IFC-2019-PEP01

IntelliFlux R&D Group

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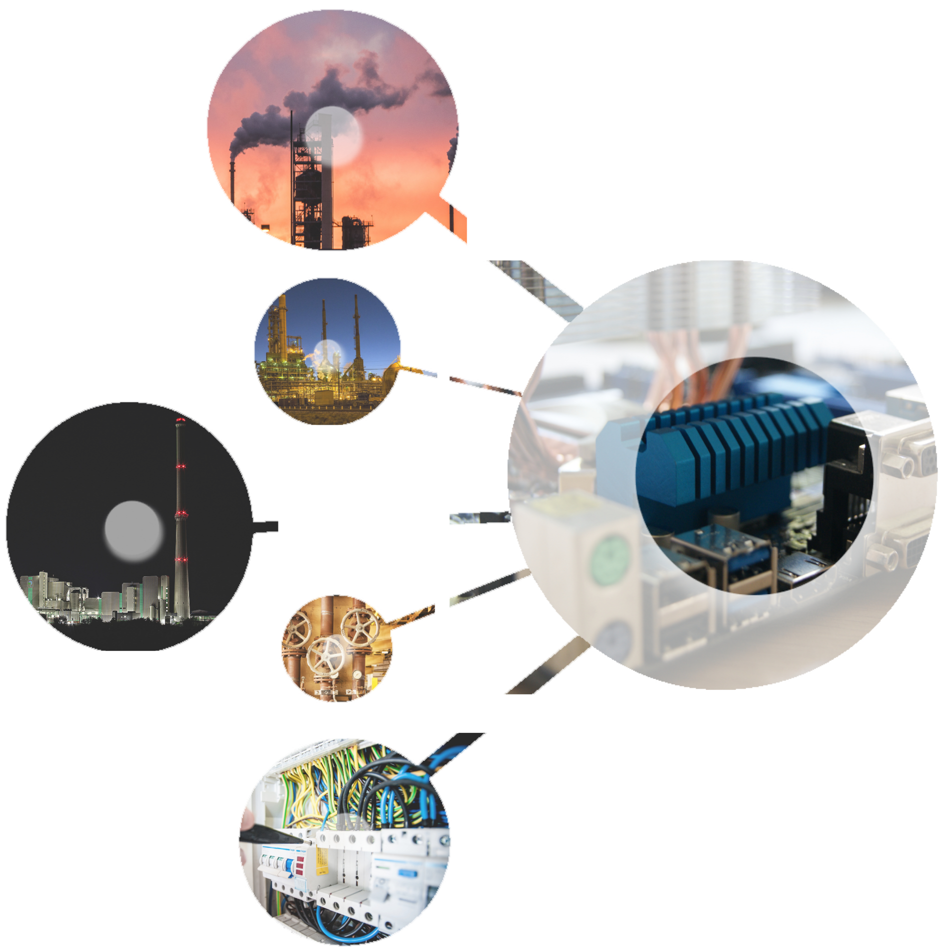
IntelliFlux®

Achieving Water Savings on an Ultrafiltration System Using IntelliFlux

APRICOT, Version 1.0.1

May 2019
Rev 1.0



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Achieving Water Savings on an Ultrafiltration System Using IntelliFlux

APRICOT, Version 1.0.1

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Final Report

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Prepared for Corporate

Abstract: IntelliFlux Controls, Inc. conducted a demonstration of its Augmented Process Recommendation & Industrial Control Optimization Toolbox (APRICOT) on an Ultrafiltration (UF) system located at the Corporate R&D facility of a large Food and Beverage Manufacturer in New York, USA. The demonstration involved retrofitting the Client 's UF system using IntelliFlux. The unit was approximately 15 years old, and had virtually no monitoring or performance reporting features in it's original control system. The six-month study demonstrated the benefits of IntelliFlux, which included its ability to monitor and report performance to multiple stakeholders, respond to influent quality variations and adaptively modulate the operations, provide decision support to operators with respect to optimal times for performing Clean in Place (CIP). Through more efficient filter cleaning, IntelliFlux significantly improved the water consumption profile of the system, yielding over 30% water savings compared to baseline.

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1 Executive Summary

The IntelliFlux® membrane fouling management and adaptive cleaning system was installed on an approximately 72 kilo-gallons/day (kgal/day) rated throughput ultrafiltration plant at Client's R&D facility for a performance demonstration. Although this was an intermittently operated on-demand plant, the project goal was to assess benefits of IntelliFlux based on this system, and rationally project the benefits for other full-scale plants owned and operated by Client. This report summarizes the findings of the demonstration.

1.1 Objectives:

The objectives of the demonstration were to:

- Provide a baseline performance monitoring of the Ultrafiltration system to assess the system performance benchmarks and establish key performance indicators (KPIs) for demonstration.
- Demonstrate the performance benefits of IntelliFlux by separately monitoring the upflow and downflow modes of filtration and cleaning.
- Demonstrate how IntelliFlux autonomously adjusts cleaning frequency and intensity, protecting the membranes from adverse fouling when water quality makes excursions, and saving water by more efficient cleaning at other times.

1.2 Key Observations

During isolated high intensity fouling events, IntelliFlux autonomously increased the frequency and intensity of backwash to prevent extensive membrane fouling and maintain system performance.

During normal operation, IntelliFlux reduced backwash intensity and increased backwash interval leading to the following savings compared to conventional operation.

The most pertinent operational benefits demonstrated were:

- 13% savings in cleaning water owing to more efficient cleaning. The net water savings per unit production time was 31% compared to baseline.
- 1.4% higher net filtrate yield compared to the baseline.
- 21% less net specific energy consumption (SEC) compared to baseline.
- 30% increase in filtration (production) time compared to baseline.

IntelliFlux demonstrated several other benefits, including

- Provide data historian, live dashboards, and regular automatically generated reports with membrane performance, production, and process information updates.
- Continuous remote monitoring including operator alerts on needs for CIP and critical event triggers.

2 Introduction

IntelliFlux Controls offers IntelliFlux Augmented Process Recommendation & Industrial Control Optimization Toolbox (APRICOT) to improve the reliability and lower OpEx of membrane filtration systems. IntelliFlux Controls and Client began discussions to explore the opportunity to install IntelliFlux on Client 's ultrafiltration and microfiltration membrane systems at it's various production facilities in early 2018. In April 2018, IntelliFlux Controls and Client signed a contract to install IntelliFlux at their corporate R&D Production Facility located in New York, USA.

A demonstration of the IntelliFlux membrane fouling management and adaptive cleaning system was conducted on an Ultrafiltration (UF) system at the R&D Center of the Client between September 2018 and April 2019. Through August and September 2018, IntelliFlux Controls and Client 's teams worked together to collect the necessary pre-installation documents including system P&ID, existing PLC program, cleaning protocol description, and any available performance information for the plant. Once IntelliFlux Controls received the pre-installation technical information, it customized the IntelliFlux software for the UF system and prepared for installation.

The UF system at the plant is designed to pre-treat municipal water prior to an RO operation, with the product water from the plant used for various R&D process requirements. The plant design throughput is approximately 70 kGals/day (50 gpm); however, it is operated intermittently on demand. The plant is typically operated during normal working hours of the R&D facility (approximately 12 hours or less per week-day), and is non-operational during the weekends and after-hours. Prior to installation of IntelliFlux, no historical data was collected from the system, and hence, there was no performance benchmark against which the performance of IntelliFlux could be assessed.

The demonstration program consisted of

1. installation of IntelliFlux on the UF system and monitor the baseline performance of the system (based on conventional operation) for multiple weeks;

2. Initiate operation in IntelliFlux mode, while assessing the differences between the upflow and downflow modes of operation of the plant for multiple weeks;

3. Continue operation in IntelliFlux mode to assess the performance of the system over four months.

4. Summarize the performance of the plant before and after the installation of IntelliFlux.

The objective of the report is to provide insight regarding how installation of advanced digital decision support and automation technologies to existing plant infrastructure can provide benefits with respect to sustainable and reliable operation of the plant, better asset management, and improvement in plant performance. This report analyzes the IntelliFlux performance information gathered during the demonstration and compares this against the baseline performance of the UF system. Attention is given to the performance metrics that can be observed instantaneously, daily, and over prolonged usage.

3 Objectives and Key Performance Indicators

3.1 Objectives

The objectives of the demonstration were to:

- Install IntelliFlux and develop the process monitoring capabilities to provide a decision support framework for monitoring the performance of the UF system. Assess baseline performance benchmarks of the UF system for multiple weeks using this system.
- Assess how IntelliFlux optimizes and ensures sustainable membrane operation, including lowering chemical and energy consumption, increasing production, and improving the decision automation framework for the operator, providing better economics of operation (lowering OPEX).
- Demonstrate how IntelliFlux automatically protects the membrane from potential high-intensity fouling events due to sudden changes in influent quality or operating conditions.

3.2 Key Performance Indicators (KPIs)

The key performance indicators agreed during the commissioning of the demonstration were:

- KPI 1: $5 - 20\%$ savings in cleaning water, owing to more efficient cleaning.
- KPI 2: Increase net filtrate yield compared to the baseline by up to 3%.
- KPI 3: Reduction In specific energy consumption (SEC) ranging between $2 - 10\%$.

Analysis of the plant performance was achieved by monitoring the temperature-normalized permeability (normalized to 20 °C), flux, transmembrane pressure, water production, and specific energy consumption (SEC). These parameters were typically aggregated over a fixed time period, *e.g.*, per calendar day, or per week. During a given calendar day, a certain time was spent filtering water (t_{filt}), another part for cleaning (t_{clean}), while the rest was assumed idle time (t_{Idle}). Water production was characterized as the gross water production, *i.e.*, filtrate flow rate, as well as the net water production, which is the net water produced after accounting for the amount of water consumed during membrane cleaning. Specific energy consumption (SEC) denotes the energy consumed during the filtration process (which includes the filtration energy as well as the energy consumption for cleaning) normalized by the volume of net water produced. Energy consumption is calculated as the amount of energy required by the feed pumps during normal filtration as well as the energy consumed by cleaning.

