Practical Experiences of Biofouling in Reverse Osmosis Systems

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ABSTRACT

Biofouling is a major problem in the water treatment industry where reverse osmosis (RO) technology is used to produce municipal and process water from brackish or sea water sources. This paper outlines the major indicators of biofouling and implications of its formation in such systems. It details some recent practical experiences of large RO systems that have experienced severe biofouling. This has had a detrimental effect on the membrane performance and plant productivity. Finally, it highlights the requirements of this industry for instrumentation to ensure early detection of biofilm formation and build-up, to allow optimised biogrowth control.

INTRODUCTION

Membrane processes are pressure-driven operations that utilise a semi-permeable membrane to separate solutes from a solvent. Reverse osmosis is capable of removing dissolved salts and other contaminants from feedstreams. RO is used worldwide for the treatment of natural water sources to produce drinking water. RO is now being seriously considered by many UK water utilities to supplement their traditional supply of tap water. Membrane technology is already used in a number of UK industries to provide process water for applications such as electronics, pharmaceutical, beer and beverage production.

The membrane type generally used for potable water treatment applications are thin film membranes made from polysulphone with an ultra-thin polyamide salt rejecting layer. The pore size of these membranes is less than 0.001 microns, and they typically reject >98% of dissolved salts and all organic particles, microorganisms and other nutrients.

RO is used to treat surface water, well water and sea water. The most commonly encountered foulants that affect the performance of RO membranes are calcium carbonate and sulphate scales, organic matter, iron and biofilm.

Biofouling has become a major cause for concern among plant operators, resulting in reduced output, increased pressure differentials, poor water quality and increased operating costs. This is particularly problematic when operating a plant in regions with high ambient water conditions where membrane biofouling is seen as a regular occurrence in reverse osmosis systems with inadequate pre-treatment or poor sanitisation procedures to control the rate of biological growth.

BIOFOULING IN RO SYSTEMS

The design of spiral wound membrane elements and the conditions at the membrane surface are perfect for the attachment, accumulation and growth of microorganisms. The environment at the separating surface is confined and high in nutrients. The narrow channel space between the membrane leaves is subjected to relatively low crossflow velocity (0.1 m/s) with limited turbulence. Once biofilm has become established, it provides an ideal environment for the further growth of microorganisms. These can form as thick biofilms within a polysaccharide and water matrix, which adheres to both the membrane surface and the plastic spacer material that separates the membrane leaves.[1–3] The resulting biofilm formed can act as a 'trap' for other particulate matter, which may quickly build up as a dense biomass.

Microorganisms present in the incoming feedwater may include bacteria, fungi and yeasts. The diversity of species present is dependent on the water source and the subsequent pre-treatment operations prior to entering the membrane. It is usual for feedwater to be chemically treated by antiscalant dosing to prevent scale formation and chlorination to eliminate or control biological growth. However, the polyamide material of RO membranes becomes irreversibly damaged when exposed to oxidising agents. Therefore, dechlorination with sodium bisulphite is carried out prior to water entering the membrane

