

IMPACT OF UV IRRADIATION ON CONTROLLING BIOFOULING PROBLEMS IN NF-SWRO DESALINATION PROCESS¹

Hassan A. Munshi, Mohamed O. Saeed, Troy N. Green, Ali A. Al-Hamza, Mohammad A. Farooque and Abdul Rahim A. Ismail

Saline Water Desalination Research Institute
Saline Water Conversion Corporation (SWCC)
P.O.Box 8328, Al-Jubail 31951, Saudi Arabia.
E-mail: rdc@swcc.gov.sa

ABSTRACT

The study was carried out to evaluate the ultra violet (UV) treatment on controlling biofouling in NF-SWRO Pilot Plant at Research and Development Center (R&DC) at Al-Jubail. The study compared two phases: regular operation (without UV) and plant operation under UV-radiation treatment ahead of the nanofiltration membranes. Water samples were collected from different locations on the pretreatment line: raw seawater (RSW), after UV unit (AUV), after media filter (AMF), after cartridge filter (ACF), nanofiltration permeate (NFP) and nanofiltration brine (NFB). 0-h Bacterial count, 48-h bacterial aftergrowth, phosphate, nitrite and TOC were estimated for these samples. The study showed a 99.15% reduction in bacterial counts of stream of NF-SWRO feed after UV-radiation treatment as compared to RSW suggesting high performance of UV sterilization. Laboratory studies showed that, incubation of UV treated samples for 48-h resulted in bacterial recovery or aftergrowth. AUV and NFP samples registered reduced TOC, nitrite and phosphate levels in the feed water indicating the presence of nutrient scavengers before the NF membrane. More declines were found in phosphate, nitrite and TOC concentrations in 48-h incubated samples indicating nutrient up-take by bacteria.

The study suggests that UV treatment have a high performance and considerably reduce bacterial load in a NF-SWRO system in the pilot plant. Bacterial aftergrowth rate of seawater treated by UV-radiation showed results which significantly lower than untreated seawater. On line, additives of NF-SWRO feed during the pretreatment course have a role into supporting the bacterial aftergrowth. Applying UV-radiation

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unit a head of NF-membranes have influence into controlling biofouling problems in SWRO desalination process.

1. INTRODUCTION

Seawater Reverse Osmosis (SWRO) desalination plants using seawater as a feed face biofouling problems from bacteria originating from feed seawater. Biofouling leads to decreased SWRO membrane performance and thus affects plants' operation. Once bacteria reach an RO membrane, they colonize the membrane surface building a biofilm causing membrane fouling.

Most disinfection strategies to control bacterial growth in SWRO plants use chemicals. Control of bacterial growth by chemical disinfectants depends on many factors, such as chemical concentration, its mode of action, contact time, density of organisms and total suspended solids (TSS) of feed water. These factors make it extremely difficult to attain absolute disinfection. In addition, chemical disinfectants like chlorine and its derivatives may be hazardous to health. Chlorine, is known to oxidize and degrade the humic substances in seawater, thus, resulting in smaller molecules, which are assimilable organic carbon (AOC) [1]. The AOC in turn is a good nutrient source for marine bacteria [2] and under such situations could also lead to rapid biofilm formation in SWRO plants [3]. Chlorination may also enhance the formation of trihalomethanes and other chlorinated by-products which are carcinogenic compound.

Filtration is an effective method to control biofouling of RO membranes and different types of filtration media are used. Permeate of nanofiltration (NF) membrane was tested earlier in Al-Junail RDC pilot plant, as a feed for SWRO [4]. NF membranes have the capability of rejecting particles/molecules down to one nanometer (nm) size. Bacterial cells are normally between 0.5-5 μ m, and are therefore mostly removed or return by on the NF membrane surface. These bacteria should be disinfected or otherwise they could form a biofilm on membrane surface. Further, bacterial disinfection is essential for the treatment of feed for NF-softening plants [5] and in water treatment by NF-RO systems [6], where it protects against biofouling and assures efficient plant performance.