These different KPI metrics were calculated using the following equations:

$$E_{filtration} = \frac{Q_{feed} P_{feed} t_{filt}}{36 \eta_{filt}} \tag{1}$$

$$E_{total} = E_{filtration} + E_{cleaning} \tag{2}$$

$$SEC = \frac{E_{total}}{V_{net}} = \frac{E_{filtration} + E_{cleaning}}{V_{gross} - V_{cleaning}} \tag{3}$$

$$Yield = 100 \frac{V_{net}}{V_{gross}} \tag{4}$$

where $E_{filtration}$ is the energy consumption of the feed pump [kWh], Q_{feed} is the feed flow rate (or the filtrate flow rate when membrane recovery is assumed 100%) [m^3/h], P_{feed} is the feed pressure [bar] (may also be considered as transmembrane pressure, or TMP, specifically for dead end filtration), t_{filt} is the time of operation in filtration mode [hours], η is the pump efficiency (assumed to be 85%), $E_{cleaning}$ is the amount of energy consumed for cleaning (backwash pump and/or air blower) over time t_{clean} [kWh], V_{net} is the net volume produced over time t_{filt} [m^3], V_{gross} is the gross volume of water produced through filtration (total filtrate volume) over time t_{filt} [m^3], $V_{cleaning}$ is the total volume of water consumed by all the cleaning procedures executed over time t_{clean} [m^3], and Net Yield is the percentage ratio of the net amount of water production from the plant to the gross production from filtration [%]. Note that these equations describe the theoretical work and energy consumed by the filtration pumps and not all supplemental energy draws, such as from valves, panels, air compressors, *etc.* The intended use of the SEC is not for full plant accuracy to predict expected energy bills, but as a tool to compare relative changes in energy consumption by the filtration system.

4 UF System Description

4.1 Basic System Description

The Client 's UF system (Figure 1) consists of a single train with six Koch Targa 8 inch diameter hollow fiber modules (TARGA II 8072-35). The system is a U-100 model built by National Water Systems. The approximate surface area of the UF membranes is ∼303 m^2 (50.5 m^2/module). These modules are operated in pressure driven inside-out (PDI) configuration during filtration. The filtration step is operated in dead-end mode.

There is no feed pump upstream of the UF system. The city feed pressure (∼110 psig) is sufficient to provide flow through the filters and UF membrane system (typical feed pressure is ∼10 psig, with permeate pressure at 8 psig). Pressure, flowrate, and turbidity measurements are present on the feed and filtrate streams of the system. The flow rate of the reject stream is measured. Upstream of the UF system, there is a 50 micron self-cleaning filter and a 15 micron cartridge filter. Cleaning and change out of these filters are based on differential pressure.

Transmembrane pressure for normal operation is calculated and displayed on the HMI of the control panel. During filtration operation, the reject flow is directed to a CIP tank (∼500 gal capacity). Table 1 describes the UF system characteristics and details.

The Client 's UF system operates in two modes, "upflow" (from bottom to top) and "downflow" (from top to bottom). The corresponding backwash and fastflush flow directions can also be reversed, whereby the filtration and back pulse cycles are operated in opposing directions. In other words, an upflow filtration is followed by a downflow back pulse, and vice versa.

A review of the process flow diagram and system specifications indicated that the feed flow rate was 80 gpm, whereas the filtrate flow rate of the system was 50 gpm. This gives a flow rate of approximately 30 gpm for the concentrate flow. In other words, the recovery of the system based on these flow rates is approximately 62.5%. This is certainly much lower than what dead end UF systems designed for pre-treating tap water typically are designed for.

Figure 1. The Client R&D facility Ultrafiltration unit on which the IntelliFlux was installed.

4.2 Automation

The system is controlled using an Allen-Bradley MicroLogix (L33) PLC. The software version used to program the PLC is RSX Logix 500 V 20.04. There is no SCADA system nor any data historian that collects any of the output parameters (flow, pressure, *etc.*) or provides any trending analysis. The UF system is mostly operated by starting and stopping the system daily. During regular daytime operation the plant operates in an intermittent manner, controlled by the state of the filtrate tank, the objective of the UF system operation being to keep the tank at a full level.

4.3 Cleaning

The UF system utilizes two modes of cleaning. The first mode is intermittent back flushing, which is executed after every 45 minutes of operation. The back flushing process is triggered automatically, and the process sequence is automated. The second mode is Clean in Place (CIP), which is conducted every six weeks, or based on operator discretion. The CIP process is triggered manually, and is semi-automated. No chemically enhanced backwash or daily maintenance cleans are performed.

4.3.1 Back Flushing

- The overall operation is based on a time sequence only.
- No turbidity or pressure readings are used to engage or stop the back flushing procedure.
- Back flushing is performed after every 45 minutes of filtration operation.
- The back flushing protocol is divided into several steps outlined in Table 2.

The fastflush pump is driven by a 15 HP motor with a rated flowrate of 450 gpm at 52.5 Hz. At the specified fastflush flow rate of 160 gpm, a rough estimation for power requirement is 5.3 HP, or 3.95 kW.

The backwash step does not involve starting a separate pump. The system hydraulics is such that the UF filtrate is continuously drawn from the UF filtrate tank to the RO system through a continuously operating filtrate pump. During back flush, a valve on the filtrate side channels a fraction of this RO feed water into the UF modules.

4.3.2 Clean In Place (CIP)

Cleaning of the membrane system is performed on a 6 week basis, with increased frequency cleans performed based on technician discretion. The system technician will generally look at the status of the pre-filtration equipment (self-cleaning filter, cartridge filter) as well as any microbiological films developing in the CIP tank. If the pressure drop across the pre-filters is too high, leading to insufficient flow through the UF membranes, the technician will trigger a CIP. If a bio film has developed on the interior of the CIP tank, the technician will also trigger a full system CIP. Such triggered effects can typically reduce the CIP frequency to once every 3-4 weeks.

The CIP steps are automated in the PLC. However, the technician needs to manually engage each sequence of the CIP procedure on the HMI. Chemical dosing is performed manually as well. The CIP consists to two sub procedures:

1. Caustic and Chlorine rinse (% w/w determined by Operator based on membrane specifications)
2. Citric Acid rinse (15% w/w)

During each sub procedure, the following steps (Table 3) occur:

Table 1. System specifications.

General Specifications	
Plant Type	Hollow Fiber Membrane Array
Plant Design Throughput (m^3/h)	50 gpm (∼12 m^3/hr).
Plant Actual Throughput (m^3/h)	Variable (System operates intermittently)
Plant daily production target (m^3/day)	272 (72,000 gallons/day) max.
Membrane System Type (HF, Tubular, Flat Sheet)	Hollow Fiber (Targa II 8072-35)
Outside-in or inside-out	Inside-out (PDI)
Number of Racks	1
Number of modules per rack	6
Membrane Material (Polymeric/Ceramic)	Polymeric (PES)
Membrane Area per module	544 sq. ft (50.5 sq. m)
Rated Module Transmembrane Pressure	30 PSI (PROD), 25 PSI (BW)
Is system a submerged system? (Y/N)	N (CARTRIDGE)
Is system in PV housing? (Y/N)	Y (PSf housing)
Crossflow or Dead-end	Dead-end (during filtration)/ crossflow (during fastflush)
Age of plant	∼15 years
Age of membranes since last replacement	$<$ 5 years (Membranes replaced every five years).
Type of Operation	Const. Flow intermittent operation
Daily Average Uptime	approx. 4 hours
Current Yield	N/A
Current Recovery	N/A (Calculated from information provided: ∼62.5%)

Table 2. Steps of the conventional back flushing process for the Client's UF system.

Step	Duration	Description
Back Flush	1.5 min	The back flush step. The normal flow path is reversed in this step. UF filtrate water is pumped from the filtrate to feed side of the HF lumens in the module.
Fast Flush A	1.5 min	The overall array has six membrane elements. During Fast Flush A, the normal operation flow path is used on half of the array (3 elements) at an elevated flow rate (160 gpm). The permeate flow valve is shut (no permeate flow). The feed used for this step is water in the CIP tank (which is reject water from normal operation, no chemicals added).
Fast Flush B	1.5 min	The same procedure from Fast Flush A is executed on the other half of the membrane array.
Rinse	1.5 min	Normal operation feed water (city water) is fed into the system in the normal operation flow path at a lower flowrate than normal operation (∼50 gpm). The permeate flow is opened and directed to the drain. After 1 minute and 30 seconds, the permeate flow is directed to the permeate storage tank, and flow is ramped up to full service.

Table 3. Steps of the CIP process for the Client's UF system.

Step	Duration	Description
CIP tank dump		Any existing water in the CIP tank is manually dumped to drain
CIP tank clean		The CIP tank is manually cleaned using a brush with Oxyfoam
CIP tank fill		The CIP tank is filled with RO permeate water to capacity
Heat	30 min	Water in the CIP tank is heated to 90 °F
Re-circulation	60 min	Chemicals are added to the heated water. The water is brought up to 110 °F and recirculated through the system for 1 hour
Backflush	20 min	UF permeate water is used to flush the system for 20 minutes. 10 minutes for upflow backflush and 10 minutes for downflow back flush
Rinse	20 min	City water is used to flush the system. 10 minutes for upflow back flush and 10 minutes for downflow back flush
Drain		System is drained

5 IntelliFlux Installation Programming & Operational Protocol Development

5.1 IntelliFlux Installation and Performance Assessment

The process flow diagram (PFD), operational logistics and directives, the process and information diagram (P&ID), as well as the PLC control program and input/output (I/O) list were reviewed and analyzed by the technical team of IntelliFlux Controls to ensure that retrofitting the plant with IntelliFlux automation system should provide a measurable performance improvement compared to the baseline operation. These preliminary calculations were used to provide projections of key performance indicators (KPIs) and benchmarks used to assess the performance of IntelliFlux vis-à-vis the conventionally operated plant. Since we did not have access to long-term operational history of the plant, during the first four weeks of operation in a passive (monitoring mode), operational data was collected and used to create the benchmarks.

The IntelliFlux retrofit consisted of installing an Industrial grade edge control device adjacent to the PLC of the UF system. The installation and commissioning were conducted in September 2018, the monitoring mode operation was conducted between September 19, 2018 – August 8, 2018, and the IntelliFlux controlled operation was conducted between August 8, 2018 – April 30, 2019. The IntelliFlux controlled operation was subdivided into two phases of study, namely Phase 1, spanning October 8 - December 31, 2018, and Phase 2, spanning January 1 - April 30, 2019. Phase 1 was divided into two sub-phases, Phase 1a involved a limited deployment of IntelliFlux in learning mode, and Phase 1b involved a deployment of IntelliFlux to independently track and control the upflow and downflow modes of operation. In Phase 2, the upflow and downflow operations were controlled in a synergistic manner by IntelliFlux.

