USE OF ADVANCED THREE-STAGE MEMBRANE SYSTEM FOR TURNING EXTREME WASTEWATER INTO BOILER FEED WATER

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Abstract

An engine manufacturer enacted a number of sustainability goals, one of which was 90% wastewater reuse. One facility in the northeast United States implemented a ceramic ultrafiltration system in 2019 to reduce labor intensity, free up footprint, and improve life cycle costs versus a polymeric ultrafiltration system. The ceramic ultrafiltration system reduced oil and grease and suspended solids by over 99% to prepare the permeate for biological treatment and achieved over 90% recovery. Subsequently, the site started up a new ceramic membrane-based membrane bioreactor in place of its activated sludge plant, the effluent of which was causing the plant to incur quality surcharges. The membrane bioreactor produced effluent of suitable quality to allow recycle of wastewater via reverse osmosis. The client decided on a spacer tube reverse osmosis system as it was proven in challenging applications and offered more reliability for treating effluent with high concentrations of organics. The reverse osmosis system was started up early in 2020. The permeate is used to displace city water for use as boiler feed water and cooling tower make-up. The permeate passes through a mixed bed ion exchange resin to polish out dissolved solids prior to being pumped to the boilers. The reverse osmosis system has delivered significant savings in resin regeneration chemical costs. The combined system has been operational for over 1.5 years, with the ultrafiltration system being operational for over 2.5 years and the membrane bioreactor over 2 years. This paper will share design experience and lessons learned from this project.

Introduction

In 2018, a major, global manufacturer of engines with a production plant in the northeast United States embarked on a multi-year project to upgrade its aging wastewater treatment facility. The 1,000,000 ft^2 production plant can produce more than 500 engines per day and has more than 1,000 employees. The production steps include receiving raw materials and components, all on a "just-in-time" basis, automated metal machining, semi-automated assembly, automated spray booth painting, and automated, robotic engine test stand quality testing.

At the time, the production facility produced over 50,000 gallons per day (gpd) of liquid wastes (Figure 1). The largest source of wastewater was the combined flow of sanitary wastewater, grey water, and cooling tower blowdown (CTBD) at 27,000 gpd. The metal working production steps in the plant produced about 22,000 gpd of wastewater (WW) laden with emulsified and dissolved oils and greases. Painting and engine testing produced about 2,600 gpd of waste paint and oils.

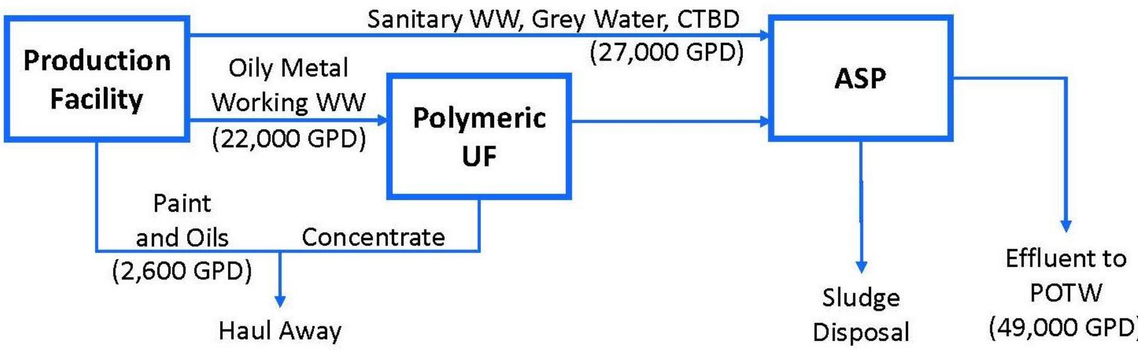

Figure 1. Engine production plant wastewater treatment process as of 2018

The original wastewater treatment process included ultrafiltration and an activated sludge plant. The oily metal working wastewater was treated with tubular polymeric ultrafiltration (UF) membranes to remove emulsified oil and grease from the water prior to biological treatment. The UF concentrate was combined with the waste paint and oils and disposed off-site. The UF permeate was combined with the non-oily sanitary wastewater, grey water and cooling tower blow down and then treated in the ASP. The waste activated sludge was disposed of off-site and the ASP effluent was sent to the local publicly owned treatment works (POTW).

The original treatment process had many issues necessitating the process upgrade. The tubular membrane system was more than 20 years old and in dire need of replacement. Most of membrane system did not work and what did operate was very labor intensive. The ASP was operating poorly resulting in numerous surcharges based on the plant's National Pollutant Discharge Elimination System (NPDES) permit.

