Efficiency Improvement of Seawater Desalination Processes:

The case of the W.E.B. Aruba N.V. on the island of Aruba

Filomeno A. Marchena

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EFFICIENCY IMPROVEMENT OF SEAWATER DESALINATION PROCESSES:
THE CASE OF THE W.E.B. ARUBA N.V. ON THE ISLAND OF ARUBA

DISSERTATION

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Filomeno Arsenio Marchena

born on the 14th of December, 1953
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Seawater: the origin of life
Seawater desalination: the origin of life's quality
Filomeno A. Marchena

To Ruth, Tristan and Darwyn
For their love, inspiration, patience and support

Acknowledgement

From the very beginning, mastering the seawater desalination and potable water treatment technology comprehending the beauty of the theoretical and practical scientific knowledge giving exergy propulsion to the desalination science it became my passion, vision and mission to excel in this important technology. At the end of this wonderful journey compiling the acquired desalination experience and knowledge, very well aware of the fact that practically every goal achieved in live is not a one person activity, I herewith take the opportunity to show my sincere gratitude to all that in one way of the other have contributed to this dissertation.

First of all I am very grateful to Prof. Dr. Ir. Johannes I. M. Halman, Head of the Chair Technology Innovation and Risk Management at the University of Twente for his knowledgeable advice, support and patience throughout the preparation of this dissertation and willingness to be my supervisor. Joop from the deepest of my heart thank you very much for the opportunity granted to me to make a long lasting dream comes true.
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I still remember our conversation (during our flight back from the UNESCO IHP Conference in Paraguay presenting our plans to establish a Desalination Chair at your university) about my intension for a PhD dissertation and that I did not know a professor willing to act as my promoter. Half asleep you promised to bring me in contact with Prof. Halman and indeed you did. Meanwhile preparing and finalizing this thesis also the dream of the UNESCO Water Technology Chair became a reality.

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Vincentico, un danki special, your support with the many graphs in this dissertation was enormous.
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To my beloved wife Ruth and sons Tristan and Darwyn words of gratefulness fail me to express my gratitude and I hope that love will compensate your support, patience and acceptance of me having another family that I also sincerely care for, my desalination family. I will dedicate my dream work to you with love and as a fatherly apology for all the hours and days not being able to enjoy with you.

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May the Lord bless all of you!
Filomeno A. (*Boey) Marchena.*

Summary

Introduction
The island of Aruba has earned worldwide throughout its desalination history an excellent reputation for the efficient application of the costly thermal seawater desalination technology for the production of one of the world's highest quality drinking water. In view of the importance of reliable production and distribution of drinking water for the population, for the economy, industry and in particular for the tourism in Aruba it is of mere importance to continuously seek for improvements to increase the efficiency of the costly desalination process. Years of practical desalination experience have pointed out the physicochemical treatment, the implementation of new technology, maintenance and innovation as the most important technical aspect to improve efficiency. In particular the human factor governing the whole spectrum of these technical aspects is of eminent importance. In this context a *Continuous Desalination Efficiency Improvement Process* (CDEIP) has been developed based on these efficiency improvement factors. The applied technologies in the case of W.E.B. Aruba N.V. validating this efficiency improvement process are thoroughly described in subsequent chapters of this thesis. This Continuous Desalination Efficiency Improvement Process is developed in accordance with the performance frame work of the *European Foundation for Quality Management* (EFQM-) model directing organizations toward excellence performance.

The desalination history of Aruba
For the early inhabitants of Aruba rain water collected in the dry river beds and well water were the only sources of drinking water. The cactus plant was used as a natural coagulant to clarify the drinking water. Seawater desalination was for the first time applied in 1903 for the production of fresh water for the gold extraction process. However, commercial desalination for the production of drinking water and industrial water started in 1932. In accordance with the development of the global desalination market the first applied thermal evaporators were from the *Multi Effect Distillation* (MED-) technology followed in the 1960's by the more reliable and efficient *Multi Stage Flashing* (MSF-) technology. In 2008 the taken over of the supremacy of this thermal technology is initiated with the introduction of the more efficient *Sea Water Reverse Osmosis* (SWRO-) technology.

The human aspect
Motivated personnel are an important key efficiency improvement factor. In the context of efficacy, efficiency improvement through effective empowerment and involvement of the work floor personnel a novel *Efficacious Motivational Leadership* (EML-) approach is developed based on the concept of inducing self-leadership and self-development.

In this model the mastery and excellence satisfaction is introduced next to the job and work satisfaction. To comprehend human behavior a simple *Passion and Fear* (PF-) and *Human Attitude* (HA-) metaphoric models have been developed by analogy with acknowledged technological models as supporting tool to enhance motivation to overcome the always existing resistance for change. The *Desalination's Hierarchy of Needs* is developed inspired by the *Hierarchy of Needs* of Abraham H. Maslow to effectively support the initiated motivation process. According to the *Two Factor theory* of Frederick I. Herzberg, company rules and policy are the factors causing the most employee dissatisfaction. To cope with this fact the employees were giving the opportunity to challenge company rules and policy without violating any of them. This so called *Mahatma Gandhi* (MG-) effect resulted to be a very effective leadership strategy. With the application of this leadership strategy and the EML-approach significant performance improvements have been realized at the Desalination Department such as decreasing frequent absenteeism and improvement of desalination operation and maintenance efficiency and yearly operation cost savings due to motivation.

The physicochemical aspect

In the desalination process chemicals are indispensable to prevent excessive foaming, biofouling, and scale formation and to inhibit corrosion in the desalination and the water distribution system. A novel non-oxidizing biocide based on the quaternary amines technology was for the first time in the world successful applied in a MSF evaporator at W.E.B. Aruba N.V. to mitigate biofouling. Likewise in cooperation with the chemical supplier a new effective high temperature antiscalant based on the poly phosphonate technology has been developed and successfully applied to eliminate the use of concentrated sulfuric acid as scale inhibitor. Instead of the enhanced lime stone hardening process the pyrophosphate/orthophosphate technology is successfully applied as corrosion inhibitor eliminating "red water" in the distribution system. A simple explanation is given for the in practice experienced foaming phenomena in MSF evaporators causing efficiency and production decay. A novel conceptual method is introduced to apply the surface tension of the recirculation brine as a control measure for the MSF additives dosing.

The aspect of Maintenance

In analogy with the EML-approach a novel *Efficacy Oriented Maintenance* (EOM-) concept has been developed based on the principle of maintenance conscience operation promoting an effective team between Production and Maintenance personnel at the work floor level. The introduction of this EOM-approach has significantly decreased pump and process failures and has increased the accumulative performance ratio of the MSF evaporators from 8.7 to 9.3 decreasing operation and maintenance costs.

Due to good maintenance and operation of the distribution system, good water quality and client services W.E.B. Aruba N.V. has managed to have the lowest percentage *Non Revenue Water* (NRW) in the region, a NRW of about 2.6-4.1% comparing with 15 to 70% in the neighboring Caribbean islands. The *Infrastructure Leakage Index* (ILI), indicating the degree of maintenance of the distribution system, is 0.5 which is less than the target stipulated by the *American Water Works Association* (AWWA-) guidelines for systems with very limited available water resources.

The aspect of Innovation

Aruba has throughout its desalination history contributed to innovation in desalination technology. Manufacturers have improved their designs due to valuable practical information gained from experienced and knowledgeable operations and maintenance personnel. Aruba has played since 1958 an important role in the development and practical application of the first worldwide successful high temperature scale inhibitors such as the ferric chloride in 1958, concentrated sulfuric acid in 1964, the innovative high temperature antiscalant GEBetz HT 15 ™ in 2005 increasing the sustainability of the thermal desalination technology. Due to the input of operation personnel the design efficiency (*Gain Output Ratio or Performance Ratio*) of the MSF evaporators of 9.0 has been optimized since its first application in the 1960's to 11.5. In 1990 an innovative chlorine gas disposal process has been designed for the successfully processing of damaged chlorine one-ton containers. Three patents have been registered for the conceptual designs of a carbon dioxide degassing tower and a hybrid *Osmosis Reverse Osmosis* (ORO-) desalination process and a conceptual design for a novel environmental friendly chemical free osmotic cleaning process for SWRO-BWRO membranes.

