THE SMART SOLUTION TO MEMBRANE FOULING DETECTION, MONITORING AND MANAGEMENT

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Abstract

Since the advent of membrane technology applications for large-scale commercial seawater desalination in the early Eighties, two critical issues in the application of the technology have emerged and persisted that drastically affected the way plant owners and operators managed these vital water production utilities, and subsequently impacted the total cost of water. The issues are the unpredictability and incidence of membrane fouling and the attainability of water conversion rates above 50%.

This paper attempts to show how the inadequacy of current methodology, innovation and field experience led to the establishment and validation of a novel approach applying certain corrections to the industry-standard performance measurement methodology (ASTM D-4516-00[1]), based on site-specific plant operating conditions, resulting in an analytical method for early-warning detection, measurement, monitoring and effective management of membrane fouling development in real-time. The originality, simplicity and applicability of this innovative approach are exhibited in open-surface plant case studies of 5 trains from 3 different SWRO desalination plants in the Arabian Gulf. The studies are based on historical operating data and SDI_{15} profiles of feed water, covering many years of operation of these plants. The plants feature different membrane configurations, models and manufactures. The data is evaluated comparatively using both the standard ASTM normalization method, as well as the proprietary corrected parameters based on site-specific conditions of each plant. The result is the establishment and constant monitoring of membrane fouling or non-fouling status for each case in the study and the measurement of its magnitude in real-time as the percentage differential between the two normalization techniques. This differential, known as the Fouling Monitor (FM), is then compared to the ASTM-normalized flux decline trending analysis, as well as the SDI_{15} profile of that plant, considered by many as a critical fouling indicator.

This results of these plant case studies will show that the SMART approach, unlike most standard fouling management practices is capable of detecting, measuring, monitoring and managing any fouling or scaling development that may occur in the system before it can cause significant and often irreversible losses in membrane performance characteristics.

It is hopeful that practical utilization of this approach at membrane desalination and filtration plants will directly lead to better operating, robust and effective O&M, monitoring and fouling management practices in order to mitigate the impact of fouling, achieve the highest attainable membrane system conversion rates and maximum plant availability. It will also enhance environmental sustainability of membrane desalination by minimizing waste effluents, membrane replacements and consumption of cleaning chemicals as well as more efficient utilization of renewable energies and green technologies. The overall and long-term benefits will be reflected into minimizing the overall cost of water.

I. INTRODUCTION

There has been an unfortunate and costly tendency in the membrane desalination industry to sustain established standards, initial membrane testing procedures and other plant operating and management practices, especially in terms maintaining key modeling assumptions that may no longer be valid in actual practice. This tendency is particularly reflected in the way fouling is being managed at the majority of plants once these plants are up and running. A key example that will be examined in detail in this paper is the utilization of the Silt Density Index (SDI_{15})[2] as well as the later devised Modified Fouling Index (MFI)[3,4,6] and Combined Fouling Index (CFI)[5]. These useful parameters are intended to be simple, handy and reproducible indicators of colloidal and particulate loading of feed water before entering the membrane desalination system, despite their known limitations and applicability.

Another example is reflected in the reliance and acceptability of the industry-standard normalization technique (ASTM D-4516-00 method[1]) to monitor the performance of RO and other membrane systems and determine when fouling or scaling occur, despite its lack of representation of real-life systems and operating dynamics and its demonstrated inability to detect and quantitatively measure fouling early enough before it has already started to cause significant losses in performance.

Despite the abundance of field data over the past 40 years that requires a major revisiting of these techniques, methods and practices, little effort has been made to come up with better, more representative empirical models for the design and operation of membrane desalination plants in the real world. The over use of and reliance on these standard practices is still being reflected in most stages of the membrane plant life, from the initial membrane system design projections to daily operational monitoring, performance evaluation, membrane cleanings and trouble shooting. The result has been that these practices significantly impacted the membrane desalination plant capital and O&M costs and hindered technology development and innovation. This is reflected in the much higher levels of energy, chemical and consumption and membrane replacement rates, as well as in the much lower effective plant operating conversions and availabilities due to higher downtime and maintenance requirements. On the positive side, this industry-wide practice, in addition to decades of experience at various SWRO plants around the world, have highlighted the true value of and need for a fresh and more practical approach that is based on analytical measurement of membrane fouling and scaling, as well as evaluating and monitoring the true performance of membrane systems in real time in order to take corrective action early on and save the plant from unforeseen consequences.

II. THE SEVEN MYTHS OF MEMBRANE FOULING – ORIGIN AND IMPACT

The following seven myths exemplify the focus on the decades-old industry practices regarding membrane fouling development, the critical need to understand the value of its early diagnosis and positive identification, real-time measurement of its magnitude and monitoring its progression. They also highlight current fouling management techniques in correlation with various indicative parameters, ad-hoc responses to stabilize or minimize its impact on the plant's availability, operational efficiency, performance and ultimately the cost of water production.

2.1 Membrane Fouling Cannot be Measured, Monitored and Managed in Real-Time

Despite major and impressive advancements made over the past 40 years, particularly in membrane manufacturing processes, system design configuration, pretreatment and conservation of energy and chemical usage, the industry has largely fallen short in recognizing the realities of membrane desalination in practice and the need to revisit early models, assumptions, practices and techniques that were put in place in the early stages of technology development under "synthetic conditions" created in the lab, test and manufacturing facilities. These no longer fit what a typical plant site today represents in terms of water conditions, system components and various other key operating parameters and limitations that significantly impact how the membrane system behaves under real-plant conditions. This has resulted in creating and sustaining fouling and attainable conversion rates as the two most critical issues in membrane desalination practice and economics. The availability of huge amounts of historical operating data that has become available at various plants around the globe has not been fully utilized. This would have resulted in replacing the old theoretical models, assumptions, approaches and procedures that are still being used since the onset of the technology till today with more empirical and site-specific ones to establish a fresh understanding of the mechanisms of fouling and how to manage it early and effectively. An example of this serious shortcoming is how many plants try to address the incidence of unpredictable membrane fouling development only when it is finally discovered and well-established or at least at the point when it is already in an advanced stage, sometimes reaching crisis levels with costly consequences. This occurs despite the common perception that membrane fouling is accounted for by plant designers and operators alike, including the incorporation of constant "*Fouling Factors*" in the design projections. Practically speaking, the introduction of these factors simply serves as safety factors rather than calculated technical parameters based on actual or reasonable fouling scenarios, typically not accounting for worst-case conditions. This is due to the fact that membrane fouling cannot be technically predicted or simulated at the design stage, unlike membrane scaling which is easily calculated and projected based on the chemistry of the raw water analysis provided and published solubility standards for various salts. It is known, however, that no membrane manufacturer warrants against fouling in their standard guarantee agreements, which remains the responsibility of the plant owner or operator. Other fouling management practices include setting certain action triggering limits or guidelines in terms of loss in actual product flow and increases membrane pressure drops and salt passage characteristics, initiating scheduled and emergency maintenance with cleaning cycles and implementing certain membrane repositioning schemes, additions and/or replacements to compensate for the impact of any developed fouling development.

The plant case studies discussed in the paper will demonstrate the viability, practicality and wide applicability of a fresh, innovative approach that addresses these issues. The real-time analytical technique takes into consideration key site-specific and plant design and operational parameters to measure, monitor and manage membrane fouling development and system performance at a very early stage. These case studies are based on analyzing massive amounts of historical operating data collected from several SWRO plants throughout the Arabian Gulf Region. The results are then compared to the actual performance and fouling histories of these plants.

2.2 SDI, MFI or CFI Are Adequate Membrane Fouling Indicators

The SDI_{15} has been introduced since the advent of commercial membrane desalination technology applications as a reliable and practical fouling indicator to protect RO plants, especially those with surface brackish and seawater feed intake systems. The methodology was designed to protect plants from the adverse effects of colloidal, silica, metal oxide and organic fouling. This has been largely aided by the apparent simplicity of measuring the SDI_{15} at the plant online despite a basic understanding of its limitations and the lack of reliable, practical and real-time monitoring techniques to detect and measure the onset of membrane fouling development as early-warning and actionable indicators. In the past 30 years or so, there have been a few real plant studies by correlating that could help plant operators better understand the real value and applicability of this monitoring tool in order to help them minimize or prevent the damaging consequences of fouling before it's too late. This paper will demonstrate the quantitative correlation, or lack thereof, between SDI_{15} history with actual membrane fouling development based on the discussed SWRO plant case studies.