Engine production plant personnel and their engineering consultant envisioned a new process to bring the wastewater treatment facility into NPDES compliance and institute a high degree of water recycle and reuse to meet the engine company's corporate sustainability goals, which included reusing about 10 million gallons per year of wastewater, about 90% of the total water flow.

There were to be three unit operations in the new treatment process. First, the UF system would be replaced with a new one allowing for efficient long-term operation with a reduced footprint to allow for additional equipment in the wastewater treatment building. Second, a membrane bioreactor (MBR) would be installed to treat the combined UF permeate and non-oily wastewater streams. Third, a reverse osmosis (RO) system would treat the MBR effluent to prepare water for recycle back into the production plant, the main uses of which would be boiler feed water and cooling tower make-up.

Ultrafiltration Membrane System Replacement

Crosstek Membrane Technology was brought into the project in 2018 to evaluate crossflow ceramic UF membrane technology in competition with the incumbent tubular polymeric membrane system supplier. After visiting the site to understand the challenges in treating the oily wastewater and conducting a demonstration of the ceramic membrane technology, Crosstek conducted a two-week pilot trial to define the design parameters of the commercial system. Based on that pilot trial, Crosstek proposed a commercial Ultressa® ceramic UF membrane system for treating the oily metal working wastewater from the engine plant.

Based on inlet total suspended solids in the range of 800 to 2,300 mg/l and emulsified oil and grease of 1,000 to 1,500 mg/l, Crosstek proposed a 16-module system capable of generating 26,500 gpd of permeate in standard production mode and up to 41,300 gpd in accelerated production mode. The difference between the two modes of operation was daily maintenance cleaning during accelerated production while the standard production mode only required a weekly chemical clean-in-place (CIP) of the membranes. Permeate backpulse could be optionally used to extend the duration between maintenance and full chemical cleanings. In order to reduce the concentration of residuals from the UF process, the feed was batch concentrated on a weekly basis to a recovery in the range of 83% to 95% depending on the quality of the feed. The permeate was projected to be less than 10 mg/l each of suspended solids and emulsified oil and grease at all times.

The general design of the proposed system is shown in Figure 2 and a layout drawing is shown in Figure 3. The system included the following:

- A 1,000-gallon skim tank and 200-µm strainer for pre-treatment
- Stainless steel feed, concentrate, and permeate piping
- 4 parallel banks of membrane modules each with 4 modules in series for a total of 16 modules
- 2 x 100% feed pumps, 2 x 50% recirculation pumps, and 1 x 100% backpulse pump
- Automatic dosing stations for cleaning chemicals