The aspect of implementation of new technology

W.E.B. Aruba N.V. was forced from 1990 to 1998, due to rapid economic growth, to increase production capacity with 5 new plants. For all these plants MSF technology was chosen because of reliability, good operation experience and lack of time to evaluate new technology. A change was forced around 2004 because of the significantly increment in the water production cost due to rapid increases in fuel oil cost introducing the new membrane technology after an intensive evaluation process. Other contributing factors are the facts that a number of the mayor hotels were considering the installation of their own SWRO units to reduce water cost and the increment in complaints from domestic consumers due to the increased cost of drinking water. The heavy membrane biofouling experienced with the new SWRO technology led to the introduction of the beach well technology for the seawater intake at W.E.B. Aruba N.V. to replace the open intake applied since 1932.

General Conclusion, contribution to science and practice and the need for further research

Aruba has taken throughout its desalination history a leading role in the efficacious operation and maintenance of the thermal evaporators and SWRO production units supporting the development and application of innovative technology. Especially in the area of scale inhibition, the non oxidizing biochemical pretreatment of the seawater feed and the effective post treatment of soft water (low hardness) produced by thermal and membrane seawater desalination. Aruba has undoubtedly succeeded to maintain its excellent reputation in the world for the solution of the water shortage problem in arid area producing efficiently drinking water (one of the highest chemical and bacteriological quality in the world) and assuring its population one hundred percent security of save drinking water. The most important contribution to science is the development and application of the Efficacious Motivational Leadership and the Efficacy Oriented Maintenance approaches based on the art of technological science to use representative models for phenomenological description of rather complex processes in nature as a very essential foundation for intimate acquirement of theoretical knowledge and comprehension. Based on these approaches clear desalination efficiency improvements have been observed during a number of years. The applied techniques and technologies in the case of the Desalination Department of W.E.B. Aruba N.V. have validated the Continuous Desalination Efficiency Improvement Process developed at the Desalination Department in accordance with the performance framework of the European Foundation for Quality Management model. Commercial desalination should be considered the important final step of the scientific research and development process evaluating new technological innovations on "real scale models" providing new practical insight for optimizing existing or generating new innovative ideas. Further research is recommended to improve the different efficiency key improvement factors, and especially for the further development of the Osmosis Reverse Osmosis (ORO-) hybrid desalination process and the *Combined Membrane Water and Power Production* (CMWPP-) process. The use of Nano Filtration technology for the application of a zero discharge chlorination process in the drinking water distribution network should be further evaluated.

Epilogue:

In Aruba we took a long journey from primitive water supply to a sophisticated modern water production and distribution company enthusiastically envisioning the journey to future Green Sustainable Desalination technology as the solution for the water shortage in the world without destruction of the environment, especially the marine ecosystem.

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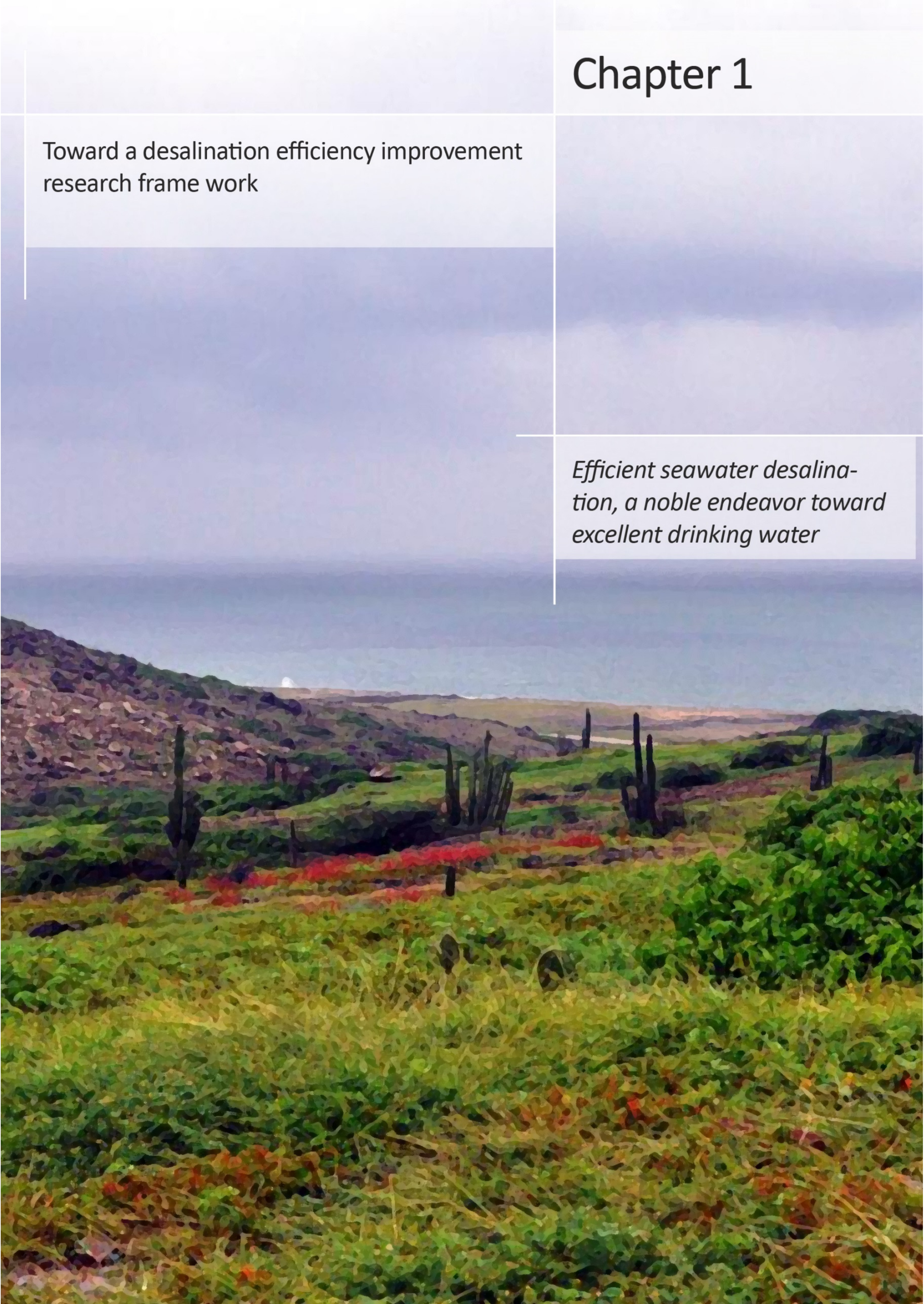
Chapter 1

Toward a desalination efficiency improvement research frame work

Efficient seawater desalination, a noble endeavor toward excellent drinking water



Chapter 1

Toward a desalination efficiency improvement research frame work

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1.1 Introduction

The thermal evaporation of seawater is known worldwide as the most important source for the production of drinking water in arid areas where there are practically no natural water resources and consequently insufficient surface water or groundwater. Since 1860 thermal evaporation has been developed 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 [1.1]. A technological breakthrough in desalination cost reduction was achieved with the development of the *Sea Water Reverse Osmosis* (SWRO-) desalination technology. This high pressure membrane technology developed around 1950 has taken over the dominant role of thermal desalination for the production of drinking water since 1995, especially due to innovations in the energy recovery system and development of new high efficiency permeable membrane materials [1.2]. This technology has an energy consumption that is about 70 to 75 percent lower than that of thermal seawater evaporators, especially the *Multi Stage Flashing* (MSF-) technology.
Globally, the last decades the main research efforts are concentrated on alternative sustainable desalination technology primarily based on solar, wind, geothermal and ocean green energy for the environmentally protection and a pollution-free Earth banning the use of conventional fossil fuel for energy production to mitigate the negative effects of global warming. According to the *"Trias Energetica"* model as developed at the Delft University of Technology, the path forward to reach sustainability is: (1) to use less energy; (2) to apply renewable energy; and (3) to use conventional fossil fuel as efficient as possible [1.3]. However, in the practical operation of conventional seawater desalination technology one important aspect of sustainability, sometimes it looks like it is forgotten, is the optimal operation efficiency to effectively reduce energy consumption and consequently reducing operation cost and environmental pollution. Therefore, toward our future with Green Energy, besides the research and development of alternative technology, the importance of efficiency improvement especially in the present application of our costly conventional desalination technology should not be neglected. In this context Efficacy, the efficiency improvement process through effective involvement and empowering of work floor personnel is of utmost importance [1.4].
The scope of this dissertation is based on the successes of the application of the basic concept of an efficacy oriented operation and maintenance process in desalination at W.E.B. Aruba N.V. In the following sections, the background, the research problem statement and the research frame work of this process toward excellence in desalination are illustrated.

