Nano Filtration Membrane Skid #2 – Fouling Issues

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Abstract — *Water treatment plants that use nano filtration membranes are affected by fouling issues when the feedwater is not controlled efficiently. The city of Hallandale Beach experienced a reduction in the filtration capacity and an increase in process pressure in Skid #2. This research used Lean Six Sigma principles that helped identify the root causes and countermeasures to mitigate or eliminate them. The DMAIC methodology was developed using its five steps: Define, Measure, Analyze, Improve, and Control. The data gathered by supervisory control and data acquisition software allowed the use of statistical tools to identify events of high flow and pressure in the process, which were analyzed to confirm that the skid does not have an effective way to control the pressure/flow, chemical dosing issues, and pressure protection failures. The proposed countermeasures fixed the pressure protection system, recommended the installation of an influent modulating valve and a new chemical dosing system.*

Key Terms — *Chemical dosing, DMAIC, fouling issues, nano filtration membranes.*

INTRODUCTION

The City of Hallandale Beach (COHB) is the 76th largest city out of 282 in Florida. It was incorporated in 1927. It has 41,217 residents over 4.4 square miles with 81 miles of water transmission and distribution lines. COHB produces approximately 7 million gallons of water per day with two different treatment process; one process, uses two nano filtration skids of 3-million-gallon capacity per each.

The skids have a total of 497 membranes elements. The Skid #2 was showing issues with pressures and performance. Membrane fouling issues are costly for the COHB Water Treatment Plant because they resulted in expenses associated with membrane replacement costs and decreased water quality. Identifying, correcting, or mitigating the variables that cause the fouling issues will allow the COHB to maintain potable water production, meet/exceed the quality standards, optimize the control process, and maintain/increase the useful life of the system.

The objectives of this project were to:

- Propose the best alternative to control the feed water for the Nano Filtration Skid system.
- Propose a reliable chemical dosing for the Nano Filtration Feed Water.
- Validate the pressure protection system conditions.

A REVIEW OF LITERATURE

Water filtration systems processes such as Nano-Filtration (NF) membranes and Reverse Osmosis (RO) membranes are used more commonly to produce potable water from different raw water sources, such as rivers, groundwater aquifers, seawater, reclaimed water, and others. These processes use the membrane as physical separation (porous media) to remove the contaminates from the raw water, contrasting each other on the size of the particles or elements that each can remove. The NF membrane can remove particles between 0.01 to 0.001 micrometers in diameter, and the RO membrane can remove particles between 0.001 to 0.0001 micrometers in diameter [1].

These water filtration processes require specific pressure values to pass the water through the membrane; the pressure will increase in proportion to the pore size reduction (porous media). Raw water contains different contaminants depending on where it comes from; these contaminants can be natural organic matter, inorganic matter, pollutants, and toxic compounds

[2]. The membrane can be affected by the accumulation of contaminants on the porous or membrane surface, creating a membrane fouling with reduced water production and increased power consumption (an increase in pressure) [3].

The water filtration processes with membranes use fouling mitigation and control techniques to reduce the accumulation of contaminants, and the fouling type and estimated frequency specify the application. Some of the methods used to control the fouling issues are feedwater pretreatment which can be chemical, by using in-line coagulation-flocculation, UV radiation, floatation, scale inhibition, etc., and using other physical media filtration, such as cartridge filters, coarse strainer, sand separators, and other [4].

METHODOLOGY

This research was conducted using the DMAIC methodology of Lean Six Sigma; this allowed to follow a logical sequence to identify the issues that cause the fouling issues with the membranes using the data recorded by the supervisory control and data acquisition (SCADA) software, which is used by water treatment plant to control and monitor the production operations. The DMAIC process involves five steps: Define, Measure, Analyze, Improve, and Control; using these methodologies and their supporting statistical tools and techniques allowed for finding the bottom-line problems that affected the process performance, obtaining feasible solutions or correction actions.