A study on UV-radiation disinfection [7] in an SWRO pilot plant showed a reduction between 90 to 99.9% in bacteria present in raw seawater after UV treatment. Bacterial (48-h) aftergrowth rate of seawater treated by UV-radiation showed results which resemble untreated seawater. Since NF product water used as feed for RO membranes is much cleaner than that of a conventional RO pretreatment feed, UV-radiation disinfection will be more efficient in controlling bacterial growth in NF treated RO feed water. Subsequently, biofouling potential of RO membranes will decrease. Moreover, UV treatment has other advantages. It has immediate germicidal effect. Being a closed system, it is safe and it requires only a small space for equipment [8]. It is well established that killing of microbial cells by UV-radiation is primarily due to its action on deoxyribonucleic acid (DNA). Bacteria, phages, viruses are also killed or reduced in population. Organic micro-pollutants by photochemical wet combustion down to or below detection limits of organic carbon [9]. However, incorrect application of UV-radiation in feed water treatment can be unsuccessful [10]. Determining the right dosage and locations of UV unit for a system is essential. Therefore UV sterilization has become a practical solution for safe disinfection of drinking water. Also, usage of medium pressure lamps with small reactors has helped to substantially reduce the capital costs of UV treatment [11]. The present study aims to evaluate the effectiveness of UV-radiation into controlling biofouling problems in NF-SWRO system.

2. EXPERIMENTAL

2.1 NF-SWRO System Description at the R&D Pilot Plant

The pretreatment section consists of a dual media filter followed by a fine sand media filter operated at a feed flow rate of 7m³/h (Figure1). Raw seawater was obtained from an open sea intake. A coagulant (0.4–0.6mg/l FeCl₃ as F³⁺) was used to reduce SDI to ≤4. UV unit consisting of a Fluid Type Medium Pressure UV Sterilization unit, (300 watt at 257.7 nm) associated with pretreatment section before NF membranes. The pretreated seawater was then stored in a 15m³ capacity holding tank. Six of these membranes were used in series. Four out of the 6 membranes were Osmonics DK4040 NF membranes (size of 4" × 40") and the rest were Trisep TS80 N membranes. The feed flow was about 3m³/h and at a feed pressure of 25bar and a pH of 6. Permeate from the NF membranes used as feed for the cellulose triacetate HFF type RO membranes [12].

2.2 Experiment Different Phases

The study was carried out during October 1999 to April 2001. Viable bacterial growth, and aftergrowth in the feed water were studied at different locations of the NF-SWRO pilot plant of the Research & Development Center (RDC) at Al-Jubail. The study was carried out at different stages of the plant:

1. Normal plant operation condition (without using UV-radiation).
2. Plant operation with UV-radiation ahead of NF membrane.

In the different phases, UV-treated and untreated samples were collected from: raw seawater (RSW), after media filter (AMF), after cartridge filter (ACF), nanofilter product (NFP), after UV-unit (AUV) and nanofilter brine (NFB) (Fig. 1).

2.3 Bio-analyses

Samples were aseptically collected in sterile polyethylene containers. Bacterial counts were carried out using standard pour plate method [13]. Within 15 min of collection, samples were serially diluted and cultured using marine agar. Plates were incubated at 30°C for 96 to 120-h [3] and the colony counts were recorded as colony forming units (CFU). Water samples were further incubated at 30°C for 48-h for bacterial aftergrowth studies

In order to monitor the changes in nutrient concentrations under UV-radiation treatment and their possible effect on bacterial aftergrowth, total organic carbon (TOC), nitrite, and phosphate were estimated. The samples used to measure TOC were collected in sterilized glass bottles. TOC was determined by measuring CO₂ released by catalytic combustion of organic carbon, using a non-depressive infrared detector. The samples were acidified and total inorganic carbon (TIC) was purged off prior to the analysis. TOC analysis was carried out using SHIMADZU TOC Analyzer Model TOC-500 [14] and USEPA method [15]. Analyses of phosphate and nitrite were carried out following the methods of Parsons *et al.* [16].

3. RESULTS

Phase-I

Viable bacterial counts in study phases are given in Table 1 and Figure 2. Phase I consists of monitoring normal operation of the NF-SWRO (without applying UV-radiation). Results showed a reduction in bacterial counts at AMF as compared to RSW. While RSW showed 1.66×10^4 CFU/ml, AMF showed 5.65×10^3 CFU/ml. Average bacterial count at ACF 1.93×10^2 CFU/ml. NFP exhibited an increase in bacterial count compared to ACF sample. Also NFB showed a slight increase in bacterial count compared to RSW. Bacterial aftergrowth studies are shown in Table 1 and Figure 3. Bacterial aftergrowth rate showed an increment in all sampling stages. Bacterial aftergrowth at AMF and ACF are similar to RSW. NFP has a significant increase in bacterial population while NFB has the highest bacterial aftergrowth compared to RSW. Average of TOC levels in RSW at 0-h was 1.29mg/l.