1.2 The background of the research

The island of Aruba one of the pioneers in the commercial seawater desalination since 1932, having the world's largest desalination capacity for a very short period of time at the end of the 1950's [1.5], is still known in the world as a role model of how a small and arid island has solved the drinking water problem for its population by means of the efficient application of seawater desalination. Likewise Aruba has given its population, in its more than 80 years of commercial seawater desalination history, due to a trustworthy water production, distribution and storage facility the security of 100 percent delivery of one of the world's highest quality drinking water. Up to now no occurrence of non-delivery of drinking water has ever been reported.
The Water- en Energiebedrijf Aruba (W.E.B.) N.V., a combined Power and Water production company is the sole energy and water producer and distributor of drinking water for the entire population of Aruba. Together with its sister company N.V. Elmar, the Electrical Power Distribution Company of Aruba, W.E.B. Aruba N.V. is (as shown in Figure 1.1) a subsidiary of the holding company Utilities Aruba N.V. owned by the Government of Aruba. Further it is noteworthy that N.V. Elmar is the sole distributor of electricity on the Island of Aruba and operates and maintains the whole power distribution grid [1.6].

Figure 1.1: The legal structure of the Utilities Aruba N.V.

The commercial seawater desalination activities of W.E.B. Aruba N.V. have followed the development trend of the global desalination market and have been until 2008 dominated by the thermal evaporation technology. The first applied thermal evaporators were from the

Multi Effect Distillation (MED-) technology. The MED technology was replaced in 1965 by the more reliable and efficient Multi Stage Flashing (MSF-) technology taking over the dominant role of the MED technology at that time.
In an attempt to reduce operation cost, W.E.B. Aruba N.V. has started in February 2008 with the application of the membrane technology for seawater desalination after more than seventy five years of successful thermal desalination. A two pass two stage SWRO production unit with a capacity of 8,000 cubic meters per day was put in operation [1.7]. The construction of a new SWRO desalination unit with a capacity of 24,000 cubic meters per day is partially completed and put in operation in the last quarter of 2012.
Necessary improvements of the pretreatment system are in progress to reach the nominal design production capacity. Commissioning and complete taking over is planned for the first quarter of 2014 and herewith officially the permanent decommissioning of four of the existing six MSF evaporators closing the supremacy of the thermal desalination in Aruba.
In view of the importance of reliable production and distribution of drinking water for the population, for the economy, industry and in particular for the tourism in Aruba it is of mere importance to continuously seek for improvements to increase the efficiency of the costly desalination process. The ultimate goal is to reach and sustain an optimal operational efficiency to effectively reduce operation cost, excelling in desalination operation. The scope of this thesis as explained in the following sections is based on the effort done at W.E.B. Aruba N.V. throughout its desalination history to increase efficiency.

1.3 The main objective of the thesis

The availability of fresh water complying with high chemical and bacteriological quality standards is essential for the health and safety of the population and for the economic development of a nation. In arid areas with in general practically no rain fall and consequently no sufficient natural water resources, desalination of seawater or brackish water is up to now the only viable option for the production of drinking water.
The desalination technology went through many innovations to reduce water production cost but it still remains a very costly process. However, given a certain applied desalination technology the only option to effectively reduce production cost is optimized efficient operation and maintenance to mitigate the commonly experienced production and efficiency decay during normal operation. Furthermore, as previously mentioned, it is next to alternative green technologies an essential process toward sustainable efficient seawater desalination. The main objectives of this thesis are therefore:

The specification and evaluation of the most important aspects in practical operations that influence sustainable efficiency in seawater desalination and to illustrate the effectiveness of a continuous desalination efficiency improvement process founded on these key efficiency-improvement aspects.

The illustration of the technologies and techniques developed and applied at the Desalination Department of W.E.B. Aruba N.V., validating and fortifying the developed continuous desalination efficiency improvement process to guarantee an environmental friendly and cost effective production and distribution of drinking water with a high chemical and bacteriological quality.

The mere importance of the objectives of this thesis, the excellence journey reaching out to sustainable efficiency improvement in seawater desalination has been already well emphasized in 1961 by the late President of the United States of America John F. Kennedy [1.8]:

"If we could ever competitively, at a cheap rate, get fresh water from saltwater, that would be in the long-range interest of humanity and would dwarf any other scientific accomplishments"

To reach this goal of excellence in sustainably reducing desalination cost it is of mere importance to know the whole spectrum of aspects leading to continuous efficiency improvement. In the following sections the research frame work toward this accomplishment is specified regarding a continuous seawater desalination improvement process developed based on practical acquired desalination experience and knowledge and the applied improvement technologies in the case of W.E.B. Aruba N.V. to validate this continuous improvement process. Furthermore, this continuous improvement process is in general applicable for all desalination activities.

1.4 The specification of the research project

The research problem statement

Man has searched practically throughout his existence for ways to treat salty water to fulfill the basic need of drinking water supply. Seawater desalination therefore can be considered one of the most valuable inventions of mankind. Since its introduction in the 18^{th} century especially for water supply on sea going ships for long voyages, research intensively concentrated on design improvement and innovations to make drinking water production reliable and more economical. However, the desalination processes are still energy intensive and therefore very costly. Given an applied desalination technology in practice one of the most valuable options to cost effectiveness is optimal operation and maintenance efficiency. In this context in accordance with the globally need to increase efficiency leading to effective reduction of pollution and desalination cost the research problem statement, in particular based on the desalination experience of W.E.B. Aruba N.V. is formulated as follows:

The identification, specification and evaluation of the most critical and important factors influencing seawater desalination operation and maintenance efficiency and optimal drinking water conditioning, forming the foundation of a continuous desalination efficiency improvement process.

The specification and evaluation of the technologies and techniques applied at W.E.B. Aruba N.V. to sustainably improve these factors optimizing water production cost and herewith validating the developed continuous desalination efficiency improvement process.

Comprehension of the basic concepts governing these factors is fundamental to encourage and to motivate changes for efficiency improvements. The criteria for successful practical application are operation friendly economical solution complying with safety, health and environmental regulations. The important questions underlying the foundation of this research are specified in the next section.

The research questions

According to the desalination operational experience at W.E.B. Aruba N.V., well designed and constructed desalination units usually pass after some adjustment in the commissioning phase the operational performance test within a specified and agreed upon period meeting practically all design criteria and nominal capacity and efficiency. However, usually after some months of operation production decay and consequently efficiency reduction (as shown in Figure 1.2) is always experienced basically due to marine biofouling, scaling and the corrosive seawater environment. With the lapse of time without an effective improvement process this efficiency decaying tendency especially enhanced by aging of the production units will become more intensive [1.9].

In the MSF evaporation technology efficiency is usually defined as the *Gain Output Ratio* (GOR), the ratio of the amount of distillate produced to the amount of low pressure steam consumed. At W.E.B. Aruba N.V., the expression *"Performance Ratio"* is historically used instead of the Gain Output Ratio as indicated in Figure 1.2.