Research work has also been reported by Salinas-Rodriguez, Amy, Schippers and Kennedy[3], Al-hadidi[4], Choi, Hwang, Lee and Hong[5], Boerlage, Kennedy, Aniye and Schippers[6] and others focusing on finding more representative alternatives to the SDI_{15} as fouling indicators, notably what is known as the Modified Fouling Index (*MFI*)[3,4,6] or Combined Fouling Index (CFI)[5]. The scope of this research has been limited to simulating the potential for RO membrane colloidal or particulate fouling and resulting flux decline via studying the mechanism of cake filtration and compaction at constant flux, using either a microfiltration membrane ($MFI_{0.45}$) for capturing large-size particles (*higher than 0.45 microns*), or an ultrafiltration membrane (*MFI-UF*) for finer particles (*between 0.02-0.45 microns*), acting as filter papers. Results obtained so far, working mainly with pretreated lake, river and tap feed water with high colloidal content, are promising. However, the same limitations of the SDI_{15} method still apply, mainly in particle size and inapplicability to more complex types of fouling common in RO plants such as biofouling and organic fouling. Moreover, a wide variability in SDI_{15} and $MFI_{0.45}$ results were reported by Al-hadidi[4] using actual seawater as the feed water in a UF-SWRO plant in the Netherland due to unaccounted changes in temperatures, pressures and filter paper membrane properties requiring "normalization" of results using standard references. Due to the lack of a quantitative tool to measure the magnitude of actual fouling developing in a membrane system, earlier work[3,4,5,6] could not provide or report such dynamic correlation.

2.3 Membrane System Design Projections Do Not Have to be Site-Specific

It is a recognized fact that membrane systems design projections are commonly based on mathematical and engineering models, not site–specific ones despite the abundance of field experience, histories and operating data that warrant a more empirical approach with a modified or corrected set of equations. At best, today's projections can adjust to certain site-specific system and element configurations, mechanical arrangements or energy-usage optimization options but only from a modular design or membrane-based point of view. A case in point is the consideration of the so-called "*Fouling Factors*", ranging typically between 0.70-0.95 and is largely based on the membrane element age or system design period, rather than any practical approach to predict fouling development in the design stage. Earlier, the pioneer membrane technology developer and manufacturer, E. I. DuPont, only included in its design projections what was known as "*Membrane Flux Retention Coefficients*" or "*MFRCs*" to calculate the projected magnitude of membrane compaction under various sets of operating temperatures and pressures, and no other "fouling factors" were used.

Most membrane models are still being tested and characterized for nominal product flows and salt passage characteristics at very low conversion rates, representing the bases for projecting the final design of new systems. Such characterizations are also still based on using synthetic seawater or a 30,000-35,000 mg/l NaCl solution as feed, 10%-15% conversion rates with the use of a single-membrane pressure vessel on a test skid, a piston pump and a 20-minute production runs. It is not clear why manufactured membranes cannot be tested and characterized in a real-life SWRO plant environment in the vicinity of the manufacturing facilities, with feed water drawn from the ocean with appropriate pretreatment and a high-pressure centrifugal pump delivering the projected design pressure and conversion rates (45%-50%), as well as incorporating an energy recovery system using a full membrane train with all standard controls and instrumentation. This way, the real performance of the membranes can be reliably and realistically measured and optimized for various applications before the membrane modules are shipped to plant sites.

By contrast, these projections do offer reasonable design configurations to account for the potential of chemical scaling development, since the chemistry and science are well-established and fairly predictable, but these are as good as the water analyses or profiles, if any, that are used as basis for the design. In many cases, however, only a few, and often one or two rough, non-representative raw seawater analyses are collected or simply assumed as the design basis, without further consideration to the site-specific raw water conditions, seasonal variability or other dynamic factors. In others, particularly in Australia, the United States and possibly others, however, several seawater quality assessment studies are routinely conducted prior to design of new membrane desalination plants.

In addition, membrane system design projections can only account for the projected loss of productivity due to new membrane compaction, typically about 15-20% mostly in the first 1000 hours of operation, which is carefully considered by most designers. Little consideration is given, however, to the impact of actual plant capacity limitations in terms of piping, pumps, valves, filters, tanks and other hydraulic limitations on the final performance of the membrane system under real conditions. Finally, in terms of predicting salt passage decay rates over the design period, most design projections simply assume a 7% annual decay rate per year, taking into account the projected membrane replacements.

2.4 ASTM Standard Normalization Method Represents Actual Membrane Performance

Since the advent of commercial membrane technology applications on a large-scale in the late Seventies, the industry, represented by the American Institute of Testing Materials (*ASTM International*), has adopted the procedure originally introduced by E. I. DuPont's *Permasep Products*, as the pioneering membrane manufacturer, to analyze and evaluate the performance of an RO system against design as the "*Standard Practice for Standardizing Reverse Osmosis Performance Data*", known as ASTM D-4516 standard method[1]. The standard is still the basis for calculations included in all data normalization software programs distributed free of charge by all membrane manufacturers to customers using their membranes. Furthermore, most of the commercial system performance warranties offered by the membrane manufacturers and suppliers require the use of their normalization software to evaluate the system performance in the event of a claim.

While this standard method may be good enough to evaluate single membrane's nominal flow output and salt passage characteristics at the manufacturer's lab or test facility under a common set of "standard conditions", using, for example, a sodium chloride standard solution concentration of 30,000-35,000 mg/l, 800 psig feed pressure at 25 °C feed temperature and 10% recovery rate for seawater membranes, it clearly did not account for real-plant raw seawater, system design, operating, hydraulic and other site-specific dynamic conditions, or more significantly, fouling potential. In other words, this means that this procedure only applies to membrane systems operating under ideal (*i.e., non-fouling*) conditions, which is almost always not the case. The method can only show a normalized flux decline trend due to membrane compaction, but if fouling is also occurring (*with or without the compaction effect*), the method cannot distinguish between the two, and identify the real cause of the developing flux decline.

The results shown by normalizing real-plant operating data, while it is only meant to indicate a trend towards fouling, can often be misleading, misrepresentative or inconclusive at best. By definition, worst of all, trending requires a minimum amount of time to be established and be exhibited before any meaningful investigative or corrective action can be taken. However, by the time a clear trend has developed indicating a serious fouling situation, it can be exhibited at the plant late in the game. This often occurs at the point where an irreversible loss of membrane performance characteristics, if not physical integrity, has already occurred, unless the plant operators have already taken some proactive or corrective measures, especially when the negative change in membrane pressure drops, product flows or salt passage rates exceeds a set limit, typically 10%-15% or more as recommended by most membrane manufactures and suppliers. Even when this is the case, the applied corrective action mainly involves initiating membrane cleaning cycles, replacements, additions or repositioning of module elements in the pressure vessels to redistribute the load of incoming fouling. The plant case studies discussed in this paper will demonstrate this deficiency in relying only on the ASTM-normalized performance trending method as compared to utilizing the real-time fouling measurement and early-warning monitoring approach innovated by the author of this paper.

2.5 Membrane Cleanings and Replacements Are Viable Solutions to the Fouling Problem

One of the misconceptions in the industry since the early days is that membrane cleanings can resolve fouling situations at the RO plants. Reasons for this widely-spread practice include the relative ease of initiating membrane cleaning cycles due to the availability of Cleaning-in-Place (*CIP*) system as a standard component of any RO system as well as an abundance of cleaning chemicals being stocked at site. This practice is a direct result of the lack of effective fouling early diagnosis, identification and control mechanisms that can be put into action before adverse irreversible deterioration in system performance characteristics, such as trans-membrane pressure drops, flow and salt rejection, are observed on site, at which point it becomes harder and harder to correct the situation and preserve the membranes. In addition, little attention is paid to what cleaning is supposed to do and what effect, if any, it has achieved since a few plants actually utilize the cleaning cycles to positively identify the type of foulants removed in order to take real corrective measures resulting in identifying the source(s) of fouling and stopping it. The simple fact is that since the main source of fouling is usually unknown, any "*corrective*" action short of identifying and stopping this source achieves nothing more than buying a little time at a significant cost, and eventually facing a situation where the fouling issue is not resolved and cleanings are no longer effective in restoring any part of the lost performance.

2.6 Low, Non-Fouling Membranes or Anti-Fouling Innovations Are Proven to Work

Since fouling has emerged as the dominant or most critical issue in membrane technology application, several "*breakthrough*" innovations to address this issue continue to surface on a regular basis. The range of these innovations, products and processes included the so called "*non or low-fouling*" membrane models, anti-fouling devices, such as vibrators installed on pressure vessels or feed water piping to minimize the potential for scale or material deposits, and new mechanisms such as stripping the phosphates off of feed water entering the membrane system to eliminate or minimize the chance of biofouling development by depriving the viable bacteria from active growth and film-building. It is unfortunate that none of these innovations or mechanisms has stood the test of time by demonstrating their effectiveness in controlling fouling via field studies supported by representative data over a reasonable period of time. This once again proves that there's no substitute to installing a sound and adequate pretreatment system, good operational and maintenance regimes, as well as close, real-time monitoring to guard against any possibility of fouling development as early as possible, which would make it much easier and feasible to control, manage and resolve before it becomes too late.