A considerable decline noticed of this value in NFP samples. After 48-h incubation of samples, TOC levels also showed decline especially in NFP samples. Average of Phosphate concentration was $4.66 \mu\text{g/l}$ and Nitrite was not detected (Table 2).

Phase-II

One UV unit was installed just ahead of the NF-membrane. Average of viable bacterial counts at RSW was 1.33×10^4 CFU/ml. AMF and ACF bacterial counts were 4.08×10^3 CFU/ml and 2.07×10^3 CFU/ml, respectively. At AUV sample, the bacterial count is 1.14×10^2 CFU/ml, with more than one magnitude reduction in bacterial load in feed at ACF samples (99.15% reduction in bacterial load in feed stream at RSW samples). Further reduction in bacterial count occurred at NFP (1.54×10^1 CFU/ml). Whereas, bacterial counts of the NFB sample resembled RSW (Table 1 and Figure 2).

Bacterial aftergrowth rate of RSW, AMF, ACF, AUV and NFB samples were comparable. NFP sample had the lowest bacterial aftergrowth rate compared to other samples in this study phase by about two magnitudes (Table 1 and Figure 3).

TOC concentration was 2.26mg/l at RSW and 1.99mg/l at AUV with further appreciable decline at NFP. Most decrease in TOC was noticed after 48-h of

incubation. Phosphate concentration was 4.89 $\mu\text{g/l}$ at RSW, 3.45 $\mu\text{g/l}$ at AUV and 0.78 $\mu\text{g/l}$ at NFP. Upon 48-h incubation, high consumption of phosphate occurred in these samples. At 0-h, the nitrite level was 3.74 $\mu\text{g/l}$ in RSW, 1.27 $\mu\text{g/l}$ at AUV and 0.51 $\mu\text{g/l}$ at NFP. At 48-h a noticeable reduction in these values was reported (Table 2).

4. DISCUSSION

The viable bacterial count at different study phases of NF-SWRO system is given in Table 1 and Figure 2. Bacterial density in most seawater samples lay in the range of 10^3 to 10^4 CFU/ml. The viable bacterial count in RSW obtained was within this range in during the study phases. Nanofiltration membrane should clear feed seawater from bacterial cells as it rejects particles of nanometers size. It was used to remove organic and humic materials from ground water. The concentration of these substances declined from 20-22 mg/l to lesser than 0.5 mg/l in ground water [17].

Bacteria were still present in NFP in this study. The data is similar to those of a similar study [18], where bacterial density of 10^1 to 10^2 CFU/ml was reported. The origin of bacteria in NFP (at that time) was uncertain. The bacterial colonies in NFP were of such tiny size of probably deformed cells or cellular fractions that would be incapable of colonizing RO membranes. Under starvation condition, bacteria produced daughter cells of spherical shape and a diameter of 0.1 to 0.2 μm [19]. Such tiny cells may escape into the NF product water. Also, some bacteria which escape filtration may be able to permeate faulted sites on the surface of these membranes [6].

Accumulations of different microorganisms on an NF membrane surface could eventually foul the membrane. Such case was reported on presence of bacterial cells deposition on an NF membrane surface, of a magnitude of 10^3 to 10^4 CFU/cm², with evidence of diatoms [20].

Disinfection efficiency of UV-radiation depends on a multitude of water quality parameters. These include TDS, TSS, organic matter, and hardness. Application of UV-disinfection is known to be more efficient in clear waters. In NF-SWRO or SWRO plants, a good site for application of this treatment is the nanofiltered water before the RO membranes. Sensitivity of microorganisms to UV-radiation also varies [21].

Seawater is usually deficient in nutrients and bacteria are under starvation conditions. Starved bacteria are more resistant to UV-radiation [22].

Denaturing the DNA molecules through photohydration brings about the lethal effect of UV-radiation. This effect is maximal in actively growing cells whereas, less active cells are more resistant to disinfections and UV-radiation. Apparently, because of starvation due to nutrient shortages, bacteria were able to withstand UV-radiation action. Also, it appeared that bacteria were able to recover from UV-radiation (photo-reactivation) [22]. Photo-reactivation of UV-radiation was reported to have activated coliforms in a secondary sewage treatment stage [23].