5.2 Optimization Set-points and Ranges

The IntelliFlux control software provides a machine learning and artificial intelligence-guided control philosophy that optimizes membrane maintenance and cleaning in response to influent water quality fluctuations and extent of membrane fouling. The technology deploys the optimal effort necessary to clean the membrane under a set of given operating and environmental conditions. The IntelliFlux hardware includes an edge control device that connects to the existing PLC running a standard operational and cleaning program. The edge control device contains the IntelliFlux client software, which interacts with the PLC and adjusts the cleaning set-points based on the performance data obtained from the system. Data is recorded and stored locally and output to the IntelliFlux cloud server for visualization and analysis via a dual-encrypted VPN tunnel. IntelliFlux only assumes control over select set-points within existing membrane cleaning protocols. These set-points were developed in consultation with the designated engineers and process control personnel from Client , and in doing so, IntelliFlux did not integrate any new programming sequences nor any overwrites of any existing PLC codes, permissives, or fail-safes. IntelliFlux developed the following restricted control zone for the cleaning operations over the following cleaning set-points within associated boundaries (Table 4).

Through control over the IntelliFlux cleaning set-points, a series of pre-defined clean settings was created by the IntelliFlux Controls engineers and made available to the edge control device/software solution through an Ethernet connection to the PLC. Each clean executed by IntelliFlux was given an intensity number representing a cleaning mode, which utilized optimized set-points within the aforementioned bounds. All set-points for a given clean, current and historical, are available from within the interactive IntelliFlux client software.

5.3 Cleaning Recipe Variable List

With instructions from the operator and engineering team of Client , the IntelliFlux cleaning modes were defined in a matrix form. The key parameters adjusted were the times of various steps of the back flush process, and the flow rates of the fastflush process. Table 5 depicts the different IntelliFlux cleaning modes used for the demonstration. The rinse flow rate was maintained fixed at 50 gpm in all cases.

Table 4. IntelliFlux set-point ranges for the Client's UF system.

Variable	Minimum	Maximum	Comments
Upflow Filtration Time, min	30	90	Default = 45 min
Downflow Filtration Time, min	30	90	Default = 45 min
Upflow Backwash duration, min	0.5	2.0	Default = 1.5 min
Upflow Backwash flow rate, gpm	80	80	Default = 80 gpm
Upflow Fastflush A duration, min	0.5	2.0	Default = 1.5 min
Upflow FastFlush A flow rate, gpm	80	240	Default = 160 gpm
Upflow FastFlush B duration, min	0.5	2.0	Default = 1.5 min
Upflow FastFlush B flowrate, gpm	80	240	Default = 160 gpm
Upflow Rinse Flow rate, gpm	50	50	Default = 50 (adjusted using valve)
Upflow Rinse duration, min	0.5	2.0	Default = 1.5 min
Downflow Backwash duration, min	0.5	2.0	Default = 1.5 min
Downflow Backwash flow rate, gpm	80	80	Default = 80 gpm
Downflow Fastflush A duration, min	0.5	2.0	Default = 1.5 min
Downflow FastFlush A flow rate, gpm	80	240	Default = 160 gpm
Downflow FastFlush B duration, min	0.5	2.0	Default = 1.5 min
Downflow FastFlush B flowrate, gpm	80	240	Default = 160 gpm
Downflow Rinse Flow rate, gpm	50	50	Default = 50 (adjusted using valve)
Downflow Rinse duration, min	0.5	2.0	Default = 1.5 min

Table 5. The 9 different cleaning mode settings employed for the IntelliFlux mode of operation.

Row #	Profile Name	BW duration (sec)	FFA=FFB duration (sec)	Rinse duration (sec)	BW Flowrate (gpm)	FFA=FFB flowrate (gpm)
0	FC0	30	30	30	80	80
1	FC1	30	30	30	80	160
2	FC2	60	30	30	80	80
3	FC3	90	30	30	80	160
4	FC4	60	60	30	80	80
5	FC5	60	90	30	80	160
6	FC6	60	60	90	80	80
7	FC7 (default)	90	90	90	80	160
8	FC8	30	90	60	80	240
9	FC9	90	120	90	80	160

6 Installation and Baseline Performance Capture

During the week of September 17th, IntelliFlux Controls performed the on-site installation of IntelliFlux's Edge Control Device (ECD) on Client 's system. The ECD is used to monitor real-time performance, adjust the cleaning protocol to changing fouling conditions, and relay the data to IntelliFlux Controls' remote cloud database. The UF system did not have any historical data logging previously. IntelliFlux began operations in monitoring only mode to create a baseline performance measurement and observe day-to-day operations and up-time. IntelliFlux remained online in this mode from September 24th through October 5th. During this time, IntelliFlux Controls and Client observed for the first time the typical system performance and water consumption of the plant. The teams realized that the system may be oversized for the level of water consumption by the production facility and that the system is in operations approximately 10 - 30% of each day. The surprisingly low daily uptime leads to fewer cleans and less opportunities for IntelliFlux to optimize the cleaning protocol performance.

The total production time during the two weeks of monitoring was 13.8 hours, of which 7 hours was in upflow mode, and 6.8 hours was in downflow mode. A total of 17 default mode (FC7 in Table 5) cleans were conducted during this period (9 upflow cleans and 8 downflow cleans). The average permeability of the system at this stage was 202.47 lmh/bar (upflow: 209.66 lmh/bar; downflow: 195.28lmh/bar). The gross filtrate production per filtration cycle of 45 minutes was 9 m^3 whereas 0.454 m^3 of filtrate was consumed per back flush (total back flush duration was 6 mins). This represents a net production of 8.546 m^3 of filtrate over a 51 (45 + 6) minute duration. The net yield is calculated as 83.8%. The power consumption per back flush was estimated at 3.04 kW, which gave a baseline energy consumption of 0.152 kWh/clean. The baseline specific energy consumption (SEC) was evaluated as 0.017 kWh/m^3 based on gross production. It should be noted that since the operation was not continuous throughout the day, we had to evaluate these numbers based on averages calculated over the net filtration uptime and net cleaning time per calendar day.

7 Operation of the Plant with IntelliFlux

The IntelliFlux mode of operation was started from October 8. During this phase IntelliFlux was deployed in two phases, Phase 1 was primarily devoted to learning the system characteristics, and assessing any difference between the upflow and downflow modes of operation, whereas Phase 2, which started from January 2019, involved combining the upflow and downflow modes into a single process, and utilizing IntelliFlux to optimize and manage the system performance. There were also severe weather conditions, and some intense influent water quality fluctuations encountered in December 2018, January 2019, and March 2019, which proved to be good test conditions to assess the efficacy of IntelliFlux.

The time traces of the three key performance variables, namely, transmembrane pressure, filtrate flux, and membrane permeability are shown in Figure 2 over the entire duration (about six months) of the UF system's operation under IntelliFlux mode of control and operation. The operation was intermittent, with the filtration system only operating durnig daytime work hours, as well as on demand when the filtrate tank was not full. The average flux of 53.36 lmh was maintained throughout the duration. In other words, the filtrate production rate was never affected. The average permeability of the membrane was 161.4 lmh/bar, which was lower than the average clean membrane permeability (attained immediately after a Clean in Place) of about 250 lmh/bar. The transmembrane pressure showed different rates of increase between October - November 2018, December - January, and February - March 2019. The TMP was restored to lower values after a CIP.

In the following, we provide detailed analysis of the system performance during Phase 1 and Phase 2 of the project.

7.1 Phase1

Following the preliminary baseline performance capture phase spanning approximately two weeks, the first phase of the IntelliFlux operation was started. This phase spanned from October 8 through December 31, 2018. During this phase IntelliFlux performed the autonomous cleaning by tracking the filtration and back washing in upflow and downflow modes separately. Figure 3 depicts various cleans performed on the system and their

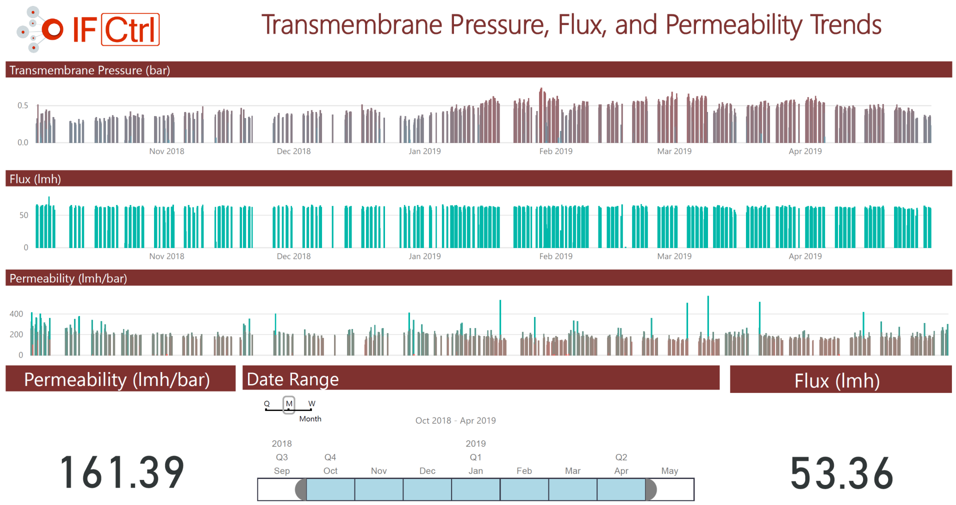

Figure 2. Time traces of the transmembrane pressure, filtrate flux, and membrane permeability during the six months of operation of the UF system under IntelliFlux mode of control. The average permeability and the filtrate flux are also depicted).

intensities in both upflow and downflow modes (refer to Table 5 for clean intensity legends). Broadly, the cleaning intensities of upflow and downflow operation varied following similar trends during the first week of operation. From the second week, the clean intensities for the two modes tend to deviate. This deviation is an indication that the cleaning response for the system is indeed occurring independently based on the knowledge of the permeabilities and permeability loss (fouling) behaviors of the upflow and downflow modes of operation. It is also evident that although there is a slight time lag between upflow and downflow cleaning responses, the trends for both modes are quite similar representing similar patterns of initial decrease during the first week, followed by an increase to the maximum intensity clean over the following two weeks, and then a gradual decrease following November 12.

