ARUBA'S DESALINATION'S KNOWLEDGE AND EXPERIENCE: CONQUERING THE SEA TOWARD DESALINATION'S SUSTAINABILITY

CONOCIMIENTO Y EXPERIENCIA DE LA DESALINIZACIÓN EN ARUBA: CONQUISTA DEL MAR HACIA LA SOSTENIBILIDAD DE LA DESALINIZACIÓN

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Abstract

The semi-arid island of Aruba has earned throughout its desalination history an excellent reputation for the efficient commercial application of the costly seawater desalination technology. Reliable drinking water production and distribution is of imminent importance for the population, the island economy, industry, and in particular, for the tourism industry. But, seawater desalination is very susceptible to many operational problems hampering stable and efficient water production. The primary operational problems are excessive foaming, biofouling, scaling and corrosion. In Aruba, due to sub-optimal conditioning of the drinking water, iron and copper corrosion in the distribution system has caused diminished water quality and leakages due to perforations of pipes in the distribution system. In the 1990's, following an intensive scientific research a Continuous Desalination Efficiency Improvement Process was developed to eliminate the aforementioned operational problems. This paper outlines the different state of the art chemical additives developed and applied in collaboration with the chemical supplier to achieve sustainable desalination. The application of the chemical additives resulted in practically 100% availability of the thermal desalination units and increased efficiency with 7% for both thermal and membrane production units. The iron concentration of the drinking water has been reduced to about 0.01 ppm, which is far less than the World Health Organization's target of 0.3 ppm for drinking water. Due to the optimal condition of the drinking water and the resulting reduction in corrosion and leakages, the Non-Revenue Water amounted to 2.6-4.7 percent versus 15-65 percent in the neighboring Islands in the Caribbean region. The different technical solutions discussed in this paper may be useful for many seawater desalination companies; especially in Small Island Developing States, to effectively solve ongoing operational problems and move toward sustainable operation.
Keywords: Seawater Desalination, Marine Biofouling, Foaming, Scaling, Desalination Sustainability.

Resumen

Durante su historia de desalinización, la semiárida isla de Aruba, se ha ganado una reputación excelente gracias a la eficiente aplicación comercial de la tecnología costosa de desalinización de agua de mar.

La producción y distribución confiable de agua potable es de inminente importancia para la populación, la economía de la isla, la industria, y en particular, la industria turística. Pero la desalinización de agua de mar es muy sensible a muchos problemas operacionales, el cual resulta en una obstaculización de la producción estable y eficiente de agua. Los problemas operacionales primarios son: la formación excesiva de espuma, bio-incrustación, incrustaciones y corrosión. En Aruba, a causa del acondicionamiento subóptimo del agua potable, la corrosión de hierro y cobre en el sistema de distribución ha causado una calidad deteriorada del agua y fugas a causa de perforaciones de tuberías en el sistema de distribución. En los años noventa, tras una investigación científica intensiva, se desarrolló un Proceso de Mejora Continua de la Desalinización Eficiente para eliminar los problemas operacionales anteriormente mencionados. Este artículo describe lo último en los diferentes aditivos químicos desarrollados y aplicados en colaboración con el suministrador químico para conseguir desalinización sostenible. La aplicación de los aditivos químicos resultó prácticamente en un 100% de disponibilidad de las unidades térmicas de desalinización y en un incremento de eficiencia de 7% para las unidades de producción térmicas y aquellas por membranas. La concentración de hierro en el agua potable ha sido reducida a aproximadamente 0.01 ppm, el cual es mucho menos que el objetivo de 0.3 ppm para el agua potable, instituido por la Organización Mundial de la Salud. A consecuencia de la condición óptima del agua potable y de la reducción de corrosión y fugas, el Agua No Contabilizada ha llegado al 2.6-4.7 por ciento frente a un15-65 por ciento en las islas vecinas en la región del Caribe. Las diferentes soluciones técnicas tratadas en este artículo pueden ser útiles para muchas plantas desalinizadoras; especialmente en los Pequeños Estados Insulares en Desarrollo para solucionar, de una manera eficiente, los problemas operacionales en desarrollo y llegar a una operación sostenible.
Palabras clave: Desalinización de agua de mar, Bio-incrustación marina, Formación de Espuma, Incrustaciones, Sostenibilidad de Desalinización.

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1. INTRODUCTION

Water is in abundance on our blue planet Earth but from the total amount of water about 97 percent is seawater and only 3 percent is fresh water suitable for human consumption (Velmurugan et al., 2007). From this total amount of fresh water 71 percent is subterranean, 27 percent is in the form of ice and only about 2 percent is present as surface water in rivers and lakes. Actually the yearly rain fall is sufficient for the whole population on Earth but unfortunately it is not uniformly distributed over the world. There are places with abundant rain fall while others have, practically the whole year long, no rain at all (Buro, 2000). The coming decades the effect of climate change may globally further enhance a detrimental impact on the emerging water shortage, especially for Small Islands Developing States (SIDS), which are particularly vulnerable to climate change. Therefore, in such arid regions with practically no natural fresh water resources the best possible solution to the water shortage problem is the use of cost effective sustainable desalination of saline water and waste water reuse (Marchena, 2013).

Seawater desalination is known worldwide as the most important technology for the production of drinking water in arid areas. Since 1860, thermal evaporation has been used as a large-scale mature technology for the production of drinking water and industrial water. Due to the high consumption of both thermal and electrical energy this technology is still an expensive process despite many innovations. A technological breakthrough in desalination cost was achieved with the development of the reverse osmosis desalination technology. This high pressure membrane technology, commercial available since the 1970's, has recently taken over the dominant role of thermal desalination. The introduction of energy recovery systems and development of new high efficiency permeable membrane materials have made this process about 70 to 75 percent more energy efficient than the thermal desalination technology (Marchena, 2013).

Desalination is now a mature commercial enterprise with desalination units surpassing 500,000 m3/day. Some state of the art desalination processes are summarized in table 1 (Kahn, 1986).