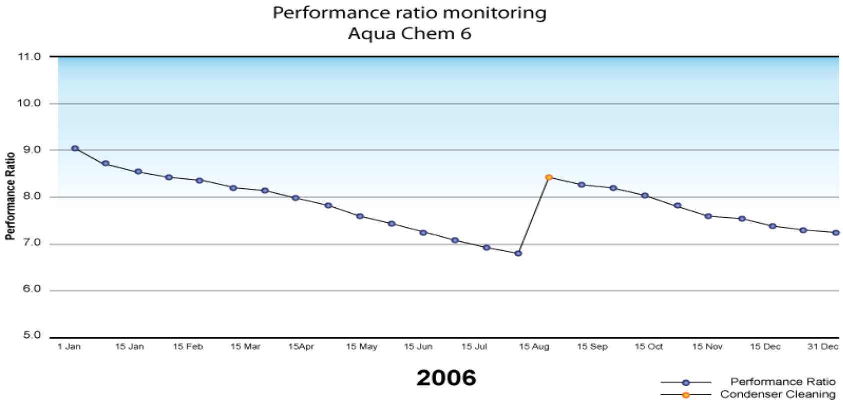


Figure 1.2: Efficiency decay after a general inspection and maintenance of an MSF evaporator at W.E.B. Aruba N.V.

Throughout its desalination history the effort of the Desalination Department of W.E.B. Aruba N.V. to mitigate efficiency decay has contributed to the practical technological knowledge improving design and operation of desalination processes. In the desalination pioneering years basically this was done more or less based on the trial and error concept. The last decades, goal oriented practical research has been done on a more scientific basis to specify and structure the challenges and problems experienced in the desalination practice and the applied solutions toward a sustainable continuous performance improvement process. Considering the experienced socio-technical challenges in the practical process of effective leadership motivating the work force toward improved performance ensuring the desalination assets to function as intended, the main research question to structure the setup of the research frame work is:

“What are the most important factors influencing desalination efficiency?”

Answering this main research question is due necessary to lay down the foundation of the research frame work. Many years of practical desalination experience exploring the possibilities to improve desalination efficiency solving the usually experienced desalination problems have given a fundamental answer on this principle question pointing out the following factors as being the most important;

- The human factor
- The physical and chemical aspect
- The maintenance aspect
- The aspect of technology innovation
- The implementation of new technology

Based on these practical founded assumptions the research frame work was further formalized based on the following questions:

1. Given an efficiency improvement aspect, what are the sub aspects of importance to effectively improve efficiency?
2. How can improvement of these factors of concern contribute to sustainable efficiency improvement?
3. What are the efficiency improvement results?

The answers to the abovementioned questions form the core of the continuous desalination efficiency improvement process and will be extensively discussed in the subsequent chapters of this thesis. Having specified guided by practical experience the human factor and the abovementioned technical aspects as the dominant desalination efficiency improvement factors the next important step toward the research frame work is answering the abovementioned second research question identifying the most essential sub aspects. The breakdown into sub aspects is also based on years of practical experiences striving to specify the improvement aspects to reach out to an efficient operation and maintenance desalination performance.

Effective leadership strategy, work floor motivation and a strategic performance improvement program are, according to experienced challenges in practice at the Desalination Department considered as the most important sub aspects of the human factor to effectively involve and empower the work floor personnel toward desalination operation and maintenance efficiency improvement.

Furthermore, a very important technical aspect greatly influencing efficiency is the physical and chemical aspect. It is beyond any doubt that up to now there is no possibility for efficient and effective saline water desalination and potabilization of the produced distillate without chemicals. Of importance is also the chemical conditioning of the drinking water to inhibit corrosion in the distribution system. This physicochemical aspect is further specified according to the main important problems encountered in seawater desalination needing effective chemical treatment:

- Biofouling
- Scaling, fouling and corrosion
- Foaming
- Distillate post treatment

The specification of the desalination improvement aspects based on the main human and technical aspect and the coherent sub aspects is schematically illustrated in Figure 1.3. The subsequent chapters where the sub aspects are described in this thesis are also illustrated in Figure 1.3.

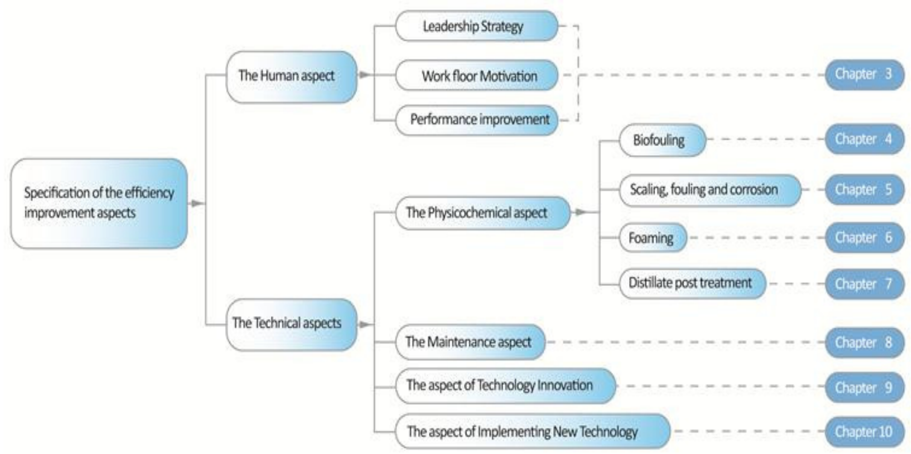


Figure 1.3: The basis of the desalination efficiency improvement research frame work

Subsequently as a reflection, the contribution to science and operational practice and limitations of this research and the need for further research with the intention to fortify and continuously broaden the existing practical and theoretical desalination knowledge to sustain and endorse continuous performance improvements are considered based on the following questions:

4. What is the contribution to science?
5. What is the contribution to the desalination operational practice in Aruba and abroad?
6. What is not considered in this research and what is important for further research?

The abovementioned aspects and questions serve as guiding principle for the setup of the research frame work toward sustainable efficiency improvement as elaborated on in the next section.

The research frame work

The basis of the research frame work

The research frame work of this thesis is in main set up according to a developed new *Continuous Desalination Efficiency Improvement Process* (CDEIP) reaching out to excellence in Desalination and is based (inspired by the ISO quality progress audit model of Kiwa) on the components of the performance frame work of the *European Foundation for Quality Management* (EFQM-) Model. This EFQM model is known as an effective descriptive supporting tool directing companies and organization toward Excellence performance. The EFQM model is also worldwide known as the *Business Excellence Model* (BEM) [1.10].

The iterative evaluation process of the CDEIP

The evaluation process of the CDEIP's improvement steps is based on the combination of the *Plan-Do-Check-Act* (PDCA-) modes of the Deming Circle with the principles of the *Engineering Design Process* (EDP) specifying the iterative evaluation steps of the PDCA modes [1.11]. This iterative evaluation process of this new Continuous Desalination Efficiency Improvement Process consists of the following steps:

The iterative evaluation process of the CDEIP's improvement steps

Deming Circle	Engineering Design process
Plan	: 1. Identify the need
	2. Research the need, gathering information
Do	: 3. Develop the best possible solutions
	4. Select the best possible solution
Check	: 5. Construct the best possible solution
	6. Test the best possible solution
Act	: 7. Present the solutions
	8. Redesign the solution

The basics of this new Continuous Desalination Efficiency Improvement Process are schematically illustrated in Figure 1.4.

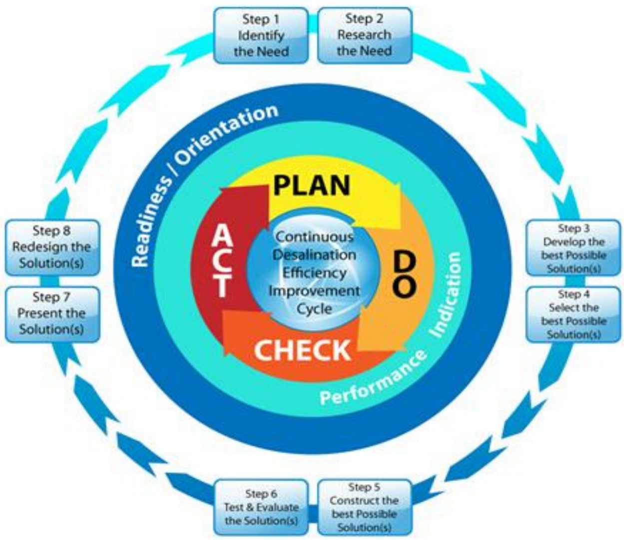


Figure 1.4: The iterative evaluation steps of the Continuous Desalination Efficiency Improvement Process

The iterative steps of the continuous efficiency improvement research frame work

Based on the abovementioned developed CDEIP cycle, the main continuous iterative steps of the desalination efficiency improvement research frame work are formulated as follows:

- The specification of the efficiency improvement factors
- Evaluation of the necessary improvements
- Test and evaluation of the proposed improvements
- Implementation of the improvements
- Evaluation and suggestions for further improvements

A schematically illustration of the iterative evaluation process of this continuous desalination efficiency improvement research frame work is given in Figure 1.5.

