongeball pass the flux increased to 154.7 gal/ft²-d. The second spongeball pass yielded 165.4 gal/ft²-d. Third and fourth spongeball passes yields permeate fluxes of 181.4 and 177.9 gal/ft²-d respectively.

During the second cleaning after spongeballs, the permeate flux ranged from 100.5 to 103.2 gal/ft²-d and averaged 102.1 gal/ft²-d. Concentrate temperatures ranged from 120 to 124 °F and averaged 123 °F. Permeate temperature ranged around 118.2 to 110.7 °F and averaged 114.5 °F.

pH, Conductivity and Turbidity

Permeate pH ranged from 9.4 to 9.6 with an average of 9.5. Concentrate pH ranged from 9.4 to 9.6 with an average of 9.5. Permeate conductivity ranged from 922 to 1144 µS/cm and averaged 1041 µS/cm. Concentrate conductivity ranged from 959 to 2230 µS/cm and averaged 1615 µS/cm. Permeate turbidity ranged from 0.99 to 6.5 NTU and averaged 2.7 NTU.

UF1-R8-SR11

UF1-R8-SR11 was started on June 18, 1998 at 14:20 and ended on June 25, 1998 at 07:02. The length of the subrun lasted 6.5 days. Subrun #11 was shutdown, because large thunderstorms filled the settling pond. Subrun #11 marked the end of the experiments for unit #1. After the system was shutdown, the concentrate in the feed tanks was purged to the tank farm.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 24.9 to 83.6 gal/ft²-

d. Permeate temperature ranged from 85.8 to 90.3 °F with an average of 87.6 °F.

Concentrate temperatures ranged from 91.2 to 92.0 °F with an average of 91.5 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content started out at 3.0 % and decreased to 4.5 % during subrun #11. The total volume of free oil that was produced during subrun #11 was 4,130 gallons. The average daily free oil production was 635.4 gallons/day.

Permeate Oil/Grease, Turbidity and Pond Effluent

Permeate O/G ranged from 2 to 5 mg/L and averaged 3.2 mg/L. Permeate turbidity ranged from 0.36 to 5.2 NTU and averaged 1.3 NTU. Pond effluent oil content ranged from 7000 to 9000 mg/L and averaged 8300 mg/L.

pH, Conductivity and Turbidity

Permeate pH ranged from 4.8 to 7.1 with an average of 5.4. Concentrate pH ranged from 5.2 to 5.5 and averaged 5.4. Permeate conductivity ranged from 228 to 476 µS/cm and averaged 346 µS/cm. Concentrate conductivity's ranged from 441 to 555 µS/cm and averaged 498 µS/cm.

UF2-R3

UF2-R3 started on January 16, 1998 at 01:10 and ended February 5, 1998 at 04:30. The run lasted for 18.1 days. The objectives of the run were: 1) monitor system performance, 2) estimate the volume of free oil that forms at the top of the concentrate

tanks and 3) conduct an oil mass balance on the system in order to note the change occurring in the system.

In Figure 4.5, permeate flux versus time for UF2-R3 is presented. In Figure 4.6, permeate turbidity versus time for UF2-R3 is presented. In Table 4.19, a summary of permeate operating parameters for UF2-R3 is presented. In Table 4.20, a summary of concentrate operating parameters for UF2-R3 is presented. In Table 4.21, a summary of permeate cleaning parameters for UF2-R3 is presented. In Table 4.22, a summary of concentrate cleaning parameters for UF2-R3 is presented. In Table 4.23, a summary of permeate O/G samples analyzed for UF2-R3, is presented. In Table 4.24, a summary of concentrate oil content samples analyzed for UF2-R3, is presented. In Table 4.25, a summary of free oil skimming samples analyzed for UF2-R3, is presented. In Table 4.26, a summary of free oil production for UF2-R3 is presented. In Table 4.27, a summary of pond effluent samples analyzed for UF2-R3, is presented.

UF2-R3-SR1

UF2-R3-SR1 was started on January 16, 1998 at 01:10 and ended on January 21, 1998 at 00:20. The length of the subrun lasted 4.96 days. The objectives of this subrun were to estimate the volume of free oil that forms at the top of the concentrate tanks and conduct an oil mass balance on the system. The total permeate volume produced was 211,890 gal. Subrun #2 was stopped because the running average reached the low set point of 29 gal/min.

D. Figure 4.5 Permeate Flux versus Time for UF2-R3

Figure 4.6 Permeate Turbidity versus Time for UF2-R3

Table 4.19. Summary of Permeate Parameters for UF2-R3

Subrun ID	Flux (gal/ft²-d) [min – max] Avg ±std	Temperature (°F) [min – max] Avg ±std	Turbidity (NTU) [min – max] Avg ±std	pH [min – max] Avg ±std	Conductivity(μS/cm) [min – max] Avg ±std	O/G (mg/L) [min – max] Avg ±std
1	[16.9 – 103.2] 34.2±21.5	[71.2 – 78.7] 75.7±2.3	[1.3 – 4.9] 2.6±1.0	[5.9 – 6.6] 6.3±0.2	[202 – 697] 518±152	[1 – 5.7] 3.9±1.6
2	[21.3 – 82.7] 38.3±13.6	[72.5 – 75.1] 73.9±1.2	[2.1 – 7.2] 3.4±1.9	[5.4 – 6.1] 5.8±0.3	[361 – 708] 504±148	[2 – 5] 3.7±1.2
3	[19.6 – 66.7] 31.0±10.5	[72.5 – 76.9] 74±1.6	[0.75 – 1.3] 1.1±0.23	[5.4 – 5.9] 5.6±0.2	[512 – 656] 536±53	[3 – 5] 3.7±1.2
4	[17.8 – 99.8] 25.3±7.3	[73.6 – 77.5] 75.6±1.2	[0.52 – 9.8] 1.9±2.4	[4.5 – 6.0] 5.4±0.5	[168 – 630] 496±134	[2 – 6] 4.0±1.3

Table 4.20. Summary of Concentrate and Pond Effluent O/G Parameters for UF2-R3

Subrun ID	Temperature (°F) [min – max] Avg ±std	pH [min – max] Avg ±std	Conductivity(μS/cm) [min – max] Avg ±std	Oil Content (%) [min – max] Avg ±std	Pond Effluent O/G (mg/L) [min – max] Avg ±std
1	[76 – 84.7] 80.6±2.6	[5.7 – 6.5] 6.2±0.3	[188 – 584] 476±147	[0.86 – 5.7] 3.1±2.1	[0.3-1.2] 0.6±0.5
2	[77 – 79.5] 78.1±1.1	[5.1 – 6.2] 5.8±0.5	[388 – 680] 568±125	[5.7 – 9.6] 7.6±2.7	[0.5-0.6] 0.55±0.07
3	[76.3 – 81.1] 78.6±1.8	[5.7 – 6.1] 5.9±0.2	[152 – 536] 372±198	[1.6 – 10.1] 5.8±6.0	[1.2-3.4] 2.3±1.6
4	[77 – 82.3] 80±1.5	[4.8 – 5.8] 5.5±0.4	[198 – 636] 446±181	[10.1 – 9.8] 8.3±2.1	[0.6-3.1] 1.3±0.9

Table 4.21. Summary of Permeate Cleaning Parameters for UF2-R3

Subrun ID	Flux (gal/ft²-d) [min – max] Avg ±std	Temperature (°F) [min – max] Avg ±std	Turbidity (NTU) [min – max] Avg ±std	pH [min – max] Avg ±std	Conductivity(μS/cm) [min – max] Avg ±std
1	[33.7 – 77.4] 54.6±3.8	[86.8 – 96.9] 92.1±2.9	[4.2 – 9.1] 6.5±1.9	[5.4 – 6.9] 6.8±0.4	[718 – 885] 809±60
2	[42.7 – 67.6] 56.4±4.5	[90.7 – 99.2] 95.8±3.4	[2.5 – 9.3] 4.1±2.2	[6.5 – 6.9] 6.7±0.1	[609 – 903] 789±86
3	[33.8 – 53.4] 43.1±1.5	[89.4 – 99.6] 95.8±3.8	[2.9 – 19.0] 8.3±5.4	[6.3 – 6.7] 6.5±0.1	[636 – 864] 758±83
4	[26.7 – 67.6] 47.9±3.5	[89.7 – 97.2] 94±2.0	[4.4 – 38.8] 13.1±12.8	[5.9 – 6.2] 6.1±0.1	[762 – 880] 835±41

Table 4.22. Summary of Concentrate Cleaning Parameters for UF2-R3

Subrun ID	Temperature (^oF) [min – max] Avg ±std	pH [min – max] Avg ±std	Conductivity(μS/cm) [min – max] Avg ±std
1	[94.7 – 107] 101.3±2.7	[5.7 – 6.8] 6.3±0.4	[1209 – 1528] 1398±122
2	[99.2 – 109.3] 104±3.4	[6.7 – 6.8] 6.7±0.1	[1266 – 1809] 1523±236
3	[98.1 – 110.1] 104.7±3.7	[6.3 – 6.7] 6.5±0.1	[1060 – 1402] 1241±150
4	[96.8 – 108.9] 103±2.8	[5.9 – 6.4] 6.2±0.1	[1751 – 1912] 1835±62

Table 4.23 Summary of Permeate O/G Samples for UF2-R3

Subrun ID	Date/Time	Sample Results (mg/L)		
		#1	#2	#3
1	1/16/98 (02:21)	4		
1	1/16/98 (19:06)			
1	1/17/98 (04:03)	5		
1	1/17/98 (16:36)			
1	1/18/98 (06:26)	6	6	5
1	1/18/98 (15:08)			
1	1/19/98 (04:52)	3		
1	1/19/98 (18:50)			
1	1/20/98 (06:27)	4		
1	1/20/98 (19:10)	1		
2	1/21/98 (11:51)	4		
2	1/22/98 (00:38)			
2	1/22/98 (13:00)	2		
2	1/23/98 (02:56)	3		
2	1/23/98 (15:21)	5		
2	1/24/98 (02:00)	4	5	5
3	1/24/98 (17:28)	3		
3	1/24/98 (00:14)			
3	1/25/98 (11:04)	3		
3	1/26/98 (02:20)			
3	1/26/98 (13:06)	5		
3	1/27/98 (03:44)			
4	1/29/98 (11:10)	4		
4	1/29/98 (23:41)			
4	1/30/98 (14:27)	4		
4	1/31/98 (03:33)	3	3	3
4	1/31/98 (14:22)			
4	2/1/98 (01:10)	3		
4	2/1/98 (12:08)			
4	2/2/98 (03:14)	5		
4	2/2/98 (11:16)			
4	2/2/98 (23:22)	6		
4	2/3/98 (11:54)			
4	2/4/98 (00:16)	2		
4	2/4/98 (13:30)			
4	2/4/98 (22:33)	4	5	5

Table 4.24 Summary of Concentrate Oil Content Samples for UF2-R3

Subrun ID	Date/Time	Sample Results (%)		
		#1	#2	#3
1	1/16/98 (01:20)	0.9	0.9	0.8
1	1/16/98 (09:02)	1.4	1.2	1.3
1	1/16/98 (21:15)	2.2	2.1	2.4
1	1/17/98 (22:30)	2.1	2.5	2.2
1	1/19/98 (00:05)	3.1	3.6	4.1
1	1/20/98 (06:27)	3.7	4.1	3.7
2	1/21/98 (04:42)	6.6	6.3	4.3
2	1/22/98 (00:36)	5.2		
2	1/22/98 (18:15)	3.2		
2	1/24/98 (09:35)	9.5	8.4	9.6
3	1/24/98 (15:50)	1.3	1.5	1.9
3	1/26/98 (23:45)	8.5	7.4	10.1
3	1/27/98 (09:00)	10.0	9.8	10.7
4	1/28/98 (03:20)	6.8	6.8	5.9
4	1/29/98 (04:22)	7.6		
4	1/31/98 (04:16)			
4	2/2/98 (11:55)	9.8	9.6	10.0
4	2/5/98 (04:20)	9.8	9.7	9.9

Table 4.25 Summary of Skimming Samples for UF2-R3

Subrun ID	Date/Time	Sample Results (%)		
		#1	#2	#3
1	1/16/98 (02:33)	80		
2	1/24/98 (23:15)	100		
3	1/25/98 (00:30)	100		
3	1/25/98 (14:20)	100		
3	1/26/98 (16:46)	100		
3	1/27/98 (17:05)	99		
3	1/28/98 (23:04)	100		
3	1/28/98 (23:53)	99		
4	1/29/98 (16:36)	99		
4	1/30/98 (07:39)	99		
4	1/30/98 (15:00)	99		
4	1/31/98 (15:13)	98		
4	2/1/98 (17:28)	100		
4	2/2/98 (04:08)	99		
4	2/2/98 (11:40)	99		
4	2/3/98 (04:57)	100		
4	2/3/98 (12:12)	100		
4	2/4/98 (04:50)	99		
4	2/4/98 (14:00)	100		
4	2/5/98 (07:13)	100		

Table 4.26 Summary of Free Oil Productions for UF2-R3

Subrun ID	Subrun Length, d	Total Free Oil, gal	Free Oil Production, gal/d
1	5.0	164	32.8
2	3.2	313	97.8
3	2.8	1,949	696.1
4	7.1	1,951	274.8

Table 4.27 Summary of Pond Effluent O/G Samples for UF2-R3

Subrun ID	Date/Time	Sample Results (mg/L)		
		#1	#2	#3
1	1/16/98 (12:10)	4,000		
1	1/17/98 (11:20)	3,000		
1	1/19/98 (18:30)	12,000		
2	1/21/98 (13:32)	5,000		
2	1/23/98 (18:35)	6,000		
3	1/25/98 (10:55)	18,000		
3	1/27/98 (07:20)	34,000		
4	1/29/98 (11:00)	31,000		
4	1/31/98 (10:30)	14,000		
4	2/1/98 (11:48)	11,000		
4	2/2/98 (11:05)	10,000		
4	2/3/98 (11:40)	6,000	7,000	6,000
4	2/4/98 (13:18)	8,000		

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 16.9 to 103.2 gal/ft²-d. Permeate temperature ranged from 71.2 to 78.7 °F with an average of 75.7 °F. Concentrate temperatures ranged from 76.0 to 84.7 °F with an average of 80.6 °F.

Concentrate Oil Content and Free Oil Production

During subrun #1, concentrate oil content started at 0.4% oil and increased to 1.2 % oil. The total volume of free oil that was produced during subrun #1 was 164 gallons. The average daily free oil production was 32.8 gallons/day.

Permeate Oil/Grease, Turbidity and Pond Effluent

Permeate O/G remained low, averaging 3.8 mg/L and ranging from 1.0 to 5.7 mg/L. Turbidity was also low, averaging 2.5 NTU and ranging from 1.3 to 4.9 NTU. Pond effluent O/G ranged from 3,000 to 12,000 mg/L and averaged 6,333.

Conductivity and pH

Permeate pH ranged from 5.9 to 6.6 with an average of 6.3. Concentrate pH ranged from 5.7 to 6.5 with an average of 6.2. Permeate conductivity ranged from 188 to 584 µS/cm and averaged 476 µS/cm. Concentrate conductivity's ranged from 202 to 697 µS/cm and averaged 518 µS/cm.

UF2-R3-SR1 Cleaning

After UF2-R3-SR1 was shutdown on January 21, 1998 at 00:20 it was cleaned at 00:50, with a 0.5 % KLD cleaning solution. Once the cleaning water was heated to

~100 °F, the system was cleaned for one hour under the regular cleaning cycle. After one hour elapsed, the system was shutdown and prepared for a spongeball sequence. Once the valves were adjusted on the system for spongeball retrieval, the system under went two spongeball passes. After the spongeball sequence was performed, the valves were readjusted to the normal mode setting. The system was then cleaned for an additional hour with the same cleaning solution. The total downtime for the cleaning was 250 minutes.

Permeate Flux and System Temperature

During the first hour of cleaning the permeate flux ranged from 33.7 to 45.0 gal/ft²-d and averaged 39.0 gal/ft²-d. Permeate temperature during the first hour of cleaning ranged from 86.8 to 94.0 °F and averaged 90.3 °F. Concentrate temperature ranged from 94.7 to 102 °F and averaged 98.6 °F.

After one hour, the system was shutdown and the valves were adjusted for the spongeball sequence. During the first pass of spongeballs, the permeate flux increased to 97.8 gal/ft²-d. The second pass of spongeballs yielded a permeate flux of 90.7 gal/ft²-d. After two spongeball passes were performed the system was cleaned for an additional hour.

In the second hour of regular cleaning, the permeate flux ranged from 66.7 to 77.4 gal/ft²-d with an average of 70.1 gal/ft²-d. Permeate temperature ranged from 90.2 to 96.9 °F with an average of 93.9 °F. Concentrate temperature ranged from 101 to 107 °F with an average of 104 °F.

pH, Conductivity and Turbidity

Permeate pH over the course of the cleaning ranged from 5.4 to 7.0 and averaged 6.8. Concentrate pH ranged from 5.7 to 6.8 and averaged 6.3. Permeate conductivity averaged 809 µS/cm and ranged from 718 to 885 µS/cm. Concentrate conductivity

averaged 1398 $\mu\text{S}/\text{cm}$ and ranged from 1209 to 1528 $\mu\text{S}/\text{cm}$. Permeate turbidity ranged from 4.2 to 9.1 NTU and averaged 6.5 NTU.

UF2-R3-SR2

UF2-R3-SR2 was started on January 21, 1998 at 04:30 and ended on January 24, 1998 at 09:40. The length of the subrun lasted 3.2 days. The total permeate volume produced was 168,230 gal. Subrun #2 was stopped before a running average of 29 gal/min was reached because the instantaneous permeate flow was had reached 24 gal/min. The system is expected to be shutdown for a long period of time in the near future for valve replacements. Thus, the system was shutdown, cleaned and restarted, to restore high permeate flow, in order to decrease high pond level concerns, during the future shutdown.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 21.3 to 82.7 gal/ft²-d. Permeate temperature ranged from 72.5 to 75.1 °F with an average of 73.9 °F. Concentrate temperatures ranged from 77.0 to 79.5 °F with an average of 78.1 °F.