The desalination of seawater has given an enormous boost to the economic development of the semi-arid Island of Aruba which is located in the Caribbean region, only a few miles from the coast of Venezuela, South America. Aruba has developed into a prosperous island primarily due to the availability of a trustworthy production of drinking water and industrial water supporting especially the flourishing tourism industry and other industrial activities. However, seawater desalination was not always a smooth operational process; in the course of time many operational problems hampering stable fresh water production and efficiency had to be solved. For example, excessive foaming during flash evaporation enhanced by natural surface active components in seawater, and biofilms formed by marine micro-organism on heat transfer tube surfaces, impeding efficient heat transfer. Additionally, macro organism plugging of tube inlets, reducing cooling seawater flow, were frequently experienced in the thermal evaporators as well as high temperature scale formation due to the decomposition of bicarbonates present in seawater.

Table 1: Commercial desalination processes

Commercial Available Desalination Technologies
Large capacity thermal desalination processes:
- Multi Stage Flashing (MSF)
- Multi Effect Distillation (MED)
- Vapor Compression (VD)
Large capacity membrane desalination processes:
- Electro Dialysis (ED)
- Electro Dialysis reversal (EDR)
- Electro Deionisation (EDI)
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A problem with the membrane technology is that it is very vulnerable to marine biofouling and if not addressed and solved properly the semi-permeable membranes can be permanently damaged. Effective chemical additives are therefore necessary to cope with these operational problems; without these additives stable and efficient desalination is practically impossible (Marchena, 2013).

In the early desalination years in Aruba, as in many other countries, these problems were addressed and mitigated by the trial and error method using commonly available chemicals. However, during the last decades a scientific research was performed to develop an efficiency improvement process based, primarily, on the experience and knowledge of the operation and maintenance work floor personnel.

In the context of this scientific approach, as will be explained in the next section, state of the art chemical additives were developed and successfully applied in a collaboration with the chemical supplier to mitigate excessive foaming, biofouling and scaling. Also an effective corrosion inhibition program has been developed to eliminate iron and copper corrosion in the distribution system (Post et al., 2002).

2. ARUBA'S EXPERIENCES IN CONTINUOUS DESALINATION EFFICIENCY IMPROVEMENT

This section outlines the technologies and techniques developed in Aruba to mitigate excessive foaming, biofouling, scaling and corrosion. It also covers the importance of the gained desalination knowledge and experience conquering the sea toward sustainable, stable and dependable seawater desalination for the production of drinking- and industrial water. The paper will be especially enlightening in the context of a "Continuous Desalination Efficiency Improvement Process" (CDEIP) in support of other "Small Islands Developing States" (SIDS) to increase their resiliency for the supply of safe and healthy drinking water.

2.1 Drinking water supply in Aruba: A brief historic overview

2.1.1.Drinking water supply before seawater desalination

Aruba is a semi-arid island with practically no natural surface water- or subterranean fresh water resources. In the rainy seasons, rain water can be abundant but most of the water flows back to the sea through the ephemeral streams leaving the Island in scarcity of drinking water. The early inhabitants mainly Arawak natives and their descendants used surface water for their daily water supply and dug wells in search for ground water, using wooden winches and wind mills to haul up the water. Later on they built houses of clay or stones with cisterns to harvest rainwater. They also discovered and applied primitive techniques for the drinking water treatment. The juice of the cactus plant and some drops of seawater were used as a primitive additive for the coagulation and flocculation process to clarify the muddy surface water. As illustrated in figure 1, they also applied a calcite stone filter to filter out colloidal particles from the drinking water and used jars of clay to keep the water fresh and cool due to the natural evaporation process (Marchena, 2013).

Figure 1. A calcite stone filter and a jar of clay

In the period of 1900 to 1914, Aruba had its very first sustainable drinking water supply company. Groundwater was pumped, using wind mills, through a distribution pipe to the ships in the harbor and the inhabitants of Oranjestad, Aruba's Capital. Desalination of seawater was introduced in the first decades of the 20th century for the production of fresh water.

2.2. Seawater desalination in Aruba: thermal and membrane technology

2.2.1. The thermal desalination technology

From 1903 to 1916, seawater of the Spanish Lagoon was desalinated for the production of boiler water for the steam engines and for the production of fresh water for the gold extraction process at the Gold Mining Company situated at Balashi. Available groundwater was limited and salty and usage of nearby Spanish Lagoon's seawater resulted in heavy scaling and explosion of boilers (Walhain, 2005).

Commercial seawater desalination started in 1932 with the production of drinking water at the drinking water facility, "*Landswater Voorziening" (LWV)*, also at Balashi. The first desalination technology applied was the *"Multi Effect Distillation"* (MED), using evaporators manufactured by the WEIR Inc. of Scotland (Birkett et al., 2002). In 1959, Aruba had for a very short period of time the largest seawater desalination facility in the world using the MED-technology. The first generation of the MED evaporators had a production capacity of 200 m^3/day and a performance ratio of 1 to 2. The "*Gain Output Ratio"* (GOR), the efficiency value historically called in Aruba the *"Performance Ratio"* (PR), is defined as the ratio of the amount of distillate produced and the amount of low pressure steam consumed. In 1958, the second generation of the MED evaporators with a capacity of 2,000 m^3/day and a PR of 5 to 6 were installed. At this time the name of the drinking water facility was changed to *"Water- en Energiebedrijf"* (WEB) due to the combined water and power production of this plant. For many years the MED process was the most important desalination technology at WEB, but in the 1960's it was replaced by the more reliable and operationally stable "*Multi Stage Flashing"* (MSF) technology. This technology is more suitable for up scaling to larger capacity.

In 1965, following the trend of the desalination market in the world, the first generation of a more efficient thermal desalination technology, the *"Multi Stage Flashing"* (MSF-) evaporators manufactured by "*Aqua Chem Inc."* from the USA, was introduced. The first MSF evaporator had a production capacity of 3,000 m^3/day. In 1983, the second generation of the MSF-evaporators with a capacity of 6,000 m^3/day and a PR of 9 were installed, closing the MED-technology's era in Aruba.