Define

This research used the Define step key activities such as display indicator performance and process flowchart. The display indicator developed allowed identifying a performance gap from the data gathered from the SCADA software, which was recorded from day one of operation of the new nano filtration membranes installed by the City on August 1st of 2020, until January 27th of 2022. During this period, the Nano Filtration Skid #2 operated for 289 days. A considerable drop in flow around day 98 per Figure 1 was detected with a reduction in production for 191 days (subtracting 98 from 289 days); in this period, the SCADA system collected 20872 data points that were normalized. Normalization data is created by comparing the actual values of operation of the process variables such as feedwater composition, feed pressure, flow, temperature, and water percentage recovery with preestablished reference values using formulas and equations; the results generated the permeate (filtered water) flow real values [5].

As shown in Figure 1, the permeate flows decreased from the established setpoint of 2080 gallons per minute (gpm) until an average of 1973 gallons per minute (gpm) between operation days 98 and 289 (gap around 287 gpm). Another valuable piece of information observed in Figure 1 was the multiple flow peaks in the trend that exceeded the set point value of 2080 gpm. These peaks at the beginning of the nano filtration operation impacted the 1st stage, thus affecting the system's overall performance.

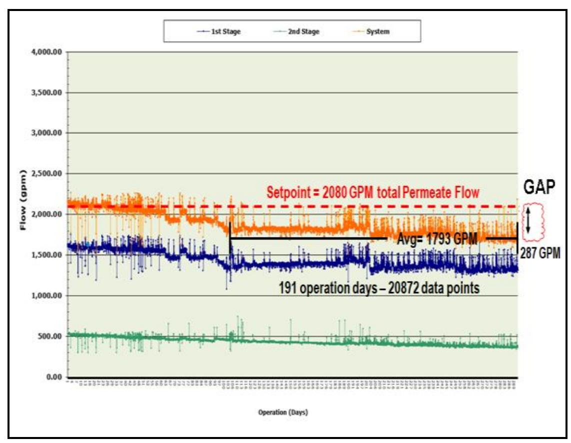

Figure 1
Display Indicator performance

As part of the Define step, a process flow chart was constructed, as is shown in Figure 2; this chart describes the different components and elements that are part of the process, who are responsible for each operation, and the overall phases in the treatment (influent, pre-treatment, water treatment).

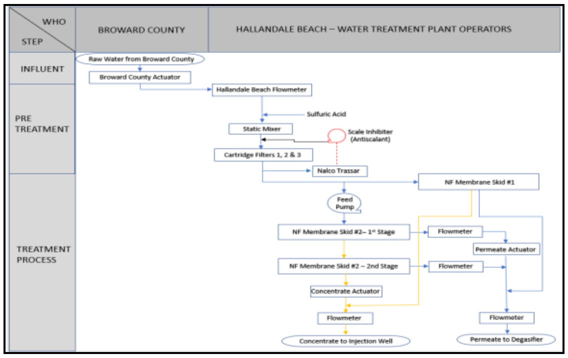

Figure 2
Process Flow Chart

Measure

The measure step focused on data stratification, histograms, and Pareto charts tools. Considering Figure 1, the normalization data were stratified using the histogram tool, selecting the highest combined permeate flow and pressure, as shown in Figure 3, obtaining 140 events. Of these 140 vents, 48 were over 2,203.5 gpm, which were above the upper specification limit (USL) per the city water treatment operation parameters, equal to 6% over the set point (2080 gpm).