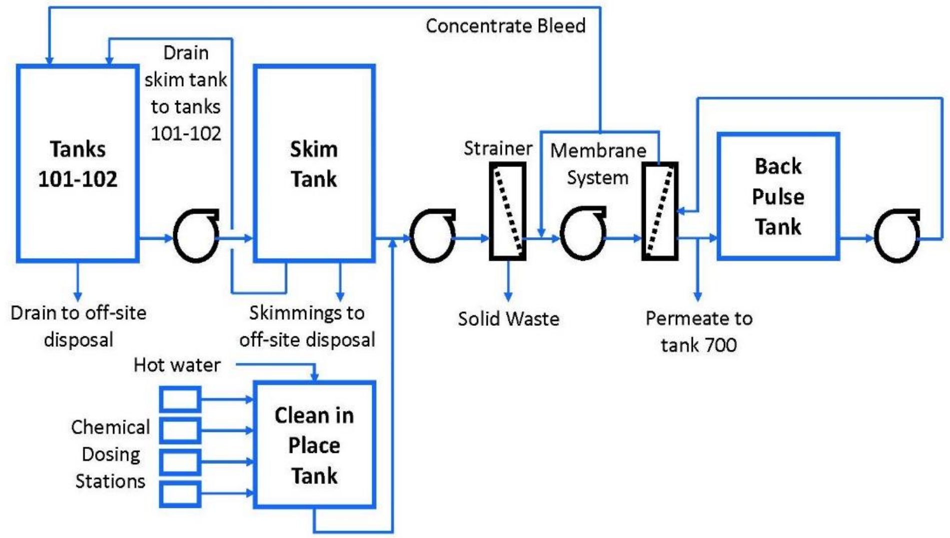

Figure 2. Ceramic UF membrane system process schematic

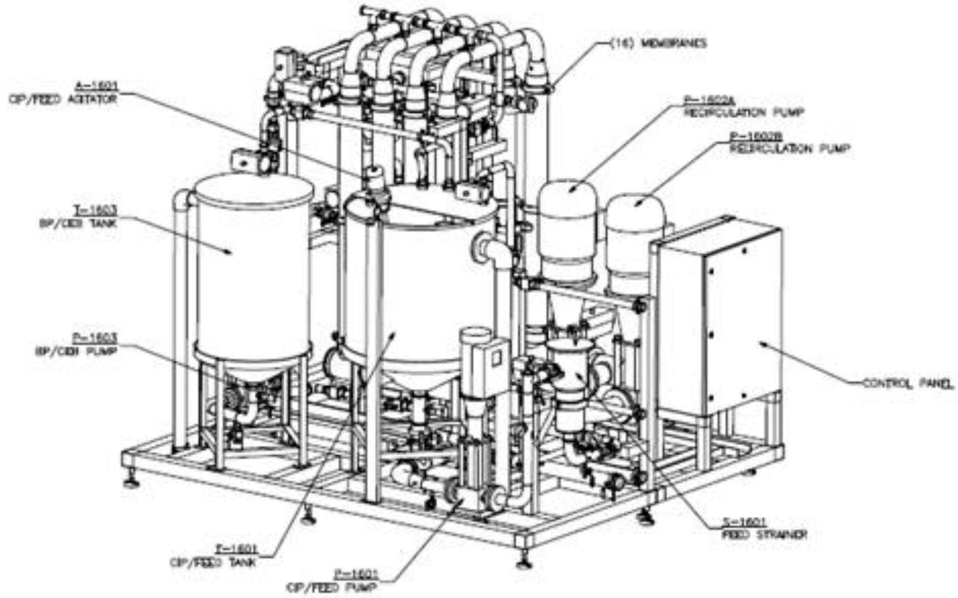

Figure 3. Ceramic UF membrane system general layout

The system was controlled with an HMI/PLC interfaced to the engine production plant control system and wirelessly connected to Crosstek's Fuzion™ data logging and operations monitoring platform. Hot water for cleaning was supplied by the engine plant.

The facility engineering group evaluated the proposals from Crosstek and the incumbent tubular UF system supplier. The comparison was based on a 20-year lifecycle analysis which included capital, installation, and membrane replacement costs. The final analysis indicated that the Crosstek system provided a 40% lower lifecycle cost, even with a higher capital cost to the engine plant.

Crosstek worked with the engine plant facilities team and their local engineer to install the UF membrane system. After commissioning and start-up, the system has run well since June 2019. Over the course of 2.5 years of operation, there have been some lessons learned. The strainer needs to have the correct mesh size and filtration area to optimize media life and pretreatment performance. Regular cleaning that maintains process permeability in the right range provides reliable week in and week out filtration productivity. For this particular system, Crosstek had to go with twin recirculation pumps to reduce system footprint. After a couple of years of operation, one of the pump motors burned out but this was not apparent to the operators because the system sounded the same. We learned that an indicator on the pump itself or the HMI was needed in this case.

A photo of the installed system and a screen shot from the Fuzion dashboard are shown in Figures 4 and 5. The ceramic membrane system was installed in roughly half the footprint of the previous tubular UF system allowing other equipment to be installed in the wastewater treatment building. The Fuzion™ data logging system maintains up to 3 years of data and allows both Crosstek and engine plant engineers to monitor and control the system remotely.

Figure 4. Ceramic UF membrane system installed in engine plant's wastewater treatment building

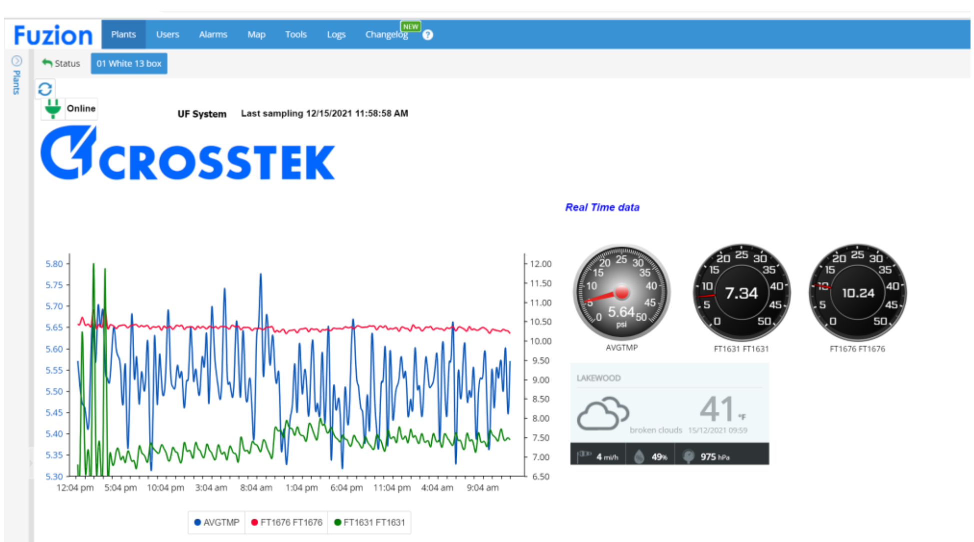

Figure 5. Screen shot from the Ultressa® ceramic membrane system's Fuzion™ data logging and operations monitoring platform