2.7 Membrane Plants Operation, Performance and Costs Cannot Be Optimized Daily

Field experience shows that optimization, as a fundamental engineering principle is an on-going practice, not a one-time or sporadic process. Since there are so many variables controlling the operation and performance of any desalination plant, there's always so much room for continual, real-time improvement, enhancement and upgrade in all critical aspects of the plant's useful life such as productivity, availability, energy and material consumption rates, maintenance requirements and subsequently O&M costs. Even if the plant is performing "as designed" or better, there's no reason to believe that no more improvements can be achieved on a daily basis since there are continual technology advancements, new materials and processes, innovative ideas, solutions to lingering technical issues and diverse experiences in the field. Most operating desalination plants are not performing to the maximum attainable levels simply because the owners and operators are satisfied with current performance as long as the plant is meeting "*guaranteed*" or "*target*" values in terms of delivered output, plant availability, specific energy consumption, or any other performance criteria. An essential part of optimization is real-time monitoring to allow the operator to gauge the pulse and status of the plant on a daily basis, which, in turn, is key to enabling opportunities for further improvements, timely upgrade of equipment, system components and processes, as well as providing the right and timely response to any developing issue.

III. THE SMART[a] SOLUTION

3.1 Current Practice: Standard Performance Normalization and Trending

By definition, ASTM trending analysis requires a statistically valid and reasonably large amount of operating data records plotted over a long period of time to establish a definite trend. The industry-wide standard method of evaluating RO performance, namely, ASTM D-4516-00[1], originally developed by the industry's pioneer and early leader, DuPont, represents only the membrane performance trend under ideal or non-fouling conditions from a membrane manufacturer's point of view based on in-house testing protocol and not on real-life and site-specific design, operating parameters and other dynamic parameters. Field experience at a large variety of membrane plants around the world in the past 30 years shows that it is virtually impossible to detect the early development of membrane fouling in a system simply by monitoring a long-term trending analysis. By the time the flux decline trend becomes well-defined, if ever, the fouling practically would have become too significant (i.*e.*, *uncleanable*) and often causing irreversible loss in performance, if not mechanical damage on the membrane cartridges. This is largely due to the fact that fouling is cumulative in nature and builds up over a long period of time, unless it is already too severe from the start, before it starts noticeably exhibiting its physical effects at the plant. Therefore, early discovery and diagnosis are critical to addressing it in a timely and effective way.

Figure 1 shows a typical RO membrane system online "*monitoring*" regime for a one-million USGPD RO/NF pilot plant at the city of Port Hueneme, California, with one RO and one NF trains running side by side with identical pretreatment. As can been seen from a plant operator's point of view, the displayed flux decline curve is simply is not actionable, if not confusing, as it is not indicative of the true status of the membrane performance and what action to take, if any. Later, this plant was investigated further and the true, real-time comparative performance of both identical RO and NF systems was determined, revealing a membrane manufacturing defect in the NF train's membrane batch that clearly distinguished its fouling tendency and behavior from that of the RO train[9].

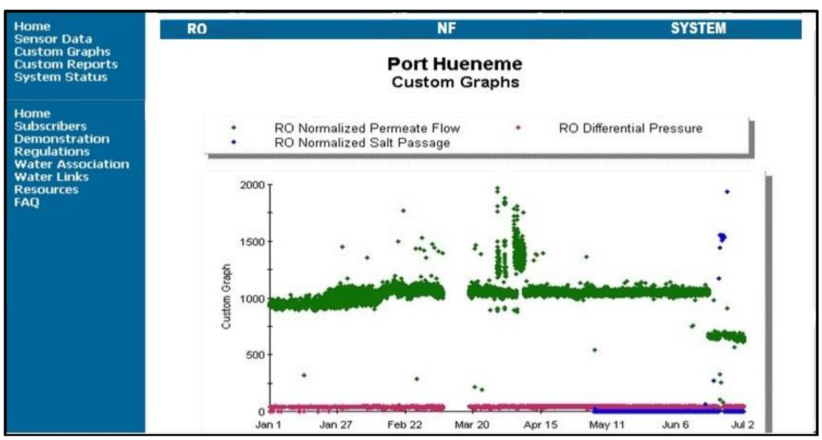

Figure 1 – Standard ASTM-Normalized Flow Profile Monitoring of an RO Plant

3.2 Real-Time Fouling Measurement and Monitoring: The Fouling Monitor (FM)

To address the critical need of RO, NF and other membrane plant operators and owners to detect and measure membrane fouling or scaling development as early as it starts to occur and to monitor the real performance of their membrane systems in real-time, the need has emerged for a *SMART*, early warning monitoring alarm system that the operator of an RO plant would use to indicate the start of fouling development in a membrane system in order to take timely and effective action to stop it and prevent

[a] *Known as the* ***S****ilent* ***M****embrane* ***A****larm in* ***R****eal* ***T****ime technology and associated MASAR® software systems*.

any potential significant or irreversible impact on the plant. Clearly, the standard ASTM normalization and performance trending method was not adequate to fill this need, as years of experience in the field shows. *Table 1* shows the criteria defined by Wikipedia encyclopedia for a SMART system:

As defined by Wikipedia, a SMART System must be:
➢ ***Specific***: Significant, Simple, Sustainable.
➢ ***Measurable***: Motivational, Manageable, Meaningful.
➢ ***Achievable***: Attainable, Actionable, Adjustable, Aligned with corporate goals, Acceptable.
➢ ***Relevant***: Realistic, Result-based, Resourceful, Reasonable, Repeatable.
➢ ***Time-bound***: Time-specific, Timely, Time-sensitive, Time/cost limited, Testable.

Table 1 – Criteria of a SMART System

The discovery of the SMART approach that serves as a practical, real-time and early-warning system followed many years of closely monitoring and trending the flux decline performance of a large RO plant in the Middle East with a biofouling history that exhibited itself suddenly after the first 2 years of operation. Detailed discussions of this approach and related real-plant case studies have been cited in prior work[7,8,9].

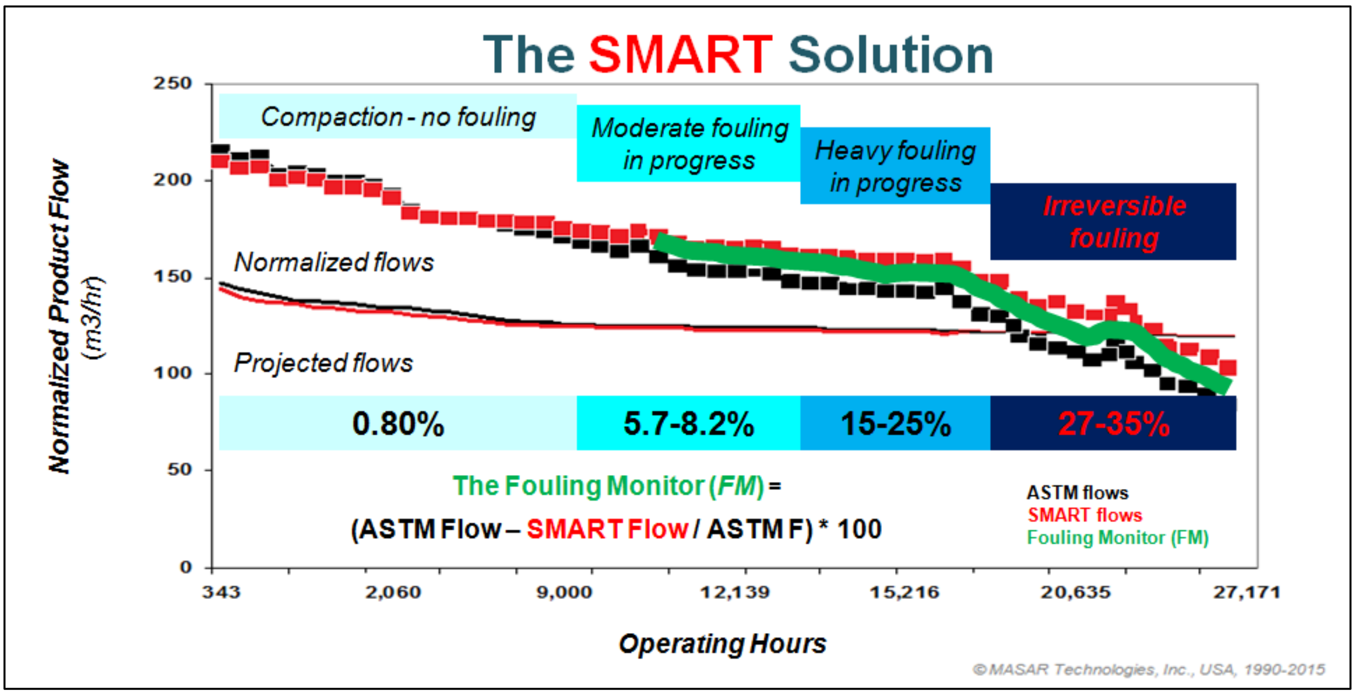

Figure 2 – Real-Time Fouling Monitor of Biofouling High-Brackish RO Plant

Figure 2 summarizes the technology and practicality of the SMART approach, as exemplified in comparative analysis of both standard ASTM-normalized flux decline curve (*expressed in terms of normalized product flows*), as well as a modified and more system- representative flux decline curve that takes into account certain site-specific and real plant design and operational parameters not accounted for in the standard method.