Concentrate Oil Content and Free Oil Production

During subrun #2 the concentrate oil content started out at 6.6 % and increased to 9.6 % at the end. The total volume of free oil that was produced during subrun #2 was 313 gallons. The average daily free oil production was 97.8 gallons/day.

Permeate Oil/Grease, Turbidity and Pond Effluent

Permeate (O/G) remained low, averaging 3.7 mg/L and ranging from 2.0 to 5.0 mg/L. Turbidity was also low, averaging 3.4 NTU and ranging from 2.1 to 7.2 NTU. Pond effluent samples ranged from 5000 to 6000 mg/L and ranged 5500 mg/L.

Conductivity and pH

Permeate pH ranged from 5.4 to 6.1 with an average of 5.8. Concentrate pH ranged from 5.1 to 6.2 with an average of 5.8. Permeate conductivity ranged from 361 to 708 $\mu\text{S}/\text{cm}$ and averaged 504 $\mu\text{S}/\text{cm}$. Concentrate conductivity's ranged from 388 to 680 $\mu\text{S}/\text{cm}$ and averaged 568 $\mu\text{S}/\text{cm}$.

UF2-R3-SR2 Cleaning

After UF2-R3-SR2 was shutdown on January 24, 1998 at 09:40 it was cleaned at 11:00, with a 0.5 % KLD cleaning solution. Once the cleaning water was heated to $\sim 100^\circ\text{F}$, the system was cleaned for one hour under the regular cleaning cycle. After one hour elapsed, the system was shutdown and prepared for a spongeball sequence. Once the valves were adjusted on the system for spongeball retrieval, the system under went two spongeball passes. After the spongeball sequence was performed, the valves were readjusted to the normal mode setting. The system was then cleaned for an additional hour with the same cleaning solution. The total downtime for the cleaning was 350 minutes.

Permeate Flux and System Temperature

During the first hour of cleaning the permeate flux ranged from 42.7 to 50.7 gal/ft²-d and averaged 47.1 gal/ft²-d. Permeate temperature during the first hour of cleaning ranged from 90.7 to 99.4 $^\circ\text{F}$ and averaged 95.8 $^\circ\text{F}$. Concentrate temperature ranged from 99.2 to 109.3 $^\circ\text{F}$ and averaged 104.4 $^\circ\text{F}$.

After one hour, the system was shutdown and the valves were adjusted for the spongeball sequence. During the first pass of spongeballs, the permeate flux increased to 117.4 gal/ft²-d. The second pass of spongeballs yielded a permeate flux of 111.2 gal/ft²-d. After two spongeball passes were performed the system was cleaned for an additional hour.

In the second hour of regular cleaning, the permeate flux ranged from 64.0 to 67.6 gal/ft²-d with an average of 65.6 gal/ft²-d. Permeate temperature ranged from 92.2 to 99.2 °F with an average of 95.8 °F. Concentrate temperature ranged from 99.1 to 109 °F with an average of 104.3 °F.

pH, Conductivity and Turbidity

Permeate pH, over the course of the cleaning ranged from 6.5 to 6.9 and averaged 6.7. Concentrate pH ranged from 6.7 to 6.8 and averaged 6.72. Permeate conductivity averaged 789 µS/cm and ranged from 609 to 903 µS/cm. Concentrate conductivity averaged 1523 µS/cm and ranged from 1266 to 1809 µS/cm. Permeate turbidity ranged from 2.5 to 9.2 NTU and averaged 4.1 NTU.

UF2-R3-SR3

UF2-R3-SR3 was started on January 24, 1998 at 15:30 and ended on January 27, 1998 at 09:15. The length of the subrun lasted 2.8 days. The total permeate volume produced was 124,430 gal. The system was shutdown, because the permeate running average reached the 29 gal/min set point.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 19.6 to 66.7 gal/ft²-d. Permeate temperature ranged from 72.2 to 76.9 °F with an average of 74.0 °F. Concentrate temperatures ranged from 76.3 to 81.1 °F with an average of 78.6 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content started out at 1.6 % and increased to 10.1 % by the end of subrun #3. The total volume of free oil that was produced during subrun #3 was 1,949 gallons. The average daily free oil production was 696.1 gallons/day.

Permeate Oil/Grease, Turbidity and Pond Effluent

Permeate O/G remained low, averaging 3.7 mg/L and ranging from 3.0 to 5.0 mg/L. Turbidity was also low, averaging 1.1 NTU and ranging from 0.75 to 1.3 NTU. Pond Effluent ranged from 12,000 to 34,000 mg/L and averaged 23,000 mg/L.

Conductivity and pH

Permeate pH ranged from 5.4 to 5.9 with an average of 5.6. Concentrate pH ranged from 5.7 to 6.1 with an average of 5.9. Permeate conductivity ranged from 512 to 656 $\mu\text{S}/\text{cm}$ and averaged 536 $\mu\text{S}/\text{cm}$. Concentrate conductivity's ranged from 152 to 536 $\mu\text{S}/\text{cm}$ and averaged 372 $\mu\text{S}/\text{cm}$.

UF2-R3-SR3 Cleaning

After UF2-R3-SR3 was shutdown on January 27, 1998 at 09:15 it was cleaned at 10:45, with a 0.5 % KLD cleaning solution. Once the cleaning water was heated to ~100 °F, the system was cleaned for one hour under the regular cleaning cycle. The total downtime for the cleaning was 2445 minutes. An acid cleaning was preformed after subrun #3 ended. Therefore a large downtime occurred.

Permeate Flux and System Temperature

During the first hour of cleaning the permeate flux ranged from 33.8 to 36.5 gal/ft²-d and averaged 34.9 gal/ft²-d. Permeate temperature during the first hour of cleaning ranged from 89.4 to 100.8 °F and averaged 95.4 °F. Concentrate temperature ranged from 98.1 to 109.9 °F and averaged 104 °F.

After one hour, the system was shutdown and the valves were adjusted for the spongeball sequence. During the first pass of spongeballs, the permeate flux increased to 69.4 gal/ft²-d. The second pass of spongeballs yielded a permeate flux of 88.9 gal/ft²-d. After two spongeball passes were performed the system was cleaned for an additional hour.

In the second hour of regular cleaning, the permeate flux ranged from 49.8 to 53.4 gal/ft²-d with an average of 51.2 gal/ft²-d. Permeate temperature ranged from 92.2 to 99.6 °F with an average of 96.2 °F. Concentrate temperature ranged from 99.9 to 110.1 °F with an average of 105.4 °F.

pH, Conductivity and Turbidity

Permeate pH over the course of the cleaning ranged from 6.3 to 6.7 and averaged 6.5. Concentrate pH ranged from 6.3 to 6.7 and averaged 6.5. Permeate conductivity averaged 758 µS/cm and ranged from 636 to 864 µS/cm. Concentrate conductivity averaged 1241 µS/cm and ranged from 1060 to 1402 µS/cm. Permeate turbidity ranged from 2.9 to 19.0 NTU and averaged 8.3 NTU.

UF2-R3-SR4

UF2-R3-SR4 was started on January 29, 1998 at 03:00 and ended on February 5, 1998 at 04:30. The length of the subrun lasted 7.06 days. The total permeate volume produced was 277,940 gal. Subrun #4 running average was far below the 29 gal/min set point, because the average never reached the system average. The permeate flow only

started out around 50 gal/min. and dropped to the mid twenties a day and a half into the subrun run. The system was not shutdown, because the instantaneous permeate flow never reached 18 gal/min. Subrun #4 marked the end of UF2-R3. After the system was shutdown the concentrate in the feed tank was purged to the tank farm.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 17.8 to 49.8 gal/ft²-d. Permeate temperature ranged from 73.6 to 77.5 °F with an average of 75.6 °F. Concentrate temperatures ranged from 77.0 to 82.3 °F with an average of 80.0 °F.

Concentrate Oil Content and Free Oil Production

Concentrate Oil content started out at 10.1 % and decreased to 9.8 % during subrun #4. The total volume of free oil that was produced during subrun #4 was 1,951 gallons. The average daily free oil production was 274.8 gallons/day.

Permeate Oil/Grease, Turbidity and Pond Effluent

Permeate O/G remained low, averaging 4.0 mg/L and ranging from 2.0 to 6.0 mg/L. Turbidity was also low, averaging 1.9 NTU and ranging from 0.5 to 9.8 NTU. Pond effluent O/G ranged from 6,333 to 31,000 mg/L over the course of the subrun.

Conductivity and pH

Permeate pH ranged from 4.5 to 6.0 with an average of 5.4. Concentrate pH ranged from 4.8 to 5.8 with an average of 5.5. Permeate conductivity ranged from 168 to 630 µS/cm and averaged 496 µS/cm. Concentrate conductivity's ranged from 198 to 636 µS/cm and averaged 446 µS/cm.

UF2-R3-SR4 Cleaning

After UF2-R3-SR4 was shutdown on February 5, 1998 at 04:30, it was cleaned at 04:40 using a 0.5 % KLD cleaning solution. Once the cleaning water was heated to ~100 °F, the system was cleaned for one hour under the regular cleaning cycle. The total downtime for the cleaning was 2151 minutes.

Permeate Flux and System Temperature

During the first hour of cleaning the permeate flux ranged from 26.7 to 40.9 gal/ft²-d and averaged 37.0 gal/ft²-d. Permeate temperature during the first hour of cleaning ranged from 89.7 to 95.9 °F and averaged 93.7 °F. Concentrate temperature ranged from 96.8 to 104.5 °F and averaged 101.4 °F.

After one hour, the system was shutdown and the valves were adjusted for the spongeball sequence. During the first pass of spongeballs, the permeate flux increased to 64.9 gal/ft²-d. The second pass of spongeballs yielded a permeate flux of 87.2 gal/ft²-d. After two spongeball passes were performed the system was cleaned for an additional hour.

In the second hour of regular cleaning, the permeate flux ranged from 64.9 to 67.6 gal/ft²-d with an average of 65.8 gal/ft²-d. Permeate temperature ranged from 94.8 to 97.2 °F with an average of 95.7 °F. Concentrate temperature ranged from 101.3 to 108.9 °F with an average of 104.6 °F.

pH, Conductivity and Turbidity

Permeate pH, over the course of the cleaning ranged from 5.9 to 6.2 and averaged 6.1. Concentrate pH ranged from 5.9 to 6.4 and averaged 6.2. Permeate conductivity averaged 835 µS/cm and ranged from 762 to 880 µS/cm. Concentrate conductivity averaged 1835 µS/cm and ranged from 1751 to 1912 µS/cm. Permeate turbidity ranged from 4.4 to 38.8 NTU and averaged 13.1 NTU.

UF2-R3-SR4 Acid Cleaning

After a regular cleaning and flush was performed on the system, an acid cleaning was implemented for one-hour. The acid cleaning started once the 600 gallons of softened water was pH adjusted to ~ 2.2.

Permeate Flux and Temperature

During the acid cleaning, the permeate flux ranged from 54.2 to 60.5 gal/ft²-d and averaged 56.8 gal/ft²-d. Permeate temperature ranged from 82.9 to 88.2 °F and averaged 85.5 °F. Concentrate temperature ranged from 85.0 to 98.0 °F and averaged 91.3 °F.

pH, Conductivity and Turbidity

Permeate pH ranged from 2.7 to 3.1 with an average of 2.9. Concentrate pH ranged from 2.5 to 3.0 with an average of 2.7. Permeate conductivity ranged from 98 to 879 µS/cm and averaged 507 µS/cm. Concentrate conductivity ranged from 136 to 1255 µS/cm and averaged 600 µS/cm. Permeate turbidity ranged from 3.3 to 9.7 NTU and averaged 5.8 NTU.

UF2-R3-SR4 Cleaning After Acid

After the acid cleaning and flush, the system was then cleaned again using a 0.3 % KLD solution for one-hour.

Permeate Flux and Temperature

During the second regular cleaning, the permeate flux ranged from 69.4 to 77.4 gal/ft²-d and averaged 70.4 gal/ft²-d. Permeate temperature ranged from 85.4 to 93.0 °F

and averaged 90.4 °F. Concentrate temperature ranged from 95 to 102 °F and averaged 98.5 °F.

pH, Conductivity and Turbidity

Permeate pH ranged from 4.5 to 5.1 with an average of 5.1. Concentrate pH ranged from 5.1 to 5.2 with an average of 5.5. Permeate conductivity ranged from 174 to 315 $\mu\text{S}/\text{cm}$ and averaged 261 $\mu\text{S}/\text{cm}$. Concentrate conductivity ranged from 325 to 424 $\mu\text{S}/\text{cm}$ and averaged 366 $\mu\text{S}/\text{cm}$. Permeate turbidity ranged from 3.0 to 10.9 NTU and averaged 4.9 NTU.

UF2-R4

UF2-R4 started on February 6, 1998 at 16:20 and February 10, 1998 at 14:00. The run lasted for 7.8 days. The objectives of the run were: 1) monitor system performance, 2) estimate the volume of free oil that forms at the top of the concentrate tanks and 3) conduct an oil mass balance on the system in order to note the change occurring in the system.

In Figure 4.7, permeate flux versus time for UF2-R4 is presented. In Figure 4.8, permeate turbidity versus time for UF2-R4 is presented. In Table 4.28, a summary of permeate operating parameters for UF2-R4 is presented. In Table 4.29, a summary of concentrate operating parameters for UF2-R4 is presented. In Table 4.30, a summary of permeate cleaning parameters for UF2-R4 is presented. In Table 4.31, a summary of concentrate cleaning parameters for UF2-R4 is presented. In Table 4.32, a summary of

permeate O/G samples analyzed for UF2-R4, is presented. In Table 4.33, a summary of concentrate oil content samples analyzed for UF2-R4, is presented. In Table 4.34, a summary of free oil skimming samples analyzed for UF2-R4, is presented. In Table 4.35, a summary of free oil production for UF2-R4 is presented. In Table 4.36, a summary of pond effluent samples analyzed for UF2-R4, is presented.

Figure 4.7 Permeate Flux versus Time for UF2-R4

Figure 4.8 Permeate Turbidity versus Time for UF2-R4

Table 4.28. Summary of Permeate Parameters for UF2-R4

Subrun ID	Flux (gal/ft²-d) [min – max] Avg ±std	Temperature (°F) [min – max] Avg ±std	Turbidity (NTU) [min – max] Avg ±std	pH [min – max] Avg ±std	Conductivity(μS/cm) [min – max] Avg ±std	O/G (mg/L) [min – max] Avg ±std
1	[15.1 – 61.4] 32.3±14.2	[68.1 – 77.9] 74.1±3.4	[1.3 – 3.8] 2.5±0.9	[5.2 – 5.7] 5.6±0.23	[91 – 425] 208±188	[2 – 3] 2.3±0.6
2	[15.1 – 87.2] 27.6±12.7	[74.8 – 78.6] 77.0±1.5	[0.5 – 5.6] 3.6±2.3	[5.4 – 5.5] 5.5±0.1	[61 – 473] 376±156	[3 – 4] 3.8±0.5

Table 4.29. Summary of Concentrate and Pond Effluent O/G Parameters for UF2-R4

Subrun ID	Temperature (°F) [min – max] Avg ±std	pH [min – max] Avg ±std	Conductivity(μS/cm) [min – max] Avg ±std	Oil Content (%) [min – max] Avg ±std	Pond Effluent O/G (mg/L) [min – max] Avg ±std
1	[72 – 83.4] 78.8±3.9	[5.2 – 6.5] 5.8±0.65	[244 – 475] 385±78	[0.4 – 5.2] 2.5±2.4	[0.6]
2	[78.4 – 83.5] 81.1±2.0	[5.6 – 5.6] 5.6	[361 – 486] 424±88	[2.2 – 2.7] 2.5±0.4	[0.5 – 0.6] 0.6±0.4

Table 4.30. Summary of Permeate Cleaning Parameters for UF2-R4

Subrun ID	Flux (gal/ft²-d) [min – max] Avg ±std	Temperature (°F) [min – max] Avg ±std	Turbidity (NTU) [min – max] Avg ±std	pH [min – max] Avg ±std	Conductivity(μS/cm) [min – max] Avg ±std
1	[28.6 – 64.0] 47.2±4.7	[93 – 100.2] 97.1±2.8	[3.3 – 37.9] 10.2±10.8	[6.1 – 6.3] 6.2±0.1	[554 – 722] 617±59
2	[77.4 – 96.0] 86.7±2.0	[105 – 111.9] 108.5±2.2	[2.0 – 3.9] 2.9±0.7	[5.1 – 5.3] 5.2±0.1	[535 – 810] 620±61

Table 4.31. Summary of Concentrate Cleaning Parameters for UF2-R4

Subrun ID	Temperature (°F) [min – max] Avg ±std	pH [min – max] Avg ±std	Conductivity(μS/cm) [min – max] Avg ±std
1	[98.7 – 109.2] 104±3.5	[6.1 – 6.5] 6.3±0.2	[703 – 1141] 903±205
2	[115.7 – 123.4] 118.9±2.5	[5.3 – 5.4] 5.3±0.01	[730 – 1260] 913±210

Table 4.32 Summary of Permeate O/G Samples for UF2-R4

Subrun ID	Date/Time	Sample Results (mg/L)		
		#1	#2	#3
1	2/6/98 (19:55)	2		
1	2/7/98 (23:33)	2		
1	2/9/98 (11:56)	3		
2	2/10/98 (15:08)	4		
2	2/11/98 (10:36)	4		
2	2/12/98 (11:48)	4	3	2
2	2/13/98 (21:36)	4		

Table 4.33 Summary of Concentrate Oil Content Samples for UF2-R4

Subrun ID	Date/Time	Sample Results (%)		
		#1	#2	#3
1	2/6/98 (16:00)	0.5	0.4	0.4
1	2/8/98 (19:28)	2.0	1.9	2.1
1	2/10/98 (09:10)	4.8	5.1	5.3
2	2/10/98 (14:15)	2.2	2.5	2.0
2	2/14/98 (20:26)	2.7		

Table 4.34 Summary of Skimming Samples for UF2-R4

Subrun ID	Date/Time	Sample Results (%)		
		#1	#2	#3
2	2/10/98 (18:26)	99		
2	2/11/98 (01:54)	100		
2	2/13/98 (12:55)	100		
2	2/14/98 (08:42)	99		
2	2/15/98 (11:45)	100		

Table 4.35 Summary of Free Oil Productions for UF2-R4

Subrun ID	Subrun Length, d	Total Free Oil, gal	Free Oil Production, gal/d
1	3.7	0.0	0.0
2	4.1	1,999	487.6

Table 4.36 Summary of Pond Effluent O/G Samples for UF2-R4

Subrun ID	Date/Time	Sample Results (%)		
		#1	#2	#3
1	2/6/98 (15:50)	5,000		
1	2/7/98 (15:40)	5,000		
2	2/10/98 (14:54)	6,000		
2	2/13/98 (12:15)	6,000	6,000	7,000

UF2-R4-SR1

UF2-R4-SR1 was started on February 6, 1998 at 16:20 and ended on February 10, 1998 at 08:50. The length of the subrun lasted 3.65 days. The total permeate volume produced was 157,870 gal. The running average never reached 29 gal/min. Therefore the instantaneous permeate flow set point of 18 gal/min was used.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 15.1 to 61.4 gal/ft²-d. Permeate temperature ranged from 68.1 to 77.9 °F with an average of 74.1 °F. Concentrate temperatures ranged from 72.0 to 83.4 °F with an average of 78.8 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content started out at 0.4 % and increased to 5.2 % during subrun #1. The total volume of free oil that was produced during subrun #1 was 0 gallons. The average daily free oil production was 0.0 gallons/day.