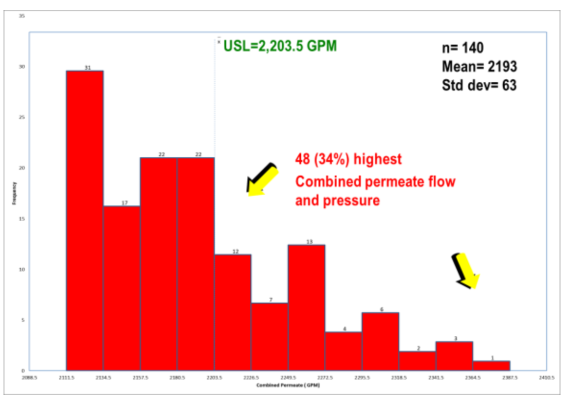

Figure 3
Stratify Problem (Histogram)

Considering the results in Figure 3, the 48 highest combined permeate flow and pressure were stratified using the Pareto chart, a tool used to organize and analyze data by ranking the different data groups. In this research, the Pareto tool was used to distinguish which were the causes of these events; a team of subject matter experts (SMEs) from the city evaluated and identified the four mains data groups: High flow (feed water), combined high flow/pressure (feed water), high pressure (feed water), and Rupture disk (Nano Filtration Skid). The Pareto Chart in Figure 4 shows the frequency of events per group, confirming that 39 events were caused by the feed water fluctuations from Broward County (variations on flow and pressure). The remaining 9 events were caused by a pressure backup from the degasifiers, a downstream process of the nano filtration skid.

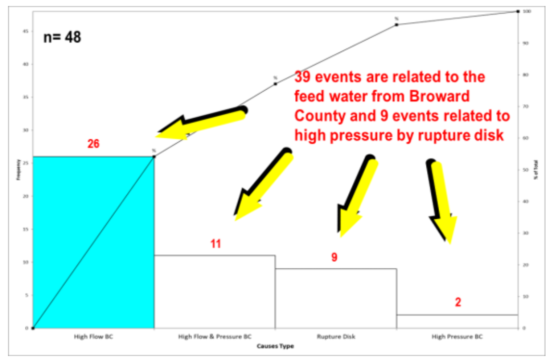

Figure 4
Stratify Problem (Pareto chart)

The SMEs evaluated the results from the Pareto chart to determine the problem statement based on the "object by defect", problem statement technique which included the adjectives for each stratification to the original "object with defect' to produce the appropriated problem statement [6]. This research's problem statement was defined as "Permeate water overproduction, and high pressures can create scaling when particles accumulate on a membrane, causing the membrane's pores to plug."

Analyze

The analyze step used the stratified data to group the potential root causes using the techniques: single case bore analysis, then the tool cause and effect fishbone to identify the root causes, and finally, the root cause verification matrix, which helped to identify them.

The single case bore analysis used the four groups of data mentioned in the measure step (high flow, combined high flow/pressure, high pressure, and rupture disk) and described them as reasons. The SMEs added another reason: "Antiscalant under-dosing," considering that a sudden increase in feed water flow can cause the antiscalant injection system to under-dose.

Then the reasons were validated per period, as is shown in Table 1, adding the frequencies of each one and then dividing by the total of occurrences to obtain a percentage of occurrences. These calculations allowed clouding the prevalent reasons as potential root causes, selecting 1, 2, 3, and 4.

Table 1
Single Case Bore Analysis

Reasons	8-3-2020	8-5-2020	9-30-2020	9-30-2020	11-1-2020	11-19-2020	11-14-2020	12-7-2020	12-12-2020	2-1-2021	2-5-2021	2-8-2021	2-9-2021	2-11-2021	2-11-2021	2-11-2021	2-14-2021	2-14-2021	2-17-2021	2-18-2021	2-19-2021	3-3-2021	3-16-2021	4-15-2021	4-15-2021	4-16-2021	4-25-2021	5-5-2021	5-5-2021	5-5-2021	5-10-2021	5-11-2021	5-16-2021	5-17-2021	5-22-2021	6-3-2021	6-4-2021	8-16-2021	9-6-2021	9-9-2021	12-7-2021	12-9-2021	12-16-2021	12-16-2021	12-29-2021	1-11-2022	1-12-2022	1-27-2022		
1) High Flow from Broward County 1	X	X	X	X	X		X	X			X			X	X	X			X	X			X			X		X	X	X					X	X	X		X		X	X	X	X					26	35%
2) High Flow and Pressure from Broward County 3										X		X					X	X			X			X	X						X	X		X												X			11	15%
3) Rupture Disk 4													X									X					X						X					X		X					X		X	X	9	12%
4) High Pressure Broward County 5						X			X																																								2	3%
5) Antiscalant Under Dosing (estimated) 2	X	X	X	X	X		X	X			X			X	X	X			X	X			X			X		X	X	X					X	X	X		X		X	X	X	X					26	35%