In the 1970's, a new vertical *"Multi Stage Controlled Flash"* (MSCF) Evaporator from "*Aquanova BV"*, a Dutch Hungarian design, was also installed but with mixed results. For the increase of desalination production capacity due to the rapid economic growth in Aruba in the 1990's, the decision was made to replace the existing plants with the more robust, reliable and efficient Aqua Chem MSF evaporators. From 1990 to 1997, five third generation Aqua Chem MSF evaporators with a nominal capacity of 6,000 m^3/day and a PR of 10 to 11 were installed.

All of the above mentioned MSF evaporators were based on the brine recirculation technology with a *"Top Brine Temperature"* (TBT) of 110 ^{o}C. This technology has outrivaled the MED process because of high reliability, stable operation with optimal control of scaling, less prone to fouling and the possibility to increase production capacity. Both of these thermal technologies are based on the high energetic phase transition of evaporation and condensation. The recently dominant reverse osmosis technology, on the contrary, only needs mechanical energy to separate fresh water from seawater through a semi-permeable membrane, making it the most energy efficient technology nowadays.

2.2.2. The Seawater Reverse Osmosis Membrane Technology

In the period of 1983 to 1985, the membrane technology was introduced in Aruba to cope with production decay due to the aging MED plants and the poor operation of the Aquanova MSCF evaporators and to mitigate the import of fresh water. This *"Sea Water Reverse Osmosis"* (SWRO) plant had a capacity of 1,000 m^3/day and was built with *"Plate and Frame"* (PF) membranes; this plant was actually the first SWRO membrane technology plant built in Aruba. The plant was operated by "*Geveke BV"* under a *"Build Own and Operate"* (BOO) contract.

In 2008, a two pass SWRO plant manufactured by "*GE Water & Process Technology"* (GE WPT) with a nominal capacity rating 8,000 m^3/day was installed for the production of drinking water. The second two pass SWRO plant was installed in 2012. This production unit was manufactured by "*Veolia Water Services"* (VWS) with a 25,500 m^3/day nominal capacity. In 2015, a mobile 12,000 m^3/day SWRO plant manufactured and operated by GE WPT went in operation. With the installation, in 2015, of the new *"Electro Deionization"* (EDI) membrane technology plant, with a capacity of 4,500 m^3/day for the production of very pure water for industrial purposes, the supremacy of thermal desalination came to an end in Aruba after more than eighty years of successful application.

In conclusion, seawater desalination was since its introduction in 1932 the main fresh water resource of Aruba and was successfully applied since then to secure drinking water supply. However, desalination of seawater was not always without problems. The most frequently encountered operational problems hampering stable desalination and drinking water quality, as will be explained more in depth in the next sections, are: (1) corrosion and erosion due to the corrosive seawater environment and shortcomings in design; (2) excessive foaming due to natural surface active components in seawater; (3) scale formation due to high temperature decomposition of bicarbonates in thermal evaporators; (4) scale formation due to concentration polarization at the membrane surfaces; (5) biofouling in thermal evaporators and SWRO units; and (6) corrosion in water distribution systems causing brown and blue water and water losses due to pipe perforations and leakages (Marchena, 2013).

2.3. Toward sustainable seawater desalination: Operational aspects of importance

According to the desalination operational experience at WEB Aruba, well designed and constructed desalination units usually pass the operational performance test in the commissioning phase; typically, and within the specified and agreed upon period, all design criteria, nominal capacity and efficiency are met after some adjustment. However, our experience is that after some months of operation decay and consequently efficiency reduction occur basically due to the operational problems mentioned in the previous section. With the lapse of time, without an effective continuous improvement process, this efficiency decaying tendency, especially enhanced by aging of the production units and corrosion, will become more intensive (Arrindell,1987).

The seawater environment and pure distillate (particularly due to its acidity) are very corrosive, making maintenance of the desalination units and material selection a very important aspect in applied seawater desalination technology. The main internal problems encountered in seawater evaporators are corrosion and perforations of the carbon steel evaporation stages where the flashing recirculating brine is flowing. Additionally, the corrosive non-condensable gasses such as oxygen and carbon dioxide emerging from the condensing vapors also cause severe corrosion in the venting system of the evaporation stages (Al-Mutaz et al., 2007). The application of stainless steel lining in these compartments was a mayor solution for these problems together with adequate improved design of the venting systems. Deareation of the seawater feed before entering the evaporator has also significantly contributed to inhibit vent side corrosion.

Flow induced erosion and corrosion at the recirculating brine tube inlets of the evaporating vessels was another form of aggressive corrosion. These problems were solved by adaptation of plant designs and adjustment of brine gates and distillate gates to reduce recirculating brine flow velocities. Many of these practical solutions have been introduced by sharing operational and maintenance experiences and knowledge with manufacturers. Furthermore, the installation of high temperature resistant polymeric inserts in the tube bundle's inlets has offered effective protection against tube leaks as a result of erosion corrosion.

The decreasing trend of the performance ratio of a MSF evaporator in the operational period before and after a condenser cleaning and minor corrective maintenance activities to improve efficiency is illustrated in figure 2 (Marchena, 2013).