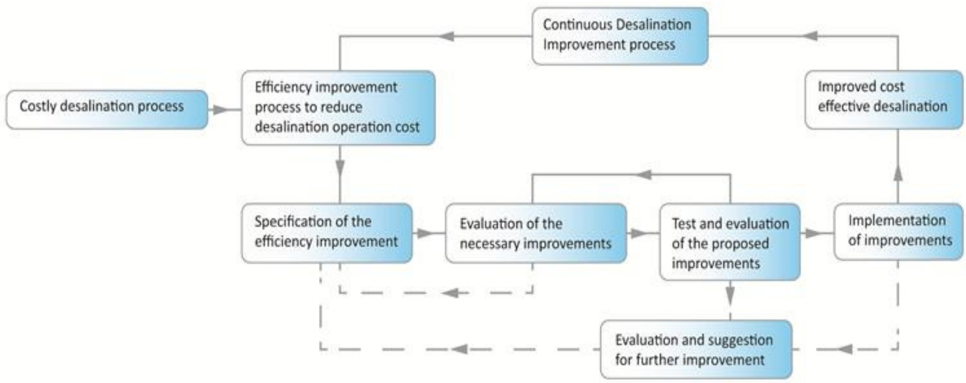


Figure 1.5: The continuous desalination efficiency improvement iterative evaluation process toward desalination excellence

The EFQM based research frame work

Considering the importance of leadership in the context of Efficacy, effective involvement and empowering of the work floor personnel to efficiently operate and maintain the Desalination assets to guarantee the production of high quality drinking water at increased efficiency to all stakeholders' satisfaction, the research frame work is based on the principles of the performance frame work of the European Foundation for Quality Management. The EFQM's performance frame work is developed in 1992 and revised in 2003 as a frame work for The European Quality Award assessment. The EFQM model is based on five Enablers criteria and four Results criteria. The Enablers criteria simply state what an organization, in this case the Desalination Department, does and the Results criteria refer to the achievements.

This model is a descriptive support for organization to reach out to Excellence Performance as envisioned by the Desalination Department and according to the EFQM model, as quoted, it is reached by:

"*Excellence, according to the model, is gained in terms of the Leadership that drives the company policy and strategy. It is also reached when leadership is able to motivate people to best use of partnerships and resources to operate and improve the organization's most important processes"* [1.10].

The EFQM performance framework is illustrated in Figure 1.6.

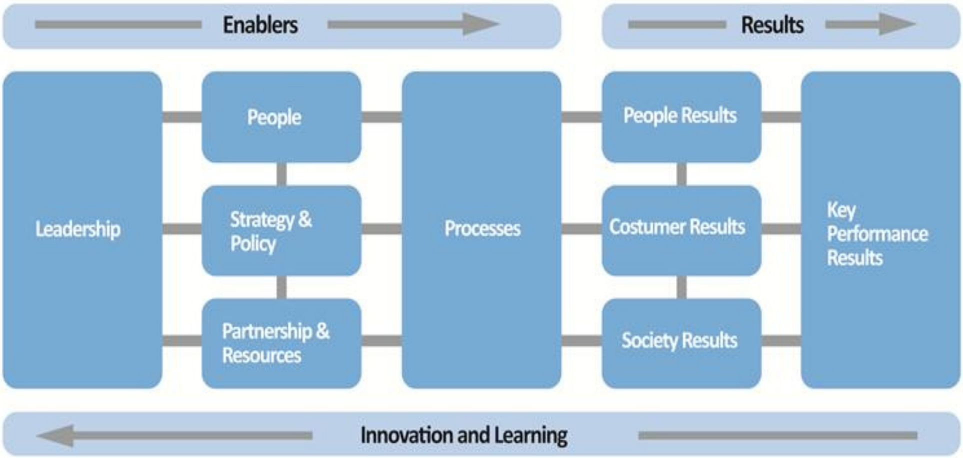


Figure 1.6: The EFQM performance frame work toward Excellence

In this performance frame work toward Excellence, with reference to the PDCA modes the criteria of Leadership and Strategy can be considered as the "Plan", People Partnerships and Resources and Processes as the "Do" and the Results criteria, People Results, Customer Results, Society Results and the Key Performance Results as the "Check" and the feedback for Innovation and Learning as the "Act" segments of the Deming Circle [1.12]. In accordance with this EFQM performance model and with reference to the specification of sub aspects as illustrated in Figure 1.3, the research frame work is developed as shown in Figure 1.7 structuring the Continuous Desalination Efficiency Improvement Process toward the envisioned Desalination Excellence Performance.

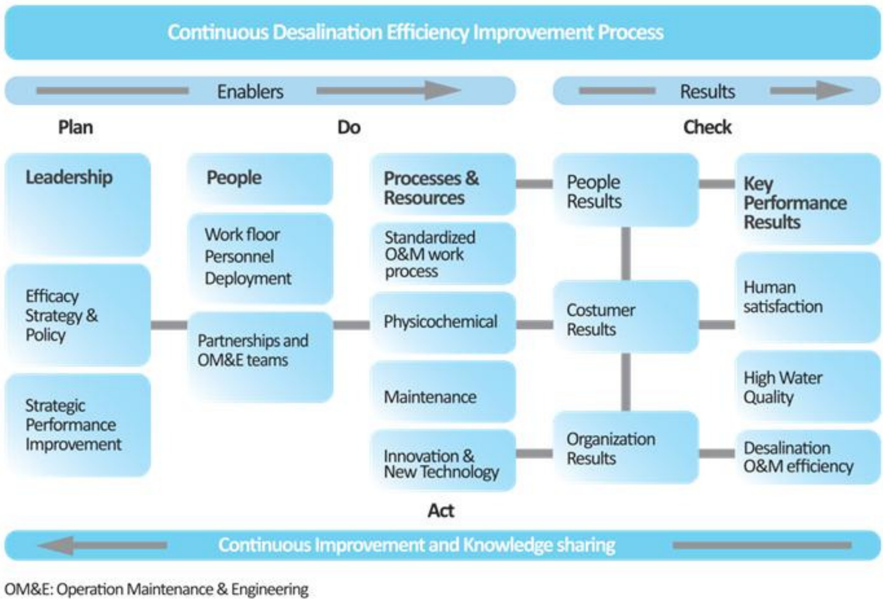


Figure 1.7: The research frame of the Continuous Desalination Efficiency Improvement Process toward Excellence

The aspect of intensive generation and evaluation of possible solutions including innovations is an important step in the Continuous Desalination Efficiency Improvement Process. However, in the case of W.E.B. Aruba N.V. this step is practically restricted by the company's policy mandating the evaluation and application of only worldwide proven technologies. As a rule of thumb, desalination technologies with 5 to 10 years of successful practical application are allowed to guarantee continuous production of drinking water as a sole producer in an Island situation. This standpoint was further intensified after the negative experiences with implementation of the new Aquanova Controlled Flash evaporation technology in the 1970's. As will be explained in Chapter 2, this controlled flash technology, considered back then as a revolution in the flashing technology, resulted to be a complete failure with the costly water import as a consequence. Subsequently, after the Aquanova experience the application of new technology innovation is practically prohibitive according to policy. However, the desalination efficiency improvement endeavor of the Desalination Department promoting safe and environmental friendly efficient operation has induced a change in this policy. Nowadays, only in exceptional cases where there are still no available effective proven technologies the development, evaluation and application of innovative technologies may be accepted under strictly defined conditions to improve safety, health and environmental operation aspects.