However, ACF, AUV and NFB samples showed presence of viable bacterial cells, whereas, NF brine samples showed the maximum increases in the bacterial counts, suggesting that the UV-sterilization was not successful in controlling their bacterial growth. The results showed that the source for increase in bacterial counts at the NFP and NFB appears to be due to recovery of bacterial growth after UV-treatment. Spores and slowly growing bacterial cells are less affected by UV-radiation than are vegetative and rapidly growing cells [21]. Since UV-radiation acts primarily on DNA, there may be no time for repair mechanisms to be put into effect when cells are rapidly replicating, whereas for less active cells, resistance to UV may be a measure of the operational repair mechanisms.

The term aftergrowth used to describe bacterial growth upon further laboratory incubation or after a biocide has neutralized. It is indicative of nutrients availability in feed water which supports bacterial growth and reflects addition of nutrients in the pretreatment course of NF-SWRO feed. Also, aftergrowth can reflect the photoreactivation of injured bacterial cells. The aftergrowth was determined following 48-h incubation time of samples at 30°C.

Torrentera *et al* [24] studied the reduction of bacteria in stored seawater after different filtration and UV treatments. They found that the UV-radiation system consisting of 1, 2 or 3 lamps were practical for water disinfection, whereas, when 4 lamps were used the treated water became sterile.

Aftergrowth counts registered increases over the initial counts. The growth of bacteria was dependent on the original nutrients level present with no additional food. Bacteria inactivated cells by UV-radiation could regenerate upon incubation and survivor's cells (escapee to expose to UV-radiation) could use dead bacterial cells as food. In both instances, an increase in numbers would result.

The aftergrowth studies conducted in the present study, showed that UV-treated samples have resulted in lower than normal bacterial counts of untreated seawater. The aftergrowth rate in phase-I (untreated seawater) reported the highest rate of the same of other UV treated phase-II (Table 1 and Figure 3).

However, an increase in bacterial count after 48-h was noticed at AMF and ACF locations. Presumably, due to recovery of bacteria at these filters and in the storage tank ACF. The high aftergrowth was at AMF, ACF and AUV, which is indicating presence of suitable source of food. The bacteria, which could not revive in the AMF, had ample time to recover in the cartridge filter (CF). Also, dead bacteria accumulated in the station next to the DMF, which is the CF. In both instances, significant growth of bacteria would result in the CF. The CF is well known to be a reproduction site for bacteria, because of its huge surface area [18].

In sum, recovery of bacteria may be attributing to reviving of cells that were inactivated but not killed by the UV-radiation or due to division of surviving cells in presence of suitable food source during pretreatment course of feed water.

Bacterial aftergrowth, are highest at NFB in phase-I, because acidification by sulfuric acid may be a source of nutrients. Acid hydrolysis liberates nitrogen from humic substance presence in seawater [25], and marine bacteria grew faster in presence of nitrogen, inclusion of yeast extract in media was found to stimulate rapid growth of marine bacteria, possibly due to its high nitrogen content [3]. The mechanism by which yeast extract could enhance bacterial growth initiation was neither specified nor explained. It is probable that components present in yeast extract some form of inducing action on dormant cells [26] or prevents unbalanced growth of starved or damaged cells [27]. Brozel and Cloete [28] observed that lower nitrogen content was beneficial to bacterial colony formation. Since, acidification is an integral component of

pretreatment of feed water of NF-SWRO of the hydrolysis liberates nitrogen from organic matter, it consider to enhance bacterial growth initiation. Continuous supply of nutrient and favorable conditions could result in rapid proliferation of bacterial cells and subsequent biofouling of SWRO facilities. Aftergrowth rates were highest in the brine reject because at this extreme point of the pretreatment line nutrients accumulate and increase in concentration leading to a corresponding increase in bacterial aftergrowth. Phosphate and nitrite concentrations were depleted as they were utilized along the pretreatment line.

Similar results were reported from study [29]; where the bacterial aftergrowth rates increased after chlorination/dechlorination. Applegate [2] also reported that the chlorine degrade humic acid (HA) into small molecules which are assimilable organic compounds (AOC) and since AOC favor bacterial growth this could result in bacterial aftergrowth. Li *et. al.* [30] found that there is a slight decay of HA after UV-treatment presumably due to its effect of decarboxylation of these compounds. Moreover, Egil, *et. al.* [31] also stated that UV-treatment of water containing humic substances may cause formation of oxidizing compounds such as singlet oxygen, hydrogen peroxide and OH-radicals. Such compounds may have an effective toxicity towards bacterial cells, and hence may also be important in controlling bacterial aftergrowth in NFB samples of study phase-II. However, Lund, *et. al.*, [32] noticed a decomposition of humic substances after a period of one week of UV-irradiation. This may be due to hydroxyl radicals. Moreover, study [7] showed that the bacterial aftergrowth rate of UV-treated seawater samples were similar to untreated when compared to doubling of bacterial growth despite application of the disinfectant. This highly pointed the efficiency of UV-radiation in to controlling the initial bacterial growth and aftergrowth, instead of lack of deep penetration and residual.