High Recovery STRO Membrane System

As part of the overall project, the engine manufacturer procured a ceramic membrane MBR to treat the combined UF permeate and non-oily wastewater from a separate vendor. The engine plant installed the MBR outside the wastewater treatment building due to the size of the system, including the above ground membrane basins.

The engine manufacturer also made the decision to procure a RO system to treat the MBR effluent in order to recycle RO permeate back into the production plant and displace the use of city water in the boilers and cooling towers. Based on the level of chemical oxygen demand (COD) in the MBR effluent, Crosstek believed that its Spacer Tube RO membrane (STRO) technology would be most applicable. The COD in the MBR effluent was in the range of 260 to 1,170 mg/l, which is well beyond the capability of standard spiral wound RO membranes with a maximum COD concentration of 10 mg/l.[1]

Crosstek has developed an in-house reverse osmosis (RO) product line for organic-laden feed streams like that of the engine plant. The initial target opportunities for Crosstek have been in challenging industrial applications such as landfill leachate treatment and brine concentration applications. The products are marketed under the AquaZoom™ brand. CrossTek sells these products worldwide including into the Chinese landfill leachate market, the largest such market in the world.

Specifically, we pursue opportunities in the US to supply systems into two general types of applications in which we use DT and STRO technology:

DTRO modules with no or limited pre-treatment
DTRO membrane modules do not have a feed spacer so there is no net or mesh to clog with suspended solids or upon which biofilms can grow. As a result, relatively little feed pretreatment is necessary, reducing process complexity for customers by eliminating RO pre-treatment equipment such as UF and membrane bioreactor systems. There could be cost savings in some instances with this solution, especially for smaller flow, challenging feed streams.

STRO modules with appropriate pretreatment
STRO modules contain spiral wound membrane elements that have an open feed spacer and high-pressure capability. These modules are used extensively for landfill leachate treatment after membrane bioreactors. While the ST module has limited capability to tolerate suspended solids like any spiral wound module, it tolerates COD and BOD levels that are orders of magnitude higher than traditional spiral wound RO modules. This presents opportunities to enhance recovery of organic-laden waters for recycle and reuse while minimizing the volume of residuals that need to be managed.

Figure 6 shows the range of feed influent parameters that are acceptable for the DTRO and STRO membrane modules as well as Crosstek's Ultressa UF membranes. As can be seen, the RO technology can accept influent with much more organics than conventional RO technology

[1] DuPont Water Solutions, "Filmtec™ Reverse Osmosis Membrane Technical Manual", Version 8, September 2021, pg. 76 of 212.

thereby requiring less feed pretreatment prior to the RO membranes. Also note that feeds with 5-minute SDI values of 5 to 13 can be reliably treated using STRO and DTRO membrane modules. And if necessary, the DTRO and STRO modules can be used to concentrate feeds beyond that of conventional RO membranes due to their ability to concentrate feeds at pressures up to 1800 psi.