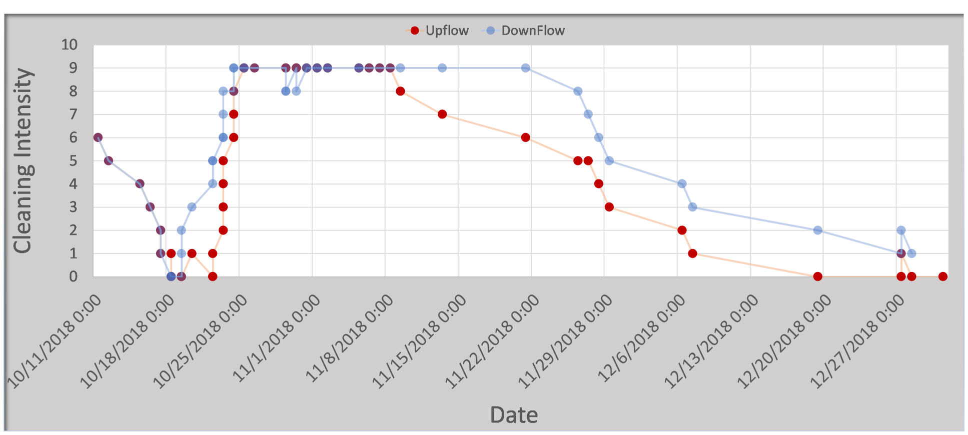

Figure 3. Different intensities of cleans performed in upflow and downflow modes during the Phase 1 of IntelliFlux operation (October – December 2018).

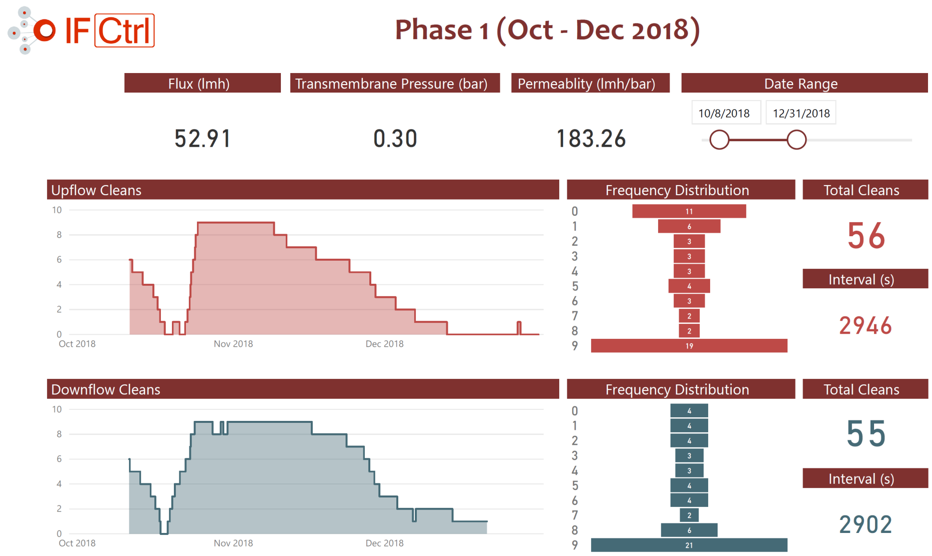

Figure 4. Average flux, transmembrane pressure, permeability, and various aggregated cleaning statistics for phase 1 operation of Client's UF system. The cleaning performance is depicted separately for upflow and downflow cleans.).

Figure 4 shows the aggregated performance of the system during Phase 1. The average flux and permeability during this period remained above 50 lmh and 180 lmh/bar despite continuously decreasing temperature during the three-month period. The total number of cleans performed during this operation phase was 111, with 56 cleans in upflow mode and 55 cleans in downflow mode. The time interval between consecutive cleans (production time) was also comparable for upflow and downflow modes of operation (2946 and 2902 seconds, respectively) giving an average production time of 48.7 minutes. A slight difference in the frequency distribution of clean levels is observed between the upflow and downflow modes. In both cases, the most frequently called clean type is FC9, which is the most intense clean setting in the cleaning matrix (see Table 5). In case of upflow, the next frequent cleaning is FC0 (the lowest intensity cleans, whereas for downflow, it was FC8. Typically, when a cleaning frequency distribution is weighted toward the extremities, there is a possibility that the cleaning matrix does not cover an optimal cleaning range.

Phase 1 was subdivided into Phase 1a (October 8 – November 12), where the system was initially exploring the cleaning regimens and optimal response phase space through its machine learning algorithms, followed by Phase 1b (November 12 – December 31), where the system was allowed to autonomously respond to changes in feed water quality and other operating condition variations. In the following, we analyze the fouling and cleaning behavior for the filtration system more closely in each of these sub-phases.

7.1.1 Phase 1a: Oct 8 – Nov 12, 2018

IntelliFlux optimized operation of the system was initiated from October 8th, and during the first phase of operation in this mode, collected information about the upflow and downflow modes of filtration and cleaning separately through December 31, 2018. During this period, daily production information was sent through an automatically generated report to Client . Weekly information exchange occurred between Client and IntelliFlux teams to review operations data and assess system performance trends. IntelliFlux Controls also provided Client access to its Online Remote Dashboard application, which displays real-time and historized system operations data (pressures, flows, total production volume, recovery %, etc.) and IntelliFlux specific variables (cleaning intensity, cleaning effectiveness, and dynamic time between cleans).

The IntelliFlux software was initially programmed to operate conservatively, as there is always a relative risk of unknown performance changes on a system with very little historical information. Both IntelliFlux Controls and Client did not have historical data to compare or project expected and accepted rates of fouling for the membranes. All membrane systems have different normal or accepted rates of fouling dependent on the system design, influent quality, cleaning protocol, and manual fouling intervention protocols. IntelliFlux Controls has observed systems with the same design, influent water quality, and membranes exhibiting different fouling propensity for different racks located right next to each other. Therefore, significant importance is attributed to historical information and expected fouling behavior when installing IntelliFlux on a brownfield (retrofit) application. As such information was not available, and since the operation of the plant was intermittent, the tuning of the machine learning and AI were set at conservative levels, and we decided to apply conservative ranges for the autonomous performance adjustment.

During IntelliFlux's first performance run (October 8 – November 12), IntelliFlux was programmed with a relatively high target of permeability ($>$ 200 lmh/bar), which leads to an increase in higher intensity cleans and a lower backwash interval. This is IntelliFlux's response when it observes higher fouling rates on a system. In ideal conditions, IntelliFlux would only use higher intensity cleans during periods of fouling upsets when the influent water quality makes excursions beyond the expected water quality design specifications. IntelliFlux typically deploys lower intensity cleans during normal influent water quality operations. This higher intensity cleaning was very effective at maintaining low fouling and higher permeability of the membranes. Client informed IntelliFlux Controls that the membrane system is normally shut down and a manual CIP is performed every 6 weeks. On account of the more intense cleaning schedule, IntelliFlux Controls was able to extend the time between CIPs to at least 8-weeks without noticeable degradation in system performance. It is very likely that IntelliFlux could be optimized to maintain high permeability and continue to expand the time window between necessary manual CIP interventions.

We will compare IntelliFlux operations against the pre-existing static cleaning protocol set-points in baseline operation mode to describe IntelliFlux's water savings benefits. Before IntelliFlux was installed, the UF system performed a multi-step 6-minute back-flush after every 45 mins of production (shown as FC7 in Table 5). Each baseline back-flush process consumed a total (gross) 675 gallons of water (based on flow rate and timing calculations), of which 120 gallons was accounted for as filtrate consumption, and the remaining (net) 555 gallons is municipal water disposed to drain. It is instructive to note that the cleaning matrix in Table 5 spans a gross water consumption range from 145 gals (FC0) to 835 gals (FC9). Table 6 depicts the percent differences in gross and net theoretical water consumption against the baseline (FC7) for different levels of clean intensity. It is clearly discernible that significant water savings can be obtained from the system if the cleaning intensity could be lowered from baseline. For instance, if for a given duration, the average cleaning intensity is FC4, the gross water consumption in cleaning will be ~60% lower than that of the baseline clean, while the net water consumption will be 67% lower than the baseline. This provides a basis for optimizing the cleaning water consumption while maintaining the productivity of the system as high as possible. This is even more significant when we consider the intermittent mode of operation of the system, as the production of water during filtration is quite limited, thereby magnifying the water consumption during cleaning, thereby artificially lowering the system yield.

Table 6. Gross and net percent variation of cleaning water consumption for different clean levels compared to baseline (FC7) water consumption. The gross baseline water consumption is 675 gallons, whereas the net baseline water consumption is 555 gallons. Negative values indicate savings in water over baseline, while positive values indicate higher consumption than baseline.

	FC0	FC1	FC2	FC3	FC4	FC5	FC6	FC7	FC8	FC9
Gross	-78.5	-66.7	-72.6	-54.8	-60.7	-13.3	-53.3	0	+20	+23.7
Net	-81.0	-66.7	-81.0	-66.7	-66.7	-9.0	-57.6	0	+38.7	+28.8

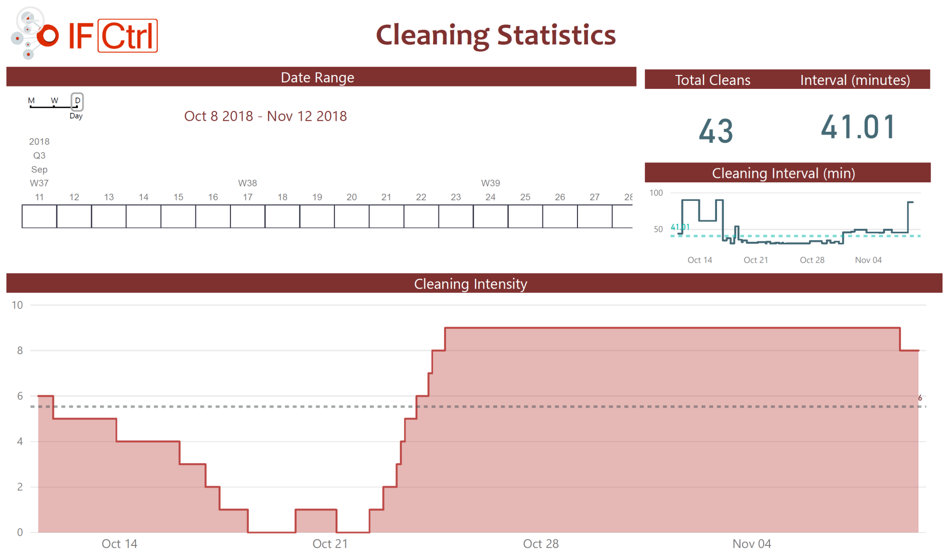

Figure 5. Cleaning statistics for the duration of October 8 – November 12, 2018 (Upflow only).

Figure 5 depicts the cleaning statistics of the upflow mode operation spanning the date range from October 8 – November 12. A total of 43 cleans were conducted in the upflow mode, with an average interval of 41 minutes between consecutive cleans. The downflow mode had very similar performances during this phase, and all aggregated results for downflow are identical to the upflow case presented here. The cleaning process was initialized at level FC7 (baseline), and then the optimization procedure began by systematically varying the clean levels and assessing it's efficacy in maintaining a high membrane permeability. As this optimization was being performed with live water, IntelliFlux was also able to adapt the cleaning level to respond to any sudden excursions in influent water quality or other operating conditions (Note the upward spike in Cleaning Intensity on Oct 20).