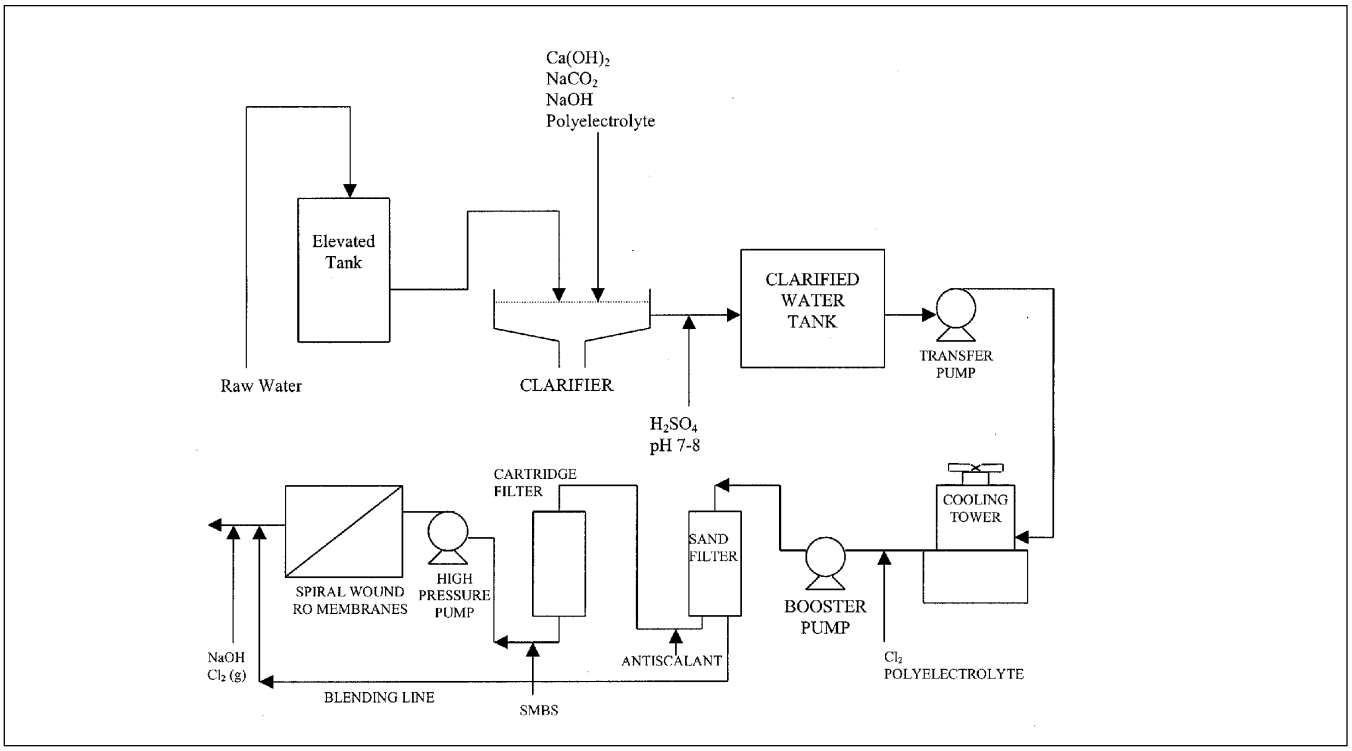

Figure 1 — ***Reverse osmosis pre-treatment plant***

elements. The usual procedure is to dechlorinate feedwater ahead of the micron cartridge filter, which results in a significant length of pipework that is susceptible to microbiological growth, hence promoting biofilm formation within the membrane system.

In well-designed systems, this risk can be minimised and biofouling does not attain a level that will significantly interfere with membrane performance and water production rate. The best way of limiting biofouling is effective removal of nutrients and existing microorganisms by pre-treatment processes such as flocculation and media filtration. Repositioning the dechlorination point after the micron filters should also be considered (Figure 1) along with periodic maintenance cleaning of the pre-treatment plant and membranes with a non-oxidising biocide.

There are a number of indicators to plant operators that biofouling is the likely cause of degraded plant performance:

- An increase in pressure differential across the plant
- Declining membrane flux and physical evidence of slimy coatings on the cartridge filters
- High planktonic bacterial counts in the feedwater

It is well practiced in the RO industry to monitor the level of planktonic counts, but as is well known from cooling water technology, planktonic counts are unreliable pointers to sessile biofilm characteristics.

Currently, the only accurate method of determining the microbiological condition of the membranes is to carry out destructive autopsy procedures to analyse foulant from the membrane surface. Unfortunately, it is not always practicable to do this and there is a significant delay between removing a fouled element and obtaining the results of microbiological analyses. Ideally, industry requires some form of on-line instrumentation that could give simultaneous indications of the microbiological condition of the membrane and information to predict the rate of further growth.

LABORATORY AUTOPSY OF BIOFOULED MEMBRANES

A large number of reverse osmosis systems have been investigated to quantify and characterise biofouling. The main objective has been to gain sufficient information to recommend effective procedures to remove accumulated biofilm and prevent re-contamination and further biofouling problems.

In addition to visual inspection of the condition of micron cartridge filters and evidence of slimy coatings on pipework or in chemical dosing tanks, membrane autopsy provides comprehensive information on the characteristics of the membrane foulant.

Standard autopsy investigation involves the dissection of a fouled membrane element to reveal the membrane leaves and plastic spacer material. Foulant

Figure 2 — *Membrane autopsy*

sample is then scraped from a known surface area for microbiological and chemical analysis (Figure 2). Results of these analyses can then be expressed in terms of foulant composition and colony forming units (cfu) per cm^2 of membrane area.

Moisture content and chemical composition of the dried deposit is determined and expressed as % of foulant. In some fouling situations, this will require humic acid analysis; this is necessary when treating high coloured surface waters such as those found in the Scottish Highlands or in areas of Northern Europe. Microbiological analysis consists of basic identification and enumeration of bacteria, fungi and yeasts. Biocide Sensitivity Tests (BST's) can be used to evaluate the performance of selected biocides on sessile organisms.