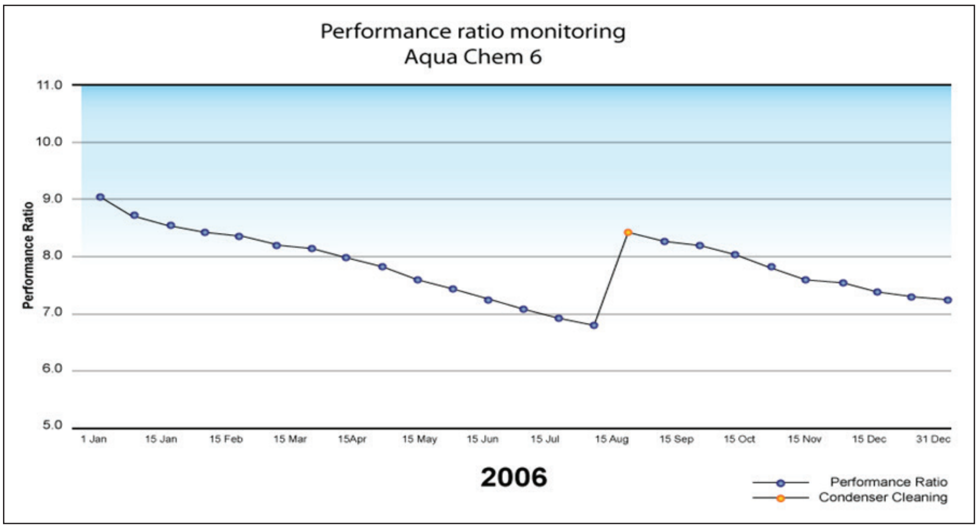

Figure 2. Performance Ratio decay of an MSF evaporator

2.3.1. Excessive foaming

Excessive foaming is inherent to the flashing process of seawater where vapor bubbles are spontaneously formed at reduced pressure in the successive evaporating stages (Auerbach et al., 1981). This foaming process is further enhanced and stabilized due to the presence of naturally occurring bio-organic surface active components in seawater. This foaming tendency of the recirculating brine is a physicochemical aspect of importance that hampers stable evaporation in thermal seawater desalination. It causes entrainment of seawater droplets in the condensing vapor which diminishes the quality of the produced distillate. Figure 3 illustrates the flashing induced foaming of the recirculating brine in a MSF evaporator (Marchena, 2013).

Figure 3. Foaming of flashing recirculating brine

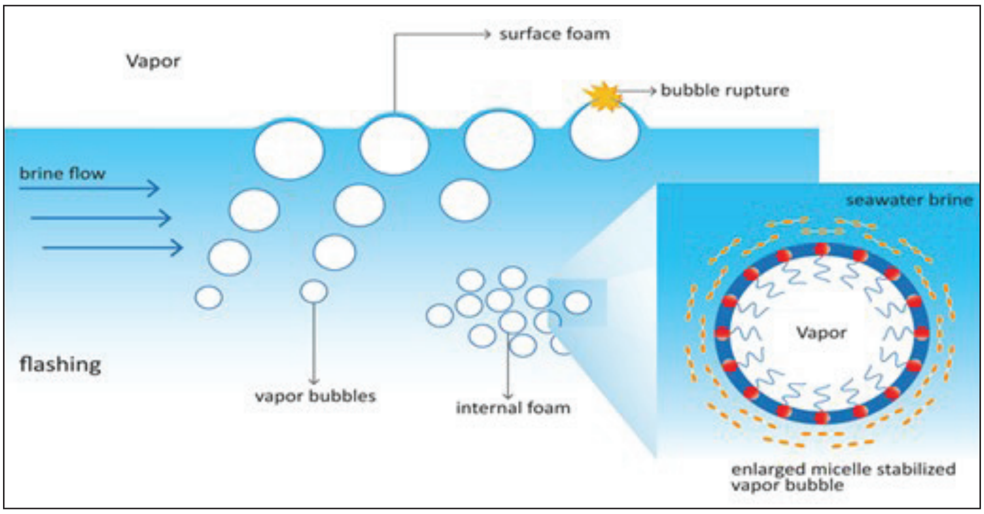

Figure 4. Foaming destabilization and stabilization in desalination

Dosing of an effective antifoaming additive to destabilize foam formation is due necessary to control violent evaporation inducing excessive foaming in the MSF evaporation (Imam et al., 2000). In cooperation with the chemical supplier an effective high temperature antifoaming agent based on the ethylene oxide-propylene oxide (EO-PO) block copolymer technology had been developed and applied in Aruba to increase desalination stability.

Although the application of this antifoaming additive was very successful, monitoring is very crucial because under- and overdosing of the antifoam has caused, respectively, increased product salinity and production decay. The effect of under dosing was obvious but production and efficiency decay because of overdosing was often not satisfactorily explained. In Aruba, the surface tension of the curved vapor liquid surface of the flashing vapor bubbles was introduced to successfully explain this observed operational phenomena. According to the developed theory, production and efficiency decay is primarily caused by internal foams stabilized by excess antifoam molecules. This in turn causes a two phase flow pattern in the recirculating brine reducing heat transfer and pumping capacity. The destabilization of surface foams and the stabilization of entrained internal foams are schematically illustrated in figure 4 (Marchena, 2013).

Effective monitoring and control of the antifoam dosing is even more pronounced when taking into consideration the fact that the necessary additives to control scaling and biofouling are surface active chemicals that significantly enhance seawater foaming.

2.3.2. Scale formation in thermal desalination

Another problem of importance encountered in seawater thermal desalination since the pioneering age is scale formation on the heat transfer surfaces due to thermal decomposition of bicarbonates normally present in seawater. In this thermal induced chemical process, calcium carbonates and magnesium hydroxide and calcium sulfates are formed which have a retrograde solubility e.g. decreased solubility with increasing temperature. These components precipitate on the heat transfer surfaces and form a non-heat conductive layer increasing resistance for heat transfer resulting in efficiency reduction. Furthermore, once a layer is formed precipitation can continue until the whole tube is plugged. Aruba was since the start of its desalination activities in 1932 a major contributor to inhibit scale formation in thermal desalination as is indicated in table 2 (Marchena, 2013).