A clear "apple-to-apple comparison" of IntelliFlux mode optimal cleaning with the baseline cleaning cannot be easily conducted as IntelliFlux dynamically changes the cleaning intensity as well as the interval between cleans. Coupled with intermittent daily operation, it becomes difficult to establish a consistent basis for comparison. Hence, we have used an approach where we computed the gross and net effective water usage averaged over the 43 cleans. This effective water usage is compared against the baseline water use for each clean of type FC7. Table 7 depicts the clean types with their respective water usage.

When IntelliFlux was in operation, even though its target for permeability was high (average permeability was 187.7 lmh/bar), it was able to save 19% of gross cleaning water (and approximately 18% net cleaning water) con-

Table 7. Total number of IntelliFlux cleans performed between Oct 8 and Nov 12, with average water consumption and approximate percent savings over baseline.

Clean Type	Count	Gross Water per Clean (gal)	Gross Cleaning Water (gal)	Net Water per Clean (gal)	Net Cleaning Water (gal)
FC0	7	145	1015	105	735
FC1	4	225	900	185	740
FC2	2	185	370	105	210
FC3	2	305	610	185	370
FC4	2	265	530	185	370
FC5	2	585	1170	505	1010
FC6	2	315	630	235	470
FC7	1	675	675	555	555
FC8	2	810	1620	770	1540
FC9	19	835	15865	715	13585
TOTAL	**43**		**23385**		**19585**
Averages					
Avg. Water per clean (gal)			543.84		455.47
Avg. Cleaning Water Relative to Baseline (%)			81%		82%
Avg. Reduction in Cleaning Water (%)			19%		18%

sumed by the system over baseline operation. On average, IntelliFlux performed a slightly less intense clean on the matrix but more frequently (after every 41 minutes of production in IntelliFlux mode vs. after every 45 mins of production in baseline mode). Another metric to assess the performance of the system is to evaluate the net waste volume generated (Average water per clean in gallons) over the effective filtration or production cycle (minutes). This quantity, in gallons per minute, reflects the savings in waste disposal per unit production time. For the period of operation covered in this section, the gross and net waste savings expressed as waste volume per unit production time was estimated as 11.6% and 9.5% compared to the baseline, respectively.

7.1.2 Phase 1b: Nov 12 – Dec 31, 2018

After reviewing the initial performance period with the Client 's team, IntelliFlux suggested implementing a slightly lower permeability target throughout the next performance period. The IntelliFlux Controls team monitored and ensured that there are no negative side effects or outcomes of allowing a lower permeability on the system and expect that gradually lowering the permeability between CIPs would be normally present in historical trends throughout the system's past if historical data were available.

IntelliFlux began a second period of production after Client operations team decided to perform a CIP on the membrane system on November 12. This second production period spanned data from November 12 through December 31th. Table 8 summarizes the aggregated performance during this time. IntelliFlux used lower intensity cleans and expanded the time between backwashes on account of the lower set-point target for permeability recovery from IntelliFlux cleans. This resulted in much more dramatic water savings and reduction of waste disposal volume while also expanding the time between backwash cleans. IntelliFlux demonstrated savings of 38% disposal volume versus the previous static baseline cleaning protocol. IntelliFlux was able to positively use a longer production time between cleans (59.0 minutes on average vs. 45 minutes) and on average, a relatively lower intensity clean compared to the baseline (5.7 vs. 7).

Table 8. Key performance indicators for the Phase 1b operation with slightly reduced permeability.

Second Production Period November 12 – December 31			
	Actual	Baseline	
Filtration (Production) time (mins)	59.0	45.0	31% more
Avg. Relative IntelliFlux Intensity	5.7	7	
Avg. Net Cleaning Wastewater (gal)	455	555	
Avg. Waste Vol / Production time	7.7	12.33	38% less

Between October to December 2018, the production demand lowered owing to holidays, and non-operation of the plant. The plant was shut down for longer duration during Thanksgiving and Christmas holidays. This intermittent mode of operation with large gaps probably affected the KPI benchmarks, but overall, it is evident that the fundamental premise of adaptive flux maintenance and membrane cleaning works quite well even for a plant with a much lower net uptime and operating demand.

7.2 Phase 2 (January – April 2019)

During the phase 1 study, the IntelliFlux Controls team decided to merge the databases pertaining to the upflow and downflow modes of operation, and determine the performance statistics in an aggregated manner. The rationale for this were twofold: First, contrary to our starting hypothesis, the upflow and downflow mode of operation did not result in dramatic differences in membrane permeability, or cleaning efficacy. They closely mirrored each other. Second, managing the database in a consolidated manner could allow obtaining better statistics for the operating and cleaning data. This was more beneficial for the machine learning algorithms, and more appropriate tuning of the system. The second approach was deemed more important because of the intermittent mode of operation, and the low daily run-time of the plant. This change was suggested to Client , and after the two technical teams agreed, the programming modifications were made and implemented in December 2018.

Starting January 2019, the UF system performance and cleaning was reported and analyzed in a consolidated manner. While upflow and downflow information can still be extracted, we chose to represent all our data in a unified manner. Figure 6 depicts the filtration and cleaning statistics for the first four months of operation in 2019 (January – April 2019). Compared to phase 1, although the filtration flux is comparable at ∼53 lmh during phase 2, the average permeability of the membrane was approximately 30 lmh/bar lower during this period, which implies that the average TMP was higher than phase 1. The total number of cleans during this phase was 302, with the highest intensity cleans (FC9) being deployed the 90 times. The average cleaning interval was 3524 seconds (∼58 minutes).

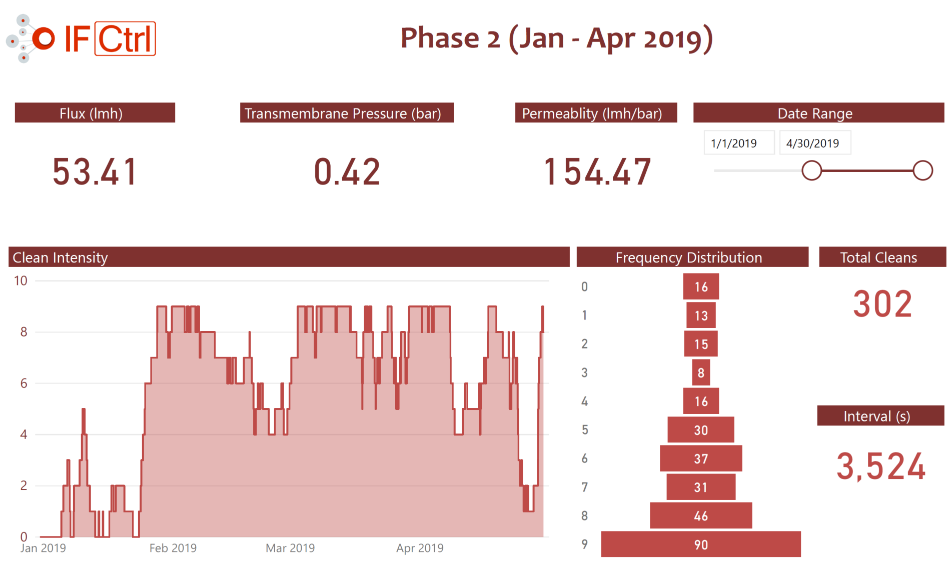

Figure 6. Average filtration performance and membrane cleaning statistics for the phase 2 operation (January - April 2019).

Table 9 shows the water consumption of the cleans during this period. The gross and net average water savings per clean during this phase was 13% and 10% of the corresponding per clean baseline water use, respectively.

Table 9. Gross and net average water consumption per clean during phase 2.

Clean Type	Count	Gross Water per Clean (gal)	Gross Cleaning Water (gal)	Net Water per Clean (gal)	Net Cleaning Water (gal)
FC0	16	145	2320	105	1680
FC1	13	225	2925	185	2405
FC2	15	185	2775	105	1575
FC3	8	305	2440	185	1480
FC4	16	265	4240	185	2960
FC5	30	585	17550	505	15150
FC6	37	315	11655	235	8695
FC7	31	675	20925	555	17205
FC8	46	810	37260	770	35420
FC9	90	835	75150	715	64350
TOTAL	**302**		**177240**		**150920**
Averages					
Avg. Water per clean (gal)			586.89		499.74
Avg. Cleaning Water Relative to Baseline (%)			87%		90%
Avg. Reduction in Cleaning Water (%)			13%		10%

The average interval between cleans (or production time) is however, significantly higher than the baseline. At ∼58 minutes, it is 30% higher than the baseline cleaning interval of 45 minutes. This implies that the production time is increased by 30%, generating a higher filtrate volume between cleans. The net average water consumption per unit production time is estimated at 8.5 gallons/minute. This KPI is 31% lower than the baseline measurement of 12.33 gallons/minute.

7.3 Cleaning Effectiveness and Permeability Recovery Trends

Figure 7 depicts the cleaning efficacy during Phase 2. The results are shown for the entire date range of Phase 2 (January – April). The main panel on the left shows the cleaning intensity distribution. A clean is triggered when the membrane permeability drops to a low value, and each clean restores the permeability to a higher value if it is effective. The direct cleaning efficacy plot in Figure 7 (top right) shows the permeability after clean against the before clean permeability corresponding to every clean. This type of scatter plot can easily show how effective a clean is. If the point is located in the yellow region of the graph, the clean was able to restore the permeability to a higher value compared to the before clean permeability, and was effective. In contrast, if a clean is in the blue region, it is ineffective in increasing the permeability of the membrane.

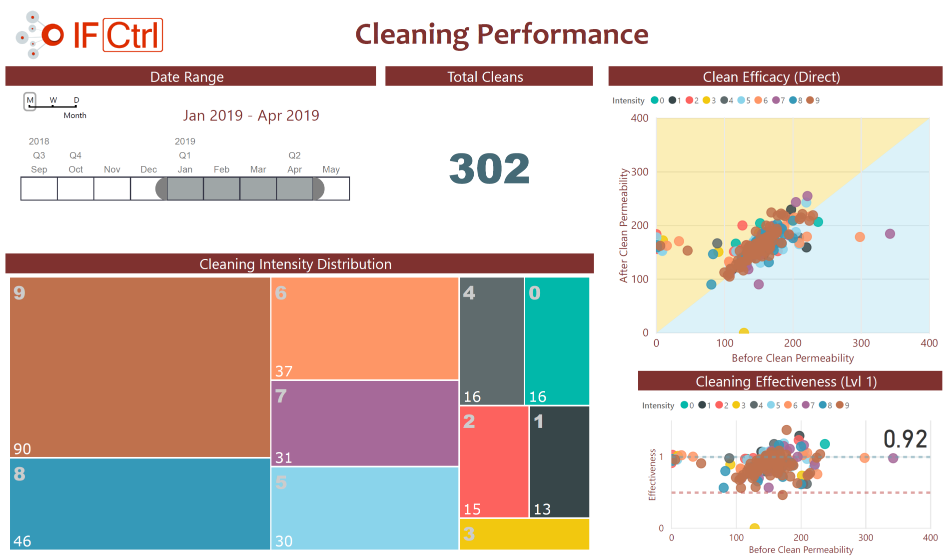

Figure 7. Distribution of different cleaning intensities and their efficacy during the phase 2 operation (January - April 2019).