Permeate Oil/Grease, Turbidity and Pond Effluent

Permeate O/G remained low, averaging 2.3 mg/L and ranging from 2.0 to 3.0 mg/L. Turbidity was also low, averaging 2.5 NTU and ranging from 1.3 to 3.8 NTU. Pond effluent O/G was constant around 6,000 mg/L.

Conductivity and pH

Permeate pH ranged from 5.2 to 5.7 with an average of 5.6. Concentrate pH ranged from 5.2 to 6.5 with an average of 5.8. Permeate conductivity ranged from 288 to

475 $\mu\text{S}/\text{cm}$ and averaged 385 $\mu\text{S}/\text{cm}$. Concentrate conductivity's ranged from 91 to 425 $\mu\text{S}/\text{cm}$ and averaged 208 $\mu\text{S}/\text{cm}$.

UF2-R4-SR1 Cleaning

After UF2-R4-SR1 was shutdown on February 10, 1998 at 08:50 it was cleaned at 10:00, with a 0.5 % KLD cleaning solution. The total downtime for the cleaning was 240 minutes.

Permeate Flux and System Temperature

During the first hour of cleaning the permeate flux ranged from 28.6 to 41.8 gal/ft²-d and averaged 35.1 gal/ft²-d. Permeate temperature during the first hour of cleaning ranged from 93 to 100.2 °F and averaged 97.1 °F. Concentrate temperature ranged from 98.7 to 109.2 °F and averaged 104 °F.

After one hour, the system was shutdown and the valves were adjusted for the spongeball sequence. During the first pass of spongeballs, the permeate flux increased to 110.4 gal/ft²-d. The second pass of spongeballs yielded a permeate flux of 114.5 gal/ft²-d. After two spongeball passes were performed the system was cleaned for an additional hour.

In the second hour of regular cleaning, the permeate flux ranged from 56.9 to 64.0 gal/ft²-d with an average of 59.3 gal/ft²-d. Permeate temperature ranged from 97.6 to 98.1 °F with an average of 95.4 °F. Concentrate temperature ranged from 98.1 to 108.1 °F with an average of 102.7 °F.

pH, Conductivity and Turbidity

Permeate pH over the course of the cleaning ranged from 6.1 to 6.3 and averaged 6.2. Concentrate pH ranged from 6.1 to 6.5 and averaged 6.3. Permeate conductivity averaged 617 $\mu\text{S}/\text{cm}$ and ranged from 554 to 722 $\mu\text{S}/\text{cm}$. Concentrate conductivity

averaged 903 $\mu\text{S}/\text{cm}$ and ranged from 703 to 1141 $\mu\text{S}/\text{cm}$. Permeate turbidity ranged from 3.3 to 37.9 NTU and averaged 10.2 NTU.

UF2-R4-SR2

UF2-R4-SR2 was started on February 10, 1998 at 14:00 and ended on February 14, 1998 at 20:26. The length of the subrun lasted 4.07 days. The total permeate volume produced was 157,670 gal. The running average was allowed to pass the 29 gal/min set point because the average reached the set point within two and a half days. The subrun ended because of a pipe rupture above the feed manifolds for the membranes. UF2-R4-SR2 marked the end of the run. Due to the pipe rupture, the system was down for several days. As a result, it was decided to acid clean the system and start with fresh pond effluent.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 15.1 to 87.2 gal/ft²-d. Permeate temperature ranged from 74.8 to 78.6 °F with an average of 77.0 °F. Concentrate temperatures ranged from 78.4 to 83.5 °F with an average of 81.1 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content started out at 2.2 % and increased to 2.7 % by the end of subrun #2. The total volume of free oil that was produced during subrun #2 was 1,999 gallons. The average daily free oil production was 487.6 gallons/day.

Permeate Oil/Grease, Turbidity and Pond Effluent

Permeate O/G remained low, averaging 3.8 mg/L and ranging from 3.0 to 4.0 mg/L. Turbidity was also low, averaging 3.6 NTU and ranging from 0.49 to 5.6 NTU. Pond effluent O/G ranged from 5,000 to 6,000 mg/L and averaged 6,000 mg/L.

Conductivity and pH

Permeate pH ranged from 5.4 to 5.5 with an average of 5.5. Concentrate pH remained constant at 5.6. Permeate conductivity ranged from 61.4 to 473 $\mu\text{S}/\text{cm}$ and averaged 376 $\mu\text{S}/\text{cm}$. Concentrate conductivity's ranged from 361 to 486 $\mu\text{S}/\text{cm}$ and averaged 424 $\mu\text{S}/\text{cm}$.

UF2-R4-SR2 Cleaning

After UF2-R4-SR2 was shutdown on February 14, 1998 at 20:26 it was cleaned on February 20, 1998 at 21:30, with a 0.5 % KLD cleaning solution. UF #2 was not cleaned for several days after the shutdown because a new stainless steel header was being built to replace the old cracked header. Once the new header was installed the system was cleaned. As a result of the new header, the system could be cleaned at 120 °F. Once the cleaning water was heated to ~115 °F, the system was cleaned for one hour under the regular cleaning cycle. After one hour elapsed, the system was shutdown and prepared for a spongeball sequence. Once the valves were adjusted on the system for spongeball retrieval, the system under went two spongeball passes. After the spongeball sequence was performed, the valves were readjusted to the normal mode setting. The system was then cleaned for an additional hour with the same cleaning solution. The total downtime for just the cleaning was 150 minutes.

Permeate Flux and System Temperature

During the first hour of cleaning the permeate flux ranged from 77.4 to 81.8 gal/ft²-d and averaged 79.3 gal/ft²-d. Permeate temperature during the first hour of cleaning ranged from 105 to 108.7 °F and averaged 107.3 °F. Concentrate temperature ranged from 115.7 to 120.5 °F and averaged 118.3 °F.

After one hour, the system was shutdown and the valves were adjusted for the spongeball sequence. During the first pass of spongeballs, the permeate flux increased to 113.4 gal/ft²-d. The second pass of spongeballs yielded a permeate flux of 115.3 gal/ft²-d. After two spongeball passes were performed the system was cleaned for an additional hour.

In the second hour of regular cleaning, the permeate flux ranged from 91.6 to 96.0 gal/ft²-d with an average of 94.0 gal/ft²-d. Permeate temperature ranged from 105.6 to 111.9 °F with an average of 109.8 °F. Concentrate temperature ranged from 114.8 to 123.4 °F with an average of 119.5 °F.

pH, Conductivity and Turbidity

Permeate pH over the course of the cleaning ranged from 5.1 to 5.3 and averaged 5.2. Concentrate pH ranged from 5.3 to 5.4 and averaged 5.3. Permeate conductivity averaged 620 µS/cm and ranged from 535 to 810 µS/cm. Concentrate conductivity averaged 913 µS/cm and ranged from 730 to 1260 µS/cm. Permeate turbidity ranged from 2.0 to 3.9 NTU and averaged 2.9 NTU.

UF2-R5

UF2-R5 started on February 21, 1998 at 00:00 and June 25, 1998 at 10:40. The run lasted for 110 days. The objectives of the run were: 1) monitor system performance,

2) estimate the volume of free oil that forms at the top of the concentrate tanks and 3) conduct an oil mass balance on the system in order to note the change occurring in the system.

In Figure 4.9, permeate flux versus time for UF2-R5 is presented. In Figure 4.10, permeate turbidity versus time for UF2-R5 is presented. In Table 4.37, a summary of permeate operating parameters for UF2-R5 (Subruns 1-11) is presented. In Table 4.38, a summary of permeate operating parameters for UF2-R5 (Subruns 12-19) is presented. In Table 4.39, a summary of concentrate operating parameters for UF2-R5 (Subruns 1-11) is presented. In Table 4.40, a summary of concentrate operating parameters for UF2-R5 (Subruns 12-19) is presented. In Table 4.41, a summary of permeate cleaning parameters for UF2-R5 (subruns 1-11) is presented. In Table 4.42, a summary of permeate cleaning parameters for UF2-R5 (subruns 12-19) is presented. In Table 4.43, a summary of concentrate cleaning parameters for UF2-R5 is presented. In Table 4.44, a summary of permeate O/G samples analyzed for UF2-R5, is presented. In Table 4.45, a summary of concentrate oil content samples analyzed for UF2-R5, is presented. In Table 4.46, a summary of free oil skimming samples analyzed for UF2-R5, is presented. In Table 4.47, a summary of free oil production for UF2-R5 is presented. In Table 4.48, a summary of pond effluent samples analyzed for UF2-R5, is presented.

UF2-R5-SR1

UF2-R5-SR1 was started on February 21, 1998 at 00:00 and ended on February 21, 1998 at 17:32. The length of the subrun lasted 0.68 days. The total permeate volume produced was 24,640 gal. Subrun #1 ended during the same day it was started because the permeate flow declined into the teens not even a half a day into the subrun. .

Figure 4.9 Permeate Flux versus Time for UF2-R5

Figure 4.10 Permeate Turbidity versus Time for UF2-R5

Table 4.37. Summary of Permeate Parameters for UF2-R5 (Subruns 1 – 11)

Subrun ID	Flux (gal/ft²-d) [min – max] Avg ±std	Temperature (°F) [min – max] Avg ±std	Turbidity (NTU) [min – max] Avg ±std	pH [min – max] Avg ±std	Conductivity(μS/cm) [min – max] Avg ±std	O/G (mg/L) [min – max] Avg ±std
1	[10.2 – 79.9] 32.9±21.1	[68.7] 68.7	[3.5] 3.5±0.0	[4.5] 4.5±0.01	[206 – 360] 283±109	[5] 5±0.0
2	[15.8 – 95.8] 44.9±24.0	[74.5 – 78.2] 76.4±2.6	[1.7 – 5.7] 3.7±2.8	[4.5 – 6.5] 5.5±1.4	[517] 517	[5] 5±0.0
3	[12.5 – 71.1] 32.8±18.8	[73.6 – 76.6] 75.6±2.8	[1.1 – 3.7] 2.4±1.8	[5.8 – 6.1] 5.9±0.2	[490] 490	[3] 3±0.0
4	[16.0 – 103.2] 35.5±20.7	[73.2 – 77.9] 76.2±2.6	[1.8 – 4.4] 2.7±1.4	[5.1 – 5.9] 5.4±0.4	[341 – 436] 390±48	[3] 3±0.0
5	[17.8 – 115.6] 37.4±22.4	[73.4 – 75.8] 74.6±1.7	[3.0 – 3.1] 3.1±0.1	[5.4 – 5.5] 5.4±0.04	[331] 331	[5] 5±0.0
6	[18.7 – 113.8] 33.2±17.5	[73.1 – 78.9] 76.0±2.5	[2.1 – 16.6] 11.8±5.8	[5.5 – 5.7] 5.6±0.1	[238 – 349] 306±45	[5] 5±0.0
7	[32.3 – 86.3] 49.5±17.8	[75.3 – 78.0] 80.3±1.1	[0.87 – 17.8] 13.4±8.4	[5.0 – 6.0] 5.5±0.5	[277 – 390] 354±52	[3 – 5] 4±1.4
8	[17.8 – 97.8] 30.9±14.4	[70.0 – 75.7] 73.4±1.9	[2.8 – 4.9] 3.7±0.9	[5.1 – 6.2] 5.5±0.4	[278 – 388] 322±37	[4] 4±0.0
9	[19.6 – 64.0] 29.3±11.4	[76.1 – 77.3] 76.7±0.9	[24.1 – 121.6] 72.9±68.9	[4.9 – 5.4] 5.1±0.4	[376] 376	[5] 5±0.0
10	[17.8 – 88.0] 23.3±8.0	[74.8 – 82.0] 78.4±1.9	[4.2 – 6.3] 5.0±0.5	[4.2 – 6.3] 5.0±0.5	[202 – 499] 354±113	[1 – 4] 3±1.4
11	[19.6 – 40.9] 29.5±6.2	[74.0 – 79.4] 75.9±1.8	[5.0 – 5.6] 5.3±0.2	[5.0 – 5.6] 5.3±0.2	[304 – 444] 356±66	[3 – 4] 3.5±0.7

Table 4.38. Summary of Permeate Parameters for UF2-R5 (Subruns 12 – 19)

Subrun ID	Flux (gal/ft²-d) [min – max] Avg ±std	Temperature (°F) [min – max] Avg ±std	Turbidity (NTU) [min – max] Avg ±std	pH [min – max] Avg ±std	Conductivity(μS/cm) [min – max] Avg ±std	O/G (mg/L) [min – max] Avg ±std
12	[16.0 – 54.2] 29.6±11.9	[74.3 – 80.7] 78.5±2.3	[5.0 – 5.7] 5.3±0.2	[5.0 – 5.7] 5.3±0.2	[324 – 442] 401±53	[3 – 4] 3.5±0.7
13	[17.8 – 67.3] 26.3±9.7	[78.9 – 82.2] 81. ±1.2	[5.1 – 5.5] 5.3±0.2	[5.1 – 5.5] 5.3±0.2	[348 – 428] 388±27	[3 – 4] 3.5±0.7
14	[20.5 – 63.1] 28.9±8.1	[77.1 – 82.8] 79.3±1.8	[5.0 – 5.5] 5.2±0.2	[5.0 – 5.6] 5.2±0.2	[166 – 463] 345±95	[3 – 4] 3.5±0.7
15	[19.6 – 71.1] 24.6±7.6	[78.7 – 81.8] 80.4±1.0	[4.5 – 5.4] 5.0±0.3	[4.5 – 5.4] 5.0±0.3	[279 – 398] 302±36	[2 – 6] 4±2.0
16	[30.2 – 113.8] 36.2±9.0	[77.8 – 81.1] 79.6±1.1	[4.7 – 6.2] 5.1±0.5	[4.7 – 6.2] 5.1±0.6	[196 – 361] 281±63	[2 – 4] 3±1.4
17	[19.6 – 71.1] 25.7±7.6	[78.4 – 87.0] 84.1±2.1	[5.1 – 5.8] 5.5±0.2	[5.1 – 5.8] 5.5±0.2	[217 – 433] 350±89	[3 – 6] 4.3±1.5
18	[19.6 – 113.8] 26.1±7.9	[80.1 – 89.8] 85.3±2.4	[5.2 – 6.2] 5.6±0.2	[5.2 – 6.2] 5.6±0.2	[207 – 523] 421±101	[1 – 8] 3.8±3.1
19	[24.9 – 49.8] 30.6±3.9	[87.2 – 90.1] 88.4±1.4	[4.8 – 5.1] 4.9±0.1	[4.8 – 5.1] 5.1±0.1	[422 – 432] 427±7	[5] 5±0.0

Table 4.39. Summary of Concentrate and Pond Effluent O/G Parameters for UF2-R5 (Subruns 1-11)

Subrun ID	Temperature (°F) [min – max] Avg ±std	pH [min – max] Avg ±std	Conductivity(μS/cm) [min – max] Avg ±std	Oil Content (%) [min – max] Avg ±std	Pond Effluent O/G (mg/L) [min – max] Avg
1	[72.7] 72.7±0.0	[4.6 – 4.7] 4.6±0.01	[442] 442	[0.6 – 1.4] 1.0±0.6	[0.6] 0.6
2	[78.2 – 83.6] 80.9±3.8	[6.3] 6.3	[442 – 605] 524±115	[1.4 – 2.2] 1.8±0.6	[0.6] 0.6
3	[78.6 – 82.7] 80.7±2.9	[4.8] 4.8	[443 – 475] 459±23	[2.2 – 3.5] 2.8±0.7	[0.5 – 0.6] 0.55
4	[75.7 – 83.6] 80.8±4.5	[5.7] 5.7	[556] 556	[3.4 – 4.0] 3.7±0.4	[0.6] 0.6
5	[77.9 – 80.8] 79.4±2.1	[6.7] 6.7	[486] 486	[4.0 – 4.8] 4.4±0.6	[0.6] 0.6
6	[78.2 – 82.9] 80.4±2.0	[5.5 – 6.0] 5.8±0.4	[212 – 422] 317±149	[4.8 – 5.2] 5.0±0.3	[0.5] 0.5
7	[79 – 81.6] 80.3±1.1	[5.2 – 5.8] 5.6±0.3	[309 – 352] 325±24	[5.2 – 6.4] 5.8±0.8	[0.6] 0.6
8	[75.0 – 80.7] 77.9±2.0	[5.0 – 6.4] 5.7±0.6	[234 – 352] 307±51	[6.4 – 7.1] 6.8±0.5	[0.6] 0.6
9	[79.5 – 80] 79.8±0.4	[5.7] 5.7	[376] 376	[7.1 – 7.2] 7.2±0.1	[0.6] 0.6
10	[78.7 – 86.1] 82.3±2.0	[4.7 – 5.4] 5.2±0.2	[202 – 499] 354±113	[7.2 – 10.0] 8.5±1.4	[0.6 – 0.8] 0.7
11	[77.0 – 83.0] 79.8±2.1	[5.0 – 5.3] 5.1±0.2	[304 – 444] 356±66	[9.9 – 10.0] 9.9±0.1	[0.7] 0.7