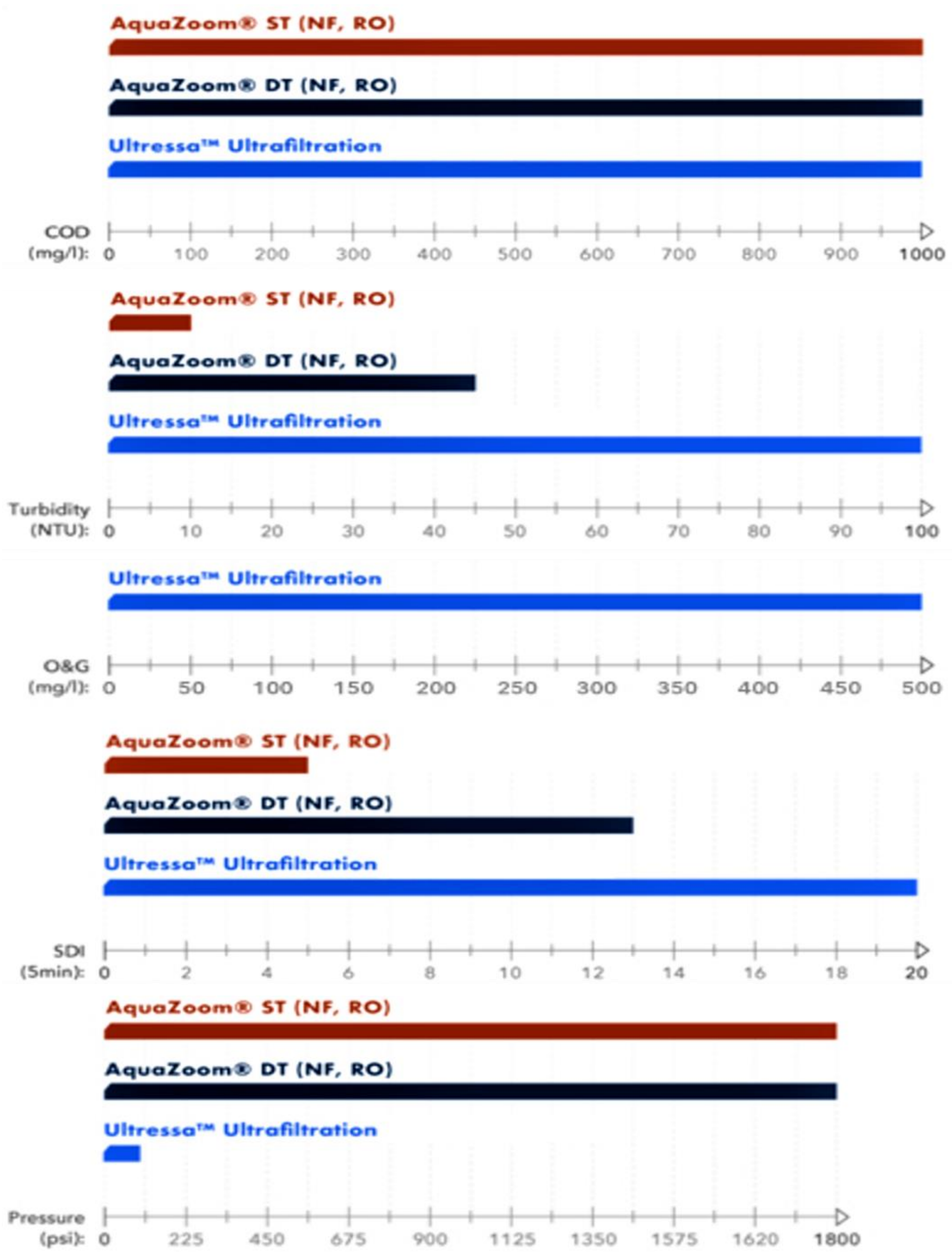

Figure 6. Influent parameters for selected Crosstek membrane technologies

Based on a discussion of Crosstek's STRO technology with the plant facility engineering team and some bench-scale pilot testing, Crosstek proposed a STRO system to treat the MBR effluent at the engine plant. The inlet feed specification upon which the STRO design was based is shown in Table 1. The inlet feed conditions to the wastewater reuse STRO system varies, as with all industrial processes, requiring robust technology to treat such feed. CrossTek's spacer tube RO system is designed to handle the contaminants and their concentrations listed below.

Table 1. MBR effluent analytical results

Parameter	**#1**	**#2**	**average**	**unit**
Ortho P, Diss	8.31	8.13	8.22	mg/l
Chloride	618	613	615.5	mg/l
Fluoride	5.5	5	5.25	mg/l
Phosphorous, total	9.31	9.01	9.16	mg/l
SiO_2 (dissolved)	30.8	26.4	28.6	mg/l
Sulfate	249	256	252.5	mg/l
Sulfide, Acid soluble	1.5	2.2	1.85	mg/l
Barium	524	491	507.5	ug/l
Calcium	160000	147000	153500	ug/l
Magnesium	25000	23900	24450	ug/l
Potassium	87300	94400	90850	ug/l
Sodium	449000	415000	432000	ug/l
Strontium	310	280	295	ug/l
Alkalinity, HCO_3 as $CaCO_3$	58.8	31.6	45.2	mg/l
Ammonia as Nitrogen	1.35	8.92	5.135	mg/l
pH			7.5	pHU
Silt Density Index (15minute)			4	
Silt Density Index (15minute) Maximum			5	
Chem. Oxygen Demand (COD)			260	mg/l
Chem. Oxygen Demand Maximum from Data:			1,170	mg/l

Design Projection: (A) Project Required 80% and (B) Feed Chemistry Maximum 90%
Using the feed definition in Table 1, reverse osmosis design projections were developed using a feed flow rate of 36,472 gpd to the STRO system. An important point should be noted: upon balancing the feed analysis, it was realized that the feed stream was supersaturated in both barium sulfate and calcium fluoride by a factor of 24.5 and 25.6 respectively. It was assumed that these species since being insoluble prior to RO feed treatment, would be removed by the MBR where there is sufficient time for completing precipitation. As such, the feed to the RO was operated assuming 100% saturation of barium sulfate and calcium fluoride.

