REVIEW OF DEVELOPMENT OF THE NEW NF-SEAWATER DESALINATION PROCESS FROM PILOT PLANT TO COMMERCIAL PRODUCTION PLANT STAGES

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ABSTRACT

A dual- and tri- nanofiltration (NF) – seawater desalination processes were developed in which the seawater feed prior to its entry to the desalination plants (membranes or thermal type) is first pretreated/partially predesalinated by the nanofiltration process. The NF pretreatment: (1) prevented SWRO membrane fouling by the removal of turbidity and bacteria, (2) prevented plants scaling by removal of scale forming hardness ions and (3) significantly lowered required pressure to operate SWRO plant by reducing TDS of seawater feed. This pretreatment changes the seawater feed chemistry with the net effect of increasing SWRO and MSF plants potable water yield and product recovery ratio. Likewise, it allowed for the operation of SWRO and MSF without the addition of antiscalant and the latter without the addition of an antifoaming agent. It also allowed for the operation of MSF plant, at top brine temperature of over 120^{o}C, on make-up made of NF product or SWRO reject from an NF-SWRO unit.

Process was first developed and applied successfully at the pilot and demonstration plant stages at R&D Center followed by its successful application to a commercial production plant by the converting of Umm Lujj SWRO Train 100, capacity 2200 m3/d, to the NF-SWRO operation. Train 100 conversion increased productivity by 42%, and raised it's the SWRO unit water recovery in dual NF-SWRO hybrid to 56% from 28% when it was operated in the conventional SWRO process. The paper reviews the process results from its inception(1996) and its application to pilot, demonstration and commercial plants(up to 2001).

Keywords: *NF, NF-SWRO, NF seawater pretreatment, Multistage flash (MSF) distillation, NF-MSF, NF-thermal seawater desalination*

الملخص

بدمج عملية معالجة مياه تغذية محطات تحلية مياه البحر بأغشية النانو مع وحدات تحلية مياه البحر التقليدية في نظام مزدوج من النانو/التناضح أو النانو /التقطير أو نظام ثلاثي من النانو / التناضح / التقطير أمكن بهذا الأسلوب الجديد التغلب على المشاكل الرئيسة التي تواجه عملة تحلية مياه البحر بطرق التحلية التقليدية التي يمكن حصرها في: (١)- التكلس (scaling) وذلك لوجود نسبة عالية من عناصر العسر بمياه البحر (٢)- ارتفاع معدل استهلاك الطاقة في عمليات التحلية نظراً لارتفاع الملوحة (٣)- تلوث معدات التحلية (Fouling) الناتج عن وجود المواد العالقة والبكتيريا بماء البحر (٤)- تآكل المعادن بسبب ارتفاع الكلوريدات ومعدل الملوحة . وقد تم تسجيل الأسلوب الجديد عالمياً كبراءة اختراع . بمعالجة مياه التغذية عبر أغشية النانو أزيلت منها المواد العالقة والجراثيم مع أيونات العسر ، إضافة إلى التغيير الجذري في التركيب الكيميائي لمياه التغذية أدت هذه العملية أيضاً إلى التحلية الأولية لمياه التغذية وذلك بإزالة جزء كبير من محتواها الملحي (TDS) ، وبهذا أصبح ممكنا تشغيل محطات التحلية سواء العاملة بنظام الأغشية أو الأنظمة الحرارية دون استعمال موانع الترسب وموانع الرغوة والمواد المعقمة وفي ظروف تشغيلية مختلفة لم يكن بالمقدور عملها سابقاً دون حصول ترسبات أو تلوث . إضافة إلى هذه الفوائد الجمة فقد ارتفع إنتاج محطات التحلية مع خفض ملحوظ في تكلفة إنتاج الماء العذب من مياه البحر . هذا وقد أثبتت التجارب التي تمت على مختلف أغشية النانو أن قدرة أغشية النانو في طرد الأملاح وخفض ملوحة مياه التغذية تختلف بحسب نوعيتها وكيفية تشغيلها . وللاستفادة من هذه الطريقة الجديدة في تحلية مياه البحر عمات المؤسسة العامة لتحلية المياه المالحة على تطبيق نظام النانو/التناضح وبنجاح باهر على أحد خطي الإنتاج (بطاقة تشغيلية ٣٦٠م^{٣}/ساعة) بمحطة أملج للتناضح العكسي ، ليرتفع إنتاج هذا الخط حوالي ٤٢% وازدادت كفاءة إنتاج وحدة التناضح به إلى حوالي ٥٦% مقارنة بـ ٢٦% حين كان نفس الخط عاملاً بنظام التناضح الفردي لوحده . وتقدم هذه الورقة مختصراً لما تم إنجازه بهذا المشروع (لعام ١٩٩٦ حتى منتصف ٢٠٠١) والذي أصبح تطبيقه ممكناً على جميع محطات تحلية مياه البحر القائمة منها أو الجديدة .