If the points in the graph are clustered near the diagonal intersecting the blue and yellow regions, it implies that the cleaning is not highly effective in improving the permeability. This can happen under many circumstances, but one obvious situation is when the membrane is already clean, and it is cleaned frequently. We can observe this is the situation in Figure 7, as the cleaning efficacy is more frequently in the blue zone on the right side of the graph (when before clean permeability is high) as opposed to the left side of the graph (when before clean permeability is low), where the points are mostly on the yellow zone. Thus, the cleans are indeed effective when the membrane becomes dirty. Furthermore, all clean types FC0 to FC9 seem to have similar clustered presence on the graph with no clear domain where any one of them work best. This can also signify that the parametric phase space over which the cleaning matrix has been defined is too constrained, and does not provide any significant room to improve the performance. It further shows that the default cleaning level and cleaning interval is set at very high and conservative levels, and the membrane can probably be maintained at an optimal operating state with less frequent and less intense cleans.

We also depict in Figure 7 the IntelliFlux internal measures of the clean effectiveness (Cleaning Effectiveness, Lvl 1), sown on the bottom right panel, which is a slightly different measure of the cleaning efficacy. If this metric is between 0.5 to 1, the implication is that the clean is reasonably effective in restoring the permeability. A value of 1 or above in this scale implies that the clean is effective in completely slowing down any irreversible fouling. The average effectiveness of the cleans was 0.93, which implies that the cleaning was effective in maintaining the irreversible permeability decline to less than 8% over the four month duration.

7.4 Daily Average Production Statistics

Figure 8 shows the daily averages of various operating conditions and filtration system performance parameters for the period of January through April 2019. The feed turbidity and temperature are the two key measured external variables that cause variations of the operating and cleaning envelope. The average feed turbidity during this period was 0.79 NTU. The feed turbidity shows intermittent excursions to values above 1 NTU. This occurred on some days in January, and then somewhat more recurrently in March and April. The average daily temperature varied within a narrow range, with an average value of 63 °F. The transmembrane pressure increased in January and March quite rapidly, which seems to correlate with the increase in turbidity observed during these periods. The average TMP during this period was 5.7 psi. Following a CIP in early February, the TMP remained nearly constant in February through early March. The TMP showed a somewhat rapid increase during the last half of March. Following another CIP, the TMP seemed to be lower during the month of April. Overall, during the four months of operation, the daily average TMP increased from January through March, but have eventually decreased to the levels the TMP were in January by the end of April. The corresponding variations in the membrane permeability are also shown in Figure 8. The average permeability was 5.78 gfd/psi (144 lmh/bar) during this period, with an upward trend between January (average permeability of 5.09 gfd/psi) through April (average permeability of 6.44 gfd/psi).

The production time of the system was ramped up from approximately 2.92 hours per day to 4.18 hours per day between January through April. Although the daily number of cleans (as well as the average cleaning intensity) were higher in March and April, the overall higher production volume, and

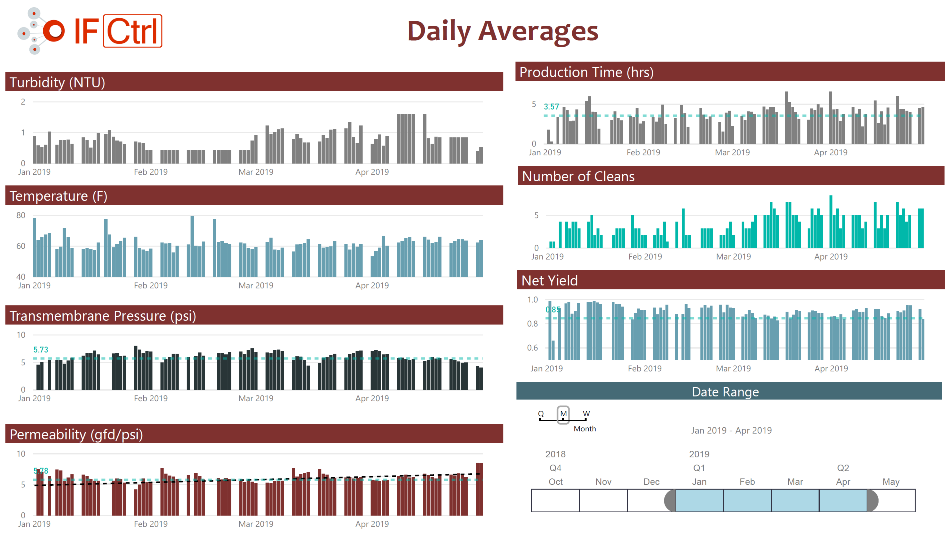

Figure 8. Daily averages of key operating conditions and filtration performance parametersduring the phase 2 operation (January - April 2019).

the higher production time led to an increase in average net Yield of the system. The average net yield of the system was 85% during this period.

In summary, IntelliFlux provides a cleaning regimen that responds to the variations in the influent water turbidity changes, and adapts the membrane cleaning to minimize irreversible permeability loss of the membrane.

7.5 Energy Consumption

We could not perform an exact monitoring of the energy consumption of the system. The following analysis is based on purely theoretical considerations, and should only be used as a relative energy consumption estimator for different types of cleans. This should in no way be construed as an actual energy consumption of the system.

To estimate the total energy consumption, we need to consider the filtration energy and the cleaning energy consumption. Since the system is driven purely by the municipal supply pressure (∼120 psi), we assume that there is no requirement of a feed pump or any additional energy to pressurize the feed flow through the UF membranes and the hollow fibers. This implies that in our calculations for the filtration energy, we can assume no energy cost during the filtration run.

For the cleaning process, the only step that uses a pump is the fastflush step during a back flush. The other two steps (back flush and rinse) use available heads to drive the flow. The fastflush pump is rated at 15 hp or 11.185 kW (driven at 52.5 Hz frequency to achieve a flow rate of 450 gpm). For lack of a better estimate, we related the flow rate and power to the frequency and approximated the power consumption for each of the clean settings through interpolation as shown in Table 10. The Energy per clean is an estimate of the energy consumption for each clean. The column titled “fraction” denotes the energy consumption of each of the clean levels compared to the baseline clean. The table shows the total number of cleans performed between January to April 2019, and the estimated total cleaning energy consumed in kWh. The average energy per clean turns out to be 0.16 kWh, which is about 4% higher than the baseline cleans.

Table 10. Cleaning energy calculations during phase 2.

Clean Type	Count	Fast Flush Flow Rate	Duration (min)	Power (kW)	Energy per Clean (kWh)	Fraction	Clean Energy (kWh)
FC0	16	80	1	1.208	0.02013	0.13	0.32
FC1	13	160	1	3.038	0.05063	0.33	0.66
FC2	15	80	1	1.208	0.02013	0.13	0.30
FC3	8	160	1	3.038	0.05063	0.33	0.41
FC4	16	80	2	1.208	0.04027	0.27	0.64
FC5	30	160	3	3.038	0.15190	1.00	4.56
FC6	37	80	2	1.208	0.04027	0.27	1.49
FC7	31	160	3	3.038	0.15190	1.00	4.71
FC8	46	240	3	7.044	0.35220	2.32	16.20
FC9	90	160	4	3.038	0.20253	1.33	18.23
TOTA	**302**						**47.52**

Although the average cleaning energy is about 4% greater than the baseline clean intensity, it should be noted that IntelliFlux performs these cleans after a greater average interval (58 minutes) compared to the baseline interval of 45 minutes. In other words, the total filtrate production volume in the IntelliFlux mode will be approximately 11.6 m^3, whereas for the baseline mode it will be approximately 9 m^3. In other words, based on the gross water production, the specific energy consumption (SEC) in the IntelliFlux mode will be 0.0135 kWh/m^3, whereas for the baseline mode, the SEC is 0.0169 kWh/m^3. This represents an approximately 19.6% reduction in specific energy consumption during Phase 2 operation compared to the baseline SEC. As IntelliFlux uses less cleaning water for back flushing (87.5 gals instead of 120 gals), it is evident that the SEC savings will be even higher if the basis was net water production as opposed to gross water production (approximately 21.5% savings).

8 Summary of Performance

The data acquisition and performance measurement of the UF system was the first attempt over its lifetime to assess and track its performance. There was no prior performance benchmark; therefore, the information collected over the past six months provide the only glimpse to how the system is operating. The first two weeks of operation in the "listen only" mode allowed us to assess the baseline operation with respect to how much water and energy is consumed by the plant utilizing baseline cleans. It also allowed us to note that the system operated only for a couple of hours per day, and in an intermittent mode. The Phase 1 study was performed to optimize the IntelliFlux mode of operation, and assess the performance in the upflow and downflow modes. After this phase, we obtained initial performance benchmarks pertaining to the upflow and downflow modes of filtration and cleaning. It was apparent that the two modes of filtration and cleaning had virtually identical performance. Hence, it was decided to consolidate the two modes in our subsequent analysis, which led to the Phase 2 study between January through April 2019.

The key performance indicators for the Phase 2 operation of the UF plant are summarized below.

8.1 Filtrate Yield

An aggregated average increase in yield (85.1%) by 1.4% over baseline yield (83.7%). In March and April, the average yield was higher by 5% and 6% over baseline, respectively.

8.2 Production time

The average production (filtration) time between two consecutive cleans ($\sim$58 minutes) was higher by 28.8% over baseline (45 minutes).

8.3 Cleaning Water Consumption

Gross and net aggregated average cleaning water savings of 13% and 10% compared to baseline, respectively.

The net average water consumption per unit production time was 31% lower than the baseline.

8.4 Energy Consumption

The average cleaning energy was 4% higher than baseline. However, the gross specific energy consumption (SEC) was 19.6% lower than the baseline, whereas the net SEC was 21% lower.