In the early years of desalination, the hard scale formed on the submerged tube bundles in the MED evaporators was removed using thermal shock and physical force (hammer and chisel). Thermo-shock was achieved by alternately permitting hot steam and cold water to flow through the tube bundle. The resulting tube contraction and expansion cracked and loosened the scales and other deposits from the surface of the tubes. This physical and mechanical approach of scale control has been practiced in Aruba from 1933 to 1958. In 1958, the first chemical scale treatment program worldwide, the dosing of a solution of ferric chloride ($FeCl_3$) became available after intensive research done by WEIR Inc. in Aruba and Curacao (Hiller, 1953; Marchena, 2013). In the period 1958 to 1963, ferric chloride was produced in Aruba, on site, through an innovative electrochemical process in which a diluted solution of hydrochloric acid and seawater was electrolyzed with iron and carbon electrodes. This ferric chloride scale control program lasted until 1963 in which year it was replaced by the use of 98% concentrated sulfuric acid as scale inhibitor.

Table 2. Scale inhibition techniques used at WEB Aruba

Period	**Scale inhibition technics**
1933-1958	Thrmo shock of the hear transfer coils; removal of scales with chisel and hammer
1958-1963	Dising of $FeCl_3$; on site production of ferric chloride; electrolyses of hydrochloric solution with iron electrodes.
1963-2007	Dosing of 98% concentrated sulfuric acid
1991-1994	Combined dosing of sulfuric acid and Belgard EV™
2004	Dosing of 100% HT antiscalant of GEBetz; technical successful trial
2006-2007	Elimination of sulfuric acid with HT 15 antiscalant of GE WPT

The first experiments with the dosing of concentrated sulfuric acid were performed on site. Concentrated sulfuric acid dosing was used successfully from 1963 to 2007. Aruba was the first to use this scale control program for commercial seawater desalination (Khan, 1986). From 1991 to 1994, a combination of acid dosing and a high temperature (HT-) antiscalant, Belgard EV™ was used as scale inhibitor. Although a decreased level of corrosion in the evaporators was experienced, this combined dosing practice was terminated due to poor overall performance caused by brine heater fouling.

Finally, in 2004 an alternative was found for the sulfuric acid dosing after an eight month successful trial with a 100% dosage of a HT-antiscalant. This effective high temperature scale inhibitor, based on the polymeric phosphonate and poly maleic chemistry, was developed in collaboration with the chemical supplier (Perez, 2005). In 2007, after approximately forty years of usage, this application resulted in the total elimination of concentrated sulfuric acid as scale inhibitor (Marchena, 2013). From the first days of the trial it was already obvious that the new scale inhibition program would be successful, since the brine heater operating conditions remained constant once the operation was stabilized. During the 180 days demonstration period the MSF evaporator had maintained very stable and efficient operating condition with, practically, a constant brine heater pressure. This was an indication that practically no fouling and scaling were occurring on the heat transfer tubes in the brine heater and the heat recovery section. The average distillate production during the trial was 6,285 m^3/day with a slightly decreasing trend as shown in figure 5 (Marchena, 2013).

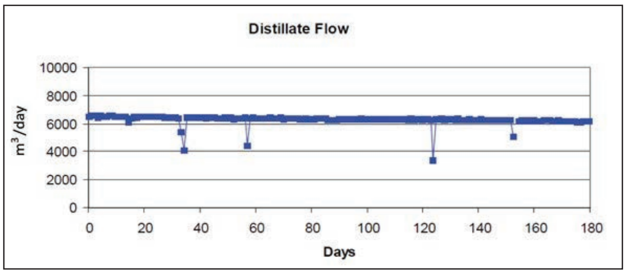

Figure 5. The distillate flow during the 180 days trial period

Additionally, the condensate flow also showed a slightly increasing trend with an average flow of 636 m^3/day and negligible high temperature fouling/scaling in the high temperature vessels and the brine heater. The trend of the condensate flow is shown in figure 6 (Marchena, 2013).

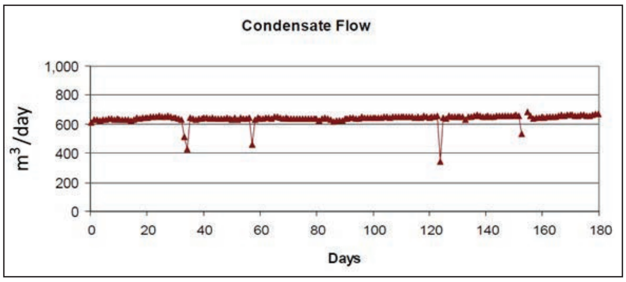

Figure 6. The condensate flow during the 180 days trial period

As a consequence the performance ratio (the ratio of the distillate production in mT/day and the condensate flow in mT/day) was practically constant. In accordance with the two graphs above, the trend of the performance ratio showed a slightly decreasing trend as indicated in figure 7 (Marchena, 2013). The performance ratio had an average value of 9.88 during the 180 days trial period.

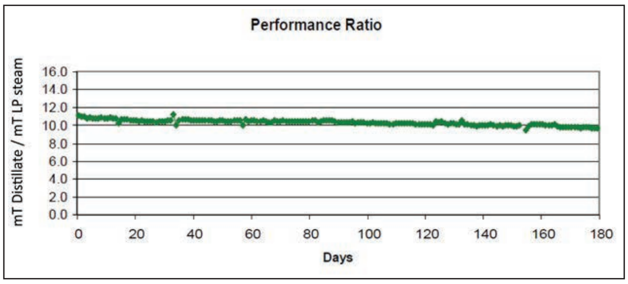

Figure 7. The Performance Ratio during the 180 days trial period

To conclude this section, the overall condition of the brine heater after eight months of operation with the new HT-antiscalant was excellent, as is illustrated in figure 8, right picture (Marchena, 2013). The condition of the same brine heater on sulfuric acid dosing (left picture) is also shown for comparison.

Figure 8. Condition of the brine heater on acid dosing and new HT-antiscalant

2.3.3. Biofouling in thermal desalination

Throughout the history of seawater desalination activities in Aruba, heavy biofouling was always a problem in the intake systems and the condensers of the seawater evaporators. Macro biofouling, especially barnacles, regularly obstructed cooling seawater flow through the condenser tubes of the thermal desalination plants.

In addition, marine biofilms on the heat transfer surfaces reduced the heat transfer, which led to decreasing production and efficiency of the MSF evaporators. Approximately every three months an evaporator had to be shut down for condenser cleaning and minor corrective maintenance to maintain optimum production and efficiency.