Careful analysis of the resulting graph representing the membrane performance of a high-brackish RO plant for the first 2 years of operation shows that the two flux decline curves for this plant were essentially identical during the first year of operation, or up to about 9,000 operating hours. This can be explained with the fact that the site-specific corrections to the ASTM normalization calculations did not make much difference due to the fact that the membranes actually performed as designed (*i.e., under non-fouling conditions*). Starting on the second year of operation, the two flux decline curves started to diverge from each other and the split or the percentage difference, now known as the Fouling Monitor (*FM*) widening with time.

This can only mean that at that time a fouling event started to develop and the membranes were no longer performing under ideal or non-fouling conditions. In reality, the plant did witness a biofouling event that started to be exhibited on site at the end of the second year of operation (*about 17,500 operating hours*), a full year after the FM actually indicated its early development. Because the plant was performing apparently well in terms of productivity and quality, the biofouling went undetected and unchecked until the flux suffered a sudden drop. Subsequent massive cleanings proved ineffective and a large number of membranes had to be replaced at a great cost and loss in availability and productivity.

This innovative and practical approach and associated software systems have been installed, tested, validated and/or licensed at over 25 seawater and brackish RO and other membrane desalination plants around the world since 1997[7,8,9], and was tested in-house under agreement and subsequently officially approved and recommended for use at RO desalination plants by *Permasep Products* of E.I. du Pont de Nemours and Company, USA, as "*an excellent tool to monitor plant performance and capable of providing an early warning if membrane fouling is occurring*"[10]. The technology and methodology have been found universally applicable to any pressure-driven membrane system with any feed source (*surface, beach well*), salinity (*brackish, seawater*), system design layout (*single and double passes*), brine-staging and membrane make, model and configuration (*hollow-fine fiber and spiral-wound*).

Table 2 shows the FM guidelines developed for most RO and NF plants in terms of fouling tendency, based on extensive field testing of the real-time methodology, as well as the recommended action for each case.

FM RANGE	*FOULING STATUS*	*RECOMMENDED ACTION*
0%-5%	No significant fouling.	Good operation. Continue to monitor.
5%-15%	Low to moderate fouling may be starting to develop.	Monitor more closely. Consider trouble-shooting if trend rise continues.
15%-25%	Moderate to heavy fouling is in progress.	Start trouble-shooting immediately to identify and eliminate source of fouling.
> 25%	Heavy to irreversible fouling is occurring.	Significant membrane replacements and/or additions required due to extensive loss of performance.

Table 2 - FM Guidelines

Despite the fact that this innovative technology has had a proven track record since it was introduced at the 1997 IDA World Congress in Madrid, Spain, including full licensing of the software systems to the Saudi Saline Water Conversion Corporation (SWCC), the largest producer of desalinated water in the world, Saudi ARAMCO and the South Australia Water Corporation (SA Water), it has yet to gain wide industry acceptance. One of the main reasons for this is that most plant personnel are focused on the busy daily aspects of plant maintenance and operation with little time or attention left to monitoring membrane performance in real-time as a critical part of the O&M functions despite the uniqueness, cost-saving benefits and universality of applying this technology. An encouraging trend has been observed recently, however, where some plants have started to assign "*Performance Managers*" to the O&M team as full-time positions with main responsibilities focusing on monitoring, analyzing and optimizing the plant's operational efficiency and performance.

IV. SWRO PLANT CASE STUDIES

The following 5 plant case histories will show the true applicability, sensitivity and representation of the FM as a real-time and early-warning fouling indicator based on the plants' operating data analyses demonstrating their performance and fouling history during the respective periods of investigation.

The operating, performance and fouling history of two large-capacity and one pilot surface SWRO plants, totaling in capacity of over 306,000 m^3/day or over 67 MIGPD, with surface feed water intake systems located on the Arabian Gulf were extensively studied. The plants operated with conventional filtration (*dual-media*) as the prime pretreatment system. The evaluation was based on historical operating data from these plants, totaling over 16,765 data records from 30 RO trains with 9 different membrane models, both hollow-fine fiber (*HFF*) and spiral-wound (*SW*) configurations, from all 5 major membrane manufactures (*DuPont, Dow Filmtec, Hydranuatics, Toyobo and Toray*). The data covered a period of over 14 years (*from January 2001 to January 2015*) with total cumulative operating hours ranging between 1,000 to over 21,000 hours. The specific identifications, locations and overall capacities of these plants cannot be disclosed due to confidentiality considerations associated with the usage of historical data of the demonstrated trains at these plants.

Due to the massive amounts of data analyzed and evaluated for the purpose of this paper, 5 representative trains from the 3 plants, with 3,412 operating data records or over 20% of the total, (*of which 74% represents spiral wound and 26% hollow fine fiber configurations*), were selected and their comparative performance and fouling history are evaluated and demonstrated in this paper. Evaluation and comparative criteria include the normalized flux decline using the standard normalization method (*ASTM D-4516*)[1], SDI_{15} history or profile as a "*fouling indicator*" and finally, the early-warning Fouling Monitor (*FM*) determined by the real-time fouling measurement and performance monitoring methodology developed by the author.

The sole purpose of this SMART evaluation demonstrated in these plant case studies under different water, site and membrane design conditions, is to show that this innovative methodology consistently measures and represents the actual magnitude and incidence of any fouling development of the membrane system in real-time and at a very early stage, unlike the ASTM normalization method or SDI_{15}. It is therefore a true, early-warning fouling indicator and a measure of performance. It is not intended as a competitive membrane to membrane comparison and therefore no recommendations in this regard can be made or concluded since each plant is different and the performance of a certain membrane model varies greatly as a function of plant site, water, operating and other conditions.

4.1 Case Study Summary: Analysis and Results

Table 3 summarizes the following 5 plant case histories demonstrated in this study:

CASE	*Membrane Configuration*	*Membrane Model*	*Feed TDS mg/l*	*Train Capacity m^3/d*	*Recovery Ratio %*	*Operating Hours*
A.1	SW	High-Pressure	44,450	6,192	35.0	21,041
A.2	HFF Twin	High-Pressure	44,450	6,072	35.0	20,964
B.1	SW	High-Rejection	38,865	12,000	46.3	7,968
B.2	SW	Low-Fouling	38,813	12,000	46.3	8,712
C	SW	Standard	40,036	82	41.0	1,014

Table 3- Summary of Plant Design & Operating Parameters

4.1.1 CASE A.1: SWRO Plant A – High-Pressure Twin Spiral-Wound Membranes (Train SW-D)

This surface SWRO plant, with a conventional multi-media filtration pretreatment system, has all trains originally outfitted with HFF twin-permeator (*with* a *high-pressure polyamide membrane model)*, which were being discontinued soon after startup. Four trains were later outfitted with a modified model of a seawater spiral-wound membranes (*high-pressure model)*. During the first year of operation, the plant reported a "biofouling" problem, and soon after, trouble-shooting was initiated at the plant in order to identify the type of fouling that was occurring. After 2 weeks of working on site, the fouling was finally identified as organic, not biological in nature, and was attributed to dosing of a cationic polyelectrolyte (*PE*) as a coagulant-aid. Earlier, before the full-scale plant was built, a one-year pilot plant study on site showed the need to dose the polyelectrolyte to attain SDI_{15} values under the required limit of 4.0.

Interestingly, the fouling was affecting only the SW, not the HFF membranes. This was shown when operating data were analyzed and evaluated using the real-time method. Later, this was confirmed by autopsies of 2 SW membranes and 2 HFF membranes on site. *Figure 3* shows the wide split between the two flux decline curves (*the red ASTM-normalized and the blue corrected one*), indicating the presence of a significant fouling situation since the beginning of the evaluation period.