(A) Project Minimum, 80% Recovery
Building upon the feed definition, a design projection was developed for the STRO system at a water recovery rate of 80%, which was the project minimum recovery. The design projection

showed that a feed pressure below 150 psig and 2ppm antiscalant dose into the feed (typical industry grade) was required to achieve treatment, and that a permeate quality with total dissolved solids below 133 mg/l was achieved using a brackish water reverse osmosis membrane. The permeate was expected to be of acceptable quality for production needs. A detailed feed and permeate analysis are shown in Table 2 below.

Table 2. Feed and Permeate Quality for 80% water recovery case

Concentrations (mg/l as ion)			
		Permeate	
Species	**Raw Feed**	**Stage 1**	**Total**
NH_4^+	5.14	0.82	0.82
K^+	90.85	7.74	7.74
Na^+	432.0	35.25	35.25
Mg^{+2}	24.45	0.95	0.95
Ca^{+2}	160.0	6.07	6.07
Sr^{+2}	0.30	0.01	0.01
Ba^{+2}	0.51	0.02	0.02
CO_3^{-2}	0.24	0.00	0.00
HCO_3^-	55.15	4.99	4.99
NO_3^-	0.00	0.00	0.00
Cl^-	884.8	67.43	67.43
F^-	5.25	0.50	0.50
SO_4^{-2}	252.5	7.09	7.09
SiO_2	28.60	1.36	1.36
Boron	0.00	0.00	0.00
CO_2	1.90	2.65	2.65
TDS	1,940	132.2	132.2
pH	7.5	6.4	6.4

The system based on this design was projected to include 12 ST+ reverse osmosis membrane elements at startup and would have space for a total of 24 ST+ membrane elements to allow for future expansion to support the engine production plant’s goals for future water reuse. The ST+ RO3 (brackish water type) elements could be employed for the project. The ST+ RO3 element could be installed into double length (e.g., ST++) membrane modules, which offer an optimal footprint design for the available floor space inside the existing wastewater treatment building of approximately 25’L x 10’W x 15’H, with the system designed to fit through a 12’W x 12’H door. A photograph of a similar size skid employing the ST++ membrane module design is shown in Figure 7 below. Of the 36,472 gpd feed treated, 29,178 gpd can be reused as permeate and 7,294 gpd of concentrate is produced.

Figure 7. ST++ module design with vertical arrangement

(B) Feed Chemistry Maximum, 90% Recovery

A maximum recovery projection was performed. In this case, the water chemistry, specifically silica concentrated in the feed, limited recovery to approximately 91.5%. To allow for potential increases in silica concentration in the RO feed, the design of the system considered 90% recovery as the maximum design water recovery. This recovery allowed approximately 16% increase in silica before the membrane scaled – see Figure 8 below.

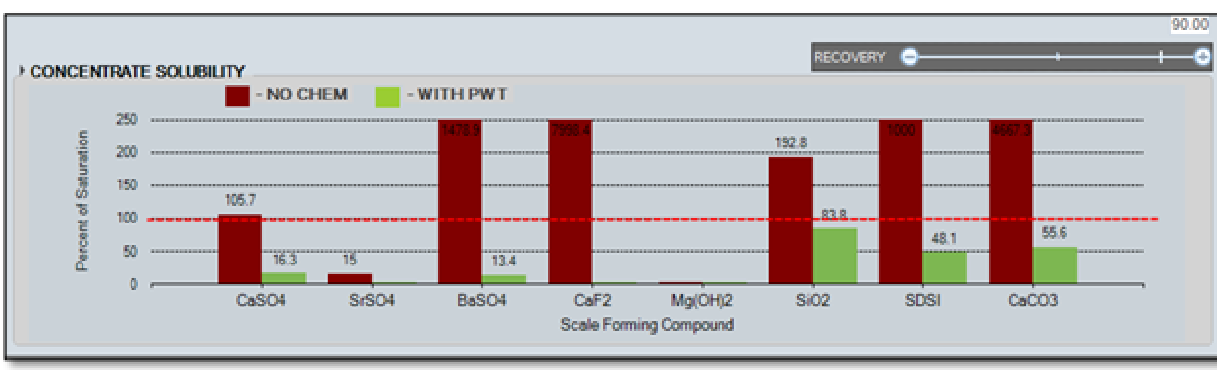

Figure 8. Scaling compound % solubility in concentrate at 90% water recovery. Green solubility bars are with antiscalant dose, red values without antiscalant dose