1. INTRODUCTION

By comparison to other forms of water desalination, seawater desalination is by far the most complicated and complex process. It has the lowest water recovery ratio (20-35%). Operation is restricted to certain operation conditions. Moreover, it tends to require extensive pretreatment, especially if the feed is taken from an open seawater intake. The process is an energy-intensive process, and for all the above factors seawater desalination is the most expensive desalination process. The major cause for the high expense and process complexity is the seawater itself, which is characterized by having: (1) high degree of hardness, (2) varying degrees of turbidity and microorganism content and (3) high TDS at pH about 8.2. Respectively, these properties give rise to the four major problems in seawater desalination: scaling, fouling including biofouling, high energy requirement as well as corrosion of the desalination equipment. These problems exert severe limitation and have pronounced effects on the performance and productivity of seawater desalination plants. Earlier studies showed that the ultrafiltration (UF) trials proved effective as secondary pretreatment in the removal of turbidity and bacteria from the feed, but failed to change the seawater chemistry by keeping the ionic composition of seawater the same [Hassan et al, 1995]. In his pioneering work,

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utilizing the NF membrane pretreatment [Hassan et al, 1997], introduced a new concept to seawater desalination by combining the NF membrane process with one or more of the conventional seawater desalination processes in one fully integrated process system to form: an NF-SWRO, an NF-MSF, and an NF-$SWRO_{reject}$-MSF, which were successfully evaluated at the pilot and demonstration plant level, and proved effective in preventing: (1) SWRO membrane fouling by the removal of turbidity and bacteria, (2) Scaling (both in SWRO and MSF) by removal of scale forming hardness ions and (3) This NF pretreatment lowered required pressure to operate SWRO plant by reducing TDS of seawater feed [Hassan et al, 1997; Hassan et al, 1998; Hassan et al, 1998; Al-Sofi et al, 1998; Hassan et al, 1999; Hassan et al, 1999; Hassan et al, 1999; Farooque et al, 1999; Hassan et al, 1999; Hassan et al, 2000; Hassan et al, 2000; Water Treatment Handbook, 1999; Hassan et al, 2002]. The net effect of this NF pretreatment, which, unlike the UF treatment, it succeeded in changing the seater feed chemistry, mainly by the removal of hardness ions and reduction of feed TDS, was to increase SWRO potable water yield by 40-100% and recovery from 30-35% without NF pretreatment to 50-70% with NF feed pretreatment. Furthermore, this NF pretreatment lowered both the process energy consumption and water cost by about 30% or better. Likewise, it increased MSF distillate recovery from 35% up to 80% without and with NF pretreatment, respectively. Moreover, it allowed for the operation of SWRO and MSF without the addition of antiscalant, and the latter also without antifoaming agent and without scale formation in MSF at top brine temperature ≥ 120°C. Also, the trihybrid, NF-$SWRO_{reject}$-MSF, arrangement allowed for the recovery of up to 90% of NF product as fresh water. Definitely, the achievement of the above results by this patented, award winning invention represents a milestone in seawater desalination technology.

A second part of the project dealt with process optimization, where the performance behavior of different NF membranes, made by different membrane manufacturers were investigated along with their influence on SWRO and MSF performance when using NF permeate as their feed. An NF SWRO demonstration unit was built utilizing commercial size NF and SWRO membranes, with the objective of establishing operating parameters for a large commercial NF-SWRO and NF-MSF plants. Results obtained confirmed finding from pilot plant trials and finding from both units allowed for the selection of NF membranes for use with SWRO or MSF plants as well as the determination of operation parameters for commercial large size seawater desalination plants.

In view of the positive and encouraging results obtained so far, the dual NF-SWRO desalination system was utilized in a third investigation to convert one of the two SWRO lines, Train 100, capacity 2203 m^3/d, Umm Lujj SWRO plant to the new dual NF-SWRO operation by the addition of an NF unit to the already existing SWRO unit and for comparison the second line Train 200, of equal design and capacity to Train 100, was kept operational in the singular SWRO mode. Also, presently in the planning is the application of the NF-SWRO process in the conversion of other SWCC SWRO plans and the operation of MSF or multieffect (ME) unit on an NF product as make-up at top brine temperature (TBT) of 120 to 160^{o}C for MSF and TBT > 65^{o}C for ME as well as for vapor compression (VC) unit coupled with NF unit.

A large number of presentation, publications and reports have been issued on this breakthrough project, and for the originality and innovative nature of the project, it received the IDA best research award at IDA World Congress on Desalination and Water Reuse, San Diego, 1999, SWCC Award (Year 2000) and Al-Marai, King Abdul Azis City for Science and Technology Award for the best innovative work in Engineering and Technology in KSA (Year 2001). The first two parts of the paper reviews the R&D work done during the past three years, while third part presents a brief description of the results obtained from the conversion and operation of the commercial Umm Lujj SWRO unit to the new NF-SWRO process.

2. FEED PRETREATMENT TO CONVENTIONAL SEAWATER DESALINATION PLANTS

Both the high degree of hardness and high TDS place limits on product water recovery, while depending on the process the presence of large turbidity, if not removed, tends to degrade plant performance. In the past, it was demonstrated that use of beach-well effectively removed turbidity and improved SWRO plant performance. Use of antiscalants proved effective in preventing scale formation but failed to increase significantly water recovery, for example, from Gulf seawater beyond 35% in both the membrane and the thermal processes. Also, the coagulation-filtration process is employed in the removal of fine particles. This process, however, does not remove the very fine particles with sizes of less than 2 μm. For removal from seawater of particles with sizes less than 2 μm, MF and UF have been used for separation of particle having sizes above 0.08 and 0.01, respectively. Other membranes that allow for fine particle separation are the RO and NF processes [Hassan et al, 1995, 1997]. The RO process deals with separation of all ionic size particles in the range of 0.001 μ or less. The NF Membrane falls in-between the RO and UF separation range, and is suited for the separation of particle sizes in the range of 0.01μ to 0.001μ. In addition to the rejection of neutral particles according to their sizes, as is the case with the MF and UF membranes, the NF rejection of inorganic matter is achieved by their electrostatic interaction with the negatively charged membrane. Moreover, the degree of rejection by the NF membrane is lesser for mono-valent ions, such as Cl^-, Na^+, than that for the divalent $SO_4^=$, Mg^{++} and Ca^{++}. The above ion selectivity allowed for the use of NF in the removal of hardness from low salinity water. For this reason the process is gaining acceptance as a major drinking water softening treatment, replacing in many cases, the conventional lime softening treatment.