Table 4.40. Summary of Concentrate and Pond Effluent O/G Parameters for UF2-R5 (Subruns 12 – 19)

Subrun ID	Temperature (°F) [min – max] Avg ±std	pH [min – max] Avg ±std	Conductivity(μS/cm) [min – max] Avg ±std	Oil Content (%) [min – max] Avg ±std	Pond Effluent O/G (mg/L) [min – max] Avg
12	[77.7 – 86.2] 82.8±3.0	[5.1 – 5.7] 5.4±0.2	[324 – 442] 401±53	[10.0 – 9.8] 9.9±0.1	[0.7] 0.7
13	[81.3 – 86.9] 84.5±2.0	[5.3 – 5.6] 5.4±0.2	[401 – 484] 460±39	[9.8 – 7.8] 8.8±1.4	[0.6 – 0.7] 0.67
14	[81.0 – 86.0] 82.9±1.4	[5.2 – 6.1] 5.4±0.4	[207 – 481] 360±97	[8.4 – 12.0] 10.1±1.8	[0.7] 0.7
15	[82.3 – 86.3] 84.5±1.4	[5.2 – 5.4] 5.3±0.1	[376 – 421] 403±24	[12.0 – 18.0] 15.9±3.6	[0.7 – 0.8] 0.75
16	[81.6 – 84.8] 83.1±1.0	[4.9 – 6.4] 5.2±0.6	[188 – 462] 309±118	[18.0 – 11.0] 12.3±1.8	[0.7 – 0.9] 0.8
17	[82.0 – 91.2] 88.1±2.5	[5.3 – 5.8] 5.5±0.1	[217 – 433] 350±89	[11.0 – 9.9] 10.2±0.6	[0.7] 0.7
18	[84.0 – 93.6] 89.9±2.2	[5.3 – 5.8] 5.6±0.2	[207 – 523] 421±101	[4.5 – 3.2] 3.8±0.7	[0.6 – 0.8] 0.74
19	[93.2 – 94.5] 94.1±1.0	[5.1 – 5.2] 5.1±0.03	[422 – 432] 427±7	[3.2 – 4.0] 3.6±0.5	[0.8] 0.8

Table 4.41. Permeate Cleaning Parameters for UF2-R5 (Subrun 1 – 11)

Subrun ID	Flux (gal/ft²-d) [min – max] Avg ±std	Temperature (°F) [min – max] Avg ±std	Turbidity (NTU) [min – max] Avg ±std	pH [min – max] Avg ±std	Conductivity(μS/cm) [min – max] Avg ±std
1	[73.5 – 98.5] 85.8±1.8	[107.2 – 114.8] 111.2±2.8	[2.0 – 14.6] 5.4±4.1	[4.9 – 5.6] 5.2±0.2	[660 – 1109] 992±142
2	[64.2 – 82.7] 77.4±2.0	[107.9 – 112.9] 111.2±1.6	[4.3 – 9.3] 6.1±1.9	NA	[716 – 984] 833±109
3	[46.2 – 85.4] 70.4±4.1	[105.3 – 110.6] 108.4±1.7	[2.6 – 15.5] 7.7±5.7	[5.5 – 5.7] 5.6±0.1	[712 – 845] 781±49
4	[37.4 – 102.3] 76.35±8.87	[62.6 – 82.9] 75.1±3.5	[4.1 – 9.1] 6.6±2.0	[5.3 – 6.6] 6.3±0.5	[176 – 249] 223±26
5	[66.7 – 142.3] 90.6±13.1	[80.9 – 91.9] 86.7±2.0	[4.2 – 6.2] 5.2±0.9	[6.7 – 6.9] 6.8±0.1	[267 – 309] 291±15
6	[62.3 – 115.6] 90.4±3.3	[110.3 – 122.5] 109±2.2	[5.1 – 11.5] 7.6±2.6	[7.0 – 7.1] 7.1±0.1	[326 – 485] 424±62
7	[142.3 – 170.8] 155.6±3.3	[107.5 – 112.0] 109.8±3.2	[7.8 – 13.9] 11.8±2.8	[9.0 – 9.3] 9.1±0.1	[734 – 784] 769±23
8	[145.8 – 168.9] 154.4±11.0	[111.9 – 115.6] 113.9±1.8	[2.2 – 5.3] 3.6±1.3	[9.0 – 9.7] 9.4±0.3	[650 – 1585] 1115±435
9	[144.1 – 170.6] 160.9±7.0	[110.6 – 118.2] 113.4±1.4	[1.4 – 4.9] 3.0±1.5	[9.5 – 9.8] 9.6±0.2	[1081 – 1241] 1147±76
10	[126.3 – 128.1] 127±0.7	[113 – 117] 115.1±2.3	[1.2 – 1.8] 1.5±0.3	[6.1 – 6.2] 6.2±0.03	[398 – 467] 437±27
11	[147.6 – 154.7] 151.2±3.1	[108.7 – 113.4] 111.5±2.0	[1.0 – 3.0] 1.8±0.9	[7.7 – 7.8] 7.7±0.02	[851 – 860] 857±4

Table 4.42. Summary of Permeate Cleaning Parameters for UF2-R5 (Subruns 12 – 19)

Subrun ID	Flux (gal/ft²-d) [min – max] Avg ±std	Temperature (°F) [min – max] Avg ±std	Turbidity (NTU) [min – max] Avg ±std	pH [min – max] Avg ±std	Conductivity(μS/cm) [min – max] Avg ±std
12	[117.4 – 149.4] 131.5±4.5	[111.2 – 114.9] 113.2±1.8	[0.6 – 1.5] 0.9±0.3	[9.0 – 9.8] 9.3±0.4	[1577 – 2190] 1884±279
13	[102.3 – 112.1] 107.6±4.5	[105.6 – 113.1] 109.6±3.3	[1.5 – 2.3] 1.9±0.4	[7.5 – 7.6] 7.6±0.1	[521 – 577] 548±27
14	[78.3 – 119.2] 99.1±1.9	[106.5 – 109.5] 108±2.1	[1.1 – 3.2] 2.4±0.9	[9.3 – 9.4] 9.4±0.02	[787 – 884] 830±44
15	[87.2 – 129.8] 111.4±3.3	[107.1 – 111.7] 109.3±1.4	[2.0 – 4.4] 3.2±1.0	[7.5 – 7.7] 7.6±0.1	[890 – 1077] 976±81
16	[106.7 – 124.5] 116.6±3.0	[105.8 – 133.6] 110.5±3.1	[0.5 – 3.9] 1.5±1.2	[9.6 – 10.0] 9.8±0.2	[864 – 986] 921±39
17	[129.8 – 140.5] 134.5±1.9	[114.3 – 119.1] 116.8±1.0	[0.8 – 1.9] 1.5±0.4	[9.3 – 9.9] 9.6±0.2	[1247 – 1534] 1383±119
18	[45.4 – 58.7] 50.3±3.1	[113.8 – 121.1] 116.6±3.3	[0.98 – 2.9] 1.6±0.8	[8.3 – 9.7] 8.9±0.7	[535 – 619] 584±42
19	[71.1 - 72.0] 71.5±0.01	[109.8 – 115.9] 112.9±1.2	[1.3 – 2.9] 2.1±0.7	[9.6] 9.6	[585 – 1400] 1089±98

Table 4.43. Summary of Concentrate Cleaning Parameters for UF2-R5

Subrun ID	Temperature (°F) [min – max] Avg ±std	pH [min – max] Avg ±std	Conductivity(μS/cm) [min – max] Avg ±std
1	[117.8 – 124.0] 121±2.2	[5.1 – 5.4] 5.3±0.1	[660 – 1109] 992±142
2	[117.9 – 124] 120.8±2.3	NA	[716 – 984] 833±109
3	[113.6 – 122.7] 118.2±2.8	[5.7 – 5.9] 5.8±0.1	[712 – 845] 781±49
4	[67.0 – 88.0] 80.2±4.4	[6.7 – 7.0] 6.8±0.1	[176 – 249] 223±26
5	[85.2 – 99.5] 93.6±2.5	[6.9 – 7.1] 7.0±0.1	[629 – 721] 694±37
6	[113.3 – 122.8] 119.3±2.5	[7.3 – 7.8] 7.4±0.2	[938 – 1153] 1039±116
7	[118.8 – 123.0] 120.9±1.3	[9.0 – 9.3] 9.2±0.1	[1241 – 1492] 1350±105
8	[120 – 126.6] 123.5±1.8	[8.9 – 9.7] 9.3±0.4	[1408 – 2540] 2018±583
9	[120.9 – 125.7] 122.9±1.6	[9.4 – 9.9] 9.6±0.2	[1981 – 2120] 2038±60
10	[121 – 126.7] 124±1.9	[6.2 – 6.3] 6.3±0.01	[411 – 556] 499±77
11	[116.3 – 124.5] 121.2±3.0	[7.8 – 7.9] 7.8±0.01	[1427 – 1451] 1441±12
12	[120.1 – 125.1] 122.5±1.6	[9.0 – 9.8] 9.4±0.4	[2480 – 3120] 2823±340
13	[115.2 – 126.3] 120.8±4.2	[7.7 – 7.8] 7.7±0.1	[995 – 1130] 1044±75
14	[114.3 – 121.9] 118.2±3.3	[9.6 – 9.7] 9.7±0.03	[1334 – 1533] 1419±83
15	[115.3 – 121.5] 118.6±1.7	[7.6 – 7.8] 7.6±0.1	[1579 – 1866] 1676±134
16	[120.0 – 126.0] 122.0±1.4	[9.5 – 9.9] 9.7±0.2	[1451 – 1687] 1536±321
17	[120.1 – 127.0] 124.0±1.8	[9.3 – 9.9] 9.6±0.3	[2120 – 2640] 2375±260
18	[120.0 – 128.0] 124±3.3	[8.3 – 9.7] 8.0±0.7	[692 – 812] 728±56
19	[119 – 125] 121±1.4	[9.6 – 9.7] 9.64±0.3	[1065 – 2270] 1475±119

Table 4.44 Summary of Permeate O/G Samples for UF2-R5

Subrun ID	Date/Time	Sample Results (mg/L)		
		#1	#2	#3
1	2/21/98 (01:57)	5		
2	2/23/98 (01:14)	3		
3	2/25/98 (01:01)	3		
4	3/2/98 (01:30)	4		
5	3/4/98 (00:01)	5	5	5
6	3/5/98 (23:18)	5		
7	3/9/98 (02:03)	5		
8	3/15/98 (02:53)	5		
9	3/16/98 (06:20)	3		
10	3/16/98 (21:23)	4		
10	3/23/98 (08:40)	4		
10	3/29/98 (10:44)	1		
11	4/3/98 (15:31)	3	4	4
11	4/6/98 (19:55)	4		
12	4/10/98 (05:06)	4		
12	4/12/98 (23:30)	3		
13	4/13/98 (23:30)	3		
13	4/15/98 (15:00)	4		
14	4/18/98 (02:09)	3		
14	4/21/98 (05:10)	4		
15	4/25/98 (08:50)	6		
15	4/27/98 (01:10)	2		
16	4/30/98 (23:30)	3	5	4
16	5/2/98 (06:40)	4		
16	5/4/98 (09:00)	4		
16	5/6/98 (15:15)	2		
17	5/8/98 (12:05)	4		
17	5/11/98 (14:35)	3		
17	5/15/98 (05:15)	6		
18	5/22/98 (07:30)	3		
18	5/28/98 (22:10)	4		
18	6/1/98 (19:50)	5		
18	6/4/98 (03:50)	8		
18	6/10/98 (12:35)	4	4	4
18	6/13/98 (05:29)	1		
19	6/26/98 (13:56)	2		

Table 4.45 Summary of Concentrate Oil Content Samples for UF2-R5

Subrun ID	Date/Time	Sample Results (%)		
		#1	#2	#3
1	2/21/98 (01:10)	0.6	0.6	0.7
1	2/21/98 (17:30)	1.4		
2	2/23/98 (05:57)	2.2		
3	2/26/98 (07:00)	3.5		
4	3/3/98 (10:00)	4.0		
5	3/5/98 (14:52)	4.8	4.9	4.9
6	3/7/98 (21:17)	5.2		
7	3/11/98 (05:18)	6.4		
8	3/15/98 (11:20)	7.1		
9	3/16/98 (12:55)	7.2		
10	4/3/98 (07:25)	8.4		
11	4/7/98 (07:00)	9.9		
12	4/10/98 (12:20)	10.0		
12	4/13/98 (11:00)	10.0		
13	4/14/98 (11:05)	9.8	9.9	9.8
13	4/17/98 (10:59)	7.8		
14	4/18/98 (08:40)	8.4		
14	4/24/98 (06:40)	10.1		
15	4/24/98 (19:20)	12.0		
15	4/30/98 (06:30)	17.9		
16	4/30/98 (20:30)	18.0		
16	5/2/98 (09:50)	13.9		
16	5/7/98 (06:35)	11.0		
17	5/7/98 (20:46)	9.9		
17	5/9/98 (12:20)	11.0	11.5	11.0
17	5/12/98 (11:44)	10.5		
17	5/18/98 (05:10)	10.4		
18	5/20/98 (20:25)	4.5		
18	5/28/98 (09:15)	11.9		
18	6/11/98 (23:20)	12.4		
18	6/16/98 (10:05)	10		
18	6/22/98 (10:45)	3.2	3.3	3.1
19	6/28/98 (10:30)	4.0		

Table 4.46 Summary of Skimming Samples for UF2-R5

Subrun ID	Date/Time	Sample Results (mg/L)		
		#1	#2	#3
4	2/28/98 (12:20)	100		
6	3/8/98 (20:20)	100		
7	3/13/98 (08:45)	100		
9	3/16/98 (16:00)	98		
10	4/4/98 (09:30)	100		
11	4/8/98 (16:50)	100	99	100
14	4/19/98 (08:59)	100		
15	4/26/98 (12:12)	100		
16	5/1/98 (11:10)	99		
17	5/8/98 (09:35)	99		
18	5/24/98 (10:20)	100		
18	5/28/98 (14:25)	98		
18	6/6/98 (21:09)	100		
19	6/27/98 (09:50)	100		

Table 4.47 Summary of Free Oil Productions for UF2-R5

Subrun ID	Subrun Length, d	Total Free Oil, gal	Free Oil Production, gal/d
1	0.68	0.0	0.0
2	1.3	370	284.6
3	2.8	272	97.1
4	3.5	770	220
5	2.0	420	210
6	2.1	466	221.9
7	3.2	593	185.3
8	3.8	2,203	579.7
9	0.93	166	166
10	15.4	4,162	275.6
11	3.4	1,508	443.5
12	3.7	1,196	323.2
13	3.0	1,144	381.3
14	6.6	1,856	381.2
15	5.4	960	177.8
16	6.3	5,029	798.3
17	9.3	4,076	438.3
18	32.6	12,953	397.3
19	3.0	890	296.7

Table 4.48 Summary of Pond Effluent O/G Samples for UF2-R5

Subrun ID	Date/Time	Sample Results (mg/L)		
		#1	#2	#3
1	2/8/98 (11:14)	6,000		
2	2/21/98 (23:43)	6,000		
3	2/25/98 (00:50)	5,000		
3	2/26/98 (06:06)	6,000		
4	3/2/98 (01:30)	6,000		
5	3/3/98 (23:50)	6,000		
6	3/7/98 (05:30)	5,000		
8	3/15/98 (07:00)	6,000		
10	3/17/98 (07:40)	6,000	6,000	6,000
10	3/28/98 (08:39)	8,000		
11	4/5/98 (12:20)	7,000		
12	4/11/98 (15:30)	7,000		
13	4/14/98 (12:00)	6,000		
13	4/16/98 (08:49)	7,000		
14	4/19/98 (12:10)	7,000		
15	4/25/98 (19:30)	7,000		
15	4/28/98 (21:12)	8,000		
16	5/1/98 (17:30)	7,000		
16	5/5/98 (09:15)	9,000		
17	5/8/98 (12:00)	7,000		
17	5/11/98 (16:19)	7,000		
17	5/13/98 (13:39)	7,000		
18	5/21/98 (15:30)	6,000		
18	5/24/98 (08:50)	7,000	7,000	6,000
18	5/28/98 (07:40)	7,000		
18	6/1/98 (13:10)	8,000		
18	6/4/98 (13:15)	8,000		
18	6/10/98 (16:20)	7,000		
18	6/13/98 (09:25)	8,000		
18	6/17/98 (11:18)	7,000		
18	6/20/98 (16:52)	8,000		
19	6/26/98 (18:19)	8,000		

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 10.2 to 79.9 gal/ft²-d. Permeate temperature was taken only once during the subrun and ranged around 68.7 °F. Concentrate temperature was taken once as well and ranged around 72.7 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content started out at 0.6 % and increased to 1.4 % by the end of subrun #2. The total volume of free oil that was produced during subrun #1 was 0 gallons. The average daily free oil production was 0.0 gallons/day.

Permeate Oil/Grease, Turbidity and Pond Effluent

Permeate O/G was constant around 5 mg/L. Permeate turbidity ranged around 3.5 NTU. Pond effluent O/G was also constant at 6,000 mg/L.

Conductivity and pH

Permeate pH ranged at 4.5. Concentrate pH 4.6 to 4.7 and averaged 4.6. Permeate conductivity ranged at 442 µS/cm. Concentrate conductivity's ranged from 206 to 360 µS/cm and averaged 283 µS/cm.

UF2-R5-SR1 Cleaning

After UF2-R5-SR1 was shutdown on February 21, 1998 at 17:32 it was cleaned on February 21, 1998 at 19:10, with a 0.5 % KLD cleaning solution. Once the cleaning water was heated to ~115 °F, the system was cleaned for one hour under the regular cleaning cycle. After one hour elapsed, the system was shutdown and prepared for a spongeball sequence. Once the valves were adjusted on the system for spongeball retrieval, the system underwent two spongeball passes. After the spongeball sequence was performed, the valves were readjusted to the normal mode setting. The system was then cleaned for an additional hour with the same cleaning solution. The total downtime for just the cleaning was 328 minutes.