The design projection showed that a feed pressure of 230 psig and 20ppm antiscalant dose into the feed (typical industry grade) was required to achieve treatment, and that a permeate quality with total dissolved solids below 220 mg/l was achieved using a brackish water reverse osmosis membrane. The permeate was expected to be of acceptable quality for the engine plant's needs. A detailed feed and permeate analysis are shown in Table 3 below.

Table 3: Feed and Permeate Quality for 90% water recovery case

Concentrations (mg/l as ion)			
		Permeate	
Species	**Raw Feed**	**Stage 1**	**Total**
NH_4^+	5.14	1.24	1.24
K^+	90.85	12.43	12.43
Na^+	432.0	56.99	56.99
Mg^{+2}	24.45	1.58	1.58
Ca^{+2}	160.0	10.14	10.14
Sr^{+2}	0.30	0.02	0.02
Ba^{+2}	0.51	0.03	0.03
CO_3^{-2}	0.24	0.00	0.00
HCO_3^-	55.15	7.91	7.91
NO_3^-	0.00	0.00	0.00
Cl^-	884.8	109.2	109.2
F^-	5.25	0.81	0.81
SO_4^{-2}	252.5	12.07	12.07
SiO_2	28.60	2.34	2.34
Boron	0.00	0.00	0.00
CO_2	1.90	3.33	3.33
TDS	1,940	214.7	214.7
pH	7.5	6.5	6.5

The system design associated with the maximum recovery projection was the same as before: 12 ST+ reverse osmosis membrane elements at startup and space for a total of 24 ST+ membrane elements to allow for future expansion to meet future requirements. As outlined before, the ST+ RO3 (brackish water type) elements could be employed and installed in double length ST++ membrane housings. Of the 36,472 gpd of feed treated, 32,825 gpd can be reused as permeate and 3,674 gpd of concentrate would be produced. The design flux was 8.7 gallons per day per square foot of membrane (gfd), which is a conservative design flux, allowing for reliable operation.

The 90% water recovery, which yields 3,674 gpd or 1.33 million gallons per year more water recovered, would come with additional operating cost and operational intensity. The system design could operate anywhere between 80% and 90% recovery, depending on water needs at the plant. When comparing 80% and 90% water recovery, salient points of difference are listed below for the 90% case:

- Approximately 44% more power is required for operation
- Approximately 100% more cleaning chemicals and cleaning water is required for operation, but still expected to be acceptable operational intensity with automation included in the system design
- Estimated ten times more antiscalant dose is required to handle the higher saturation of scaling compounds.

The STRO membrane module can reliably achieve 90% recovery with feed having a COD of 260 mg/l on average and a maximum of 1,170 mg/l in the feed and a reject COD concentration greater than 2,000 mg/l on average with spikes of more than 10,000 mg/l.

The Crosstek AquaZoom® STRO system was selected by the engine manufacturer for their recycle process. Crosstek won the bid because of the higher recovery of water for reuse (up to 15%), which would displace city water that would have been used for boiler feed water and cooling tower make-up. The cleaner RO permeate would extend the life of the mixed bed ion exchange resin used to polish the water prior to being sent to the utility boilers. This would result in significantly lower ion exchange regeneration chemical costs. It would also reduce the safety risk for facility personnel in having to handle the regeneration chemicals. And like the UF membrane system, Crosstek won the bid with a higher capital cost due to the much lower lifecycle operating cost.

The process schematic for the integrated STRO system is shown in Figure 9. The MBR and the effluent transfer system are located outside of the wastewater treatment building. Having the MBR outside does have an effect on treatment effectiveness during the winter. Inside the building, the STRO system runs automatically generating RO permeate for the boilers and cooling towers in production.