Membrane biofilms have been characterised by our laboratory to provide enough basic information to evaluate the cause, degree of accumulation and ease of removal.

The following characteristics are typical for many biofouled plants we have investigated:

- >90% moisture content
- of dried deposit, >80% total organics
- up to 40% humic substances as % of total organics in high coloured waters
- low inorganic composition
- high microbiological counts (>10^6 cfu/cm^2) including bacteria, fungi and sometimes yeasts

There are many more standard microbiological techniques available such as ATP, protein and carbohydrate determinations; but in most cases, the above information has been sufficient for making informed decisions on future plant treatment and operation.

The following bacteria are regularly identified on the membrane surface: *Corynebacterium, Pseudomonas, Arthrobacter, Actinomyces, Flavobacterium* and *Aeromonas*. One or more of the following fungal genera have also been found in the majority of samples, sometimes in significant numbers: *Penicillium, Trichoderma, Mucor, Fusarium* and *Aspergillus*. It is not common practice in the industry to enumerate or identify planktonic fungal species, but our studies have found this to be a significant contributor to sessile fouling.

Typically, the bacterial counts found on a biofouled membrane will range between 10^6 and 10^8 cfu/cm^2. Theoretically, microorganisms should not be present on the permeate side of the membrane due to their size, but it is common to find significant counts on the product water carrier.

Autopsy has also enabled samples of fouled membrane, spacer and product water carrier to be exposed to biocide formulations or tested with cleaning formulations in a flat sheet test cell to determine suitable cleaning or sanitising procedures. Samples are often inspected by scanning electron microscopy (SEM) and surface analysis such as X-Ray Photoelectron Spectroscopy (XPS).

BIOFILM DETECTION AND MONITORING

The traditional methods used to monitor and detect biofilms in RO systems are planktonic water analyses or visual inspection of the pre-treatment plant including the micron filters. Autopsy procedures are regularly carried out in systems where the cause of plant fouling is not readily apparent from a routine plant survey. However, this destructive technique is not the ideal choice. The autopsy procedure will usuallybe carried out only when a biofilm or fouling layer has established itself to a level that is detected by marked changes in plant performance and efficiency. Pressure drop, flux or percentage salt rejection would be the main performance indicators. There is also a significant time lag between sampling and analytical results.

The RO industry needs reliable and accurate on-line techniques capable of predicting or measuring biofilms in their initial stages of attachment. Such an instrument may provide rapid results that would enable operators to act quickly to prevent further accumulation of biofilm by modifying the pre-treatment or removing the fouling by cleaning.

MEMBRANE CLEANING

Cleaning recommendations to remove biofilms are specific to each individual plant. The cleaning chemicals used, frequency and number of cleaning cycles are determined by the biomass composition, the membrane material and the degree of fouling.

Cleaning procedures have been developed to remove biofouling. These are usually three or four stage cleaning schedules that incorporate alkaline surfactant cleaners and a non-oxidising biocide.

Cleaning is recommended when pressure differentials or membrane flow rates change by 15% of the design specification. The cleaning solutions are most effective when circulated at elevated temperature, preferably 30°C with alternating periods of soaking and recirculation. The following procedure has proven effective in the majority of biofouling plants. However, the real cause of biogrowth is seldom solved, requiring repeated use of the procedure at increasingly shorter time intervals.

CLEANING SCHEDULE FOR BIOFOULING REMOVAL

The membranes were rinsed with chlorine-free water between each stage of the cleaning procedure:

Step 1: Alkaline surfactant and chelating agent, to condition and break down organic fouling.

Cleaning conditions: pH 10.5, 30°C, 4 hour recirculation and soaking.

Step 2: Broad-spectrum non-oxidising biocide, to stop microbiological growth.

Cleaning conditions: 30°C, 6 hour recirculation and soaking.

Step 3: Alkaline surfactant, to remove microorganisms and organic debris.

Cleaning conditions: pH 10.5, 30°C, 4 hour recirculation and soaking.

Step 4: Optional acidic clean, to remove traces of inorganic scale and iron oxide.

Cleaning conditions: pH 3.6, 25°C, 2 hour recirculation and soaking.

Suitable biocides must comply with a long list of specifications that includes: broad-spectrum, membrane compatible, non-filming, anionic or nonionic, non-oxidising and preferably fast acting. The industry is in need of new effective biocide formulations compatible with polyamide membrane systems, but the likelihood of identifying new formulations is low due to the impending European Biocidal Products Directive.