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3. PILOT AND DEMONSTRATION PLANTS – R&D WORK

3.1 Experimental

All experimental work was done first on a pilot plant scale capacity 20m^3/d [Hassan et al, 1997; 1998, 1999], which was scaled up to demonstration units [Hassan et al, 2000; Hassan et al, 2002], capacity 80 to 220g m^3/d. Results obtained from both pilot and demonstration plants were utilized in the design conversion and operation of the NF-SWRO unit at Ummlujj seawater desalination plant [Hassan et al, 2002]. A general schematic flow diagram of the NF-SWRO pilot plant is given in Figure 1, which also shows the integration of NF-SWRO with an MSF pilot plant distiller comprising 2 and 4 stages of heat rejection and recovery, respectively. Moreover this last arrangement allows for utilization of seawater from MSF heat rejection section as needed, specially in winter season in raising the NF feed water temperature by blending it with seawater to produce feed temperature less than 32^{o}C.

The pretreatment unit consists of seawater supply system, dual media filter followed by fine sand filter, 5 micron cartridge filter, feed tank. (Before start of trails sand media was replaced with new finer sand in all sand filters). The NF unit consists of the high pressure pump and three NF modules arranged in series, each containing two commercial NF membrane elements size 4"x40" in pilot plant and size 8"x40" in the demonstration unit. The feed is supplied to the first modules, and then its reject is fed to its following module, while the reject from the second module constitutes the feed to the final third module. The SWRO unit is made of a high pressure pump followed by three SWRO modules, each contains two commercial spiral wound or hollow fine fiber membrane elements (size 8.0"x40"), all arranged in series. After its filtration with and in some trails without coagulation, the filtrate was passed to the NF membrane under pressure, initially of about 18-25 bars. This was followed by passing the NF product to the SWRO unit, or alternatively NF permeate or SWRO reject from an NF-SWRO pilot plant, to the MSF unit as shown in Figures 1.

During the whole NF-SWRO and NF-MSF experiments no chemicals were added as scale control acid treatment to the SWRO and MSF feed consisting of NF product. Chlorine when present in the feed was removed prior to the NF unit by dosing of sodium bisulfite. Chemical, biological analyses, and membrane system performance parameters were measured for the seawater, the permeate and reject at the various stages of the process on a routine basis.

3.2 Results & Discussion

3.2.1 Quality of Pretreated Feed

With the replacement of sand filter media with high quality and finer particle size sand and in some cases thicker sand media, the quality of the pretreated feed improved significantly and was exceptionally good. This is in spite of feed non-chlorination and minimum use of coagulant, i.e., 0.4 ppm Fe^{+3}. Most of the time, the pretreated feed quality, as measured by SDI, was less than 3, and for more than 50% of the time, SDI $\leq$ 2.0. Occasionally the SDI $\leq$ 4 was observed but it never exceeded this value, which is less than SDI ≤ 5, as required by the NF membrane makers. These SDI values compare to SDI ≤ 1.0 for the NF permeate. The differential pressure across the NF membranes (ΔP) remained steady and low. Thus, no SWRO membrane fouling was expected, as already was observed here and earlier, when the SWRO feed consisted of NF permeate.

3.2.2 Bacteriological Study of NF Process

Obviously, and as is expected, the number of bacteria count in colony forming unit/ml (CFU) should be at maximum and minimum values in raw seawater and in NF permeate; respectively. Furthermore, the CFU count in feed should decrease with feed pretreatment. This is illustrated in Figure 2, which shows the CFU count for feed samples taken at various stages of the seawater pretreatment and the NF membrane process. The plotted data are the average CFU count per month for the months of May, 1998 to Dec., 1999. The bacteria count is reported in CFU before dual media filter (BDMF), after dual media filter (ADMF), after micron cartridge filter (AMCF), in NF brine (NFB) and in NF permeate (NFP). When compared to CFU in raw seawater (BDMF) and in pretreated feed after dual media and after micron cartridge (AMCF) filters, the results indicate that the NF pretreatment is very effective in reducing CFU, sometimes to nill, in NF permeate. It is noticed that the monthly average of CFU in raw seawater (BDMF), in pretreated feed, and in brine are greater during the hot months of June to September than they are during the months of October to December, and regardless of the season, they are by far the least in NF permeate (NFP).