In a collaboration with the chemical supplier a novel non-oxidizing biofouling treatment was developed based on the quaternary amine n-alkyldimethylbenzyl ammonium chloride (ADBAC) technology to control biofouling. Quaternary amines are cationic surfactants with an excellent biocidal efficacy against macro bio-organism (Post et al., 2003). An evaluation trial was performed with the objective to prolong stable operation of the evaporators for at least one year without condenser cleaning. The challenge during this trial period was that the nominal production capacity of 6,000 m^3/day and a performance ratio above 9 should at least be maintained. The trial was successfully concluded after 7.5 months with an average production and efficiency of respectively 6,267 m^3/day and 9.6. As a matter of fact, the MSF evaporator used for the test continued in operation for 15 months after the initial dosing of the non-oxidizing biocide without the necessity for condenser cleaning.

Different visual inspections carried out during this period showed the condenser to be in excellent clean condition without any form of macro biofouling. Another observation was that the optimal temperature difference between the condenser and the evaporation vessels in the heat regeneration section indicated practically no micro biofouling on the heat transfer surfaces.

To monitor the fouling condition of a condenser, the desalination department of WEB, developed and introduced the condenser fouling ratio. This fouling ratio is defined as the ratio of the seawater flow and the distillate flow. Normally when the condenser is fouling the distillate production steadily decays and the cooling seawater flow is increased resulting in an increased condenser fouling ratio. A constant trend of the condenser fouling ratio indicates that practically no fouling is taking place on the condenser's tubes. The trend of the condenser fouling ratio during the aforementioned trial with the non-oxidizing biofouling additive is depicted in figure 9 (Marchena, 2013).

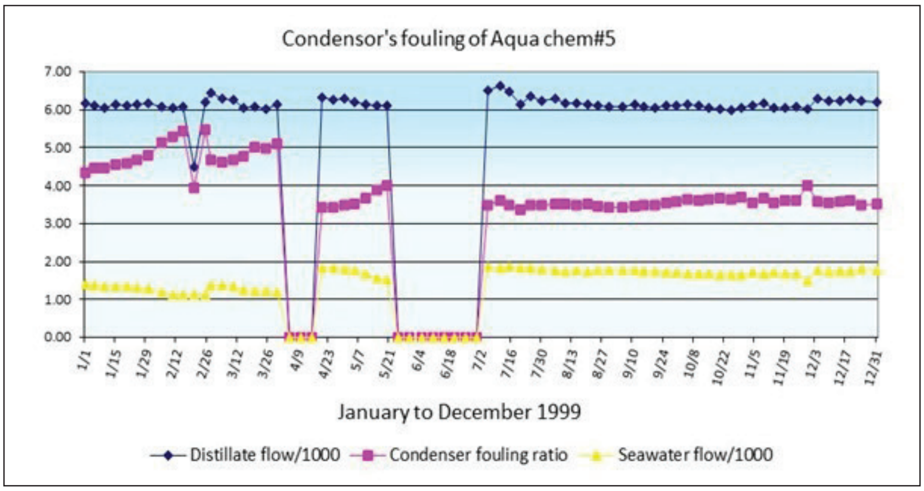

Figure 9. Condenser fouling ratio of Aqua Chem#5 in 1999 during trial

In conclusion of this section the condition of the condenser of the MSF evaporator before and after application of the new biocide is illustrated in figure 10 (Marchena, 2013).

Figure 10. The effectiveness of the non-oxidizing biocide additive

2.3.4. Scale formation and biofouling on SWRO membranes

Fouling of SWRO membranes can be very pronounced if the pretreatment of the seawater feed fails or the pretreatment system is not adequately designed. Membrane fouling can drastically reduce fresh water production and its quality. If not taken care of effectively, membranes can be permanently damaged in a very short period of time. The major contributions to the membrane fouling processes are the physicochemical depositions and biofouling due to attachment and proliferations of marine microorganism on the membrane surfaces. The physicochemical fouling process consists of: (1) precipitation of supersaturated inorganic chemical components; (2) organic fouling; and (3) colloidal fouling.

The precipitation of inorganic salts on the membrane surface occurs mainly due to concentration polarization. This process is inherent to the water diffusion through the membrane following the convective mass transfer from the bulk to the membrane surface and back diffusion from the boundary layer toward the liquid bulk (Van der Meer, 2003). Defined also as crystalline fouling, mineral scale is deposited or forms on the membrane surface as a result of exceeding the solubility limits of the respective minerals. Figure 11 illustrates schematically the concentration polarization process on a semi-permeable membrane (Marchena, 2013).

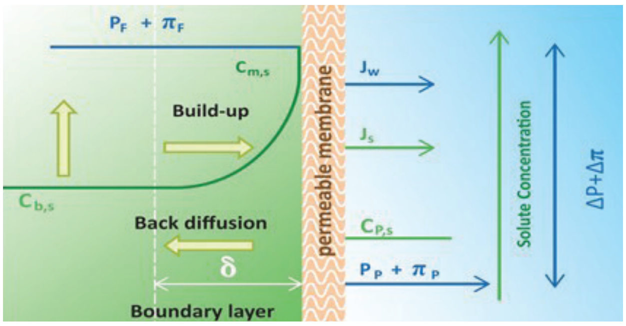

Figure 11. The concentration polarization process

Organic fouling on the other hand is adsorption of organic molecules onto the membrane surface where they remain, unable to diffuse through the membrane or re-dissolve into the feed bulk solution. These can be dissolved humic or fulvic acids from decomposing vegetable matter as well as oils and grease (van der Helm, 2007).

The third form of physicochemical fouling is colloidal fouling which involves coating of the membrane surface by particles that cannot pass through the membrane. This includes deposition of materials such as clay, silt, colloidal silica and particulates attracted especially by undissolved organic matter such as humic substances. Physicochemical fouling can furthermore enhance attachment of microorganism leading to severe biofouling. Biofouling of SWRO membrane surfaces is defined as the deposition, accumulation, and growth of microbiological organisms on membrane surfaces. Also included are other foulants that support and act as nutrients for the biofilm. A biofouling layer will continue to grow thicker and denser, drastically reducing permeation of fresh water through the membrane.