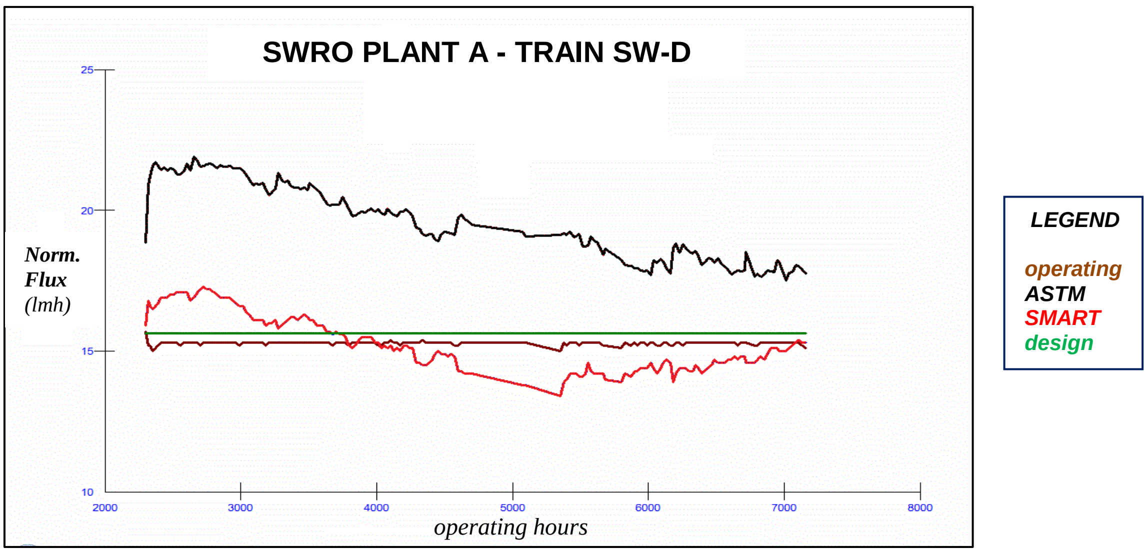

Figure 3 – Real-Time Normalized Flux Decline Profiles of Train SW-D at Plant A with Fouling SW Membranes

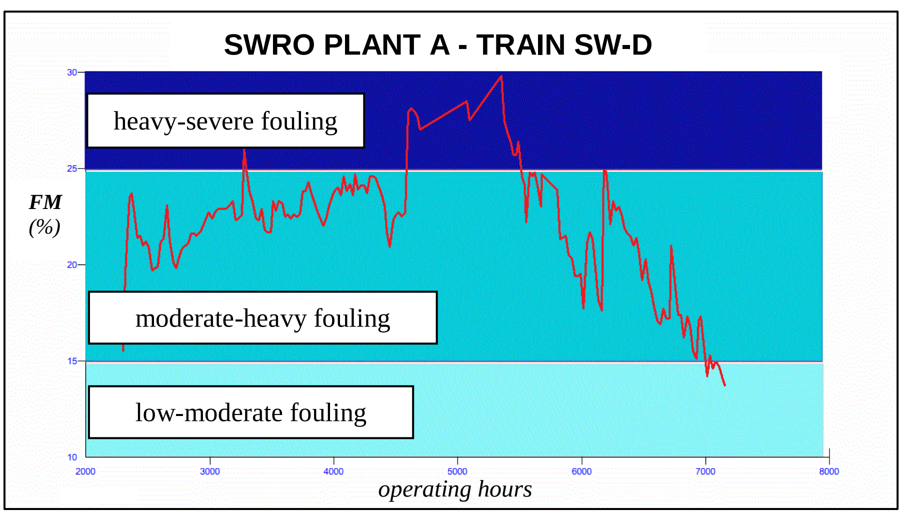

Figure 4 – Real-Time Fouling Monitor of Train SW-D at Plant A with Organically Fouling SW Membranes

Prior to that period (*roughly after 5,500 operating hours*), the dosing rate of the main coagulant, $FeCl_3$, was also recommended to be raised from 1.0 ppm to 3 ppm for better effectiveness. That triggered a steady reduction in the FM from a high value of close to 30% to 15-20% (*Figure 4*). Finally, the dosing of the PE was recommended to be stopped in order to stop the source of fouling. Immediately after, the FM continued to decline sharply for the SW train (*Figure 4*) to values under 10%. As *Figure 3* demonstrates, the ASTM-normalized flux decline (*red curve*) only shows a steady decline from the beginning while the normalized flow was significantly above the guaranteed value without a sudden or alarming drop before the fouling started to intensify. As a matter of fact, the normalized flow shows a relative stabilization and above the guaranteed (*or design*) value from about 6,000 hours of operation while the fouling situation was not yet resolved, as clearly exhibited by the FM (*Figure 4*).

4.1.2 CASE A.2: SWRO Plant A – High-Pressure Hollow Fine Fiber Membranes (Train HFF-E)

Conversely, *Figure 5* shows a totally different behavior and performance of the non-fouling HFF train operating at the same plant during the same period. It shows the two curves stayed well in the proximity

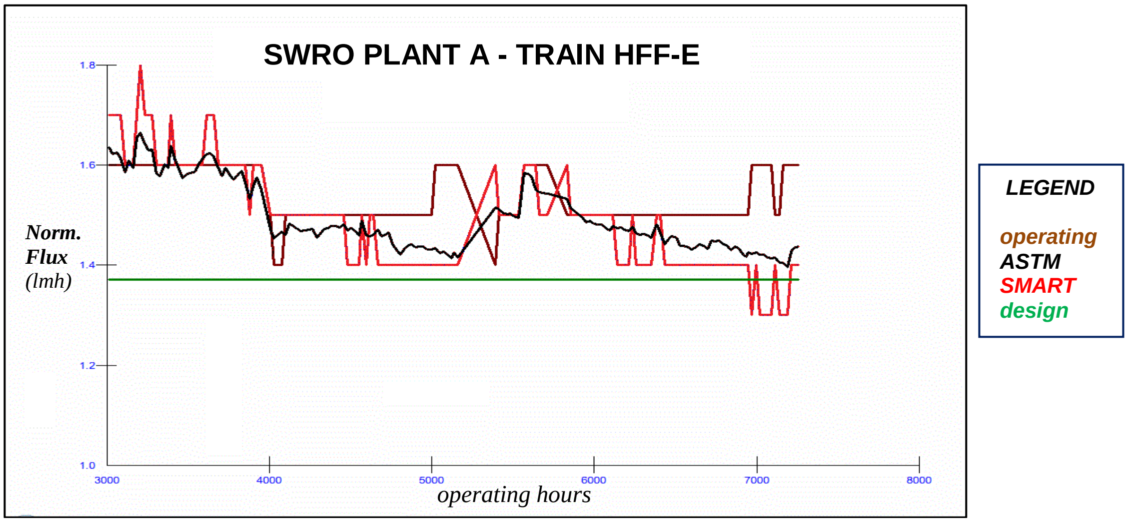

Figure 5 – Real-Time Normalized Flux Decline Profiles of Train HFF-E at Plant A with Non-Fouling HFF Membranes

of each other for most of the period, with the corresponding FM averaging 1.77% (*Figure 6*), indicating non-fouling conditions (*Table 2*).

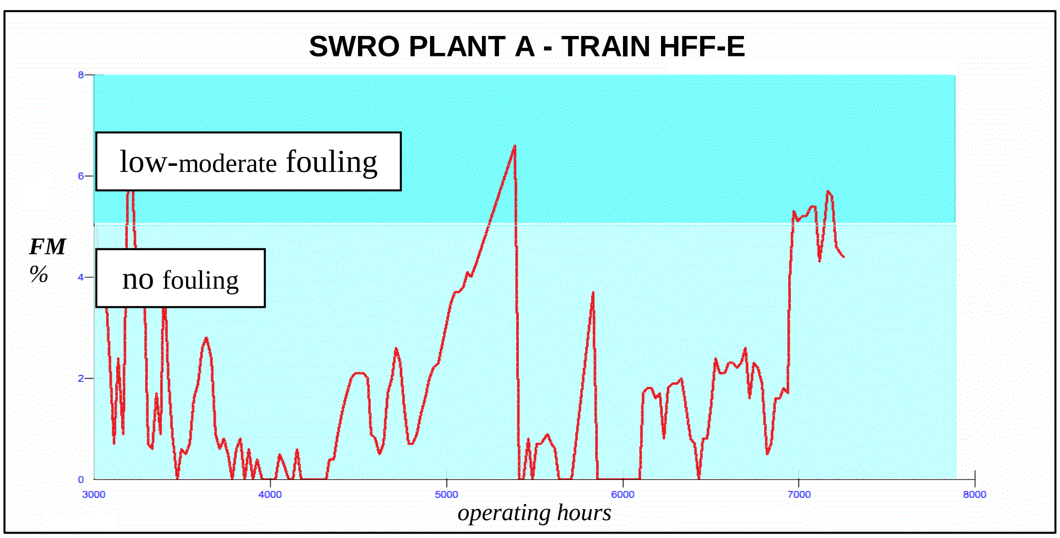

Figure 6 – Real-Time Fouling Monitor of Train HFF-E at Plant A with Non-Fouling HFF Membranes

As mentioned before, the train's operating and performance history, as well as the on-site membrane autopsy results (*Figures 6.1 & 6.2*) confirmed the non-fouling status of this train with hollow-fine fiber membrane configuration, as compared with the SW train impacted by organic fouling from the cationic PE dosing. This was attributed to its spiral-wound flat-sheet configuration with abundance of negatively-charged surface area.