Permeate Flux and System Temperature

During the first hour of cleaning the permeate flux ranged from 73.5 to 79.0 gal/ft²-d and averaged 75.7 gal/ft²-d. Permeate temperature during the first hour of cleaning ranged from 101 to 106 °F and averaged 103 °F. Concentrate temperature ranged from 118 to 124 °F and averaged 121 °F.

After one hour, the system was shutdown and the valves were adjusted for the spongeball sequence. During the first pass of spongeballs, the permeate flux increased to 105.2 gal/ft²-d. The second pass of spongeballs yielded a permeate flux of 117.3 gal/ft²-d. After two spongeball passes were performed the system was cleaned for an additional hour.

In the second hour of regular cleaning, the permeate flux ranged from 93.9 to 98.5 gal/ft²-d with an average of 95.8 gal/ft²-d. Permeate temperature ranged from 108.6 to 114.8 °F with an average of 111.2 °F. Concentrate temperature ranged from 117.8 to 124 °F with an average of 121 °F.

pH, Conductivity and Turbidity

Permeate pH over the course of the cleaning ranged from 4.9 to 5.6 and averaged 5.2. Concentrate pH ranged from 5.1 to 5.4 and averaged 5.3. Permeate conductivity averaged 992 $\mu\text{S}/\text{cm}$ and ranged from 660 to 1109 $\mu\text{S}/\text{cm}$. Concentrate conductivity averaged 1369 $\mu\text{S}/\text{cm}$ and ranged from 1049 to 1505 $\mu\text{S}/\text{cm}$. Permeate turbidity ranged from 2.0 to 14.6 NTU and averaged 5.4 NTU.

UF2-R5-SR2

UF2-R5-SR2 was started on February 21, 1998 at 23:00 and ended on February 23, 1998 at 05:57. The length of the subrun lasted 0.68 days. The total permeate volume produced was 57,090 gal. Subrun #2 was ended because the instantaneous permeate flow decreased to 17 gal/min with 1.29 days.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 15.8 to 103 gal/ft²-d. Permeate temperature ranged from 74.5 to 78.2 °F. and averaged 76.4 °F. Concentrate temperature ranged from 78.2 to 93.6 °F and averaged 80.9 °F. Permeate flux decreased rapidly during the duration of the subrun.

Concentrate Oil Content and Free Oil Production

Concentrate oil content started out at 1.4 % and increased to 2.2 % during subrun #2. The total volume of free oil that was produced during subrun #2 was 370 gallons. The average daily free oil production was 284.6 gallons/day.

Permeate Oil/Grease, Turbidity and Pond Effluent

Permeate O/G remained constant at 5 mg/L. Turbidity ranged from 1.7 to 5.7 NTU and averaged 3.7 NTU. Pond effluent also remained constant at 5,000 mg/L.

Conductivity and pH

Permeate pH ranged from 4.5 to 6.5 with an average of 5.5. Concentrate pH was constant at 6.3. Permeate conductivity ranged from 442 to 605 $\mu\text{S}/\text{cm}$ with an average of 524 $\mu\text{S}/\text{cm}$. Concentrate conductivity was constant at 517 $\mu\text{S}/\text{cm}$.

UF2-R5-SR2 Cleaning

After UF2-R5-SR2 was shutdown on February 23, 1998 at 05:57 it was cleaned at 07:50, with a 0.5 % KLD cleaning solution. The total downtime for just the cleaning was 421 minutes.

Permeate Flux and System Temperature

During the first hour of cleaning the permeate flux ranged from 64.2 to 70.7 gal/ft²-d and averaged 67.1 gal/ft²-d. Permeate temperature during the first hour of cleaning ranged from 107.9 to 112.4 °F and averaged 110.4 °F. Concentrate temperature ranged from 117.9 to 123 °F and averaged 120.5 °F.

After one hour, the system was shutdown and the valves were adjusted for the spongeball sequence. During the first pass of spongeballs, the permeate flux increased to 121.4 gal/ft²-d. The second pass of spongeballs yielded a permeate flux of 100.7 gal/ft²-d. After two spongeball passes were performed the system was cleaned for an additional hour.

In the second hour of regular cleaning, the permeate flux ranged from 79.9 to 82.7 gal/ft²-d with an average of 81.4 gal/ft²-d. Permeate temperature ranged from 110.9 to 112.9 °F with an average of 111.9 °F. Concentrate temperature ranged from 118 to 124 °F with an average of 121 °F.

pH, Conductivity and Turbidity

Permeate and concentrate pH were not available during the cleaning because of the pH probe mal-functioning. Permeate conductivity averaged 833 $\mu\text{S}/\text{cm}$ and ranged from 716 to 984 $\mu\text{S}/\text{cm}$. Concentrate conductivity averaged 1414 $\mu\text{S}/\text{cm}$ and ranged from 1174 to 2120 $\mu\text{S}/\text{cm}$. Permeate turbidity ranged from 4.3 to 9.3 NTU and averaged 6.1 NTU.

UF2-R5-SR3

UF2-R5-SR3 was started on February 23, 1998 at 12:38 and ended on February 26, 1998 at 07:04. The length of the subrun lasted 2.80 days. The total permeate volume produced was 45,880 gal. Subrun #3 reached the 29 gal/min set less than a day into the subrun. The system was allowed to run because it reached the set point so fast. However the permeate flow did not level out. Subrun #3 was ended because the instantaneous permeate flow decreased to 14 gal/min.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 12.5 to 71.1 gal/ft²-d. Permeate temperature ranged from 73.6 to 76.6 °F. and averaged 75.6 °F. Concentrate temperature ranged from 78.6 to 82.7 °F and averaged 80.7 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content started out at 2.2 % and increased to 3.5 % during subrun #3. The total volume of free oil that was produced during subrun #3 was 272 gallons. The average daily free oil production was 97.1 gallons/day.

Permeate Oil/Grease, Turbidity and Pond Effluent

Permeate O/G remained constant at 3 mg/L. Turbidity ranged from 1.1 to 3.7 NTU and averaged 2.4 NTU. Pond effluent O/G ranged from 5,000 to 6,000 mg/L and averaged 5,500 mg/L.

Conductivity and pH

Permeate pH ranged from 5.8 to 6.1 with an average of 5.9. Concentrate pH was constant at 4.8. Permeate conductivity ranged from 443 to 475 $\mu\text{S}/\text{cm}$ with an average of 459 $\mu\text{S}/\text{cm}$. Concentrate conductivity was constant at 490 $\mu\text{S}/\text{cm}$.

UF2-R5-SR3 Cleaning

After UF2-R5-SR3 was shutdown on February 26, 1998 at 07:04 it was cleaned at 23:00, with a 0.5 % KLD cleaning solution. The total downtime for just the cleaning was 1250 minutes.

Permeate Flux and System Temperature

During the first hour of cleaning the permeate flux ranged from 46.2 to 62.3 gal/ft²-d and averaged 57.5 gal/ft²-d. Permeate temperature during the first hour of cleaning ranged from 105.3 to 108.7 °F and averaged 107.2 °F. Concentrate temperature ranged from 113.6 to 121.3 °F and averaged 117.4 °F.

After one hour, the system was shutdown and the valves were adjusted for the spongeball sequence. During the first pass of spongeballs, the permeate flux increased to 140.2 gal/ft²-d. The second pass of spongeballs yielded a permeate flux of 107.6 gal/ft²-d. After two spongeball passes were performed the system was cleaned for an additional hour.

In the second hour of regular cleaning, the permeate flux ranged from 81.8 to

85.4 gal/ft²-d and averaged 83.2 gal/ft²-d. Permeate temperature ranged from 108.2 to 110.6 °F and averaged 109.4 °F. Concentrate temperature ranged from 117.4 to 122.7 °F with an average of 119.4 °F.

pH, Conductivity and Turbidity

Permeate pH ranged from 5.5 to 5.7 and averaged 5.6. Concentrate pH ranged from 5.7 to 5.9 and averaged 5.8. Permeate conductivity averaged 781 µS/cm and ranged from 712 to 845 µS/cm. Concentrate conductivity averaged 1530 µS/cm and ranged from 1407 to 1697 µS/cm. Permeate turbidity ranged from 2.6 to 15.5 NTU and averaged 7.7 NTU.

UF2-R5-SR4

UF2-R5-SR4 was started on February 27, 1998 at 19:50 and ended on March 3, 1998 at 10:01. The length of the subrun lasted 3.54 days. The total permeate volume produced was 162310 gal.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 16.0 to 103.2 gal/ft²-d. Permeate temperature ranged from 73.2 to 77.9 °F. and averaged 76.2 °F. Concentrate temperature ranged from 75.7 to 83.6 °F and averaged 80.8 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content started out at 3.4 % and increased to 4.0 % during subrun #4. The total volume of free oil that was produced during subrun #4 was 770 gallons. The average daily free oil production was 220 gallons/day.

Permeate Oil/Grease, Turbidity and Pond Effluent

Permeate O/G ranged around 3 mg/L. Turbidity ranged from 1.8 to 4.4 NTU and averaged 2.7 NTU. Pond Effluent O/G ranged around 6,000 mg/L.

Conductivity and pH

Permeate pH ranged from 5.1 to 5.9 with an average of 5.4. Concentrate pH was constant at 5.7. Permeate conductivity ranged from 341 to 436 $\mu\text{S}/\text{cm}$ with an average of 390 $\mu\text{S}/\text{cm}$. Concentrate conductivity was constant at 556 $\mu\text{S}/\text{cm}$.

UF2-R5-SR4 Cleaning

After UF2-R5-SR4 was shutdown on March 3, 1998 at 10:01 it was cleaned at 10:55, with a 0.5 % KLD cleaning solution. The flush tank had to be used for the cleaning after subrun #4, because the new CIP tank developed several holes. The holes developed after the tank was used once. The heater at the bottom of the CIP tank was found to be too powerful for the plastic tank. A stainless steel CIP tank has been ordered, as a result of the problem. The flush tank is going to be used until the new CIP tank arrives. As a result the water is not preheated before the cleaning, for there is no heater in the flush tank. The total downtime for just the cleaning was 253 minutes.

Permeate Flux and System Temperature

During the first hour of cleaning the permeate flux ranged from 37.4 to 72.0 gal/ft²-d and averaged 51.1 gal/ft²-d. Permeate temperature during the first hour of cleaning ranged from 62.6 to 72.8 °F and averaged 69.2 °F. Concentrate temperature ranged from 67.0 to 81.0 °F and averaged 74.3 °F.

After one hour, the system was shutdown and the valves were adjusted for the spongeball sequence. During the first pass of spongeballs, the permeate flux increased to 115.6 gal/ft²-d. The second pass of spongeballs yielded a permeate flux of 115.6 gal/ft²-

d. After two spongeball passes were performed the system was cleaned for an additional hour.

In the second hour of regular cleaning, the permeate flux ranged from 100.5 to 102.3 gal/ft²-d with an average of 101.6 gal/ft²-d. Permeate temperature ranged from 79.1 to 82.9 °F with an average of 81.0 °F. Concentrate temperature ranged from 84.0 to 88.0 °F with an average of 86.0 °F.

pH, Conductivity and Turbidity

Permeate pH ranged from 5.3 to 6.6 and averaged 6.3. Concentrate pH ranged from 6.7 to 7.0 and averaged 6.8. Permeate conductivity averaged 223 µS/cm and ranged from 176 to 249 µS/cm. Concentrate conductivity averaged 569 µS/cm and ranged from 537 to 597 µS/cm. Permeate turbidity ranged from 4.1 to 9.1 NTU and averaged 6.6 NTU.

UF2-R5-SR5

UF2-R5-SR5 was started on March 3, 1998 at 14:14 and ended on March 5, 1998 at 14:40. The length of the subrun lasted 2.03 days. The total permeate volume produced was 76,930 gal. Subrun #5 was ended because the permeate running average reached the low set.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 17.8 to 115.6 gal/ft²-d. Permeate temperature ranged from 73.4 to 75.8 °F. and averaged 74.6 °F. Concentrate temperature ranged from 77.9 to 80.8 °F and averaged 79.4 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content started out at 4.0 % and increased to 4.8 % during subrun #5. The total volume of free oil that was produced during subrun #5 was 420 gallons. The average daily free oil production was 210 gallons/day.

Permeate Oil/Grease, Turbidity and Pond Effluent

Permeate O/G ranged at 5 mg/L. Turbidity ranged from 3.0 to 3.1 NTU and averaged 3.1 NTU. Pond effluent O/G ranged at 6,000 mg/L.

Conductivity and pH

Permeate pH ranged from 5.4 to 5.5 with an average of 5.4. Concentrate pH was constant at 6.7. Permeate conductivity was constant at 331 $\mu\text{S}/\text{cm}$. Concentrate conductivity was also constant at 486 $\mu\text{S}/\text{cm}$.

UF2-R5-SR5 Cleaning

After UF2-R5-SR5 was shutdown on March 5, 1998 at 14:40 it was cleaned at 17:00, with a 0.5 % KLD cleaning solution. The flush tank had to be used for the cleaning again. The water was recirculated for a few hour in order to raise the concentrate temperature, before adding the KLD. The total downtime for just the cleaning was 320 minutes.

Permeate Flux and System Temperature

During the first hour of cleaning the permeate flux ranged from 66.7 to 80.9 gal/ft²-d and averaged 72.9 gal/ft²-d. Permeate temperature during the first hour of cleaning ranged from 80.9 to 85.3 °F and averaged 83.1 °F. Concentrate temperature ranged from 85.2 to 91.9 °F and averaged 89.9 °F.

After one hour, the system was shutdown and the valves were adjusted for the spongeball sequence. During the first pass of spongeballs, the permeate flux increased to

124.5 gal/ft²-d. The second pass of spongeballs yielded a permeate flux of 151.1 gal/ft²-d. After two spongeball passes were performed the system was cleaned for an additional hour.

In the second hour of regular cleaning, the permeate flux ranged from 92.5 to 142.3 gal/ft²-d with an average of 108.2 gal/ft²-d. Permeate temperature ranged from 88.0 to 91.9 °F with an average of 90.2 °F. Concentrate temperature ranged from 95.2 to 99.5 °F with an average of 97.3 °F.

pH, Conductivity and Turbidity

Permeate pH ranged from 6.7 to 6.9 and averaged 6.8. Concentrate pH ranged from 6.9 to 7.1 and averaged 7.0. Permeate conductivity averaged 291 µS/cm and ranged from 267 to 309 µS/cm. Concentrate conductivity averaged 694 µS/cm and ranged from 629 to 721 µS/cm. Permeate turbidity ranged from 4.2 to 6.2 NTU and averaged 5.2 NTU.

UF2-R5-SR6

UF2-R5-SR6 was started on March 5, 1998 at 20:00 and ended on March 7, 1998 at 21:17. The length of the subrun lasted 2.05 days. The total permeate volume produced was 93,570 gal. Subrun #6 was ended because the permeate running average reached the low set.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 18.7 to 133.8 gal/ft²-d. Permeate temperature ranged from 73.1 to 78.9 °F. and averaged 76.0 °F. Concentrate temperature ranged from 78.2 to 82.9 °F and averaged 80.4 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content started out at 4.8 % and increased to 5.2 % during subrun #6. The total volume of free oil that was produced during subrun #6 was 466 gallons. The average daily free oil production was 221.9 gallons/day.

Permeate Oil/Grease, Turbidity and Pond Effluent

Permeate O/G ranged at 5 mg/L. Turbidity ranged from 2.1 to 16.6 NTU and averaged 11.8 NTU. Pond effluent O/G ranged at 5,000 mg/L.

Conductivity and pH

Permeate pH ranged from 5.5 to 5.7 with an average of 5.6. Concentrate pH ranged from 5.5 to 6.0 and averaged 5.8. Permeate conductivity ranged from 238 to 349 $\mu\text{S}/\text{cm}$ and averaged 306 $\mu\text{S}/\text{cm}$. Concentrate conductivity ranged from 212 to 422 $\mu\text{S}/\text{cm}$ and averaged 317 $\mu\text{S}/\text{cm}$.

UF2-R5-SR6 Cleaning

After UF2-R5-SR6 was shutdown on March 7, 1998 at 21:17 it was cleaned at 22:30, with a 0.5 % KLD cleaning solution. The total downtime for just the cleaning was 163 minutes.

Permeate Flux and System Temperature

During the first 40 minutes of cleaning the permeate flux ranged from 62.3 to 73.8 gal/ft²-d and averaged 68.3 gal/ft²-d. Permeate temperature ranged from 105.4 to 111.6 °F and averaged 108.4 °F. Concentrate temperature ranged from 113.3 to 122.5 °F and averaged 118 °F.

After 40 minutes, the system was shutdown and the valves were adjusted for the spongeball sequence. During the first pass of spongeballs, the permeate flux increased to

131.6 gal/ft²-d. The second pass of spongeballs yielded a permeate flux of 133.4 gal/ft²-d. After two spongeball passes were performed the system was cleaned for an additional 40 minutes.

In the second 40 minutes of regular cleaning, the permeate flux ranged from 110.3 to 115.6 gal/ft²-d with an average of 112.4 gal/ft²-d. Permeate temperature ranged from 108.8 to 110.3 °F with an average of 109.6 °F. Concentrate temperature ranged from 118.1 to 122.8 °F with an average of 120.3 °F.

pH and Conductivity

Permeate pH ranged from 7.0 to 7.1 and averaged 7.1. Concentrate pH ranged from 7.3 to 7.8 and averaged 7.4. Permeate conductivity averaged 424 µS/cm and ranged from 326 to 485 µS/cm. Concentrate conductivity averaged 1039 µS/cm and ranged from 938 to 1153 µS/cm. Permeate turbidity ranged from 5.1 to 11.5 NTU and averaged 7.6 NTU.