3.2.3 Chemical Composition of NF Permeates

The concentration of the hardness ions of Ca^{++}, Mg^{++}, $SO_4^{=}$ and HCO_3^{-} in NF permeate from the first NF membrane trial was 92 ppm, 192 ppm, 206 ppm and 46 ppm, respectively, as compared to their concentration in seawater of : 481 ppm, 1608 ppm, 3200 ppm and 128 ppm. The rejections of those ions Ca^{++}, Mg^{++}, $SO_4^{=}$ and HCO_3^{-} from the feed was: 81%, 88%, 93% and 63%, respectively. In addition to the reduction of hardness ion in the NF pretreatment, the Cl^{-} ion is also reduced from 22,780 ppm in seawater feed to an average of about 14,600 ppm in NF permeate or a reduction of about 36%. Similar reduction is expected for the Na^{+} and K^{+} ions. The net effect of this reduction by the NF treatment in Cl^{-}, Na^{+} and K^{+} ions together with the reduction in hardness ions causes reduction in TDS from 44,046 ppm in seawater to an average of 24,550 ppm for the NF pretreated feed, for a reduction of 44%. The pH of the feed of 8.2 is also reduced to an average of 7.85 in the NF permeate. The reduction in hardness ions (Ca^{++}, Mg^{++}, $SO_4^{=}$ and HCO_3^{-}), TDS and Cl^{-} ions in Gulf seawater, Al-Jubail, by the NF membranes process is illustrated in a bar chart representation in Figure 3, which considers as examples the variance in ionic reduction for seven NF membranes, defined here as “A” “B” “C” “D” “E” “F”and “G”. At an applied feed pressure of 17.4 to 22 bar, the concentration of hardness ions in the NF permeate of the various membranes examined differs from one NF membrane to another. In all cases, the NF pretreatment of seawater feed reduced the $SO^{=}_4$ content from 3200 in seawater to less than 70 ppm in NF permeate, for $SO^{=}_4$

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rejection of better than 98%. For some membranes, such as NF membrane "B", the $SO^{=}_4$ rejection is better than 99.7% and in some cases approached 100%.

The reduction in concentration of hardness cations of Ca^{++} and Mg^{++} in seawater caused by the NF pretreatment varied over a wide range from one NF membrane to another. This is clearly illustrated in Figure 3. For example, the Ca^{++} concentration in permeate from NF membranes "A" and "B" are 52 and 68 ppm for a percentage rejection of 89 and 86.5%, respectively. By comparison, the Ca^{++} concentration in permeates from NF membranes "C" and "E" are 136 and 264 ppm, respectively, for a percentage rejection by the former of 72% and by the latter membrane by only 45%. The same trend is observed for the rejection of the Mg^{++} ions. The Mg^{++} content is again lowest in permeate of NF membranes "B"(57 ppm) and "A" (90 ppm) for a rejection of better than 96% by the former membrane and for better than 94% by the latter one. These values compare to Mg^{++} concentration of 146 and 518 ppm in NF permeate from NF membranes "C" and "E", respectively, for Mg^{++} rejection by the former membrane of 91% and only for 68% by the latter one. The M-alkalinity was reduced from 128 in seawater to 30 ppm (pH=6.6) in NF permeate from "A" membrane, for a rejection of 77%, as compared to M-alkalinity of 50 ppm (rejection of 61%) in NF permeate from "C" and "E" (pH=6.85) membranes and 40 (pH=6.6) and 44 (pH=6.7) ppm in NF permeate from "B" and "D" membrane, respectively. The M-alkalinity is pH dependent and part of the observed variation in this value is due to pH of the permeate. Maximum reduction in seawater conductivity (TDS) and, therefore, maximum total ion rejection by the NF pretreatment follows, more or less, the same order as the NF membrane arrangement in Figure 3. This tends to be the case for rejection of Cl^- ions and also expected for the Na^+ and K^+ (although concentrations of the latter two ions are not shown in Figure 3).

3.2.4 Scaling Potential of NF Permeate

Scaling in the desalination processes occurs when the concentration of scale forming ions (hardness ions) exceeds the saturation points (solubility limit) at which after a certain time, scales nucleation starts followed by the precipitation of scale. Antiscalants are normally added to interfere with the nucleation process, therefore, preventing up to a certain concentration and temperature level the scale formation, and thus, allowing for the operation of the seawater desalination plants at high saturation of hardness ions in seawater. The scale control additives are known to act in two ways (i) threshold effect and (ii) crystal distortion effect. Here in this investigation, both evaporation techniques and the scaling threshold which, are defined as the maximum permissible concentration factor of salt water samples at fixed temperature before nucleation begins were utilized in determining the effectiveness of NF pretreatment (which causes, among other changes in seawater qualities, a high degree of hardness ions rejection) on retardation of scale formation as compared to the antiscale additive approach. In both evaporation and the scaling threshold experiments, no antiscalant was added to the NF permeate. Only the results obtained from the evaporation experiment will be described here.

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Evaporation results which were made in four consecutive steps for permeates from four different NF membranes having the samples composition as shown in Figure 3. The permeate solution turbidity remained zero up to 90 and 94% permeate evaporation and without scale matter precipitation. The results point out that at 95^{o}C, it should be safe to evaporate up to 90% of the NF permeate without scale formation. This means that at least up to 90% distillate (product) recovery can be realized without scale formation. Actually, this was observed at least for the NF "A" permeate at the MSF pilot plant level, where the MSF unit was operated on NF "A" permeate as make-up at 120^{o}C and distillate recovery of over 80% without scale formation [Hassan et al, 1997; Hassan et al, 1998; Hassan et al, 1998; Al-Sofi et al, 1998; Hassan et al, 1999]. By comparison precipitates were observed at 20% and about 30% evaporation of seawater with and without antiscalant, respectively.