The data enforce the role of solar UV-radiation and its influence in maintaining balanced microbial mass in steady states in natural aquatic environments. Details of chemical changes under UV-treatment are not clear at this point. It was apparent that despite UV-treatment, bacterial aftergrowth also resulted. Therefore, it appears that the mode of UV bactericidal action closely resembles chlorine oxidation. It has been observed that the percentage kill of bacteria by the UV-radiation was subject to fluctuations at different sampling dates. This is to be expected because it is known that

the efficiency of UV-radiation is affected by the suspended matter in water column. The action of UV-radiation and its poor disinfection influence on bacterial aftergrowth is evident from decline in the percentage of kill in turbid conditions.

Although, phosphate and nitrite are present in extremely low concentrations, marine bacteria show exceptional ability of extracting these nutrients from water, and make use of them together with the relatively abundant TOC.

The heterotrophic bacteria in Arabian Gulf at Al-Jubail, had adapted to grow in low organic concentration. Presence of glucose as easily assimilable carbon source had no significant effect on bacterial initial growth, suggesting that carbon source was not a growth stimulatory factor for bacteria in this environment [3]. This observation was similarly noted in study [33], where correlation between AOC level and microbial growth had been poor. These findings further confirm that carbon source is not a growth limiting factor for bacterial cells in this environment.

Nitrite is one source of nitrogen to organisms and only those organisms possessing necessary enzymes can utilize nitrite as a source of cellular nitrogen [21]. Nitrite levels were below the detection limit at phase-I and a reduction in nitrite levels were found at AUV and NFP samples at phases-II compared to RSW. The laboratory observations also showed further reduction of 0.29-2.56ppb nitrite (nitrogen) during 48-h incubation time at 30⁰C. These results suggest that the bacteria consumed a portion of the nitrite during its growth. In the present study, a reduction of 0.33-2.41 ppb PO₄-P was also found during the same time. This reduction also showed that after inoculation of bacteria, the concentration of phosphate in the water rapidly decreased. The decrease was related to phosphorus content of the microbial biomass [34]. It was also noticed that if the water was enriched with inorganic nitrogen source, bacterial growth was faster. In natural systems, the phosphate is released from bacteria when grazed by silicates [35]. However, at different phases of study NFP had similar phosphate levels.

TOC values also showed a slight reduction after UV-treatment at study phase-II. Active bacteria exude dissolved organic matter in connection with the decomposition of organic material [36]. In static systems, the process consists of hydrolysis of particulate carbon using extra-cellular enzymes and later the dissolved organic substrates are

assimilated by the bacteria. The TOC value therefore depends on concentration of substrate, rate of bacterial metabolism including assimilation [37]. Study [38] showed that substrates at low concentrations were utilized more efficiently in the presence of inert particles such as sand but not in the absence of such substrate or when they are present in high concentrations. Apparently the TOC reduction observed at AUV in the present study is due to physical and chemical changes caused by UV-radiation. In study by Li, *et. Al.*, [30] they stated that UV treatment could result in decarboxylation of compounds including humic acids. However, further decline in TOC at the NFP appears to be due to consumption by bacteria. Results of the laboratory study also showed reduction in TOC levels associated with bacterial 48-h aftergrowth. More than 50% reduction in TOC was evident after 48-h of RSW samples in study phase-I, whereas, lower than this percentage yielded on UV treated samples in study phase-II.

The hypothesis which considered AOC to be the main nutrient factor determining the bacterial growth in water [35,39], represents only part of the fact under certain conditions Nitrogen sources and nitrogen rich compounds [3] and phosphorus [40] can be growth limiting factors for the bacterial growth.

Interestingly, a survey study conducted on different waters plants in Norway [41] reported increases in AOC levels during the plant treatment employing chemical disinfection. Three other plants which applied UV-radiation as disinfection agent yielded the lowest reduction in biodegradable organic matter. The high performance of these plants suggested that there was not any enrichment in AOC by UV-radiation treatment.