UF2-R5-SR7

UF2-R5-SR7 was started on March 8, 1998 at 00:00 and ended on March 11, 1998 at 05:18. The length of the subrun lasted 3.22 days. The total permeate volume produced was 105,990 gal. Subrun #7 reached the 29 gal/min set point with in one days of operation. The running average did not exceed 29 gal/min though. As a result the system was allowed to stay in operation until the instantaneous permeate flow of 18 gal/min was reached.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 17.1 to 86.3 gal/ft²-d. Permeate temperature ranged from 75.3 to 78 °F. and averaged 76.5 °F. Concentrate temperature ranged from 79.0 to 81.6 °F and averaged 80.3 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content started out at 5.2 % and increased to 6.4 % during subrun #7. The total volume of free oil that was produced during subrun #7 was 593 gallons. The average daily free oil production was 185.3 gallons/day.

Permeate Oil/Grease, Turbidity and Pond Effluent

Permeate O/G ranged from 3 to 5 mg/L and averaged 4 mg/L. Turbidity ranged from 0.87 to 17.8 NTU and averaged 13.4 NTU. Pond effluent O/G ranged 7,000 mg/L.

Conductivity and pH

Permeate pH ranged from 5.0 to 6.0 with an average of 5.5. Concentrate pH ranged from 5.2 to 5.8 and averaged 5.6. Permeate conductivity ranged from 277 to 390 $\mu\text{S}/\text{cm}$ and averaged 354 $\mu\text{S}/\text{cm}$. Concentrate conductivity ranged from 309 to 352 $\mu\text{S}/\text{cm}$ and averaged 325 $\mu\text{S}/\text{cm}$.

UF2-R5-SR7 Cleaning

After UF2-R5-SR7 was shutdown on March 11, 1998 at 05:18 it was cleaned at 11:30, with a 0.5 % KLD cleaning solution. The total downtime for just the cleaning was 582 minutes.

Permeate Flux and System Temperature

During the first 40 minutes of cleaning the permeate flux ranged from 142.3 to

147.6 gal/ft²-d and averaged 145.1 gal/ft²-d. Permeate temperature ranged from 107.5 to 112.0 °F and averaged 109.8 °F. Concentrate temperature ranged from 118.8 to 122.1 °F and averaged 120.6 °F.

After 40 minutes, the system was shutdown and the valves were adjusted for the spongeball sequence. During the first pass of spongeballs, the permeate flux increased to 169.2 gal/ft²-d. The second pass of spongeballs yielded a permeate flux of 160 gal/ft²-d. After two spongeball passes were performed the system was cleaned for an additional 40 minutes.

In the second 40 minutes of regular cleaning, the permeate flux ranged from 161.9 to 170.8 gal/ft²-d with an average of 166.1 gal/ft²-d. Permeate temperature ranged from 110.1 to 110.8 °F with an average of 110.5 °F. Concentrate temperature ranged from 121.3 to 119.7 °F with an average of 121.3 °F.

pH, Conductivity and Turbidity

Permeate pH ranged from 9.0 to 9.3 and averaged 9.1. Concentrate pH ranged from 9.0 to 9.3 and averaged 9.2. Permeate conductivity averaged 769 µS/cm and ranged from 734 to 784 µS/cm. Concentrate conductivity averaged 1350 µS/cm and ranged from 1241 to 1492 µS/cm. Permeate turbidity ranged from 7.8 to 13.9 NTU and averaged 11.8 NTU.

UF2-R5-SR8

UF2-R5-SR8 was started on March 11, 1998 at 15:00 and ended on March 15, 1998 at 10:30. The length of the subrun lasted 3.77 days. . The total permeate volume produced was 157,390 gal. Subrun #8 reached the 29 gal/min set point with in a day and a half of operation. The running average did not exceed 29 gal/min though. As a result the system was allowed to stay in operation until the instantaneous permeate flow of ~18 gal/min was reached.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 17.9 to 97.8 gal/ft²-d. Permeate temperature ranged from 70.0 to 75.7 °F. and averaged 73.4 °F. Concentrate temperature ranged from 75.0 to 80.7 °F and averaged 77.9 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content started out at 6.4 % and increased to 7.1 % during subrun #8. The total volume of free oil that was produced during subrun #8 was 2,203 gallons. The average daily free oil production was 579.7 gallons/day.

Permeate Oil/Grease, Turbidity and Pond Effluent

Permeate O/G ranged at 4 mg/L. Turbidity ranged from 2.8 to 4.9 NTU and averaged 3.7 NTU. Pond effluent O/G ranged at 6,000 mg/L.

Conductivity and pH

Permeate pH ranged from 5.1 to 6.2 with an average of 5.5. Concentrate pH ranged from 5.0 to 6.4 and averaged 5.7. Permeate conductivity ranged from 278 to 388 µS/cm and averaged 322 µS/cm. Concentrate conductivity ranged from 234 to 352 µS/cm and averaged 307 µS/cm.

UF2-R5-SR8 Cleaning

After UF2-R5-SR8 was shutdown on March 15, 1998 at 10:30 it was cleaned at 12:00, with a 0.5 % KLD cleaning solution. The total downtime for just the cleaning was 230 minutes.

Permeate Flux and System Temperature

During the first 40 minutes of cleaning the permeate flux ranged from 145.8 to 168.9 gal/ft²-d and averaged 154.4 gal/ft²-d. Permeate temperature ranged from 111.9 to 114.8 °F and averaged 113.8 °F. Concentrate temperature ranged from 121.5 to 124.7 °F and averaged 123.4 °F.

After 40 minutes, the system was shutdown and the valves were adjusted for the spongeball sequence. During the first pass of spongeballs, the permeate flux increased to 199.1 gal/ft²-d. The second pass of spongeballs yielded a permeate flux of 188.5 gal/ft²-d. After two spongeball passes were performed the system was cleaned for an additional 40 minutes.

In the second 40 minutes of regular cleaning, the permeate flux ranged from 112 to 142.3 gal/ft²-d with an average of 126.3 gal/ft²-d. Permeate temperature ranged from 111.8 to 115.6 °F and averaged 113.9 °F. Concentrate temperature ranged from 120 to 126.6 °F and averaged 123.7 °F.

pH, Conductivity and Turbidity

Permeate pH ranged from 9.0 to 9.7 and averaged 9.4. Concentrate pH ranged from 8.9 to 9.7 and averaged 9.3. Permeate conductivity averaged 1115 µS/cm and ranged from 650 to 1585 µS/cm. Concentrate conductivity averaged 2018 µS/cm and ranged from 1408 to 2540 µS/cm. Permeate turbidity ranged from 2.2 to 5.3 NTU and averaged 3.6 NTU.

UF2-R5-SR9

UF2-R5-SR9 was started on March 15, 1998 at 14:20 and ended on March 16, 1998 at 12:35. The length of the subrun lasted 0.93 days. The total permeate volume produced was 36,900gal. Subrun #9 never reached the 29 gal/min set point. The permeate flow dropped into the lower twenties a half a day into operation. The system was therefore, shutdown and recleaned.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 19.6 to 64.0 gal/ft²-d. Permeate temperature ranged from 76.1 to 77.3 °F. and averaged 76.7 °F. Concentrate temperature ranged from 79.5 to 80 °F and averaged 79.8 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content started out at 7.1 % and increased to 7.2 % during subrun #9. The total volume of free oil that was produced during subrun #9 was 166 gallons. The average daily free oil production was 166 gallons/day.

Permeate Oil/Grease, Turbidity and Pond Effluent

Permeate O/G ranged at 5 mg/L. Turbidity ranged from 0.67 to 8.42 NTU and averaged 2.2 NTU. Pond effluent O/G ranged at 6,000 mg/L.

Conductivity and pH

Permeate pH ranged from 4.9 to 5.4 with an average of 5.1. Concentrate pH ranged ~ 5.7. Permeate conductivity ranged from 352 to 378 µS/cm and averaged 365 µS/cm. Concentrate conductivity ranged ~ 376 µS/cm.

UF2-R5-SR9 Cleaning

After UF2-R5-SR9 was shutdown on March 16, 1998 at 12:35 it was cleaned at 17:30, with a 0.5 % KLD cleaning solution. The total downtime for just the cleaning was 485 minutes.

Permeate Flux and System Temperature

During the first 30 minutes of cleaning the permeate flux ranged from 144.1 to

160.1 gal/ft²-d and averaged 151.2 gal/ft²-d. Permeate temperature ranged from 113.6 to 118.2 °F and averaged 115.4 °F. Concentrate temperature ranged from 122.1 to 125.7 °F and averaged 123.9 °F.

After 30 minutes, the system was shutdown and the valves were adjusted for the spongeball sequence. During the first pass of spongeballs, the permeate flux increased to 220.3 gal/ft²-d. The second pass of spongeballs yielded a permeate flux of 203.4 gal/ft²-d. The third and fourth spongeball passes yielded flux of 203.4 and 199.1 gal/ft² -d. After four spongeball passes were performed the system was cleaned for an additional 30 minutes.

In the second 30 minutes of regular cleaning, the permeate flux ranged ~ 170.6 gal/ft²-d. Permeate temperature ranged from 110.6 to 112.0 °F and averaged 111.3 °F. Concentrate temperature ranged from 120.9 to 123.3 °F and averaged 121.9 °F.

pH and Conductivity

Permeate pH ranged from 9.5 to 9.8 and averaged 9.6. Concentrate pH ranged from 9.4 to 9.9 and averaged 9.6. Permeate conductivity averaged 1147 µS/cm and ranged from 1081 to 1241 µS/cm. Concentrate conductivity averaged 2038 µS/cm and ranged from 1981 to 2120 µS/cm. Permeate turbidity ranged from 1.4 to 4.9 NTU and averaged 3.0 NTU.

UF2-R5-SR10

UF2-R5-SR10 was started on March 16, 1998 at 20:40 and ended on April 4, 1998 at 07:31. The length of the subrun lasted 15.4 days. . The total permeate volume produced was 557,460 gal. Subrun #10 reached to 29 gal/min set point during the third day of operation. The system was allowed to stay in operation because the instantaneous permeate flow leveled out in the mid- twenties and did not decline for the rest of the subrun.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 20 to 99 gal/ft²-d. Permeate temperature ranged from 74.8 to 82.0 °F. and averaged 78.4 °F. Concentrate temperature ranged from 78.7 to 86.1 °F and averaged 82.3 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content during subrun #10 started at 7.2 % and increased to 9.9%. The total volume of free oil that was produced during subrun #10 was 4,162 gallons. The average daily free oil production was 275.6 gallons/day.

Permeate Oil/Grease, Turbidity and Pond Effluent

Permeate O/G ranged from 1 to 4 mg/L and averaged 3 mg/L. Turbidity ranged from 0.67 to 8.4 NTU and averaged 2.2 NTU. Pond Effluent Oil content ranged from 6,000 to 8,000 mg/L and averaged 7,500 mg/L.

Conductivity and pH

Permeate pH ranged from 4.2 to 6.3 with an average of 5.0. Concentrate pH ranged from 4.7 to 5.4 and averaged 5.2. Permeate conductivity ranged from 120 to 392 µS/cm and averaged 287 µS/cm. Concentrate conductivity ranged 202 to 499 µS/cm and averaged 354. µS/cm.

UF2-R5-SR10 Cleaning

After UF2-R5-SR10 was shutdown on April, 1 1998 at 07:37 it was cleaned on April 3, 1998 at 19:00 with a 0.5 % KLD cleaning solution. Once the system temperature reached ~ 115 °F. The cleaning lasted one hour without any spongeballs pass. The reason for the different cleaning method was because a new spongeball system was in the processes of installation. The spongeball section of the system was temporally disassembled.

Permeate Flux and System Temperature

During the 60 minute cleaning the permeate flux ranged from 142 to 144 gal/ft²-d and averaged 142.3 gal/ft²-d. Permeate temperature ranged from 113 to 117 °F and averaged 115.1 °F. Concentrate temperature ranged from 121 to 126.7 °F and averaged 124 °F.

pH, Conductivity and Turbidity

Permeate pH ranged from 6.1 to 6.2 and averaged 6.2. Concentrate pH ranged from 6.2 to 6.3 and averaged 6.3. In Table 4.28 conductivity of permeate and concentrate are presented. Permeate conductivity averaged 437 µS/cm and ranged from 398 to 467 µS/cm. Concentrate conductivity averaged 499 µS/cm and ranged from 411 to 556 µS/cm. Permeate turbidity ranged from 1.2 to 1.8 NTU and averaged 1.5 NTU.

UF2-R5-SR11

UF2-R5-SR11 was started on April 3, 1998 at 20:38 and ended on April 7, 1998 at 07:17. The length of the subrun lasted 3.4 days. The total permeate volume produced was 154,590 gal. Subrun #11 ended because additional work on the new spongeball tank was needed. The valve gaskets on the new header also needed replaced.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 19.6 to 40.9 gal/ft²-d. Permeate temperature ranged from 74.0 to 79.4 °F. and averaged 75.9 °F. Concentrate temperature ranged from 77.0 to 83.0 °F and averaged 79.8 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content during subrun #11 started at 9.93 % and increased to 10.0 %. The total volume of free oil that was produced during subrun #11 was 1,508 gallons. The average daily free oil production was 443.2 gallons/day.

Permeate Oil/Grease, Turbidity and Pond Effluent

Permeate O/G ranged from 3 to 4 mg/L and averaged 3.5 mg/L. Turbidity ranged from 0.55 to 3.1 NTU and averaged 1.7 NTU. Pond Effluent Oil content ranged from 6,000 to 7,000 mg/L and averaged 6,500 mg/L.

Conductivity and pH

Permeate pH ranged from 5.0 to 5.6 with an average of 5.3. Concentrate pH ranged from 5.0 to 5.3 and averaged 5.1. In Table 30 conductivity is presented. Permeate conductivity ranged from 202 to 434 µS/cm and averaged 306 µS/cm. Concentrate conductivity ranged 304 to 444µS/cm and averaged 356. µS/cm.

UF2-R5-SR11 Cleaning

After UF2-R5-SR11 was shutdown on April, 7 1998 at 07:17 it was cleaned on April 9, 1998 at 17:00 with a 0.5 % KLD cleaning solution. The total downtime for just the cleaning was 60 minutes, however the system was down for days due to the new spongeball system.

Permeate Flux and System Temperature

During the 60 minute cleaning the permeate flux ranged from 147.6 to 154.7 gal/ft²-d and averaged 151.2 gal/ft²-d. Permeate temperature ranged from 108.7 to 113.4 °F and averaged 111.5 °F. Concentrate temperature ranged from 116.3 to 124.5 °F and averaged 121.2 °F.

pH, Conductivity and Turbidity

Permeate pH ranged from 7.7 to 7.8 and averaged 7.7. Concentrate pH ranged from 7.8 to 7.9 and averaged 7.8. Permeate conductivity averaged 857 µS/cm and ranged from 851 to 860 µS/cm. Concentrate conductivity averaged 1441 µS/cm and ranged from 1427 to 1451 µS/cm. Permeate turbidity ranged from 1.0 to 3.0 NTU and averaged 1.8 NTU.

UF2-R5-SR12

UF2-R5-SR12 was started on April 9, 1998 at 20:00 and ended on April 13, 1998 at 11:02. The length of the subrun lasted 3.7 days. The total permeate volume produced was 145,070 gal. Subrun #12 was allowed to stay in concentration mode even though the permeate running average dropped below 29 gal/min. The reason being, the system was going to be shutdown regardless, because of new spongeball tank work.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 16 to 54.2 gal/ft²-d. Permeate temperature ranged from 74.3 to 80.7 °F. and averaged 78.5 °F. Concentrate temperature ranged from 77.7 to 86.2 °F and averaged 82.8 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content during subrun #12 remained relatively constant starting out at 10.0 % and ending at 9.8 %. The total volume of free oil that was produced during subrun #12 was 1,196 gallons. The average daily free oil production was 323.2 gallons/day.

Permeate Oil/Grease, Turbidity and Pond Effluent

Permeate O/G ranged from 3 to 4 mg/L and averaged 3.5 mg/L. Turbidity ranged from 0.7 to 6.3 NTU and averaged 1.7 NTU. Pond Effluent Oil content ranged at 0.7 %.

Conductivity and pH

Permeate pH ranged from 5.0 to 5.7 with an average of 5.3. Concentrate pH ranged from 5.1 to 5.7 and averaged 5.4. Permeate conductivity ranged from 352 to 449 μ S/cm and averaged 416 μ S/cm. Concentrate conductivity ranged 324 to 442 μ S/cm and averaged 401. μ S/cm.

UF2-R5-SR12 Cleaning

After UF2-R5-SR12 was shutdown on April, 13 1998 at 11:02 it was cleaned on April 13, 1998 at 13:30 with a 0.5 % KLD cleaning solution. The total downtime for just the cleaning and work performed on the spongeball tank was 1438 minutes.

Permeate Flux and System Temperature

During the first 40 minute cleaning the permeate flux ranged from 135.2 to 149.4 gal/ft²-d and averaged 141.9 gal/ft²-d. Permeate temperature ranged from 111.6 to 114.9 °F and averaged 113.4 °F. Concentrate temperature ranged from 120.1 to 123.9 °F and averaged 122.2 °F.

The system was then set up for spongeballing. During the first spongeball pass the permeate flux increased to 177.8 gal/ft²-d. The second pass yielded a permeate flux of 168.9 gal/ft²-d. The third passes yield a permeate flux of 176.5 gal/ft²-d.

During the second 40 minutes of regular cleaning, the permeate flux ranged from 117.4 to 124.5 gal/ft²-d and averaged 121 gal/ft²-d. Permeate temperature ranged from 111.2 to 114.9 °F and averaged 112.9 °F. Concentrate temperature ranged from 120.3 to 125.1 °F and averaged 122.7 °F.

pH, Conductivity and Turbidity

Permeate pH ranged from 9.0 to 9.8 and averaged 9.3. Concentrate pH ranged from 9.0 to 9.8 and averaged 9.4. In Table 4.33 conductivity of permeate and concentrate are presented. Permeate conductivity averaged 1884 µS/cm and ranged from 1577 to 2190 µS/cm. Concentrate conductivity averaged 2823 µS/cm and ranged from 2480 to 3120 µS/cm. Permeate turbidity ranged from 0.6 to 1.5 NTU and averaged 0.9 NTU.