3.2.5 Performance of Various NF Membranes

The NF membranes performance was measured in terms of permeates flow, recovery and their conductivity. Two pressure vessels, each contain two NF elements, arranged in series in a brine staging operation, were utilized in the performance evaluation. Again, as is the case in their hardness rejection and in their ability to reduce seawater feed TDS, these various membranes exhibited vast differences in permeate: flow and recovery. In general, the NF membranes with high permeate flow rate have low rejection of $Ca^{++}$and Mg^{++}, while the reverse is true for membranes with low flux. The observed differences in salt rejection and permeate flow and thus recovery ratio among the various NF membranes examined here, can be explained in terms of the membranes physical structure. Membranes with tight structure, thus small size pores, are likely to have high salt rejection but low permeate flow, while the reverse tends to be the case for membranes with less of a tight structure and larger size pores. The former tight structure membrane resembles RO membrane in behavior, while the latter membrane with more of an open structure resembles UF membranes in behavior. Rejection of $SO^{=}_4$, which as seen in Figure 3 is more than 98% for all membranes, is not governed by the physical structure of the NF membranes alone, but rather by the membrane surface composition, which is negatively charged. Evidently, all the NF membranes shown in Fig. 3 have sufficient negative charge to perform the observed excellent $SO^{=}_4$ rejection, but not a high rejection of Ca^{++} and Mg^{++} cations.

The effect of feed: applied pressure, flow and temperature at different operating conditions on NF permeate flow, recovery and conductivity are described in detail in the various references under Hassan, *et.al*. Both permeate flow and recovery are increased as either or both the feed applied pressure or temperature are increased. On the average, this increase was about 6% and 3.4% for a rise in applied pressure by 1 bar and for a rise in temperature by 1°C, respectively. Increasing feed flow had lesser effect on increasing permeate flow than that occurred when increasing either feed applied pressure or temperature, but it is the recovery, which is markedly increased with decrease in feed flow. On the other hand, permeate conductivity tends to decrease as the feed flow rate or applied pressure or both are increased, while it tends to increase as the feed temperature is increased. From the above trials it can be concluded that the three operating variables: pressure, temperature and permeate flow exert different influence on NF recovery and product quality. Increasing feed pressure increases both permeate flow as well as recovery and improves its quality. Improvement in permeate flow and recovery can be achieved also by increasing feed temperature which leads to a moderate decline in permeate quality. Increasing feed flow improves both permeate flow and quality but it has a marked influence on lowering permeate recovery. Additionally, the salinity of the feed to NF unit has a marked influence on NF membrane performance, where both the quantity and recovery of the product are increased as the feed salinity is decreased. For proper plant operation, by optimizing NF permeate yield and quality, a balancing act of operating plant at best values of feed: flow, temperature and pressure are to be identified and selected.

Based on their performance and ion rejection, as discussed here in this section and in later sections, the various NF membranes examined in this investigation can be classified into three groups: Group "A" characterized by having high ion rejection but very low flow as compared to Group "C" reversing the order by having high product flow but relatively low rejection, while Group "B" has a balanced properties inbetween the two groups with good flow as well as good to very good ion rejection. A group B type membrane was utilized in the NF unit in Umm Lujj NF-SWRO line, which is now in successful operation [Hassan et al, 2002].

3.2.6 Effect of NF Permeate Feed Quality on SWRO Membrane Performance

This is discussed in some detail in reference [Hassan et al, 1999]. Here, it suffices to discuss the effect of variation in NF permeates TDS and hardness ions concentration on SWRO membrane performance. The SWRO performance measured by permeate: a. flow, b. recovery and c. conductivity is plotted vs. feed applied pressure in Figure 4. Feed to the SWRO unit consisted of the NF permeate of A, or conventionally pretreated seawater but without NF pretreatment. In both cases the yield and SWRO permeate recovery increased as the applied feed pressure is increased. The SWRO permeates yield and their recovery, however, are much greater when using NF permeate as SWRO feed than when using seawater as feed. Moreover, the rate of increase in both values (yield and recovery) is inversely related to seawater feed TDS. Thus, at pressure of 60 bar, the SWRO permeate yield and recovery are at maximum values of 7.1 l/min and 70.7%, respectively, when the feed consisted of NF A permeate, TDS = 13,700 ppm, and the (yield and recovery) are at minimum values of 3.6 l/min and 36% when the SWRO feed consisted of seawater. The SWRO permeate yield and recovery when using the NF B, C and D permeates as feed to SWRO, fall in-between the above two ranges. This dependence of SWRO yield and recovery on feed TDS is very well established through the equation: $P_{net} = \Delta P_{appl} - \Delta\ \pi$, where P_{net} equals the effective pressure, P_{appl} is the applied pressure, and π is the osmotic pressure. Obviously, as the feed TDS is increased the P_{net}, which drives the permeate through the membrane, will decrease and consequently the quantity of permeate is also decreased. As shown in Figures 4, permeate starts to flow from SWRO membrane as the applied feed pressure exceeds the osmotic pressure, which is for permeate of NF A, Figure 4 equals 9.6 bar, as compared to 31 bar for seawater. Also major differences are noticed in SWRO product quality as measured by conductivity, which at 60 bar pressure equals less than 500 μs/cm when the SWRO feed consists of product from NF A and is about 2200 μs/cm when it consists of seawater, requiring in the latter case further treatment in a second brackish water type RO stage to reduce its conductivity to drinking water standards.