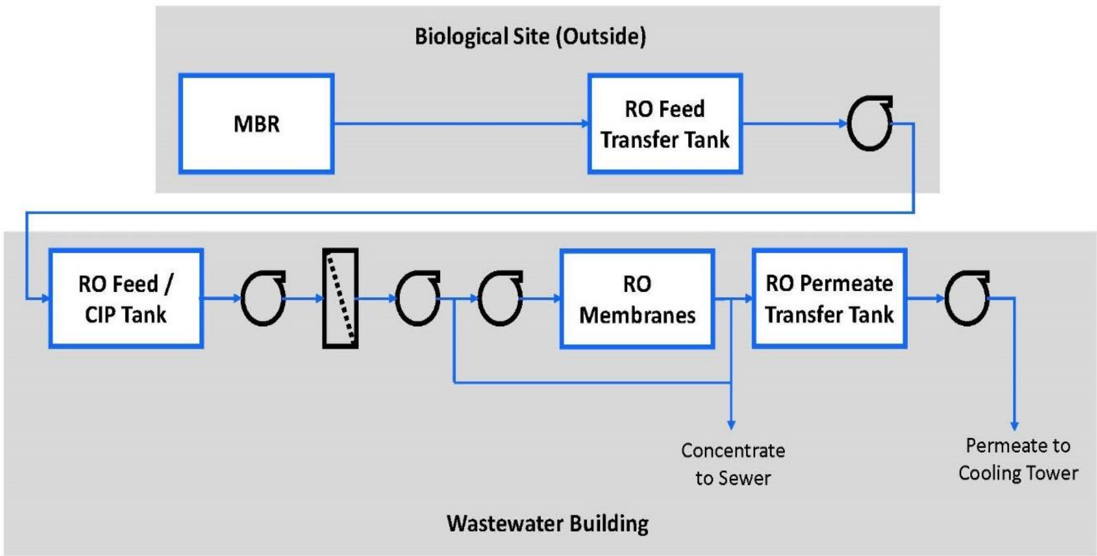

Figure 9. STRO system integration process schematic

A photograph of the STRO system is shown in Figure 10. The ST++ double length membrane modules can be seen in the center of the system. High and low voltage panels were used to reduce personal safety risk. Chemical dosing systems for antiscalant and chemical cleanings located of the left-hand side of the system.

Figure 10. STRO system installed at engine production plant

A screenshot from the STRO system's Fuzion™ data logging and monitoring platform is shown in Figure 11. As with the ceramic UF system, the Fuzion platform can log up to 3 years of data and allows remote monitoring and operation of the STRO system.

Figure 11. Screen shot from STRO system's Fuzion™ data logging and operations monitoring platform

Since February 2020 when the STRO system started up, we have accumulated several lessons learned regarding the operation of this system. We found higher organics concentration in the STRO feed during the winter when the uninsulated and uncovered MBR had somewhat degraded performance. This variation had a modest affect on STRO performance. Crosstek also found that the use of sulfuric acid prior to the RO for scale control was preferable to citric acid as the citric acid encouraged biomass build-up in the strainer in front of the STRO system.

Summary

The wastewater treatment facility upgrade at this engine production plant is complete. In addition to changes inside the plant which reduced overall wastewater generation, there were three substantial changes. An overview of the new process is shown in Figure 12.

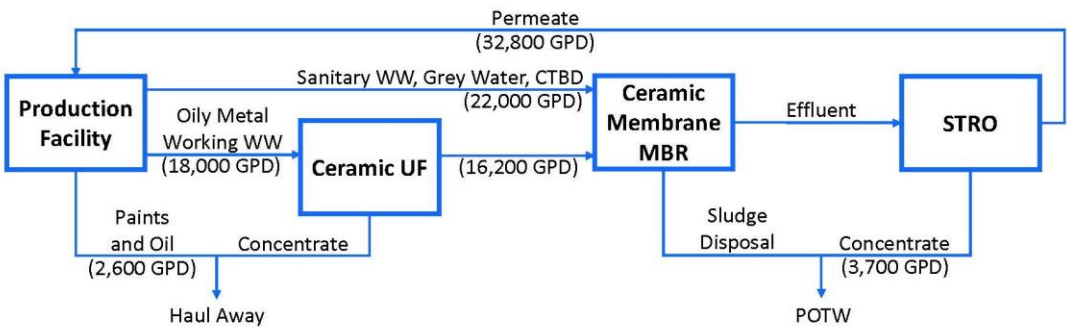

Figure 12. Newly upgraded engine plant wastewater treatment process

The basic process approach is the very similar with UF membrane deoiling of the oily metal working wastewater prior to biological treatment of the combined UF permeate and non-oily wastewater. The differences are the ceramic UF system in place of the polymeric tubular system and the ceramic membrane MBR in place of the old ASP. The new process includes the STRO system which allows for the recycle of water back into the production facility for the boilers and cooling towers. This saves about 10 million gallons of water per year and the overall system reduces residuals outputs outside of the facility saving the plant money on disposal fees and reducing strain on the environment.