It is further worth mentioning that this desalination efficiency improvement research is based on two main axiomatic guiding principles founded on practical desalination experiences of the Desalination Department of W.E.B. Aruba N.V.:

Efficacious leadership and motivated work floor personnel being close to the production units comprehending and governing the whole spectrum of the technical aspects are the most important efficiency key improvement factors in seawater desalination.

There is no possibility of sustainable and stable desalination operation and drinking water conditioning without the use of effective chemicals.

The technology and techniques introduced and applied at W.E.B. Aruba N.V. with reference to the human factor and technical aspects and the results obtained will be worked out and discussed in detail in subsequent chapters of this thesis. An introductory brief summary of the chapters is illustrated in the next section.

1.5 The content of the thesis

Chapter 2: History background
In this chapter, the endeavor of Aruba that resulted in a journey from primitive water supply and water treatment to sophisticated commercial seawater desalination is described after a brief history of the desalination development in the world. Seawater desalination started in Aruba in 1903 in the area of Balashi for the production of process water for the Gold Mining Company and since 1932 for the commercial production of drinking water and in 1958 for the production of industrial water. The applied desalination technologies will be briefly described.

Chapter 3: The human factor
In this chapter, the importance of the human factor and the applied motivational strategies and the basic strategic quality approach are described in depth. The developed simple Passion and Fear (PF-) and Human Attitude (HA-) models to comprehend human behavior and the motivational leadership strategies such as the Efficacious Motivational Leadership (EML-) and the Mahatma Gandhi (MG-) leadership strategy are intensively described. These motivational strategies to improve desalination efficiency were developed in the context of efficacy, efficiency improvement through effective empowerment and involvement of the work floor personnel.

Chapter 4: The biofouling physicochemical aspect
In this chapter, the physicochemical aspect greatly influencing efficiency, the marine biofouling on the condenser tubes and on the SWRO membranes is described. The

successful application of a novel non oxidizing biocide based on the quaternary amine technology increasing efficiency of the MSF evaporators and the applied improved *Clean In Place* (CIP) and sanitation techniques increasing the SWRO production and efficiency are illustrated.

Chapter 5: The scaling and corrosion physicochemical aspect
This chapter illustrates another important physicochemical aspect affecting efficiency namely the scaling and fouling due to thermal decomposition of bicarbonates in the seawater and deposition of corrosion products. The history of scale inhibition techniques applied in Aruba during the years in the attempt to mitigate scaling and the implementation of a novel high temperature antiscalant that eliminated the use of 98% sulfuric acid as scale inhibitor are described in detail.

Chapter 6: The foaming physicochemical aspect
This chapter describes a novel approach based on the surface energy concept to optimize the dosing of the antifoam and the surface active biocide and the antiscalant to effectively control the foaming potential of the evaporating seawater in MSF evaporators. An explanation is given for the effect on production efficiency and distillate conductivity of under- and overdosing of the antifoam agent. The foam stabilization mechanism is explained in accordance with the natural flow from a high energy level to a low energy level, on the contrary to the Gibbs-Marangoni's mechanism.

Chapter 7: The distillate post treatment physicochemical aspect
This chapter describes in depth the pyrophosphate and orthophosphate based post treatment process of drinking water as applied at W.E.B. Aruba N.V. since 1990, practically eliminating the occurrence of red water (iron corrosion) and blue water (copper corrosion) and water leakages due to corrosion. High drinking water quality combined with a well maintained and operated distribution system resulted in a percentage Non Revenue Water (NRW) of about 2.6-4.11 % and an Infrastructure Leakage Index (ILI) of 0.51, actually the lowest as compared to the Dutch Caribbean Islands.

Chapter 8: The maintenance aspect
In this chapter, the developed Efficacy Oriented Maintenance (EOM-) concept based on the principle of *Maintenance Conscience Operation* and *Operation Conscious Maintenance* promoting an effective team between Production and Maintenance personnel at the work floor level is in depth described. The introduction of this EOM concept has significantly decreased pump and process failures and has contributed to the increment of the availability, reliability and capacity utilization of the Multi Stage Flashing (MSF) evaporators and the Sea Water Reverse Osmosis (SWRO) production unit.

Chapter 9: Technology Innovation

In this chapter, the contribution of Aruba throughout its desalination history to innovation especially in the development and application of new scale inhibitors is addressed. The developed innovative chlorine gas discharge hood assembly, the patented conceptual designs of a carbon dioxide degassing tower, a hybrid *Osmosis Reversed Osmosis* (ORO) desalination process and an innovative environment friendly chemical free osmotic membrane cleaning process are described. Further the conceptual design for a *Membrane Combined Water and Power Production* plant (CCWPP) eliminating the use of fossil fuel is introduced.

Chapter 10: Implementing New Technology

In this chapter a historical overview of the application of new desalination technologies in Aruba in accordance with the global desalination market development to increase desalination efficiency is shown. From 1932 up to 2008 thermal desalination technology dominated the desalination activities in Aruba. The drastic increase in fuel oil cost and development in the local market contributed firmly to the evaluation and introduction of the SWRO as the new main desalination technology at W.E.B. Aruba N.V. The evaluation process is described in detail.

Chapter 11: Contributions, limitations and further research

This chapter gives a reflection on the continuous desalination efficiency improvement research and will elaborate on the contribution to science, the desalination operation in Aruba and abroad, limitations of this research directing the need for further evaluation and research still to be done.

1.6 References

1.1. Khan, A. H., Desalination Processes and Multistage Flash Distillation Practice, Elsevier Science Publishers B.V., Amsterdam, 1986, 4.

1.2. Spiegler, K. S., El-Sayed Y. M., A Desalination Primer, Balaban Desalination Publications, Italy, 1994, 111.

1.3. http://dewiki.nl/index.php/Trias_energetica

1.4. Marchena, F. A., Efficacy Oriented Operation and Maintenance; An important Step Toward Sustainable Conventional and Green Desalination Technology., Our Future With Green Energy Conference, Oranjestad, Aruba, September 2010.

1.5. Birkett, J. D., Arrindell, E. M., Aruba’s Early Experiences in Desalination, Caribbean Desalination Conference, Oranjestad, Aruba, June 2002.

1.6. www.elmar.aw/info/content/wp_elmar_home.jsp

1.7. Marchena, F. A., Hodgson, J. W., et al., The Decision Process to Use Membrane Desalination after 75 Years of Successful Thermal Desalination., International Desalination Conference, Oranjestad, Aruba, June 2007.
1.8. http://www.newswatersupply.org/news/quotes.htm
1.9. Arrindell, E. M., Considerations for Increasing Overall Plant Life and Efficiency, Caribbean Desalination Seminar Technical Proceedings, June 1987, Antigua West Indies.
1.10. Martina, I. S., Regulation in Splendid Isolation: A Framework to Promote Effective and Efficient Performance of the Electricity Industry in Small Isolated Monopoly Systems, ISBN-978-90-79787-08-1, PhD Thesis University of Technology of Delft, 2008.
1.11. Khandani, S., Engineering Design Process, Industry Initiative for Science and Math Education (IISME), Solectron Company, August 2005.
1.12. Bakker, C. G., Steenbergen-Meertens, E., Integrale Kwaliteitszorg en Verbeteringen IKZ, ISBN 978-90-01-05083-2, Wolters-Noordhoff Croningen/Houten, 2005.