3.2.7 NF-MSF and NF-SWRO$_{reject}$-MSF Trials

Only the preliminary results obtained from the NF-MSF trials will be described in this paper. More of the results are described in separate articles [Hassan, et.al, 1998, Al-Sofi et al, 1998]. Additional work is being done now at high TBT ≈ 130°C at RDC Jubail and shall be described in a separate article. From these results, it can be concluded that the scaling potentials in the MSF system have been significantly reduced and it was safe to operate the MSF plant on NF make-up or on make-up made of SWRO reject from the NF-SWRO unit at high temperature of 120 °C without addition of antiscalant or antifoam chemicals. At the same operating conditions, the concentration of the scale forming ions of Ca^{++}, and $SO_4^{=}$ were 168 and 410 ppm in the NF-product make-up case, and 232 and 1020 in the SWRO reject make-up case, are low when compared to 882, and 5830 ppm in the brine recycle stream of conventional MSF. These observation, especially the drastic reduction in $SO_4^{=}$, Ca^{++} and Mg^{++}, are encouraging to project MSF operation at higher TBT in the range of 120 °C to 160°C or higher, thus improving plant production and hence water cost. Operation of MSF plants at higher temperature should increase the gained output ratio (GOR) in $Kg_{product}/Kg_{steam}$ and the performance ratio (PR) in $Kg_{product}$/1000 Kj, while decreasing the energy consumption in Kj/Kg product. Same conclusions can be extended to the operation of multieffect distillation (MED) or vapor compression distillation (VCD), with significantly improved performance, on make-up made of NF product or SWRO reject from an NF-SWRO unit at higher TBT ≥ 65°. Their present TBT limit is 65°C.

4. CONVERSION OF UMM LUJJ TRAIN 100 FROM THE SINGULAR SWRO TO THE DUAL NF-SWRO OPERATION

Figure 5 shows a schematic flow diagram for the present configuration of Trains 100 and 200 at Umm Lujj SWRO Desalination plant after the conversion of the former Train 100 to an NF-SWRO operation, while leaving the latter Train 200 in its original single SWRO operation. As built in 1986, both trains had identical design, which for each train consists of one SWRO desalination stage followed by a second brackish water stage with a final product output from each of 91.8 m^3/h from seawater feed of 360 m^3/h for a total recovery of 25.5%. The conversion was done by placing the NF unit ahead of the SWRO unit. A photo of the NF skid is shown in Figure 6. Although the photo shows an array of 12 horizontal x 9 vertical lines of pressure vessels, each vessel is to house 6 of 8" x 40" NF elements, only the first three vertical lines with 27 vessel and 162 NF DK 8040F elements are being utilized to provide feed for the

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existing SWRO unit. Plant design and operation was based on the actual production data obtained first from operating of the demonstration units at RDC pilot plant [Hassan et al, 2000] and at Umm Lujj under the plant prevailing operating conditions [Hassan et al, 2002].

The NF and SWRO operation parameters used in the operation of the dual NF-SWRO unit were set to the following values, which were slightly modified after plant commissioning:

Unit	***NF***	**SWRO**
Recovery	65%	58%
Feed	13.3 m^3/h per vessel	3.25 m^3/h per vessel
Pressure	30 bar	65-66 bar

The feed quality to NF remained the same as provided by the pretreatment unit without the use of any additional chemicals: pH = 6.0, SDI <3.5. Antiscalant and disinfectant normally used in pretreatment were SHMP (4 ppm) and $CuSO_4$ (4 ppm), respectively. Plant commissioning, operation and data collection were done jointly by the Umm Lujj O&M groups, researchers and engineers on the project from RDC and SWCC Western Province.

Figure 7 shows the chemical analysis for the hardness ions ($SO_4^=$, HCO_3^-, Ca^{++} and Mg^{++}), the Cl^- and TDS ions in both seawater feed and NF permeate, where the NF unit was operated at the above operating conditions. The ionic rejection for $SO_4^=$, Mg^{++} , Ca^{++} , HCO_3^-, and total hardness were : 99.9% , 98%, 91%, 56% and 97%, respectively. This very high rejection of hardness ions compares to a rejection of only 24% for the monovalent Cl^- ion, and 38% rejection of TDS ions, where the seawater feed TDS of about 45,460 was reduced to 28,260 in the NF product.

At a feed flow of 360 m^3/h, the permeate flow was steady at 234 m^3/h for a targeted recovery ratio of 65%. Due to a gradual decline in seawater temperature, permeate conductivity declined gradually with operation from about 46,000 to about 44,500 μs/cm. The differential pressure across the NF membranes (ΔP) was 2.79 bar and remained nearly constant at this value for the rest of the unit operation.

During the continuous operation, the product flow of SWRO unit in the dual NF-SWRO hybrid was 130 m^3/h from 232.6 m^3/h NF product as feed, and remained steady because the SWRO membrane receives a very high purity NF permeate as feed, which is void of turbidity, bacteria, hardness and it has only 62% of the seawater salinity. By comparison, a permeate yield of 91.8 m^3/h was obtained from 360 m^3/h of seawater pretreated feed when this same SWRO unit (Train 100) was operated in the singular mode in a two stage SWRO process (see Figure 5). Due to the conversion of Train 100 to an NF-SWRO operation the increase in line productivity was 38.2 m^3/h for a percentage increase of 42%. In Train 100, the SWRO product recovery ratio was 56% as compared to only 28% when the same SWRO unit with the same membrane was in operation earlier for 8 months in the singular mode, one SWRO stage, prior to its conversion to an NF-SWRO mode. This means that the SWRO operated in the dual system of NF-SWRO and received NF product with low TDS as feed, has twice the recovery of the same SWRO unit when it was operated in the singular mode as a SWRO unit fed on pretreated seawater. The product quality at the start of continuous operation, as measured by permeate conductivity, was 600 µs/cm. It decreased gradually to about 520 µs/cm after 1800 hours of operation due to the gradual decline under nearly same operation conditions in feed temperature from about 32^{o}C at the start to 28.9^{o}C after 800 hours of operation. Temperature has a pronounced effect on product conductivity of both NF and SWRO membranes.