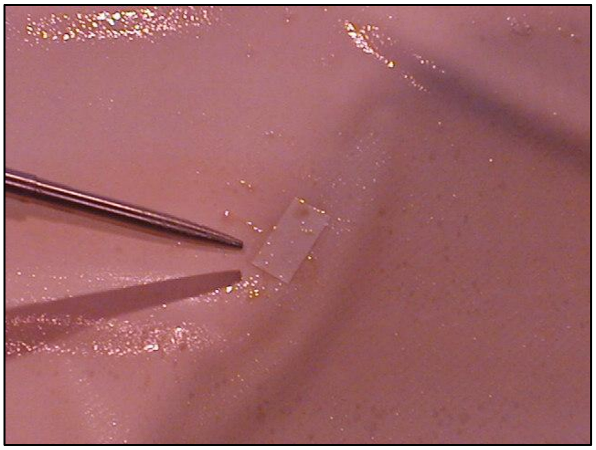

Figure 7.1 Organic fouling on the SW membrane

Figure 7.2 Non-fouling HFF membrane

Curiously, as *Figure 5* shows, the ASTM-normalized flux decline (*red curve*) of this non-fouling train at this plant actually showed a more rapid deterioration during the entire period than that for the fouling SW train, shown by the red curve in *Figure 3*!

The SDI_{15} history of the plant shown in *Figure 8* during this period indicates a relatively steady period (*2,000-5,000 hours*) while the fouling was well in progress. The fouling only started to escalate after 5,000 hours of operation, and it witnessed a sharp downward trend after the coagulant level was increased and the PE dosing reduced and stopped (*see red circle*).

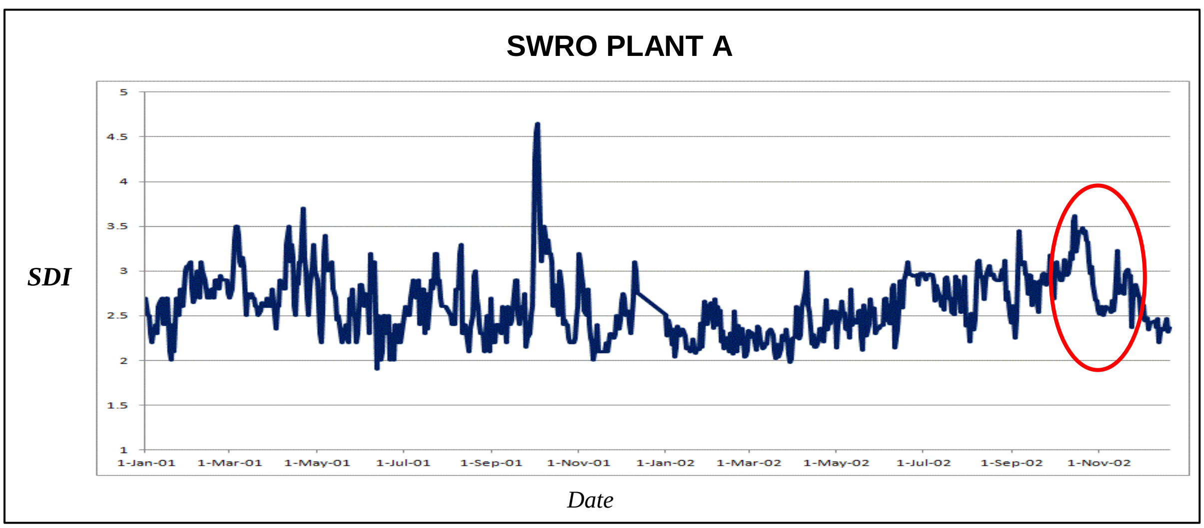

Figure 8 – SDI_{15} Profile of SWRO Plant A

4.1.3 CASE B.1: SWRO Plant B – High-Rejection Spiral-Wound Membranes (Train SW-11)

This surface SWRO plant with a conventional multi-media filtration pretreatment system, has one train outfitted with SW membranes (*high-rejection model*), and another with another SW membranes (*low-fouling model*). Historical operating data over a full one-year period were obtained for both trains for a dynamic evaluation of their performance and fouling tendencies operating at the same plant and under the same feed water, pretreatment and other conditions.

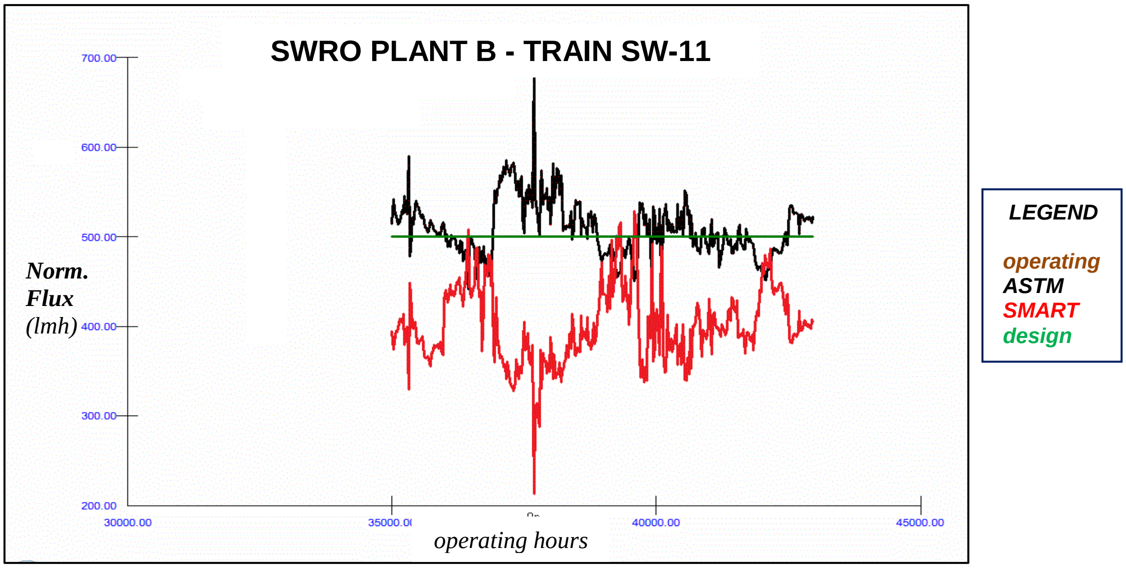

Figure 9 – Real-Time Normalized Flux Decline Profiles of Train SW-11 at Plant B with Fouling HR Membranes

Figure 9 shows the development of fouling for the *High-Rejection* (*HR*) membranes at this plant from the start of the evaluation period at 35,000 hours of operation. It quickly started to be mitigated with time, as indicated by the flux decline curves converging on each other. As soon as the converging was completed, the two curves started diverging again indicating worsening of the fouling. This pattern was repeated 2 more times, with a very brief period of stabilization, all the way to the end of the period at 42,968 hours for a total of 7,968 total cumulative operating hours.

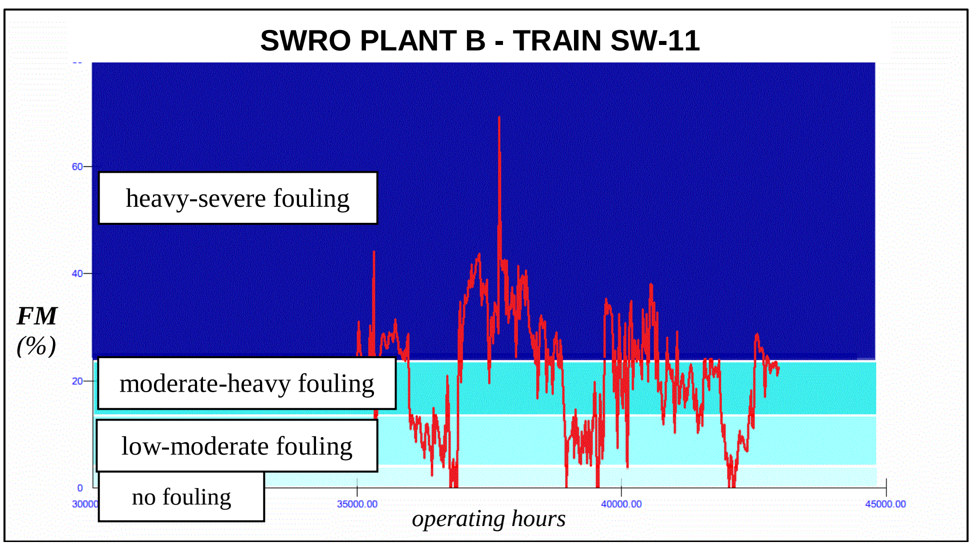

Figure 10 – Real-Time Fouling Monitor of Train SW-11 at Plant B with Fouling HR Membranes

Figure 10 shows the corresponding FM for this train, averaging 21.5%, indicating a moderate to heavy fouling in progress (*Table 2*). As *Figure 9* shows the ASTM-normalized flux decline (*red curve*) of this train exhibiting nearly the same pattern as that of the FM, with a steep decline commencing immediately. This is obviously due to the nature of heavy fouling developing very quickly, although if the train is being monitored only via this standard method, as is the case at most plants today, no corrective action can be taken regarding the fouling situation until this trend is confirmed after it has already become too late to correct it.