Chapter 2

The development of the desalination technology and the history of desalination in Aruba

Efficient seawater desalination, the viable solution for the drinking water

Chapter 2

The development of the desalination technology and the history of desalination in Aruba

Table of Contents:

Abstract

In the pre-industrial era of Aruba, surface water and rain water collected in the dry rivers beds, and ground water were sufficient for the primitive small population, mainly emigrated Indians from the main land of South America. In the colonial period houses were built with rain catching basins to effectively collect rainwater. In those days the cactus juice was applied as a primitive natural coagulation treatment process to improve the quality of the drinking water. The first application of the seawater desalination technology started already in the period of 1903 to 1917 for the production of process water for the Gold Mining Company in Aruba. Commercial seawater desalination for the production of drinking water and industrial water started in 1932 as a consequence of the economy boost due to the establishment of the Esso oil refinery, The Lago Oil & Transport Company ltd, in 1929 in Aruba. The desalination technology has followed the desalination development trend in the world. The first generation of applied thermal desalination technology consists of the Multi Effect Distillation from 1932 to 1983. The second generation consists of the Multi Stage Flashing evaporators in 1965 to present. Aruba has gained worldwide throughout its seawater desalination history an excellent reputation for the successful efficient application of the costly thermal desalination and for its contribution, due to excellent practical operations and maintenance knowledge, to the design improvement of the thermal evaporators. After seventy five years of successful application of thermal desalination the Seawater Reverse Osmosis membrane technology is introduced in 2008 to reduce the increasing desalination cost as a consequence of the rapid increment in heavy fuel oil cost. In this chapter the primitive water supply and drinking water treatment, the desalination history of Aruba and the development of the global desalination technology are described. The applied desalination technologies will be briefly discussed.

2.1 Introduction

Water is a fundamental necessity of life for all known life forms on Earth and is with food the primary needs of men. It is therefore not surprising that men have always looked for ways to desalinate brackish water or seawater to produce drinking water in arid areas. Actually water is in abundance on Earth but from the total amount of water 94 percent is seawater and only 6 percent is fresh water suitable for human consumption. From this total amount of fresh water 71 percent is subterranean, 27 percent is in the form of ice and about 2 percent is present as surface water in rivers and lakes [2.1]. The yearly rain fall is sufficient for the whole population on Earth but unfortunately it is not uniform in the world. There are places with abundant rain fall while others have practically the whole year long no rain at all. Therefore, in such arid regions with practically no sufficient natural fresh water resources the best possible solution to the water shortage is the cost effective sustainable desalination of saline water.

The desalination of seawater has given an enormous boost to the economic development of the Island of Aruba. As indicated in Figure 2.1, Aruba is located in the Caribbean region, only a few miles out of the coast Venezuela, South America.

Figure 2.1: The geographical location of the Island of Aruba [2.2]

This leeward Dutch island, in former times denoted as *"Isla Inutil*" (useless island) by the Spanish Conquistadores, has developed as a prosperous island since then primarily due to the availability of a trustworthy production of drinking water and industrial water supporting the flourishing tourism industry and other industrial activities such as the oil refinery. Also Aruba has contributed with its more than eighty years' experience in seawater desalination to the further development of the desalination technology. The applied technologies have been adapted and improved during the years by the manufacturers through the important input gained on the island from the experienced and knowledgeable operations and maintenance personnel of the water production company. Actually, as

indicated in Chapter 1, Aruba was in the late 1950s for a very short period of time the largest producer of drinking water using the seawater desalination technology. The first place is now taken over by countries such as Israel and Oman Sur in the Middle East with their desalination capacity of more than 500,000 cubic meters per day.
Aruba has assured its population during the years the hundred percent security of continuous availability of drinking water of both chemical and bacteriological high quality because of a trustworthy efficient production, distribution and storage of drinking water. It is a small semi-arid island in the sub-tropical Caribbean Region with practically no natural resources of drinking water that still is considered in the world as a role model for the effective solution of the water shortage problem for its population. In this chapter a short description is given of the development of the desalination technology in the world and a short description of the desalination technologies applied in Aruba. Further the water supply and water treatment prior to the desalination period, the desalination history and the actual production capacity and process of Aruba are addressed too.

2.2 The desalination of seawater

The development of the desalination technology
The desalination of brackish water and seawater is considered as one of the most valuable inventions of mankind that has enormously contributed to the economic development and industrial activities in arid areas with the availability of sufficient brackish water and seawater. The desalination of brackish water and water treatment to purify fresh water has been known by men already for thousands of years. References of this can be found in the bible [2.3]. Aristotle has already pointed out about 2500 years ago that fresh water can be obtained by the distillation process of seawater. The first modern desalination units have been used for the first time more than 200 years ago on sea going ships for the supply of fresh drinking water during long sea voyages [2.4]. The first desalination units were the thermal single stage evaporators. The first one ever installed in the Western Hemisphere in the early 1860's was a 27 m^3/day rated single effect evaporator manufactured by the Company de Normandy in London, to support the military base Fort Zachery Taylor on the Island of Key West, Florida in the early 1860s [2.5].
Desalination is the process of removing salt from saline water to produce fresh water for human consumption. According to the *World Health Organization* (WHO) and the *United States Public Health Service* (USPHS) water with in general a concentration of *Total Dissolved Salts* (TDS) lower than 1000 parts per million (ppm) is considered suitable as drinking water [2.6].
The available fresh water on Earth is the result of the natural solar evaporation process of seawater. In the atmosphere, vapor is condensed to water droplets and snowflakes that reach the ground as rain and snow. Melted snow and rain flow over the ground again to the sea. During this transport a part of it is absorbed by the porous surface layers as

groundwater. Further during this transport to sea, minerals of the ground are dissolved in the flowing water. Through the continuous repeating process of evaporation and condensation and mineral dissolution the water gets more salty. In lower parts of the ground the flowing water can be retained as surface water. This natural hydrological cycle is the origin of rivers, lakes and subterranean water. The solar natural evaporation and condensation process in Aruba is illustrated in Figure 2.2.

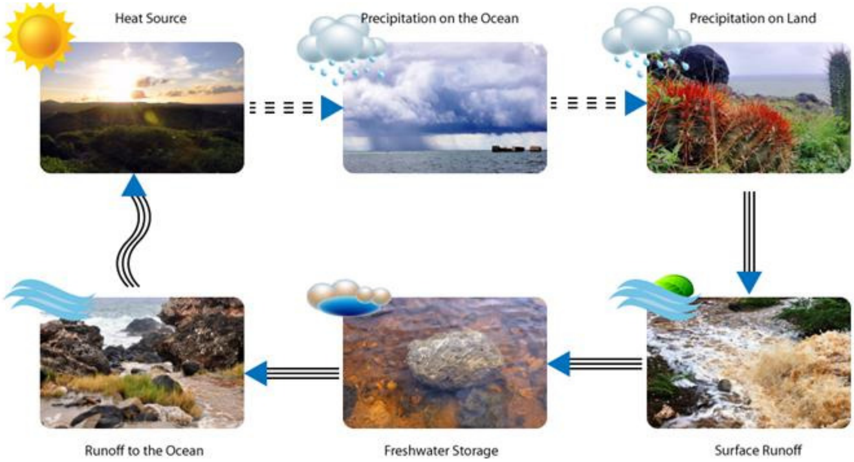


Figure 2.2: The natural solar evaporation process in Aruba

The desalination process designed by man is in principle the imitation of this natural evaporation process by using generated thermal energy to evaporate seawater and then to condensate the vapor to fresh water. The remaining brine flow is then redirected to the sea. At the end of the nineteenth century single stage evaporators were built using low pressure saturated steam as the source of thermal energy. After the Second World War the thermal evaporation technology grew enormously, especially because of the awareness of the armies of the vital necessity of desalination in arid areas and the discovery and exploitation of oil fields in the Middle East [2.1].

In 1960 evaporators with a production capacity of 8,000 cubic meters per day were manufactured. Though, even with the up scaling to larger capacity production units the thermal desalination is still onto present day a costly endeavor.

A tremendous breakthrough to reduce desalination cost came in the 1970's with the availability of commercial membrane technology for seawater desalination through Electro Dialysis and Reverse Osmosis processes. With further innovation in this technology resulting in efficient membranes and energy recovery devices the supremacy of the costly but robust reliable thermal evaporators came to an end. In Figure 2.3 the graphical representation of the development trend of the desalination technology of both the thermal and the membrane technology since 1980 is illustrated [2.7]. In this graph the decreasing trend of the thermal desalination with the introduction of SWRO in the market is very obvious.