By receiving a highly purified NF permeate as feed, the ΔP for the SWRO membrane remained very low, but with a slight decline with operation time, from ΔP = 0.6 bar to 0.5 bar. The low ΔP value indicates no membrane fouling. It is worth mentioning that the SWRO membrane was in operation for about 8 months in the singular SWRO arrangement prior to its conversion to the dual NF-SWRO form. Possibly during their 8 month operation some, but very little, build-up of fouling material on membrane surface took place which is being gradually cleaned by the high purity, low hardness NF permeate feed to SWRO membranes.

The same trend, is more or less, was observed when comparing the productivity and recovery of SWRO units in Trains 100 and 200. At the start of the trial, the product from SWRO in Train 200 was about 88m^3/h from about 350m^3/h feed, for a recovery of 25.4%, and gradually, as shown in Figure 12 b and c, decreased with decline in seawater feed temperature to about 80 m^3/h from 340 m^3/h seawater feed after 1750 hours of operation, for a reduced product recovery to 23.5% as compared to a productivity and a recovery of 130 m^3/h and 56%, respectively, for SWRO unit in Train 100, which was operated in the NF-SWRO mode. In addition to this significant improvement, ΔP in SWRO unit in Train 100, which as mentioned above was only 0.5 bar, and remained constant at this value, was much lower than the ΔP=2.5 bar for the SWRO membrane in Train 200 [Hassan, et al., 2002]. Initially, the product ratio of SWRO unit in Trains 100 to that in Train 200 was 144%, at seawater feed operation temperature of 32^{o}C, rising gradually with decrease in temperature to over 160%. Clearly, there is an increase in this SWRO product ratio in spite of operation of both lines at same pressure of 65 bar and at a much higher feed of 340 to 350 m^3/h to SWRO unit in Train 200 as compared to about 2/3 this value or less (about 232.6 m^3/h) for NF product feed to SWRO unit in Train 100.

5. **CONCLUSIONS (**As relate only to Umm Lujj Train 100 Operated in the NF-SWRO mode)

1. The NF DK 8040F showed a fantastic, excellent rejection of hardness ions of $SO_4^{=}$, Mg^{++}, Ca^{++}, HCO_3^- and total hardness of 99.9%, 98%, 91%, 56% and 97%, respectively. Rejection of TDS equaled 38%.

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2. Total fresh water production from the dual NF-SWRO Train 100 was 130 m^3/h as compared to only 91.8 m^3/h for its operation in the conventional SWRO mode utilizing two RO stages (Figure 1), for an increase in train production capacity by 42%.

3. Product water recovery ratio from SWRO unit in dual NF-SWRO : Mono SWRO was doubled to the ratio of 56% **:** 28%.

4. The ΔP of SWRO unit in the dual NF-SWRO : Mono SWRO was 0.5 **:** 2.5 bar.

6. RECOMMENDATIONS

1. With the encouraging, excellent results obtained by the conversion of Train 100 at Umm Lujj SWRO plant from a singular SWRO operation mode to the dual NF-SWRO mode, it was recommended to extend this conversion to Train 200 at Umm Lujj as well as other SWRO plants.

2. The NF pretreatment of feed to seawater desalination plants can be extended with great benefits to the operation of thermal plants in the dual-hybrid (NF-thermal) or trihybrid of NF-$SWRO_{reject}$-Thermal where the thermal unit could be an MSFD, MED, VCD or MED/VCD.

3. In order to increase NF product recovery and therefore NF-SWRO recovery, further work is needed on system optimization which is ongoing.

4. Equally important in raising the NF-SWRO recovery is the development by membrane manufacturing companies of high recovery, high flux NF membranes.

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Fig. 1: Schematic Flow Diagram of NF, SWRO and MSF Pilot Plants

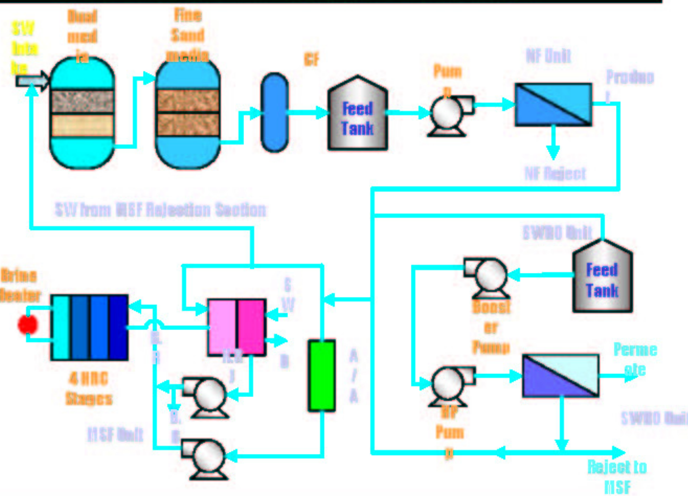

Fig. 3: Ionic Concentration of a. Hardness Ions, b. Total Hardness and c. Cl & TDS in Seawater and NF Permeates of Seven Different NF Membranes (Feed to NF Membranes Seawater, TDS 44,000)