5. CONCLUSIONS

1. The data is highly pointed to the influence of UV-radiation in controlling the bacterial biofouling (aftergrowth) rate at NF products (NFP and NFB).
2. Installation of UV-radiation, just a head of (NF or RO) membranes would control the bacterial fragment numbers released from pretreatment process.

3. The recovery of bacteria may be attributed to reviving of cells that were less sensitive to the UV-radiation or due to division of surviving cells in presence of suitable food sources during pretreatment course of feed water.
4. In achieving aftergrowth bacteria were able to extract (very low concentration) phosphate and nitrite from seawater.
5. The aftergrowth studies can predict and evaluate the biofouling status of SWRO facilities.

6. RECOMMENDATIONS

1. It is very important to adopt appropriate disinfection strategy to protect SWRO plants performance.
2. Review the current pretreatment process of the feed of NF-SWRO existing operation conditions so as to reduce biofouling rates on membranes.
3. Application of UV-radiation at the right position and in the right dose, on pretreatment line of SWRO feed would control the biofouling problem on RO membranes.

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Table 1. Viable Bacterial and 48-h aftergrowth Estimation (CFU/ml) of Feed of NF-SWRO plant at Study Phases

Sample	Study Phase			
	Phase-I at 0-h	Phase-II at 0-h	Phase-I at 48-h	Phase-II at 48-h
RSW	(1.66±0.61)10 ⁴	(1.33±0.69)10 ⁴	(7.81±5.24)10 ⁵	(2.65±1.84)10 ⁵
AMF	(5.65±8.60)10 ³	(4.08±3.64)10 ³	(5.21±4.83)10 ⁵	(2.38±0.93)10 ⁵
ACF	(1.93±0.76)10 ²	(2.07±2.43)10 ³	(6.28±5.04)10 ⁵	(3.45±1.51)10 ⁵
AUV	Without using UV	(1.14±0.81)10 ²	Without using UV	(3.99±1.31)10 ⁵
NFP	(5.08±8.64)10 ²	(1.54±1.49)10 ¹	(7.05±8.03)10 ⁴	(7.30±4.44)10 ³
NFB	(1.77±2.50)10 ⁴	(1.56±1.40)10 ⁴	(1.36±1.44)10 ⁶	(6.03±3.16)10 ⁵

Pour plate count in marine agar medium, 0-h count is computed after 72 to 96-h incubation at 30°C. Phase I is the normal operation phase without UV-radiation; Phase II, with UV unit installed before NF membranes. Means estimated using 90% confidence intervals

Table 2. Average of Phosphate, Nitrite (ppb) and TOC (ppm) at 0 and 48-hr at Study Phases

Sample	0-h			48-h			
	P-PO ₄	N-NO ₂	TOC	P-PO ₄	N-NO ₂	TOC	
Phase-I	RSW	4.66	ND	1.29	2.36	ND	0.66
	NFP	1.14	ND	0.72	0.17	ND	0.46
Phase-II	RSW	4.89	3.74	2.26	2.48	2.18	1.74
	AUV	3.54	1.27	1.99	1.72	0.42	1.51
	NFP	0.78	0.51	0.82	0.45	0.22	0.16

Not Detected

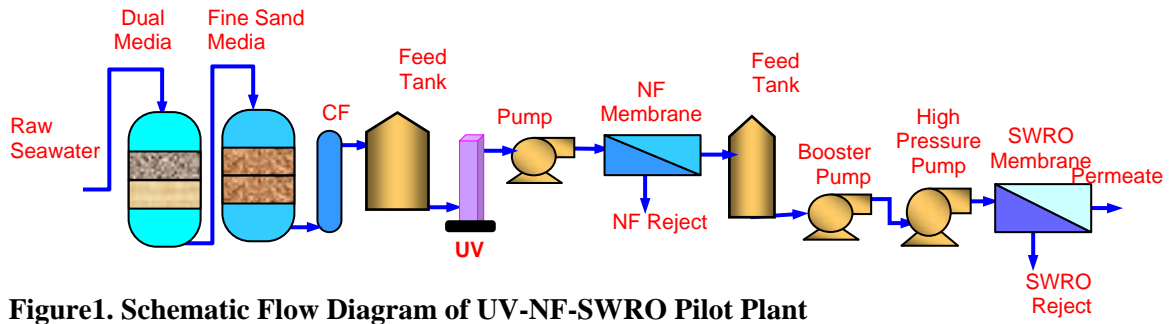


Figure1. Schematic Flow Diagram of UV-NF-SWRO Pilot Plant