Biofouling of membranes is a major technical issue in practically all water treatment processes. A biofilm quickly forms on all surfaces exposed to almost any feed water. It is a serious problem for all reverse osmosis systems using surface waters as feed water (Sheikholeslami, 2007).

Severe membrane fouling, a combination of both physicochemical- and biofouling is also experienced in the Aruba plants with the new SWRO membrane technology, as illustrated in figure 12 (Marchena, 2013).

Figure 12. Disassembled SWRO membrane showing biofilm matrix

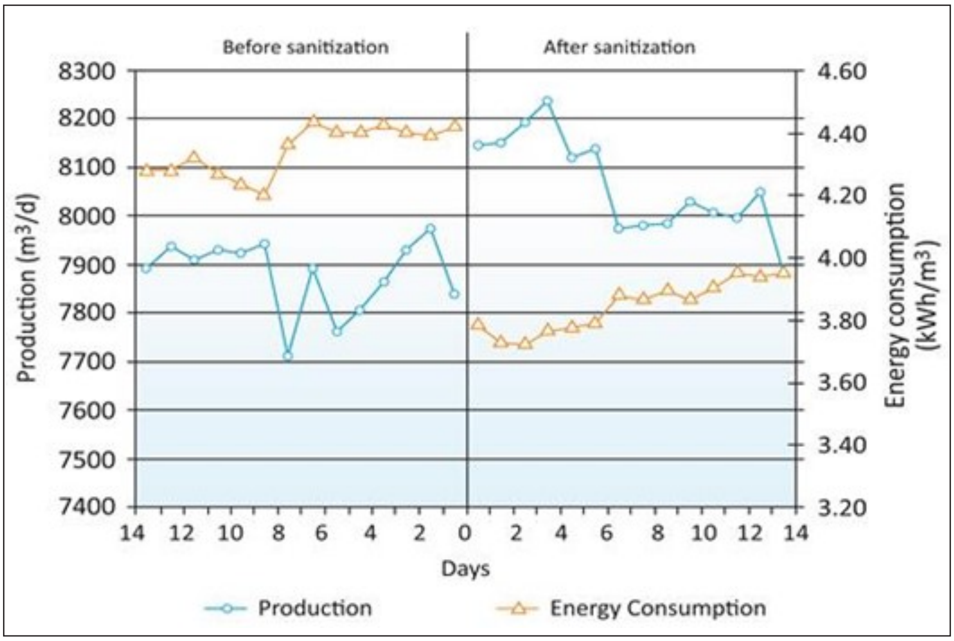

Figure 13. Effectiveness of the osmotic cleaning process

In cooperation with the manufacturer, different membrane cleaning procedures have been applied to mitigate membrane biofouling, however with mixed results. Further on, a novel osmotic membrane cleaning and sanitation method was developed and applied which effectively increased production and efficiency above design values (Marchena, 2012).

After the application of this innovative osmotic membrane cleaning process and the intensified sanitation, the energy consumption dropped, for the first, time to 3.72 kWh/m^3, 7% lower than the target design value of 4.00 kWh/m^3. In Figure 13, the trend of the energy consumption and production prior and after the application of this novel osmotic membrane cleaning process is illustrated to demonstrate its effectiveness to increase efficiency (Marchena, 2013).

2.4. Corrosion in Potable water Distribution Systems

Thermal distillation and membrane desalination plants produce potable water of the very highest purity and quality. The distillation process, in particular, eliminates all of the many contaminants which commonly occur at low levels in potable water produced from surface water and well water supplies. Although distilled and membrane treated water is pure, it is corrosive to the pipes, storage tanks, valves, and meters that comprise the water distribution system. Corrosion reduces the useful service life of the system, reduces the carrying capacity of the pipes, and releases undesirable corrosion products, such as red iron oxides (rust), into the drinking water.

The methods available for controlling corrosion in potable water systems are very limited due to the requirement that any material added to the water must be certified as safe for human consumption, and should not affect the taste of the water. Since the very beginning of the thermal desalination activities in Aruba, the hot distillate has been cascaded over a bed of natural coral stones in the “Coral House” and sodium hexametaphosphate (SHMP) was used as a corrosion inhibitor. From the late 1980s until 1990, the community of Aruba experienced brown water problems throughout the island due to corrosion in the distribution piping system, with the iron content far beyond WHO-standards.

In 1990, after a comprehensive corrosion survey of Aruba’s Potable Water Distribution System the SHMP corrosion inhibitor program was replaced with a new treatment program consisting of low levels of both zinc and pyrophosphate. This treatment program, in effect from 1990 to 1996, successfully cleaned up the system and eliminated the “brown water” complaints. By 1996, the bulk of the iron products had been removed from the system and efforts were re-focused on further reducing corrosion. Around that time the zinc product was replaced by an orthophosphate/zinc blend and the pyrophosphate dosage was reduced. Occasionally, WEB Aruba has also observed blue water in their distribution system; this is caused by corrosion in the smaller copper distribution lines.

This section provides a summary description of the corrosion processes causing the occurrence of brown water, blue water and corrosion induced perforations of distribution pipes.

Refined metals, such as steel and copper are inherently unstable. In the natural environment, these metals are found as their oxides, hydroxides, sulfides, and ionic solutions, which are more stable than the refined metal. Corrosion is simply an electrochemical reaction of the refined metal with its environment that returns the metal to its natural oxidized state (Fontana, 1986). For example, when steel pipe corrodes in water, it reverts to iron oxide, commonly known as “rust”. Some of the rust adheres to and accumulates on the surface of the pipe. These accumulations, known as tubercles or tuberculation are more voluminous than the refined steel, restricting the flow in pipes. Some of the rust breaks free from the surface, imparting an unsightly red, orange, and brown color to the water or blue-green in the case of copper corrosion. Over the long term, corrosion causes a loss of pipe wall thickness and eventual perforation, resulting in water leaks. The pictures in figures 14 are vivid examples of corrosion in steel and copper used in potable water systems (Post et al., 2002).