8.5 Membrane Permeability

The average monthly membrane permeability increased from 5.09 gfd/psi in January 2019 to 6.44 gfd/psi in April 2019, reflecting approximately 24% increase over the four months. Although the permeability dropped sharply in January, and again in March due to water turbidity excursions, the membrane permeability could be restored using CIP. The average CIP interval during the demonstration was 6 weeks.

8.6 Cleaning Efficacy

The average cleaning effectiveness results demonstrate that the rate of decline in physically irrecoverable permeability is approximately 8% during the four months.

8.7 Monitoring and Reporting

IntelliFlux provides an automated online dashboard for live monitoring of the results, and automatically generates daily reports for key plant stakeholders. Figure 9 depicts the dashboard and the sample report page.

IntelliFlux also provides a responsive, customizable, and extensive analytical toolkit to analyze and display historical performance data. The figures in this report are provided from the toolkit. The data can be represented as time series plots, various averages, and correlations. The report pages can be customized to provide appropriate performance metrics. For instance, Figure 10 shows how a calendar representation can be made showing the daily variations of several parameters (for instance, Temperature in °F and permeability, in gfd/psi) over a month. The color scale provides a simple visual representation of the range and variations of these parameters. The average represents the monthly average for each parameter. Each parameter in the check box can be highlighted individually to provide it's monthly variations,

Figure 9. Sample screenshots of the dashboard and the daily report.

providing the user a quick visual feedback regarding the performance trends of the UF system. Such dynamic dashboards can allow experts to visually identify correlations between different variables over different time ranges.

Another example of such dynamic dashboards is depicted in Figure 11 where the cleaning effectiveness of each type of clean deployed over a given month can be individually highlighted. It is interesting to note that in March the clean intensity range deployed varied from FC5 to FC9. Clean intensities 0 through 4 were not deployed at all during March 2019. In the Figure, the statistics related to two clean types, namely, FC7 and FC9 are highlighted, for the month of March. During this month, the clean type 7 was deployed only 14 times as opposed to clean type 9, which was deployed 38 times. The average effectiveness fo clean type 7 was 0.95, whereas it was less effective for clean type 9 (effectiveness = 0.86). Combining the observation that the cleaning was deployed using higher level settings in the cleaning matrix, and the modest effectiveness of these cleans, it is discernible that in March, the water quality was frequently off-specification, and that the membrane fouling was more aggressive. This is corroborated by the observation of the feed turbidity (NTU) in March 2019 (see Figure 12, where on most days, the average turbidity was more than two times higher than the design turbidity of 0.5 NTU (common in conventional tap water). The monthly average turbidity was 0.96.

It should be noted that the performance of IntelliFlux manifested in this demonstration with the discrete cleaning matrix, limited range of set-points, and inability to optimize the sustainable flux, represent some of the limitations imposed during installation of this software in retrofit plants. Furthermore, during this demonstration phase, the operation of IntelliFlux was

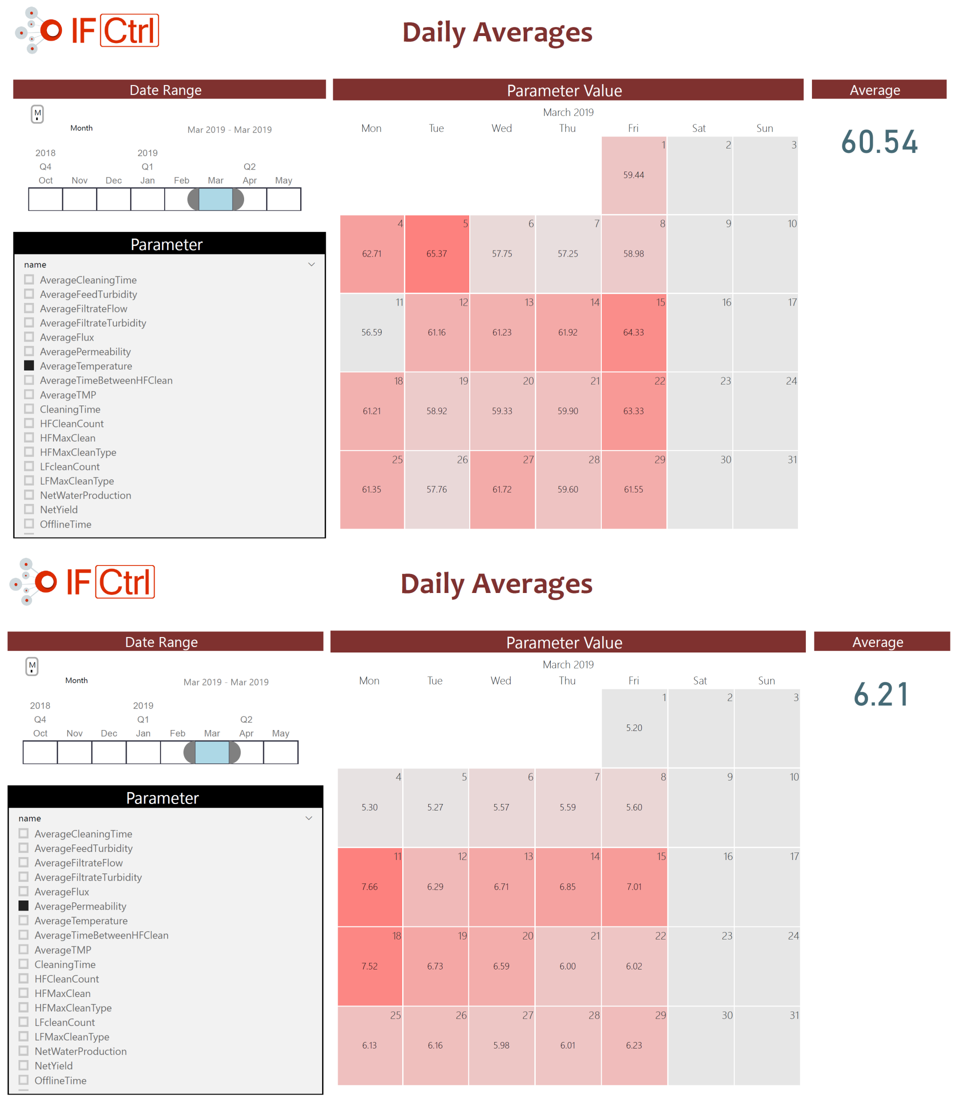

Figure 10. Sample screenshots of the graphical report showing the calendar tool with daily variations of temperature (top) and permeability (bottom) during March 2019. The temperature in is °F and the permeability is in gfd/psi.

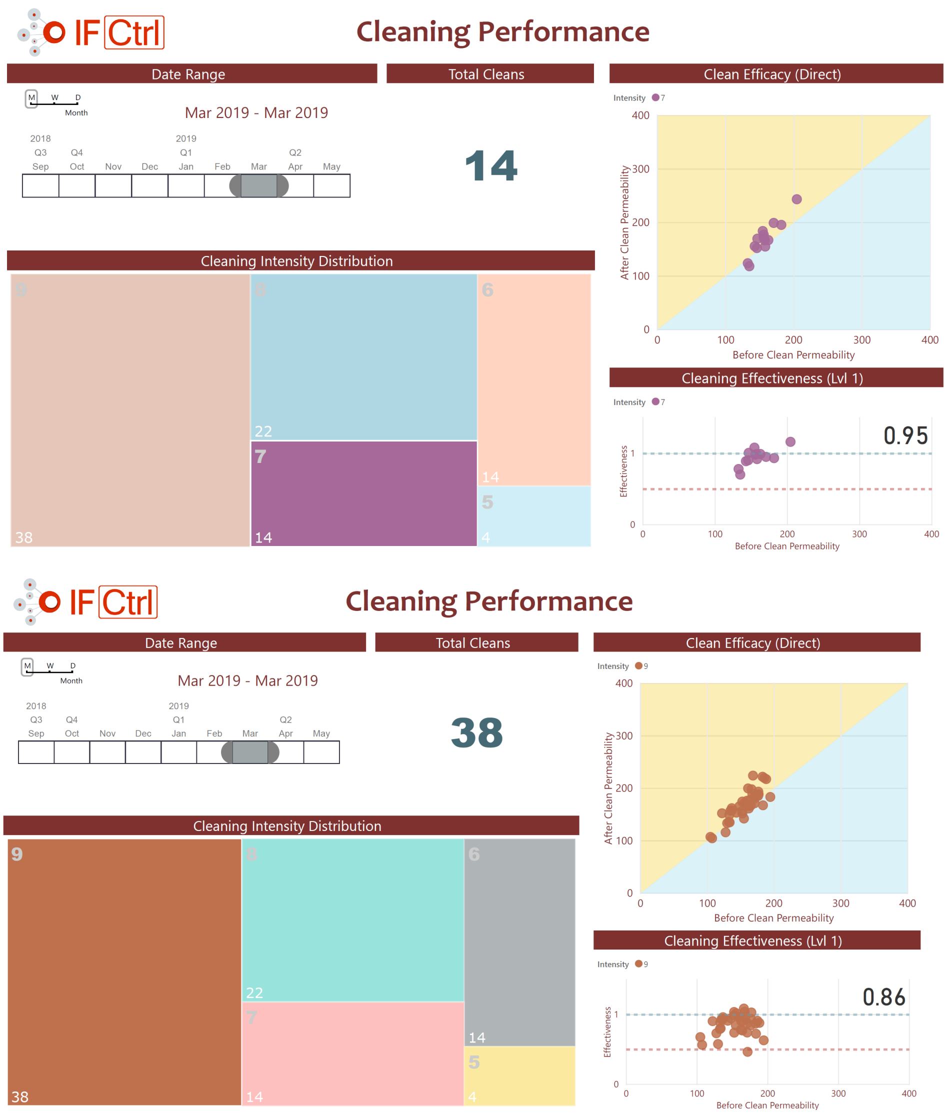

Figure 11. Sample screenshots of the graphical report showing the cleaning effectiveness analysis tool for clean type FC7 (top) and FC9 (bottom) during March 2019. The temperature in is °F and the permeability is in gfd/psi.