CASE STUDIES

In a number of severe fouling situations at large RO installations in Europe and the USA, it has been fully justified to temporarily shut down the plant and remove a representative membrane element for autopsy. The following outlines the results of some recent autopsy investigations. Cleaning recommendations were made and, in some cases, proposals to modify the existing pre-treatment or monitoring practices to restore the membranes to their original design output.

MUNICIPAL PLANT, SOUTHERN EUROPE

An autopsy was carried out on a fouled membrane from a large municipal RO plant. The plant has 8" polyamide membranes installed and is currently operating between 70 and 80% recovery. The feedwater from various wells is chlorinated with sodium hypochlorite and fed to sand filters. Sulphuric acid is dosed to control pH and sodium bisulphite to remove the residual chlorine. A phosphonate antiscalant is dosed to successfully prevent scale formation. The plant has been in operation for 2 years and recently suffered significant increases in pressure drop, suspected as being due to biofouling.

On inspection, the membrane layers appeared moist and uniformly covered with foulant. A fawn-coloured deposit was visible on the leaves but not on the plastic spacer material.

The foulant contained 96% moisture. Chemical analysis of the dried deposit identified organics (76%), silica (7%), calcium as calcium phosphate (4%), calcium as calcium sulphate (3%) and iron as iron oxide (3%) as the major foulants. Humic acid determinations found the organic composition to be 44% humic substances.

Surface analysis (XPS) identified the presence of mercury on the membrane surface. Further analysis on a sample of foulant detected 0.4% mercury. This was an unusual observation.

Microbiological analysis of the fouled membrane showed 2.88×10^6 cfu/cm^2 of bacteria present on the surface with 1.81×10^5 cfu/cm^2 on the plastic spacer material. No fungi or yeasts were isolated, but significant numbers of bacteria were identified on the product water carrier.

Only one genus of bacteria was identified as predominating on the membrane surface; this is unusual in biofouled systems. The organisms detected were *Pseudomonas vesicularis* and *Pseudomonas fluorescens*. *Pseudomonas* is recognised as a prolific slime producer, often predominating in water systems.

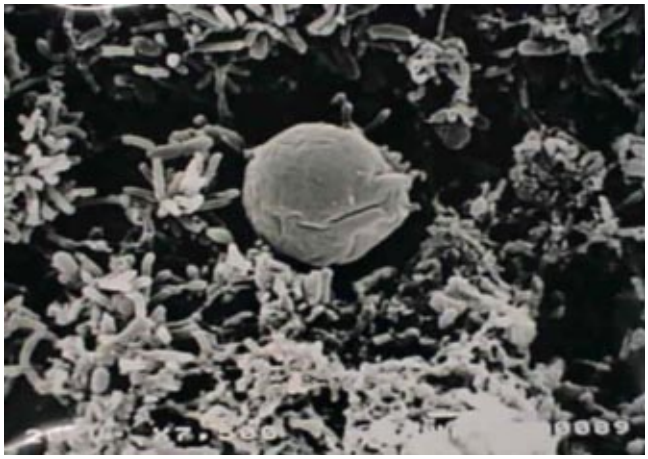

Figure 3 — *SEM of biofouled membrane. Magnification x7,500.*

SEM micrographs clearly showed the presence of large quantities of biofilm material but relatively small numbers of bacteria on the fouled membranes (Figure 3). This biofilm had unusual characteristics. Although the pressure drop across the system had greatly increased, the membrane flux was not significantly affected. This indicated that the biofilm had properties that affected the hydraulic resistance and drag resistance of the feedwater flow but did not affect the porosity of the membranes.

This biofilm was particularly difficult to remove using standard cleaning procedures. The only success in removing the foulant was with a surfactant clean at pH 13, which exceeds the normally advised pH limits stated by the membrane manufacturers.

MUNICIPAL PLANT, USA

The reverse osmosis plant treats water from 20 wells. Pre-treatment includes manganese greensand to remove the iron and dosing of antiscalant and acid to control scale. The plant has an output of 4.5 MGD, operating at 83% recovery and 100 psi feedwater pressure. The plant was originally designed to produce 6 MGD but has suffered from heavy biofouling problems for some time.

The main composition of foulant on the membrane was found to consist of organic material (96%). The percentage of iron in the foulant was low (0.9%). Microbiological analysis of the membrane foulant identified bacteria in large numbers up to 3.6 x 10^6 cfu/cm^2 of membrane. The bacteria were identified as being predominately *Corynebacterium*. Small numbers of yeast and fungi were also identified, but the numbers were not high enough to be the primary cause of fouling.