In more scientific terms, corrosion can be understood as an electrochemical process, essentially a battery operating under uncontrolled conditions. There are four basic elements to the corrosion cell: (1) anode, where the metal gives up electrons and dissolves into solution; (2) cathode, where the electrons given up at the cathode are released to solution; (3) conductor (base metal), which conducts the flow of electrons; and (4) electrolyte (water solution), where the flow of ions in solution completes the circuit. Figure 15 illustrates schematically the electrochemical aspects of the corrosion cell for steel in a water system (Marchena, 2013).

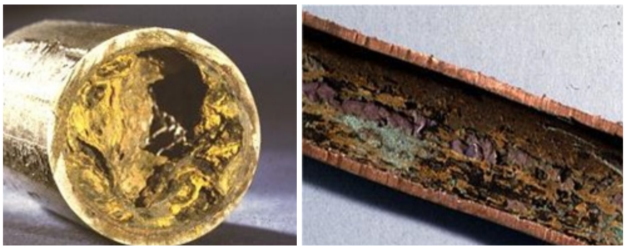

Figure 14. Iron and copper corrosion in distribution pipes

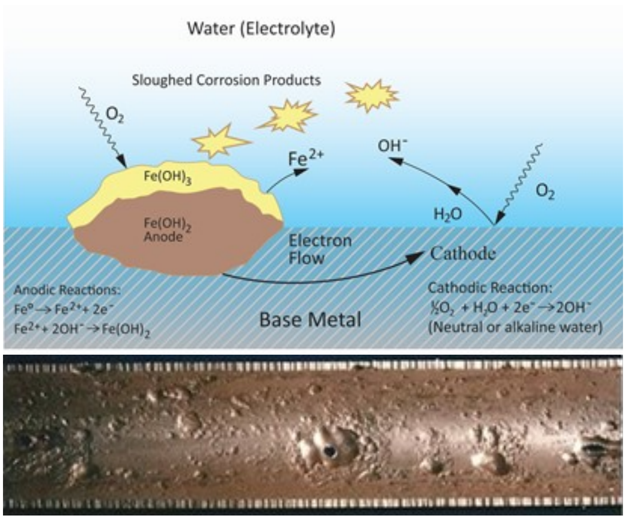

Figure 15. Electrochemical iron corrosion cell in water systems

For copper, the natural corrosion process at neutral or alkaline pH is limited by the rate of copper dissolving into solution at the anode. In Figure 16, a diagrammatic representation of the flow accelerated pitting corrosion of copper producing blue water in drinking water distribution pipe lines is illustrated (Hollander, 1990; Marchena, 2013).The mechanism of copper pitting corrosion is very complex. Different oxidation-reduction reactions (as shown in figure 16) take place forming different copper oxides and salts deposits.

As noted earlier, the desalination process removes practically all ions including calcium, magnesium and carbonates giving desalinated water significantly different characteristics from naturally occurring water and a different treatment methodology is required. The application of the pyrophosphate based corrosion inhibition program in Aruba has effectively mitigated corrosion in the water distribution network eliminating the occurrence of brown water, blue water and corrosion induced perforations of distribution pipes. The water losses are significantly reduced, with Aruba having the lowest percentage *"Non-Revenue Water"* (NRW) in the region of about 2.6 to 4.7 % as compared with 15 to 65% in the neighboring islands; the low *"Infrastructure Leakage Index"* (ILI) reflects the well-maintained condition of the distribution network (Marchena, 2013).

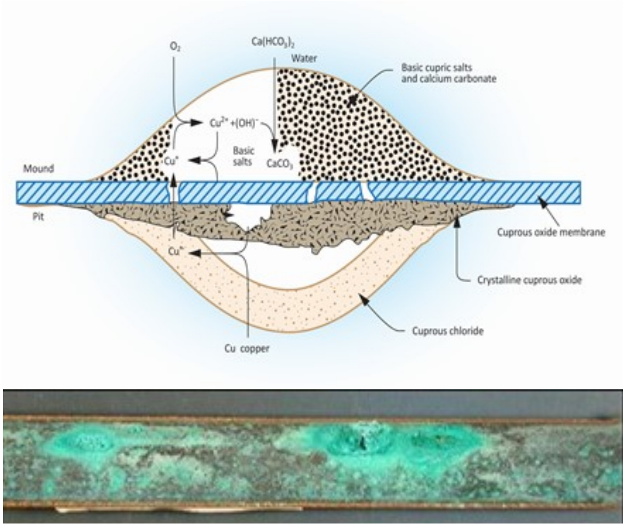

Figure 16. Chloride induced copper corrosion in water

3. DISCUSSION AND CONCLUSIONS

This paper has outlined the different techniques that have been developed and successfully applied in Aruba in cooperation with manufacturers and chemical suppliers to solve the operational problems hampering efficient fresh water productions experienced with desalination. Especially the gained operational and maintenance experiences of the work floor personnel have been a determinative factor toward many solutions of the desalination problems. This was also the basis of the Continuous Desalination Efficiency Improvement Process to effectively involve the work floor personnel.

Aruba's journey starting from a primitive water supply system to sophisticated seawater desalination facilities, resolving most of the desalination problems encountered, is worth sharing with other Small Island Developing States in semi-arid and arid areas. A great challenge, however, is still the reduction of the impact of desalination on the coastal marine ecosystem. In this context further research is necessary to improve the osmotic membrane cleaning process to eliminate the intensive chemical cleaning of the SWRO membranes. A contribution to the development of zero liquid discharge seawater desalination technologies and the forward osmosis technology are near future desalination challenges of importance in Aruba to mitigate or eliminate the contamination of the coastal marine ecosystem.

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