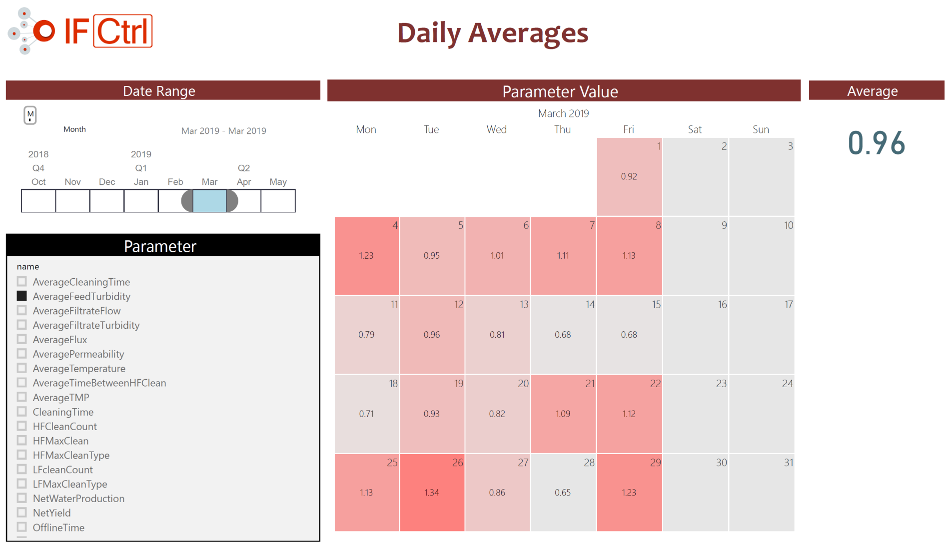

Figure 12. The daily average turbidity (NTU) encountered by the UF system during March 2019.

interrupted on multiple occasions owing to operator intervention, equipment (such as sensors or pump) failure, communication errors, manual shutdowns, and feed-water quality excursions. In many situations, IntelliFlux was able to warn the operators of equipment malfunctions. These are all standard challenges of IntelliFlux installation in retrofit scenarios with already specified hardware and existing operating procedures. Such hardware restrictions lead to different extents of performance enhancement in retrofit plants after installation of IntelliFlux. Notwithstanding these restrictions, our ability to adapt IntelliFlux to these variations makes IntelliFlux different from competition, and uniquely positioned to serve the retrofit plant upgrade markets. This is why, in retrofit installations we do not *a priori* claim fixed economic benefits of IntelliFlux, and propose to our customers to install the software on their plant and assess the value propositions before making a long-term purchase commitment. Clearly, the flexibility of IntelliFlux is much higher when it can be implemented during the design and integration of a new plant.

9 Concluding Remarks

The six-month operation of the UF plant with IntelliFlux demonstrated that optimization and performance improvement of an existing UF plant can be achieved through a simple automation retrofit, whereby an artificial intelligence (AI) and machine learning (ML) based software program can be added to the existing PLC and SCADA automation framework. Based on flow, pressure, temperature, and turbidity measurements, this software from IntelliFlux was able to perform automatic adjustments to the operation and cleaning regimens of the UF system to ensure sustainable performance.

Minor modifications to the cleaning cycle set-points and operating ranges were implemented, leading to quite significant improvement in the operation. Notably, the interval between consecutive cleans was significantly increased (~30%). The system also used less intense cleans when the water quality was conducive to such lower intensity cleans, thereby saving water and energy on the average. The system, however, responded with higher intensity cleans whenever the influent water turbidity or other operating conditions led to an enhanced rate of membrane fouling. The net effect of this intelligent mode of operation was savings in cleaning water, energy, and increased rate of production or higher capacity utilization. The operation at the plant also did not require constant operator or expert intervention, which is mandatory in a water treatment plant optimization.

The installation at the plant is operational intermittently only during a few hours every week day (shut down during most weekends). For such a small-scale plant, and with a mere three to five hours of daily production time, the capacity utilization and production volumes are too little to warrant a detailed economic benefits calculation. However, the results from this plant can be utilized to develop economic models for estimating the economic and sustainability benefits of installing IntelliFlux on other larger plants owned by Client .

The easy adaptability and scalability of IntelliFlux with respect to installation in brownfield plants lends itself to rapid deployment in multiple plants, and integration of the information from all these plants into a centralized asset management and enterprise resource planning (ERP) framework. Such a framework can not only manage each asset intelligently, it can also provide learning tools and comparative analytics to manage performance of multiple assets, allowing a centralized platform to monitor plants in multiple locations.

IntelliFlux can not only manage operation of UF systems, but it can implement the technology to assist automated operation and digitalization of multiple water treatment technologies, such as RO, media filters, ion exchangers, biological treatment, etc. In this respect, IntelliFlux could provide a comprehensive decision automation framework to Client for management of its water treatment assets.

Appendix A: About IntelliFlux

A.1 Overview of the Product Offering

IntelliFlux is an expert system for process control, helping operators of process and water treatment plants to lower OpEx, and improve plant efficiency through intelligent decision-making. IntelliFlux is based on an expert knowledge-base and engineering fundamentals of the processes it controls, and is driven by machine learning and artificial intelligence engines that enhance the knowledge-base for specific plant adaptations.

The core software platform underlying IntelliFlux product lines is referred to as **Augmented Process Recommendation & Industrial Control Optimization Toolbox (APRICOT)**. Engineered with novel machine learning algorithms, the software enables optimization of multiple process components at a plant individually or synergistically. It means that IntelliFlux can optimize any process sequence containing multiple treatment technologies, such as media filtration, coagulation, bio-processes, thermal and reactive systems. With this added capability, IntelliFlux Controls can now provide end-to-end decision automation for water treatment and process plants.

IntelliFlux provides immediate response to process condition variations, as well as thoughtful and learned response based on its machine learning and predictive analytics. The result is a continuously improving smart automation framework that progressively improves it's knowledge of plant operation, enhancing efficiency, adaptability, and reliability of the plant.

IntelliFlux consists of hardware and software components that augment the supervisory control and data acquisition (SCADA) and/or the distributed control system (DCS) framework at a process or water treatment plant to deliver:

- Autonomous optimization of the unit operations or processes at the plant, providing real-time feedback control and adaptive set-point regulation.
- Improved learning from event logs through predictive analytics, statistical correlations, and advanced AI modules, delivering an improved decision support and automation framework that not only provides operators

better insight about the plant, but also circumvents performance loss or plant damage arising from influent quality fluctuations or unexpected perturbations.

The award-winning IntelliFlux filtration software provides an artificial intelligence-guided control philosophy that optimizes flux maintenance and cleaning protocols in filtration operations in response to influent water quality fluctuations and fouling – the technology deploys cleaning only when it is necessary. Furthermore, the intensity and nature of the cleaning deployed is also commensurate with the extent of fouling. This provides unprecedented improvement in system recovery, water use, uptime, cleaning chemical usage, and energy consumption. This product line is mainly applicable to membrane and media filtration processes. Other variations of the software are also available, and IntelliFlux can be customized for reverse osmosis, biological treatment, mixing, and full plant process control.

A.2 How IntelliFlux Works

Figure A1 depicts the hardware-software architecture of IntelliFlux. IntelliFlux delivers the services as a virtual assistant to the plant operator and engineer using a client-server architecture. The IntelliFlux Client is installed at the customer plant site, where it performs all the real time process control and optimization tasks for the plant. The IntelliFlux server is hosted by IntelliFlux Controls remotely, and provides advanced machine learning, predictive analytics, system identification and optimization tasks to deliver process information to the customer to assist in operational decision-making. This server engine acquires data from the IntelliFlux Client through a secure dedicated connection, processes this information to provide advanced analytics, and delivers decision support to the designated operators and plant personnel. In Ultrafiltration applications with high solids and turbidity influents, difficult to treat waters, as well as highly fluctuating feeds, IntelliFlux has a demonstrated track record of lowering OpEx, energy intensity, chemical consumption, and waste volume, as well as extending membrane useful life, thereby providing tremendous life cycle treatment cost benefits for such plants. Furthermore, the ability to autonomously mitigate water quality excursions and resulting downtime, unscheduled maintenance, and membrane damage improves the reliability and sustainability of the membrane plant.

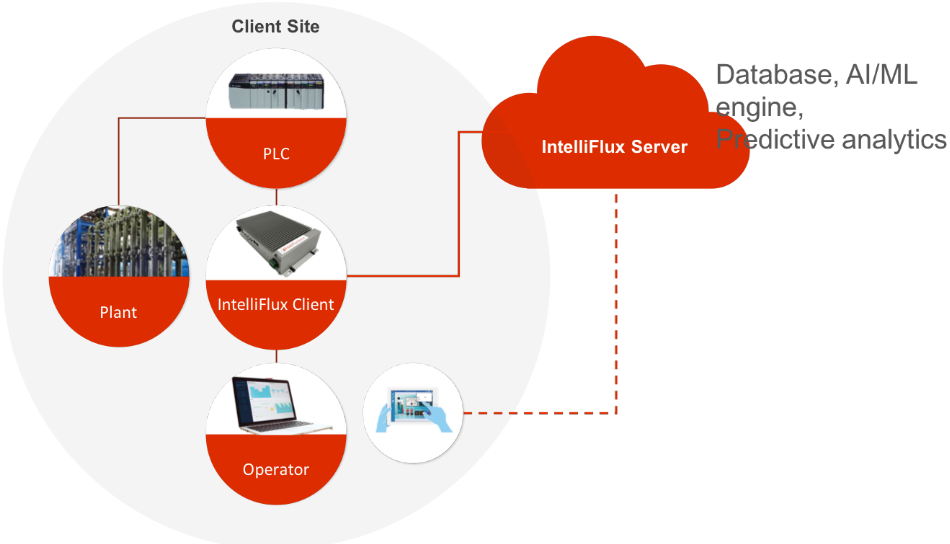

Figure A1. How IntelliFlux works. The system can be easily integrated into any existing plant and starts delivering values immediately after installation and commissioning.

A.3 Applications

IntelliFlux has been deployed on several water treatment plants spanning many types of applications, including

- tertiary treatment of secondary clarifier effluent from municipal sewage plants,
- recycle of cooling tower blow-down water in conjunction with a chemical de-silication process at a power plant,
- wastewater treatment in the food and beverage industry to meet discharge regulations,
- treatment of bioreactor effluent from a mobile sewage treatment plant,
- treatment of oilfield produced water for agricultural reuse, and
- Membrane bioreactors, among other applications.

A.4 Benefits

The key benefits of IntelliFlux include:

- Lower specific energy consumption

- Lower cleaning chemical consumption
- Extended component (cartridges, filter modules, etc.) life
- Increased uptime of plants
- Reduced chances of catastrophic failure or fouling of membranes arising from uncharted excursions of the influent water quality from standard operating range

Depending on the influent water quality and application, the system provides $5-40\%$ savings in system OPEX, $15-70\%$ savings in chemical consumption, between $5-50\%$ energy savings, $20-60\%$ savings in waste volumes, and generally a $2-7\%$ increase in net UF process water recovery.

Application Case Studies

Version: IntelliFlux Ultrafiltration APRICOT™

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