UF2-R5-SR13

UF2-R5-SR13 was started on April 14, 1998 at 11:00 and ended on April 17, 1998 at 11:15. The length of the subrun lasted 3.0 days. The total permeate volume produced was 115,780 gal. Subrun #13 never reached the 29 gal/min set point due to a rapid decline in permeate flux during the first day. The system was allowed to stay in operation because valve CV-1 was leaking. To prevent a long shutdown period, the system was allowed to keep running until pipe fitters were able to work on it.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 17.8 to 62.3 gal/ft²-d. Permeate temperature ranged from 78.9 to 82.2 °F. and averaged 81.1 °F. Concentrate temperature ranged from 81.3 to 86.9 °F and averaged 84.5 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content during subrun #13 decreased starting out at 9.8 % and ending at 7.8 %. The total volume of free oil that was produced during subrun #13 was 1,144 gallons. The average daily free oil production was 381.3 gallons/day.

Permeate Oil/Grease, Turbidity and Pond Effluent

Permeate O/G ranged from 3 to 4 mg/L and averaged 3.5 mg/L. Turbidity ranged from 0.8 to 2.8 NTU and averaged 1.5 NTU. Pond Effluent Oil content ranged 6,000 to 7,000 mg/L and averaged 6,500 mg/L.

Conductivity and pH

Permeate pH ranged from 5.1 to 5.5 with an average of 5.3. Concentrate pH ranged from 5.3 to 5.6 and averaged 5.4. Permeate conductivity ranged from 348 to 428 μ S/cm and averaged 388 μ S/cm. Concentrate conductivity ranged 401 to 484 μ S/cm and averaged 460 μ S/cm.

UF2-R5-SR13 Cleaning

After UF2-R5-SR13 was shutdown on April, 17 1998 at 11:15 it was cleaned on April 17, 1998 at 17:30 with a 0.5 % KLD cleaning solution. Once the system temperature reached ~ 115 °F. The system was not spongeball cleaned during this cleaning because the new spongeball screen inside the tank was being worked on. The cleaning consisted of just a one hour cleaning with a 0.5 % KLD solution. The total downtime for just the cleaning and work performed on valve CV -1 was 550 minutes.

Permeate Flux and System Temperature

During the 60 minute cleaning the permeate flux ranged from 102.3 to 112.1 gal/ft²-d and averaged 107.6 gal/ft²-d. Permeate temperature ranged from 105.6 to 113.1 °F and averaged 109.6 °F. Concentrate temperature ranged from 115.2 to 126.3 °F and averaged 120.8 °F.

pH, Conductivity and Turbidity

Permeate pH ranged from 7.5 to 7.6 and averaged 7.6. Concentrate pH ranged from 7.7 to 7.8 and averaged 7.7. In Table 4.35 conductivity of permeate and concentrate are presented. Permeate conductivity averaged 548 µS/cm and ranged from 521 to 577 µS/cm. Concentrate conductivity averaged 1044 µS/cm and ranged from 995 to 1130 µS/cm. Permeate turbidity ranged from 1.5 to 2.3 NTU and averaged 1.9 NTU.

UF2-R5-SR14

UF2-R5-SR14 was started on April 17, 1998 at 20:25 and ended on April 24, 1998 at 06:46. The length of the subrun lasted 6.6 days. The total permeate volume produced was 283,070 gal. Subrun #14 was shutdown because new actuators and valves needed to be installed on the new spongeball loop. The permeate running average was also at the 29 gal/min set point.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 20.5 to 63.1 gal/ft²-d. Permeate temperature ranged from 77.1 to 82.8 °F. and averaged 79.3 °F. Concentrate temperature ranged from 81.0 to 86.0 °F and averaged 82.9 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content during subrun #14 started at 10.5 % and decreased to 9.8 % by the end of the subrun. The total volume of free oil that was produced during subrun #14 was 1,856 gallons. The average daily free oil production was 381.2 gallons/day.

Permeate Oil/Grease, Turbidity and Pond Effluent

Permeate O/G ranged from 3 to 4 mg/L and averaged 3.5 mg/L. Turbidity ranged from 0.2 to 1.6 NTU and averaged 0.6 NTU. Pond Effluent Oil content ranged at 7,000 mg/L.

Conductivity and pH

Permeate pH ranged from 5.0 to 5.5 with an average of 5.2. Concentrate pH ranged from 5.2 to 6.1 and averaged 5.4. Permeate conductivity ranged from 166 to 463 μ S/cm and averaged 345 μ S/cm. Concentrate conductivity ranged 207 to 481 μ S/cm and averaged 360 μ S/cm.

UF2-R5-SR14 Cleaning

After UF2-R5-SR14 was shutdown on April, 24 1998 at 06:46 it was cleaned at 16:50 with a 0.5 % KLD cleaning solution. The total downtime for just the cleaning and work performed on the spongeball tank was 195 minutes.

Permeate Flux and System Temperature

During the first 40 minute cleaning the permeate flux ranged from 78.3 to 83.6 gal/ft²-d and averaged 80.7 gal/ft²-d. Permeate temperature ranged from 106.5 to 109.5 °F and averaged 108 °F. Concentrate temperature ranged from 114.3 to 121.9 °F and averaged 118.2 °F.

The system was then set up for spongeballing. During the first spongeball pass the permeate flux increased to 124.5 gal/ft²-d. The second pass yielded a permeate flux of 145.8 gal/ft²-d. The third passes yield a permeate flux of 151.2 gal/ft²-d.

During the second 40 minutes of regular cleaning, the permeate flux ranged from 115.6 to 119.2 gal/ft²-d and averaged 117.4 gal/ft²-d. Permeate temperature ranged from 107.6 to 109.3 °F and averaged 108.5 °F. Concentrate temperature ranged from 117.4 to 120.4 °F and averaged 118.9 °F.

pH, Conductivity and Turbidity

Permeate pH ranged from 9.3 to 9.4 and averaged 9.4. Concentrate pH ranged from 9.6 to 9.7 and averaged 9.7. Permeate conductivity averaged 830 µS/cm and ranged from 787 to 884 µS/cm. Concentrate conductivity averaged 1419 µS/cm and ranged from 1334 to 1533 µS/cm. Permeate turbidity ranged from 1.1 to 3.2 NTU and averaged 2.4 NTU.

UF2-R5-SR15

UF2-R5-SR15 was started on April 24, 1998 at 19:00 and ended on April 30, 1998 at 06:42. The length of the subrun lasted 5.4 days. The total permeate volume produced was 207,540 gal. Subrun #15 was shutdown because additional valves and piping were being installed on the new spongeball loop.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 19.6 to 71.1 gal/ft²-d. Permeate temperature ranged from 78.7 to 81.8 °F. and averaged 80.4 °F. Concentrate temperature ranged from 82.3 to 86.3 °F and averaged 84.5 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content during subrun #15 started at 10.2 % and increased to 18.0 % by the end of the subrun. The total volume of free oil that was produced during subrun #15 was 960 gallons. The average daily free oil production was 177.8 gallons/day.

Permeate Oil/Grease, Turbidity and Pond Effluent

Permeate O/G ranged from 2 to 6 mg/L and averaged 4 mg/L. Turbidity ranged from 0.3 to 21.3 NTU and averaged 5.8 NTU. Pond Effluent Oil content ranged at 7,000 mg/L.

Conductivity and pH

Permeate pH ranged from 4.5 to 5.4 with an average of 5.0. Concentrate pH ranged from 5.2 to 5.4 and averaged 5.3. Permeate conductivity ranged from 279 to 398 μ S/cm and averaged 302 μ S/cm. Concentrate conductivity ranged 376 to 421 μ S/cm and averaged 403 μ S/cm.

UF2-R5-SR15 Cleaning

After UF2-R5-SR15 was shutdown on April, 30 1998 at 06:42 it was cleaned at 17:50 with a 0.5 % KLD cleaning solution. The total downtime for just the cleaning was 199 minutes.

Permeate Flux and System Temperature

During the first 30 minute cleaning the permeate flux ranged from 87.2 to 96.9 gal/ft²-d and averaged 93.8 gal/ft²-d. Permeate temperature ranged from 109.5 to 111.7 °F and averaged 110.6 °F. Concentrate temperature ranged from 117.7 to 121.5 °F and averaged 119.9 °F.

The system was then set up for spongeballing. During the first spongeball pass the permeate flux increased to 124.5 gal/ft²-d. The second pass yielded a permeate flux of 142.3 gal/ft²-d.

During the second 30 minutes of regular cleaning the permeate flux ranged from 128.1 to 129.8 gal/ft²-d and averaged 128.9 gal/ft²-d. Permeate temperature ranged from 107.1 to 108.7 °F and averaged 107.9 °F. Concentrate temperature ranged from 115.3 to 119.5 °F and averaged 117.2 °F.

pH, Conductivity and Turbidity

Permeate pH ranged from 7.5 to 7.7 and averaged 7.6. Concentrate pH ranged from 7.6 to 7.8 and averaged 7.6. Permeate conductivity averaged 976 µS/cm and ranged from 890 to 1077 µS/cm. Concentrate conductivity averaged 1676 µS/cm and ranged from 1579 to 1866 µS/cm. Permeate turbidity ranged from 2.0 to 4.4 NTU and averaged 3.2 NTU.

UF2-R5-SR16

UF2-R5-SR16 was started on April 30, 1998 at 20:04 and ended on May 7, 1998 at 06:45. The length of the subrun lasted 6.3 days. The total permeate volume produced was 351,070 gal. Subrun #16 was shutdown because the new spongeball tank and screen were ready to be installed and tested.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 30.2 to 113.8 gal/ft²-d. Permeate temperature ranged from 77.8 to 81.1 °F. and averaged 79.6 °F. Concentrate temperature ranged from 81.6 to 84.8 °F and averaged 83.1 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content during subrun #16 started at 18.0 % and decreased to 11.0 % by the end of the subrun. The total volume of free oil that was produced during subrun #16 was 5,029 gallons. The average daily free oil production was 798.3 gallons/day.

Permeate Oil/Grease, Turbidity and Pond Effluent

Permeate O/G ranged from 2 to 4 mg/L and averaged 3 mg/L. Turbidity ranged from 0.2 to 4.2 NTU and averaged 0.9 NTU. Pond Effluent Oil content ranged at 7,500 mg/L.

Conductivity and pH

Permeate pH ranged from 4.7 to 6.2 with an average of 5.1. Concentrate pH ranged from 4.9 to 6.4 and averaged 5.2. Permeate conductivity ranged from 196 to 361 μ S/cm and averaged 281 μ S/cm. Concentrate conductivity ranged 188 to 462 μ S/cm and averaged 309 μ S/cm.

UF2-R5-SR16 Cleaning

After UF2-R5-SR16 was shutdown on May 7 1998 at 06:45 it was cleaned at 12:50 with a 0.5 % KLD cleaning solution and pH adjusted to 10. The total downtime for just the cleaning was 493 minutes.

Permeate Flux and System Temperature

During the first 30 minute cleaning the permeate flux ranged from 106.7 to 113.8 gal/ft²-d and averaged 111.2 gal/ft²-d. Permeate temperature ranged from 105.8 to 113.6 °F and averaged 110.5 °F. Concentrate temperature ranged from 120 to 126 °F and averaged 122.5 °F.

The system was then set up for spongeballing. During the first spongeball pass the permeate flux increased to 160.1 gal/ft²-d. The second pass yielded a permeate flux of 156.5 gal/ft²-d. The third and fourth spongeball passes yielded permeate fluxes of 160.1 and 161.9 gal/ft²-d respectively.

During the second 30 minutes of regular cleaning the permeate flux ranged from 117.4 to 124.5 gal/ft²-d and averaged 122.0 gal/ft²-d. Permeate temperature ranged from 111.4 to 111.7 °F and averaged 111.6 °F. Concentrate temperature ranged from 120.4 to 122.0 °F and averaged 121.3 °F.

pH, Conductivity and Turbidity

Permeate pH ranged from 9.6 to 10.0 and averaged 9.8. Concentrate pH ranged from 9.5 to 9.9 and averaged 9.7. Permeate conductivity averaged 921 µS/cm and ranged from 864 to 986 µS/cm. Concentrate conductivity averaged 1536 µS/cm and ranged from 1451 to 1687 µS/cm. Permeate turbidity ranged from 0.5 to 3.9 NTU and averaged 1.5 NTU.

UF2-R5-SR17

UF2-R5-SR17 was started on May 7, 1998 at 20:23 and ended on May 18, 1998 at 05:15. The length of the subrun lasted 9.3 days. The total permeate volume produced was 360,880 gal. Subrun #17 was shutdown because all of the valve seals for the whole system were being replaced. The original valve seals were not compatible with the oily waste the systems process.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 19.6 to 71.1 gal/ft²-d. Permeate temperature ranged from 78.4 to 87.0 °F. and averaged 84.1 °F. Concentrate temperature ranged from 82.0 to 91.2 °F and averaged 88.1 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content during subrun #17 started at 11.0 % and decreased to 9.9 % by the end of the subrun. The total volume of free oil that was produced during subrun #17 was 4,076 gallons. The average daily free oil production was 438.3 gallons/day.

Permeate Oil/Grease, Turbidity and Pond Effluent

Permeate O/G ranged from 3 to 6 mg/L and averaged 4.3 mg/L. Turbidity ranged from 0.75 to 14.3 NTU and averaged 5.9 NTU. Pond Effluent O/G ranged from 7,000 to 9,000 mg/L and averaged 8,000 mg/L.

Conductivity and pH

Permeate pH ranged from 5.1 to 5.8 with an average of 5.5. Concentrate pH ranged from 5.3 to 5.8 and averaged 5.5. Permeate conductivity ranged from 120 to 403 μ S/cm and averaged 287 μ S/cm. Concentrate conductivity ranged 217 to 433 μ S/cm and averaged 350 μ S/cm.

UF2-R5-SR17 Cleaning

After UF2-R5-SR17 was shutdown on May 18 1998 at 05:15 it was cleaned on May 20, 1998 at 14:30 with a 0.5 % KLD cleaning solution and pH adjusted to 10. The total downtime for just the cleaning was 550 minutes not including the time for work on the valve replacement.

Permeate Flux and System Temperature

During the first 30 minute cleaning the permeate flux ranged from 129.8 to 133.4 gal/ft²-d and averaged 131.3 gal/ft²-d. Permeate temperature ranged from 116.7 to 119.1

°F and averaged 118.2 °F. Concentrate temperature ranged from 120.1 to 125.6 °F and averaged 123.1 °F.

The system was then set up for spongeballing. During the first spongeball pass the permeate flux increased to 177.9 gal/ft²-d. The second pass yielded a permeate flux of 172.5 gal/ft²-d. The third spongeball pass yielded a permeate flux of 172.5 gal/ft²-d.

During the second 30 minutes of regular cleaning the permeate flux ranged from 135.2 to 140.5 gal/ft²-d and averaged 137.7 gal/ft²-d. Permeate temperature ranged from 114.3 to 115.9 °F and averaged 115.3 °F. Concentrate temperature ranged from 122.1 to 127 °F and averaged 124.6 °F.

pH, Conductivity and Turbidity

Permeate pH ranged from 9.3 to 9.9 and averaged 9.6. Concentrate pH ranged from 9.3 to 9.9 and averaged 9.6. Permeate conductivity averaged 1383 µS/cm and ranged from 1247 to 1534 µS/cm. Concentrate conductivity averaged 2375 µS/cm and ranged from 2120 to 2640 µS/cm. Permeate turbidity ranged from 0.8 to 1.9 NTU and averaged 1.5 NTU.

UF2-R5-SR18

UF2-R5-SR18 was started on May 20, 1998 at 20:10 and ended on June 22, 1998 at 10:52. The length of the subrun lasted 32.6 days. The total permeate volume produced was 1,315,340 gal. Subrun #18 was shutdown because all of the valve seals for the whole system were being replaced. The original valve seals were not compatible with the oily waste the systems process.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 19.6 to 113.8 gal/ft²-d. Permeate temperature ranged from 80.1 to 89.8 °F. and averaged 85.3 °F. Concentrate temperature ranged from 84.0 to 93.6 °F and averaged 89.9 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content during subrun #18 started at 4.5 % and decreased to 3.2 % by the end of the subrun. The total volume of free oil that was produced during subrun #18 was 12,953 gallons. The average daily free oil production was 397.3 gallons/day.

Permeate Oil/Grease, Turbidity and Pond Effluent

Permeate O/G ranged from 1 to 8 mg/L and averaged 3.8 mg/L. Turbidity ranged from 0.19 to 17.7 NTU and averaged 2.9 NTU. Pond Effluent O/G ranged from 6,000 to 8,000 mg/L and averaged 7,400 mg/L.

Conductivity and pH

Permeate pH ranged from 5.2 to 6.2 with an average of 5.6. Concentrate pH ranged from 5.3 to 5.8 and averaged 5.6. Permeate conductivity ranged from 102 to 523 μ S/cm and averaged 398 μ S/cm. Concentrate conductivity ranged 207 to 523 μ S/cm and averaged 421 μ S/cm.

UF2-R5-SR18 Cleaning

After UF2-R5-SR18 was shutdown on June 22, 1998 at 10:52 it was cleaned on May 22, 1998 at 12:40 with a 0.5 % KLD cleaning solution and pH adjusted to 10. The total downtime for just the cleaning was 215 minutes.

Permeate Flux and System Temperature

During the first 40 minute cleaning the permeate flux ranged from 45.4 to 51.6 gal/ft²-d and averaged 47.1 gal/ft²-d. Permeate temperature ranged from 114.6 to 121.1 °F and averaged 117.9 °F. Concentrate temperature ranged from 121 to 128 °F and averaged 124 °F.

The system was then set up for spongeballing. During the first spongeball pass the permeate flux increased to 72.4 gal/ft²-d. The second pass yielded a permeate flux of 79.8 gal/ft²-d.