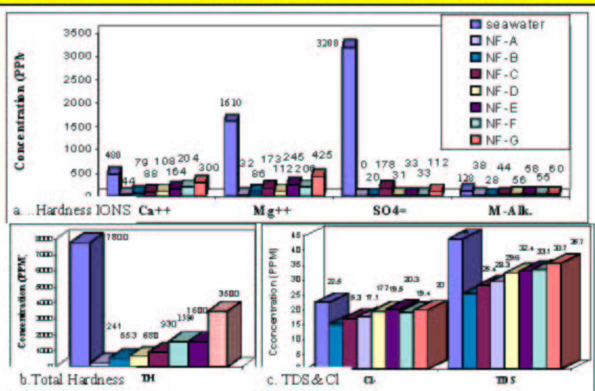

Fig. 2: Bacteria count at different sampling points in NF pilot plant

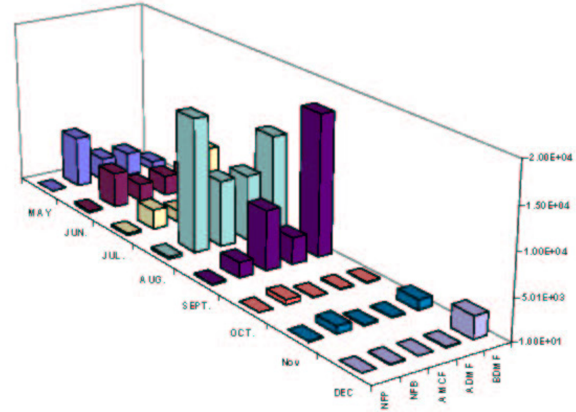

Fig. 4: Performance of SWRO with and without NF

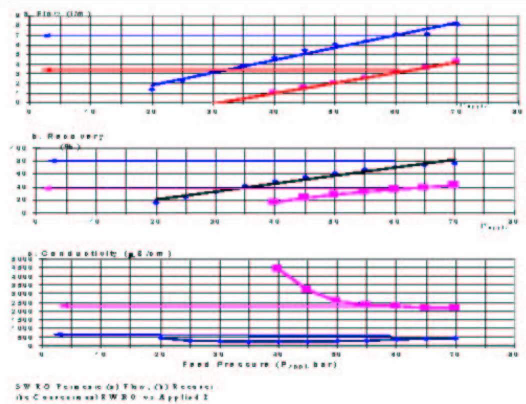

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Figure 5. Umm Lujj SWRO Plant Flow Diagram a. SWRO Arrangement as Built in 1986 (Train 200) b. NF-SWRO Arrangement as Converted to NF-SWRO System Sept. 2000 (Train 100)

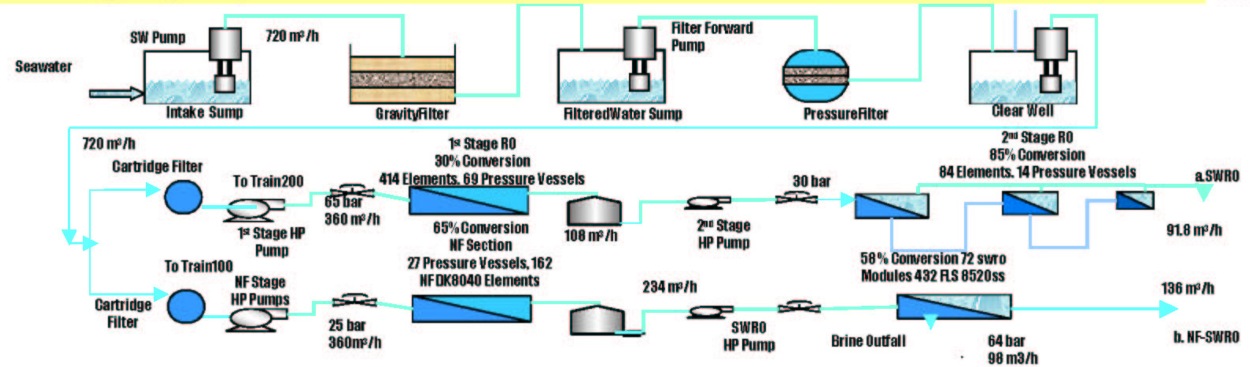

Fig. 6. A View of the Final NF-SWRO Plant with NF Unit in Front and SWRO Unit in the Back of Photo

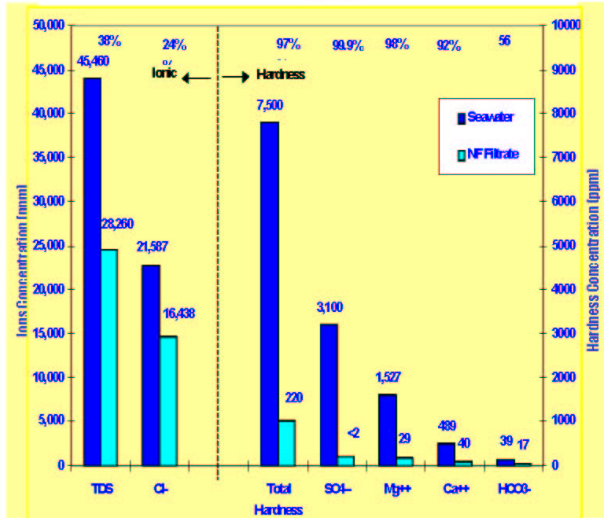

Fig.7. Effect of New NF Pretreatment Process on Removal of Hardness and TDS Ions at Ummlujj NF-SWRO (Train 100)

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