4.1.4 CASE B.2: SWRO Plant B – Low-Fouling Spiral-Wound Membranes (Train SW-15)

The results of evaluating the performance and fouling history of the SW train with *Low-Fouling (LF)* membranes (*Figure 11*) shows a similar pattern as that of the HR train's. The only difference in this case was the relatively longer stabilization period exhibited between 38,000-43,000 hours.

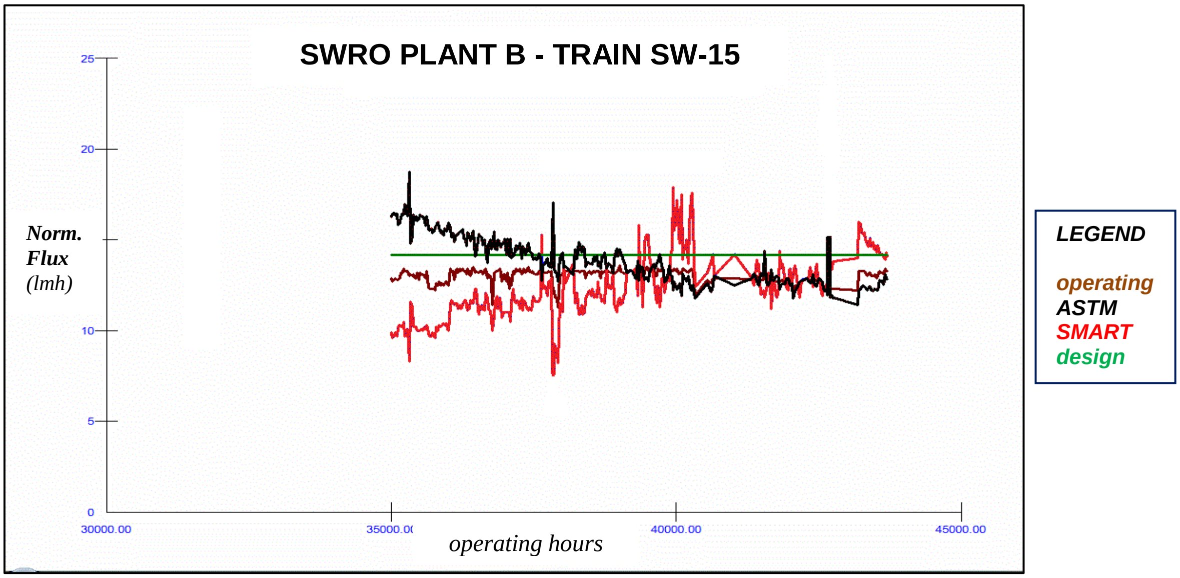

Figure 11 – Real-Time Normalized Flux Declines of Train SW-15 at Plant B with Fouling LF Membranes

The average FM for the LF train for the same period of operation after 8,712 total cumulative hours of operation was 18.4% (*Figure 12)*, indicating a moderate to heavy fouling in progress (*Table 2*).

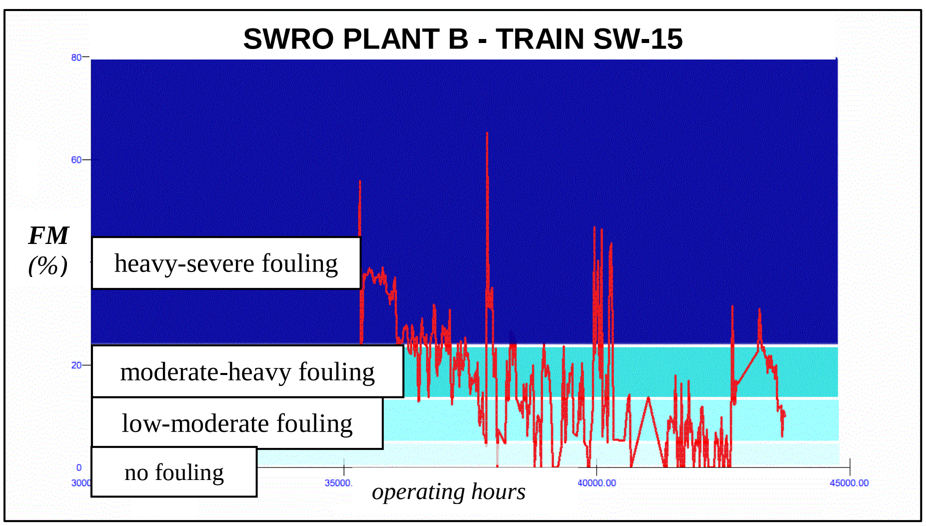

Figure 12 – Real-Time Fouling Monitor of Train SW-15 at Plant B with Fouling LF Membranes

A more interesting difference is the behavior of the ASTM-normalized flux decline, shown in the red curve (*Figure 11)*. In this case, a steep, almost uninterrupted downward trend is observed, only leveling off at about 41,000-43,000 hours. After that, a steep incline commences.

Finally, the SDI_{15} profile for this plant (*Figure 13*), with the same feed water source and pretreatment for all trains, shows a relatively rapid decline from the start up to 42,000 hours, followed by a relative stabilization for the rest of the period (*end of 2014*). Again, this behavior, as that of the ASTM-normalized flux decline trending is not indicative of the real-time fouling development witnessed on site and confirmed by the actual pressure drop profiles of both trains.

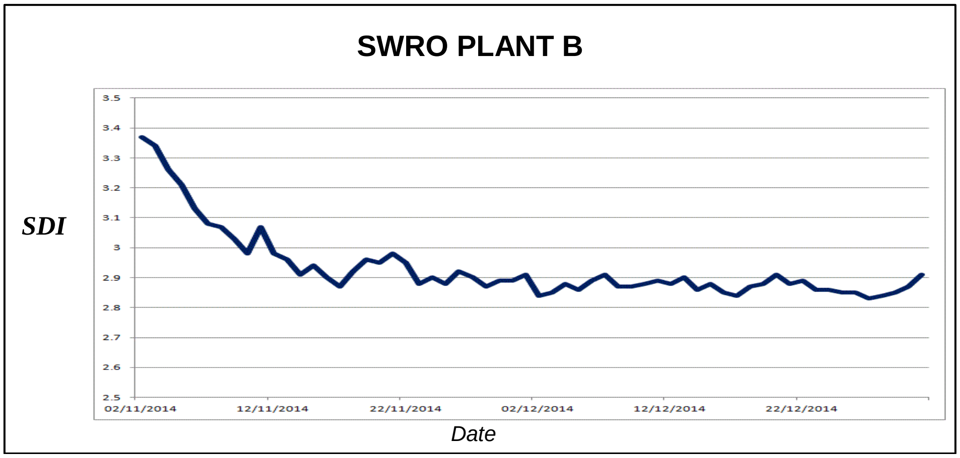

Figure 13 – SDI_{15} Profile of SWRO Plant B

4.1.5 *CASE C: SWRO Pilot Study - Standard Spiral-Wound Membrane (Test Skid)*

This SWRO plant, with a conventional membrane pretreatment system and a 7-element pressure vessel, was operated for several months as a feasibility study for a full-scale plant at the same location. Historical operating data taken hourly for about 2 months were obtained and evaluated. The plant consisted of one pressure vessel with 7 membrane elements of an older standard SW model.