During the second 40 minutes of regular cleaning the permeate flux ranged from 51.6 to 58.7 gal/ft²-d and averaged 53.5 gal/ft²-d. Permeate temperature ranged from 113.8 to 117.2 °F and averaged 115.3 °F. Concentrate temperature ranged from 120 to 127.9 °F and averaged 123.9 °F.

pH, Conductivity and Turbidity

Permeate pH ranged from 8.3 to 9.7 and averaged 8.9. Concentrate pH ranged from 8.3 to 9.7 and averaged 8.9. Permeate conductivity averaged 584 µS/cm and ranged from 535 to 619 µS/cm. Concentrate conductivity averaged 728 µS/cm and ranged from 692 to 812 µS/cm. Permeate turbidity ranged from 0.98 to 2.89 NTU and averaged 1.6 NTU.

UF2-R5-SR19

UF2-R5-SR19 was started on June 25, 1998 at 10:40 and ended on June 28, 1998 at 10:30. The length of the subrun lasted 3.0 days. The total permeate volume produced was 140,410 gal.

Permeate Flux and System Temperature

Over the course of the subrun, the permeate flux ranged from 24.9 to 49.8 gal/ft²-d. Permeate temperature ranged from 87.2 to 90.1 °F. and averaged 88.4 °F. Concentrate temperature ranged from 93.2 to 94.5 °F and averaged 94.1 °F.

Concentrate Oil Content and Free Oil Production

Concentrate oil content during subrun #19 started at 3.2 % and increased to 4.0 % by the end of the subrun. The total volume of free oil that was produced during subrun #19 was 890 gallons. The average daily free oil production was 296.7 gallons/day.

Permeate Oil/Grease, Turbidity and Pond Effluent

Permeate O/G ranged at 5 mg/L. Turbidity ranged from 1.9 to 5.4 NTU and averaged 2.3 NTU. Pond Effluent O/G ranged from 8,000 mg/L.

Conductivity and pH

Permeate pH ranged from 4.8 to 5.1 with an average of 5.0. Concentrate pH ranged from 5.1 to 5.2 and averaged 5.1. Permeate conductivity ranged from 234 to 351 μ S/cm and averaged 394 μ S/cm. Concentrate conductivity ranged 422 to 432 μ S/cm and averaged 427 μ S/cm.

CHAPTER 5

DISCUSSION

In this chapter the following topics will be discussed: 1) the development of an operating plan for the systems, 2) the effect on free oil production with in the concentration tanks, 3) the development of the mass balance model on oil, 4) and the role of concentration polarization and membrane fouling on permeate flux.

DEVELOPMENT OF AN OPERATING PLAN FOR THE TUBULAR UNITS

System operation is described in detail in Chapter 3. In the following section, the method used to assure that the system was operating at maximum efficiency is discussed.

Permeate Flux Set Points

Each system was design to produce 40,000 gallons of permeate per day to meet the demands of the plant. This corresponded to a permeate flow of 29 gal/min (25.8 gal/ft²-d). A permeate running average was used to track the average permeate flow throughout a subrun. The running average takes into consideration; the time the system was down or not producing permeate, the total length of the subrun and the total volume of permeate produced. In Figure 5.1 a typical running permeate average is presented. The equation that was used to determine the permeate running average throughout a subrun is as follows:

Figure 5.1 Running Permeate Average versus Time

$$Q_{\text{permeate}} = V_{\text{permeated}} / (T_{\text{operation}} + T_{\text{downtime}})$$

Where:

Q_{permeate} = Running permeate flow average (gal/min)

$V_{\text{permeated}}$ = Total volume of permeate produce from t to t+1 (gallons)

$T_{\text{operation}}$ = Total amount of time the system was operating t = minutes

T_{downtime} = amount of time the system was down for routine cleanings t = minutes

The system was shutdown and cleaned if the permeate running average was significantly less than 29 gal/min.

Another set point that was established was the instantaneous permeate flow. The instantaneous permeate flow was not allowed to decrease below 18 gpm (16.0 gal/ft²-d). The set point was based on advice from the membrane manufacturer who said that operating the system at low permeate flow could decrease membrane life.

MODIFIED TREATMENT PROCESS

The modified treatment plan is present in Figure 5.2. The Proposed treatment plan is present in Figure 3.1 Many changes were made to the original treatment plan due to the performance of the full-scale tubular UF system. These changes were the result of water quality, free oil production and concentrate oil content.

Figure 5.2 Current Treatment Plan

Water Quality

In Tables 4.1, 4.10, 4.19, 4.28, 4.37, a summary of the results from UF1-R8, UF2-R3, UF2-R4 and UF2-R5 are presented. For all runs, permeate (O/G) was consistently low, ranging from 1 to 9 mg/L and averaging 3.1 mg/L.

The pilot-scale UF system significantly reduced O/G concentrations, however concentrations were still above the discharge limits. Thus, the wetlands were necessary in the preliminary design to further degrade the remaining O/G in the UF effluent. However, the full-scale system produced permeate that was of high quality and did not require further polishing. Removal efficiencies were consistently above 99.9%. As a result the wetlands were deemed unnecessary and the permeate could be directly discharged into the river.

Free Oil Production

As concentration occurred, an unexpectedly large amount of free oil separated out of the concentrate and accumulated at the top of the concentration tanks. The total amount of free oil collected during UF1-R8 was 49,484 gallons with a daily average of 394 gallons. The total amount of free oil collected during UF2-R5 was 39,034 gallons with a daily average of 355 gallons. Daily averages were similar for all other runs. The volume that formed was far beyond what was expected. In the original plan, coalescers were too dewater any free oil that might form at the top of the concentration tanks. The oil content of the free oil was consistently above 98% oil. As a result, the skimmed free oil could be directly transferred to the storage facility for offsite recycling. Thus, the coalescers were no longer needed.

Due to the volume and oil content of the free oil forming at the top of concentration tanks, the concentrate oil content typically remained below the 16% oil content set point for a vast majority of the runs. Recall in the preliminary design, the residual from the tubular was to be sent to a HSR-UF when the oil content reached 16 %. However, because of the free oil formation, the oil content within the tubular seldom reached a high enough level to warrant purging. Thus, the HSR-UF system was not needed.

Concentrate Oil Content

An oil mass balance was performed on the UF system in order to note any change in the system. In Figure 5.3, the oil mass balance diagram is presented. The mass balance equation was calculated as follows:

$$(OC_{n+1}) = [(V_{perm})(OC_{pond}) - (V_{perm})(OC_{perm}) - (V_{skim})(0.00349 \text{ kg/gal})(\% \text{ oil}) - (V_{leak})(OC_{leak}) + (V_{sys})(OC_n)] / V_{sys}$$

where,

V_{sys} = System volume at 11.0 feet in concentration tanks (14,561 gallons)

OC_{n+1} = Concentrate oil content for current day (kg/gal)

OC_{pond} = Pond effluent oil content (kg/gal)

V_{perm} = Volume permeate removed from system from t_1 to t_2 (gallons)

OC_{perm} = Permeate oil content (kg/gal)

V_{skim} = Volume oil skimmed from concentrate tank (gallons)

% oil = % oil of skimmings

V_{leak} = Volume of leaks (gallons)

OC_{leak} = Oil content of leaks (kg/gal)

OC_n = Concentrate oil content for previous day kg/gal

0.00349 kg/gal = density of oil package.

The predicted oil content was calculated daily during a run, after the free oil was skimmed from concentration tanks. In Figure 5.4, actual and predicted oil contents for

Figure 5.3 Mass Balance Diagram

UF1-R7 mass balance are presented. In Figure 5.5, actual and predicted oil contents for UF1-R8 mass balance are presented. In Figure 5.6, actual and predicted oil contents for UF2-R3 mass balance are presented. In Figure 5.7, actual and predicted oil contents for UF2-R4 mass balance are presented. In Figure 5.8, actual and predicted oil contents for UF2-R5 mass balance are presented.

Also presented in Figures 5.4, 5.5, 5.6, 5.7, and 5.8, is the oil content of the concentrate solution if no free oil formed in the concentration tanks. The oil content would have reached the 16 % set point in less than 10 days for both UF1-R8 and UF2-R5. However, because of free oil formation, the concentrate almost always remained at an oil content below 16 %.

In UF1-R7, UF2-R3 and UF2-R4 the predicted oil mass balance model adequately predicted the actual oil content. Unfortunately, the runs did not last long. The systems were designed to concentrate the waste to 32X or 16 % oil content. During the runs UF1-R7, UF2-R3 and UF2-R4, the systems were shutdown due to either logistical reasons or system malfunction (e.g. valve replacement or pipe rupture) and the 32X set point was never reached. Consequently, for all three runs the systems had to be drained to repair the problems and the systems were down for long periods of time. As a result, it was decided that a new run should be started after the system was repaired and cleaned.

UF1-R8 on the other hand, lasted significantly longer than previous runs. UF1-R8 lasted for 125 days. Similar to past runs an oil mass balance was calculated daily, to monitor changes in the systems. During UF1-R8, the actual oil content increased to ~ 12% oil after the first 35 days of operation. Over a period of the next 40 days of

Figure 5.4 Actual and Predicted Oil Contents for UF1-R7 Mass Balance

Figure 5.5 Actual and Predicted Oil Contents for UF1-R8 Mass Balance

Figure 5.6 Actual and Predicted Oil Contents for UF2-R3 Mass Balance

Figure 5.7 Actual and Predicted Oil Contents for UF2-R4 Mass Balance

Figure 5.8 Actual and Predicted Oil Contents for UF2-R5 Mass alance

operation, the oil content remained within the range of 10 to 15% oil. The oil content peaked above 16 % oil only once around 79 days into UF1-R8, however declined and remained below the 16 % set point the remainder of the run. As presented in Figure 5.4, the oil content of the concentrate solution would have reached the 16% oil content set point in less than 10 days if no free oil was formed and removed in the concentration tanks. However, because of free oil formation, the concentrate almost always remained at an oil content below 16 % oil.

UF2-R5 also was in operation for a long period of time. UF2-R5 lasted for 109 days. During the first 35 days of operation, the oil content increased to ~ 12 % oil. Similar to UF1-R8, the oil content remained constant between 10 and 15 % for a period of about 20 days. The concentrate oil content increased to 18 % when the oil skimmer was not functioning and oil was not removed from the concentration tank. After repairs were made, skimming resumed and the oil content dropped to a constant concentration of ~ 12 % oil. It was theorized that because the free oil was not being removed, the oil layer began to accumulate. The accumulating oil decreased the amount of available space for the concentrate in the concentration tank. As the volume decreased, the quiescent conditions in the concentration tank, which normally favor free oil formation, also decreased and the concentrate mixed more readily. Thus, the rate of free oil breaking out of the concentrate decreased, allowing for a net increase in oil content

THE ROLE OF CONCENTRATION POLARIZATION AND MEMBRANE FOULING ON PERMEATE FLUX

Concentration Polarization is the build up of solute molecules close to or on the membrane's surface. Solute is brought to the membrane's surface by convective

transport. As water permeates the membrane, solute molecule larger than the MWCO of the membrane are retained. The retained solute, builds up causing a decline in flux due to either an increased resistance in the boundary layer or an increased osmotic pressure decreasing the driving force. Concentration polarization is effected by operating parameters, such as cross-flow velocity, temperature, pressure, and feed concentration. The effects of operating parameters in concentration polarization are presented in Figure 2.10.

Membrane Fouling on the other hand is due to the deposition of particles on the membrane's surface or precipitation of particles within the membrane pores. Similar to concentration polarization, membrane-fouling results in a decrease in permeate flux. However, concentration polarization is not membrane fouling. Membrane fouling is primarily time-dependent and partially concentration dependent. Depending on the system flux decline may occur in one or more stages. Typically, a rapid decline in flux is observed followed by a more gradual decline with time. Since fouling is the result of interactions between the membrane and feed solutes and perhaps between adsorbed solute and other solutes in the concentrate stream, it is difficult to establish general rules about the nature and extent of the fouling (Cheryan, 1986).

During the full-scale operation of the tubular UF systems, permeate flux over time typically had an exponential decline in nature. It was hypothesized that concentration polarization had the majority of influence on flux decline, however, there was uncertainty whether membrane fouling was also occurring. In order to determine if membrane fouling was occurring five fouling models were applied to the data to determine the

degree of fouling if any. The simplest models relate permeate flux to time and or the volume permeated. The models were as follows:

Model #1 - Kuo and Cheryan (1983)

$$J = J_o(t^{-b})$$

Where: J = flux at any time t
t = time in days
J_o = initial permeate flux at time = 0
b = fouling index

Model #2 - Merin and Cheryan (1980)

$$J = J_o(V^{-b})$$

Where: J = flux at any time t
J_o = initial permeate flux at time = 0
V = volume permeated
b = fouling index

Model #3 – Pore Plugging

$$J = J_o(e^{-bt})$$

Where: J = flux at any time t
J_o = initial permeate flux at time = 0
t = time in days
b = fouling index

Model #4 - Concentration Polarization and Adsorption

$$J = J_{ss} + B \exp(-kt)$$

Where: J = flux at any time t
J_{ss} = steady state permeate flux
t = time in days
B = constant determined by linearization (y int)
k = fouling index

Model #5 Cake Formation

$$J = J_o / (1 + J_o k t)$$

Where: J = flux at any time t

J_o = initial permeate flux at time = 0

t = time in days

k = fouling index

Modeling Flux Decline

Of the five models, model #4 fit the data the best. In Figure 5.9 the actual and predicted permeate flux for UF1-R7 using Model #4 is presented. In Figure 5.10 the actual and predicted permeate flux for UF1-R8 (subruns 1-6) using Model #4 is presented. In Figure 5.11 the actual and predicted permeate flux for UF1-R8 using Model #4 (subruns 7-10) is presented. In Figure 5.12 the actual and predicted permeate flux for UF2-R3 using Model #4 is presented. In Figure 5.13 the actual and predicted permeate flux for UF2-R4 using Model #4 is presented. In Figure 5.14 the actual and predicted permeate flux for UF2-R5(subruns 1-6) using Model #4 is presented. In Figure 5.15 the actual and predicted permeate flux for UF2-R5(subruns 7-12) using Model #4 is presented. In Figure 5.16 the actual and predicted permeate flux for UF2-R5 (subruns 13-18) using Model #4 is presented. In Table 5.1, model index values (k) for all subruns are presented. The model index characterizes the declining nature of permeate flux over time. The concentration polarization and adsorption-fouling model consistently fit the actual data and predicted the steady-state fluxes. However, a single average model index could not predict the behavior over the entire run, due to the wide range of model index values.

Figure 5.9 Actual and Predicted Permeate Flux for UF1-R7 using Model #4

Figure 5.10 Actual and Predicted Permeate Flux for UF1-R8 (subrun 1-6) using Model #4

Figure 5.11 Actual and Predicted Permeate Flux for UF1-R8 (subrun 7-10) using Model #4

Figure 5.12 Actual and Predicted Permeate Flux for UF2-R3 using Model #4

Figure 5.13 Actual and Predicted Permeate Flux for UF2-R4 using Model #4

Figure 5.13 Actual and Predicted Permeate Flux for UF2-R5 (Subrun 1-6) using Model #4

Figure 5.15 Actual and Predicted Permeate Flux for UF2-R5 (Subrun 7-12) using Model #4

Figure 5.16 Actual and Predicted Permeate Flux for UF2-R5 (Subrun 13-18) using Model #4

Table 5.1 List of Model Indexes (k) for All Subruns

Run ID	Subrun ID	Model Index, k
UF1-R7	1	-2.10
	2	-1.77
	3	-1.71
	4	-3.21
UF1-R8	1	-0.32
	2	-0.66
	3	-11.59
	4	-1.83
	5	-3.06
	6	-1.78
	7	-0.75
	8	-2.88
	9	-0.71
	10	-4.32
	11	-3.56
UF2-R3	1	-1.88
	2	-1.21
	3	-2.05
	4	-0.61
UF2-R4	1	-1.33
	2	-3.35
UF2-R5	1	-9.88
	2	-7.52
	3	-2.53
	4	-2.31
	5	-26.60
	6	-38.36
	7	-12.07
	8	-2.67
	9	-94.14
	10	-2.39
	11	-0.48
	12	-1.18
	13	-3.22
	14	-1.87
	15	-6.38
	16	-70.47
	17	-7.69
	18	-2.63
	19	-1.27

The predicted initial permeate flux was consistently lower than the actual permeate flux. This difference was due to the cleaning solution present in the system during the start up of a subrun. The cleaning solution decreases the surface tension at the membrane pores allowing water to pass through more readily, thus a high permeate flux occurs. Within a few minutes of the subrun, the concentrate circulating through the system diluted the cleaning solution. When the concentrate diluted the cleaning solution adequately, the predicted permeate fluxes closely resembled the actual data. In Figure 5.16, actual and predicted permeate flux for models 1, 2, 3 and 5 are presented for UF2-R5-SR3. The results presented in Figure 5.16 were similar in all subruns.

Figure 5.17, Actual and Predicted Permeate Flux for UF2-R5-SR3 using Models 1, 2, 3, and 5

CHAPTER 6

CONCLUSION

In starting up and optimizing performance of the tubular UF systems the following tasks were completed. The objective of the entire study was to develop a standard operating plan for the entire oily-waste system. In partial fulfillment of this objective, the following goals were achieved:

5. Development of an operating plan for tubular UF system that optimizes system performance.
6. Determined free oil production rates.
7. Developed a mass balance model on oil for tubular UF system.
8. Investigated the role of concentration polarization on permeate flux.

Several positive outcomes occurred from the implementation of the full-scale tubular UF system to treat oily waste. Effluent O/G concentrations were consistently low, yielding 99.9% removal efficiencies. Thus, the wetlands treatment process were not required. Due to the unexpected purity and large volumes of free oil forming at the top of the concentration tanks, system oil content remained below 16 %. As a result, there was no need to purge and treat the concentrate. Thus, installation of the HSR-UF system was deemed unnecessary. The concentration polarization and adsorption fouling model consistently fit and predicted steady-state fluxes, however, was unable to predict the behavior of an entire run using a single average fouling index value.

Future research is going to be performed on the system during the winter months in order to verify that the high shear rotary UF systems are not needed. It is hypothesized that the amount of free oil separating from the concentrate will be significantly less causing the concentrate oil content to increase beyond 16 % set point. Thus purging the concentrate to the HSR-UF system might have to be implemented.

CHAPTER 7

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