SMEs conducted a cause-and-effect fishbone analysis to identify and evaluate the potential root causes. The analysis concluded the following:

- "A" No effective way to regulate the flow coming to the Nano Filtration Skid. (From reasons 1, and 3).
- "B" No feedback from the analyzer to adjust the dosing pump, antiscalant chemical underperforming. (From reason 2).
- "C" Rupture Disk: Backup pressure protection failure, feed power failure on RIO 2.1, and PLC sequence failure. (From reason 4).

The identified potential root causes were included in the root causes verification matrix in Table 2. The estimated impact on the gap was obtained by adding the prevalent reason results from the single case bore analysis (Table 1).

Table 2
Root Verification Matrix

	Potential Root Cause	How Verified?	Estimated Impact On Gap (H,M,L)	Root Cause or Symptom
A	No effective way to regulate the flow and pressure coming to the NF skid system	The root cause was discussed with SMEs, and after reviewing documentation and data, it was concluded that NF Membrane Skids do not have protection to prevent or regulate high flow and pressure entering the system	53%	Root Cause
B	No feedback from the analyzer to adjust the dosing pump, analyzer miscalibration, antiscalant chemical underperforming	The root cause was discussed with SMEs, and after reviewing documentation and data, it was concluded that the antiscalant system needed to be evaluated and updated to provide an optimized system response to changes in the process	35%	Root Cause
C	Backup pressure protections failure, feed power failure on RIO 2.1, and PLC sequence failure	The root cause was discussed with SMEs, and after reviewing documentation and data, it was concluded that the City needs to verify and update the pressure protection devices, the power reliability and the PLC sequence.	12%	Root Cause

Improve

This step developed and implemented the countermeasures to reduce or eliminate the verified root causes. The countermeasures were selected to act as direct remedies to the root causes of the problems. The improve step tools and techniques used in this research were the countermeasures matrix and the process flowchart (with countermeasures).

The countermeasures matrix helped the SMEs to link the relationship between the problem, the root causes, and the countermeasures to evaluate which countermeasures should be implemented. As is shown in the countermeasures matrix in Table 3, each countermeasure was rated numerically for effectiveness and feasibility, then multiplied to obtain overall values that were validated again by the SMEs for implementation.

Table 3
Countermeasures Matrix

Problem Statement	Verified Root Causes	Countermeasures	Effective-ness	Feasibility	Overall	Take Action? Yes/No
Permeate water overproduction, and high pressures can create scaling when particles accumulate on a membrane, causing membrane's pores to plug."	A-No effective way to regulate the flow and pressure coming to the NF skid system	A1- Installation of an influent pressure/flow modulating valve for the source water from Broward County.	5	4	20	Y
	B-No feedback from the analyzer to adjust the dosing pump, analyzer miscalibration, antiscalant chemical underperforming	B2- Update the antiscalant analyzer and update the designed control system.	5	4	20	Y
	C-Backup pressure protections failure, feed power failure on RIO 2.1, and PLC sequence failure	C1- Repair/replace/recalibrate the relief valve at the degasifier	4	4	16	Y
		C2- Evaluate reducing the pressure rating of the rupture disk	4	5	20	Y
		C3- Modify the PLC control sequence of the actuators	4	5	20	Y
		C4- Update the power backup of the RIO 2.1	4	5	20	Y