SEM micrographs revealed a heavily contaminated membrane surface with large numbers of rod-shaped

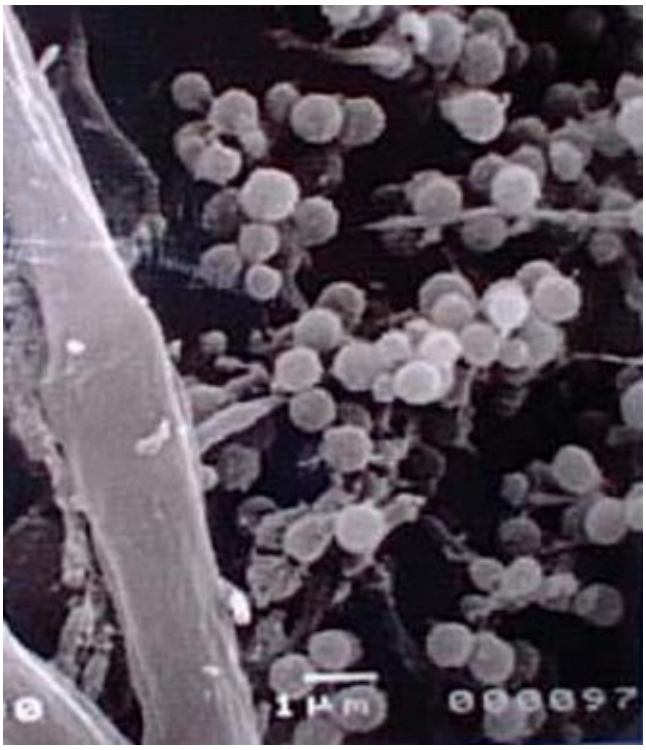

Figure 4 — *SEM of bacteria on biofouled membrane. Magnification x7,500.*

bacteria in evidence (Figure 4). Modifications have since been made to the pre-treatment plant and some of the wells are no longer supplying the plant. The pre-treatment plant was sanitised and some pipework replaced. Performance has now improved considerably.

INDUSTRIAL PLANT, NORTHERN EUROPE

The plant treats a mixture of well water (30%) and permeate from a tubular reverse osmosis installation to produce industrial process water. The feed capacity is 100 m^3/hr at 18 bar inlet pressure and 25°C feed temperature. The design recovery of the plant is 75% to 80%. The membranes have suffered severe fouling problems and reduced product flows.

A heavy deposit was visible on the membrane surface. It was noticeable that there were many areas of severe localised fouling on the leaves. The fouled membranes had a strong odour. Analysis of the deposit identified organics (66%), silica (12%), calcium as calcium carbonate (9%), calcium as calcium phosphate (5%) and aluminium as alumina (3%) as the major foulants.

Microbiological analysis of fouled membrane found bacteria on the membrane surface at levels of 4.88 x 10^6 cfu/cm^2 and 5.84 x 10^6 cfu/cm^2 on the plastic spacer material. These numbers are high and are typical for a severely biofouled membrane. The bacteria were identified as rod-shaped species.

No fungi were isolated, but high numbers of yeasts were found on the membrane and plastic spacer. The number of yeasts enumerated were 4.8 x 10^7 cfu/cm^2 on the membrane and 2.4 x 10^8 cfu/cm^2 on the spacer material. It is unusual to find such high number of yeasts on a fouled membrane. The yeast was identified as *Candida*.

Significant number of microorganisms were identified on the product water carrier: 3.44 x 10^5 cfu/cm^2 bacteria and 4.0 x 10^6 yeasts.

The plant is now sanitised and cleaned on a regular basis with an alkaline surfactant and a non-oxidising biocide. The biofouling situation has been controlled to a tolerable level.

In each of the examples detailed above, the quantity of biofilm accumulation was significantly affecting plant performance. In all cases, successful recommendations for cleaning or modifications to pre-treatment were made to minimise the fouling. However, the development of an effective biofilm monitor would alert operators of biofilm formation at an earlier stage of fouling without the need for destructive membrane autopsy procedures.

CONCLUSIONS

Biofouling is a major concern for operators and owners of reverse osmosis installations. Many of the problems concerning biofilm formation is due to poor pre-treatment design or failure of these systems. The industry is in need of techniques and instrumentation that can be used to predict and monitor the biofilm risk.

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