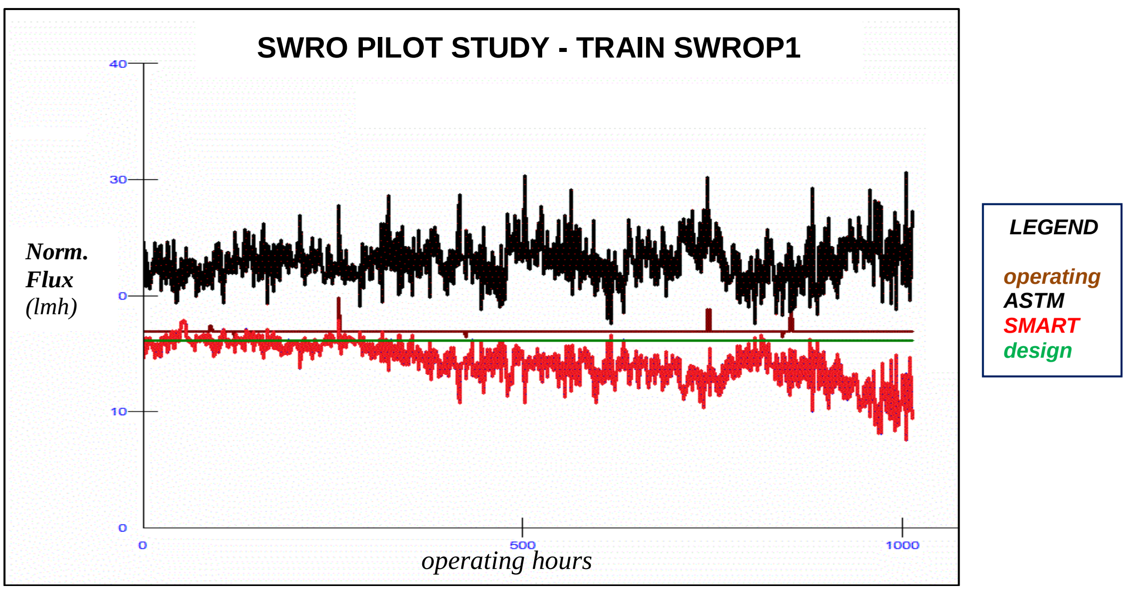

Figure 14 – Real-Time Normalized Flux Decline Profiles of SWRO Pilot Study with Fouling SW Membranes

As *Figure 14* shows, the membranes at this plant witnessed the onset of a significant fouling development period from the onset. The magnitude of the fouling was steady during the first 300 hours of operation, starting with FM values around 30%, after which it started to progressively increase, with a major shift upward at around 880 hours, with FM values reaching up to 60%.

The average FM for this plant during the entire 1,000 hours or so of operation was 36.9%, as shown by *Figure 15*, which indicates a heavy to irreversible fouling in progress (*Table 2*). It averaged 28.9% during the first steady region (*1-300 hours*), 38.5% during the second region (*301-880 hours*), and

47.4% during the third and final region (*881-997 hours*).

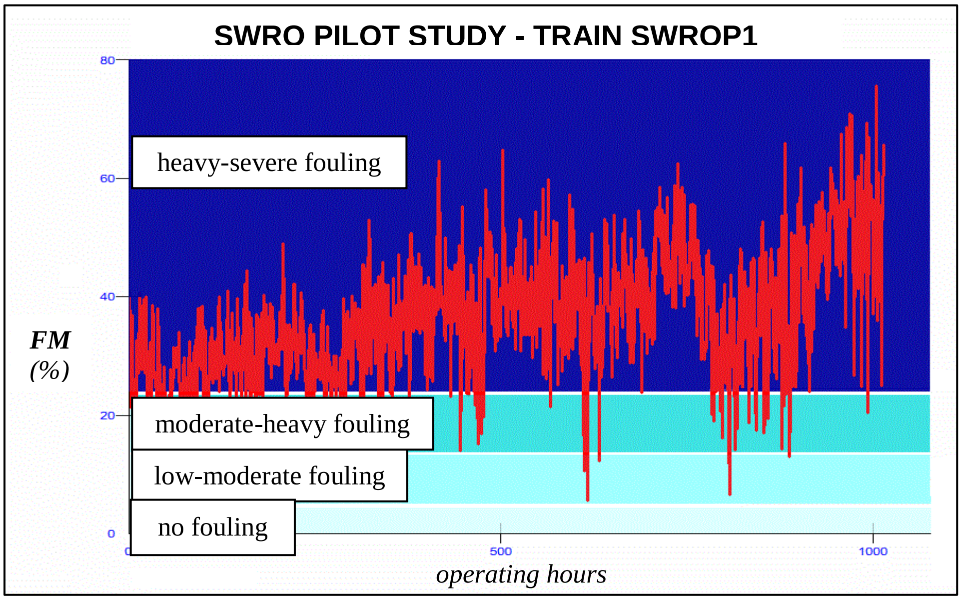

Figure 15 – Real-Time Fouling Monitor of SWRO Pilot Study with Fouling SW Membranes

The ASTM-normalized flux decline for this plant, on the other hand, shows several stabilized and up-and-down trending regions up to 800 hours, with all indicating better than the "guaranteed" or design or projected value, when the fouling became more acute, as shown by *Figure. 14* (*red curve*).

Interestingly, the SDI_{15} profile (*Figure 16*) shows a steadily decreasing trend from startup to about 325 hours, averaging 3.0, stabilizing between 326-555 hours and averaging 2.47, and finally increasing again after 555 hours and averaging 3.02 till the end of the evaluation period at 997 hours. Again, this pattern is not consistent with the actual fouling development determined by the real-time methodology and to some extent by the ASTM normalization, except for the last period when fouling was at the worst stage of development.

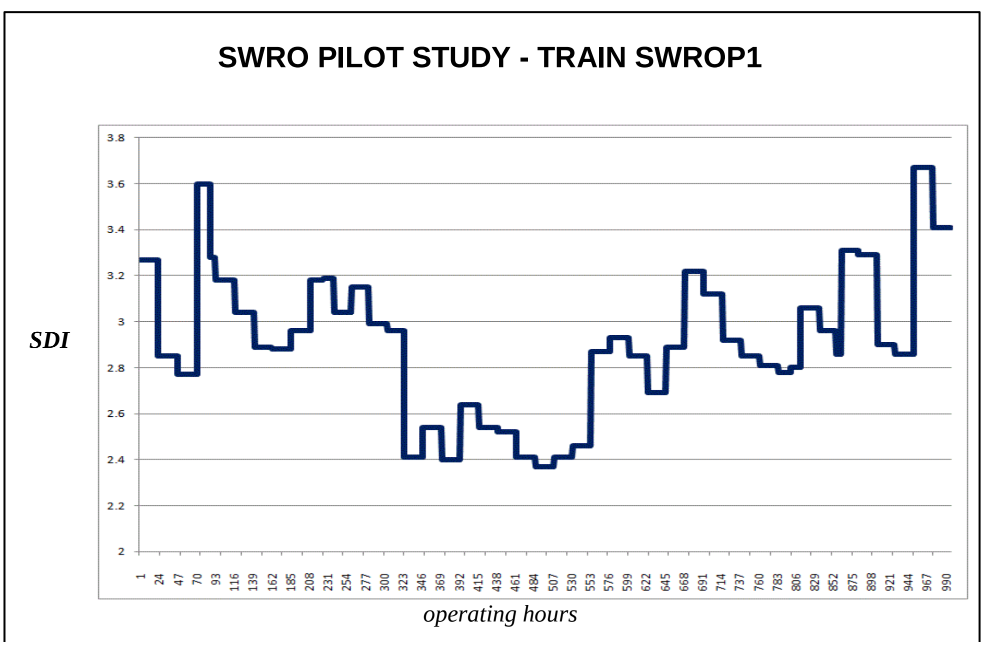

Figure 16 – SDI_{15} Profile of SWRO Pilot Study

IV. CONCLUSIONS

Over 4 decades of field-tested experience in membrane technology application for water desalination have taught us the critical need to rethink the old ways, theories and practices. The main driver is how to achieve the most efficient operation of the plant under real, site-specific water and operating conditions, not accounted for in the design, O&M procedures, standards and upgrade philosophies largely in use throughout the industry. This paper demonstrates an original, viable and innovative alternative solution that allows the measurement, monitoring and effective management of membrane fouling, the most critical issue in membrane desalination.

The presented plant case histories in this paper and numerous prior work clearly show that monitoring the performance and potential fouling development of the membrane system using the SDI_{15} monitoring or the standard ASTM normalization method is not adequate to address the fouling situation and its significant impact on the plant in a timely or meaningful way. The alternative SMART approach and analytical methodology was shown to be a far more effective, realistic and preventative way in fouling management as well as in performance optimization on a day-to-day basis. It allows the plant operator to manage the membrane fouling and optimize the plant as it operates under changing conditions as we enter the mega membrane desalination plant and renewable resources utilization era.

The SMART approach also has the potential to allow attaining higher conversion rates based on the actual and changing water and plant conditions by monitoring and optimizing them in real-time on a daily basis. This study could represent a significant step towards achieving superior, long-term plant performance, operational efficiency, sustainable environmental friendliness and more affordable cost of membrane desalination for a better world.

V. REFERENCES

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