5=Extreme; 4=High; 3=Moderate; 2=Somewhat; 1=Little

After validating the seven countermeasures from Table 3, an action plan was developed to outline how they will be implemented. A brief explanation per Table 3 on how each countermeasure was implemented is described as follows:

- "A1" to implement this countermeasure, a project will be developed to include the design, procurement, and implementation phases of influent modulating valve. Estimated time for project completion is 12 months.
- "B1" this countermeasure required installing a new Antiscalant analyzer, and flowmeter to measure the chemical injection, and control the dosing pump. The new equipment's were ordered (lead time of six months).
- "C1" this countermeasure was completed on February 3rd, 2023. The manufacturer tested the valve, adjusted the settings, and completed the calibration.
- "C2" this countermeasure required the reduction of the rupture disk rating from 85 psi to 50 psi (SMEs recommendation) and was requested to the manufacturer; the lead time two months (April 2023).
- "C3" this countermeasure was completed on February 6th, 2023. The programmable logic control (PLC) sequence was updated, and the failure mode configuration on the actuators was changed from fail-to-closed to fail-to-open action.
- "C4" this countermeasure required the update of the power backup for the remote inputs/outputs panel 2.1. (RIO 2.1), which was completed on February 2nd; the existing uninterrupted power system (UPS) was replaced and updated from 750 VA to a new unit with 1500 VA per the city electrical engineer's recommendation.

Control

In this process step, the completed countermeasures were integrated into the process; the SMEs updated the process flowchart to incorporate the new countermeasures, as shown in Figure 5, which detailed the exact location of each one in the process.

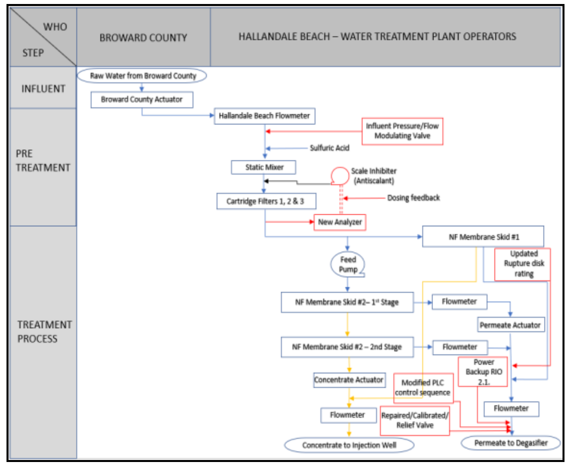

Figure 5

Process Flow Chart (Standarize Countermeasures)

Conclusion

This research focused on finding the root causes of the Nano Filtration Skid #2 fouling issues using the DMAIC methodology of Lean Six Sigma. The corrective actions applied to the pressure relief valve, the power backup RIO 2.1, and the PLC control sequence eliminate the root cause that a backup pressure affects the membranes. This research helped to confirm the importance of controlling the feed water flow and pressure, their relationship with the antiscalant dosing system, and the impact of downstream degasifier process failures on the nano filtration Skid #2.

Due to the required design, procurement, testing, and evaluation, the countermeasures pending for implementation in this research will require further analysis in operation. The influent pressure/flow modulating valve shall be incorporated using a new PLC control sequence to allow the operational parameters to change when the two nano filtration skids are running simultaneously versus the regular operation of one. The new antiscalant analyzer, the flow meter, and the dosing pump shall be included in the PLC control sequence to adjust the injection accurately with the changes in flow. Feedwater is usually pretreated before its processing in a membrane-based unit to minimize the chances of fouling. Varying pretreatment schemes can be designed based on the feedwater's properties and chemical composition. These schemes are generally classified into conventional and nonconventional methods; for this study, the focus was applied to physical mitigation characteristics like flow, pressure, and chemical mitigation using antiscalant. Other feedwater pretreatment schemes as pH adjustment, temperature control, sand separator, acid dosing, etc., can be developed and included in future research to increase the scope of process control strategy and reduce the probability of fouling issues.

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