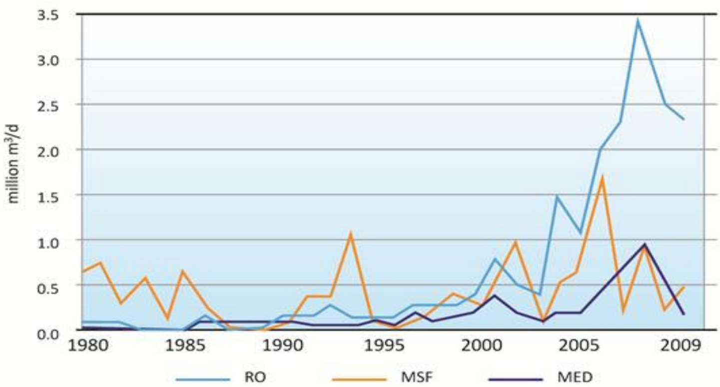


Figure 2.3: The development trend of the desalination technology [2.7]

The desalination technology grew within a period of fifty years to an important mature commercial enterprise making possible the construction of both thermal and membrane desalination units surpassing production capacities of 500,000 cubic meters per day. The now commercial available desalination processes can be subdivided as follows [2.1]:
Large capacity desalination processes:

- Thermal processes
  - Multi Stage Flash (MSF) evaporators
  - Multi Effect Distillation (MED)
  - Vapor Compression (VC)
- Membrane processes
  - Electro Dialysis (ED)/ Electro Dialysis Reversal(EDR)
  - Reverse Osmosis
    - Cellulose acetate membranes till 1990
    - Polyamide and polysulfone since 1990

Small capacities desalination processes:

- Freezing technology
- Membrane Distillation
- Solar evaporation

The desalination processes for the production of fresh water can differ in technology but all have practically the same basic principle as shown in Figure 2.4.

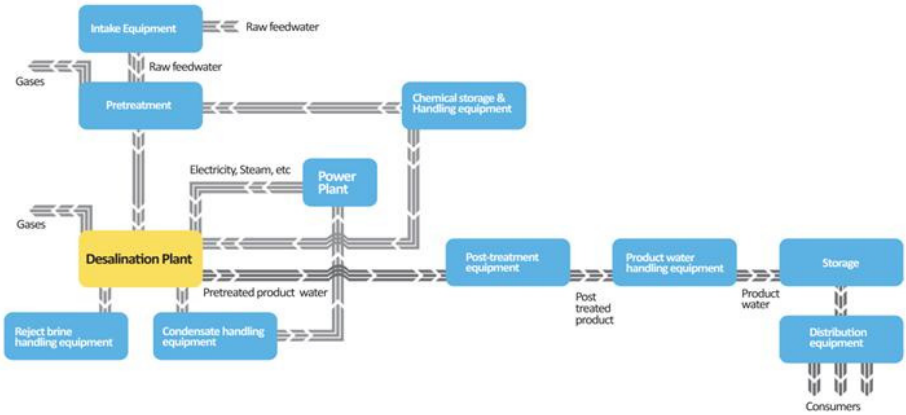


Figure 2.4: The basic principle of the desalination process [2.4]

The three main desalination technologies, the Multi Effect Distillation, the Multi Stage Flashing and the Seawater Reverse Osmosis applied in Aruba will be briefly described in the following sections.

A short description of the Multi Effect Distillation process

The first thermal evaporators applied for the desalination of seawater were of the *Multi Effect Distillation* (MED-) technology. In the chemical process industry this technology was already applied for the evaporation of sugar solution and for the concentration of brine. The principle of this evaporation technology is based on the evaporation of seawater heated to the boiling temperature with saturated steam and to condense the vapor in a condenser with cold seawater [2.8]. The MED technology represents about 2 percent of the total world water produced with desalination. Nowadays MED production units with a capacity of 20,000 cubic meters per day are commercial available. The evaporation process can be achieved by heating up the seawater or by flashing due to pressure reduction. In a single stage evaporator in principle one kilogram of distillate can be produced by condensing one kilogram of steam. The *Gain Output Ratio* (GOR) defined as the ratio of the amount of distillate produced and the amount of steam consumed is one (1). In spite of preheating the incoming seawater flow a great part of the enthalpy is lost in the condenser as waste heat. The multi effect configuration, a combination of single stage evaporators in series, is applied to reuse the amount of waste heat in the condenser to increase production. These single stage evaporators are called effects. In the MED technology two or more effects are used with the succeeding effects operating at successively lower pressure and temperature.
A schematic flow diagram of the submerged tube MED process, as used in Aruba during its early desalination activities, is shown in Figure 2.5.

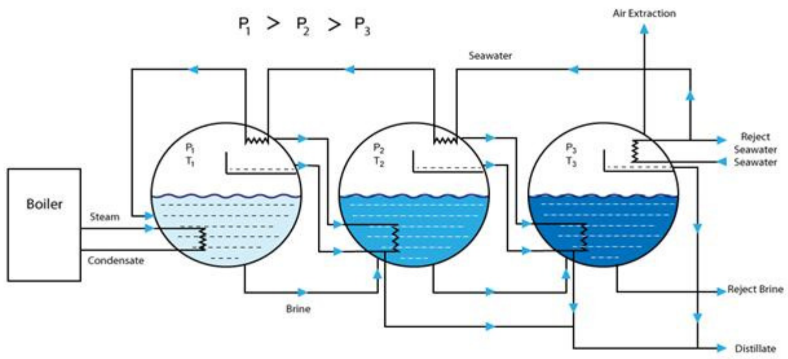


Figure 2.5: A schematic flow diagram of the submerged tube MED evaporators [2.4]

As can be seen in Figure 2.5, the incoming seawater flow is heated up in the first effect by condensing steam. Low pressure steam can be obtained from back pressure and extraction turbines or be produced on site with low pressure steam boilers. The vapor produced in the first effect passes through a demister and is partially sent to the heating tubes of the second effect to evaporate the seawater. The other part is sent to the preheater section of the first effect to preheat the seawater feed. The demister separates seawater droplets entrained by the vapor. This is important for the quality of the vapor and the produced distillate.

The vapor condenses on one side of the heater and on the other side of the tube bundle seawater is preheated by the heat of condensation. Non evaporated seawater then flows from the brine sump to the next effect where a part of it is evaporated by flashing. The repeated evaporation in the different effects, increasing the effectiveness of the consumed low pressure steam in the first effect has given this technology its name. The evaporation process can continue until there is enough temperature difference between the condensing vapor and the evaporating brine.

Only through pressure reduction in the successive effects it is possible to reuse the evaporation and condensation heat. The recirculation brine boils at a lower temperature than in the effect before and in the last effect the concentrated brine is rejected as blow down to the sea. The vapor in the last effect is cooled with seawater in the condenser. A great part of the cooling seawater is pumped back to the sea and the other part is used as preheated seawater feed for the MED evaporator. The seawater feed is chemically treated to inhibit scale formation on the heating surfaces and oxygen together with non-condensable gasses is removed in the degasser to prevent vent space corrosion and gas blanketing. The seawater feed is pumped to the preheating section of the different effects where it is heated up to its boiling temperature by condensing vapors. The seawater feed is then evaporated with low pressure steam in the first effect. The effects are vented with an ejectors system to maintain the pressure difference. Theoretically the GOR is equal to the number of effects because as stated before in every effect an amount of one kilogram distillate can be produced with one kilogram of steam consumed. In practice this is not true because of the increased latent heat at reduced pressure, heat losses because of not optimal isolation and the amount of steam necessary to preheat the incoming seawater feed. A rule of thumb is a GOR of 0.7-0.89 for every effect consuming one kilogram of steam [2.4]. For years the MED process was the most important desalination technology but in the 1960's it was replaced by the more reliable and operational stable Multi Stage Flashing technology that is also more suitable for up scaling to larger capacity. The MSF technology will be briefly described in the next section.

A short description of the Multi Stage Flashing process

The *Multi Stage Flashing* (MSF-) Technology was already in the 1960's the most popular and dominant thermal process for the desalination of seawater due to a reliable performance without major problems with precipitation of scaling products on the heat transfer surfaces. With the MSF technology it was possible to construct evaporators with larger production capacity. Already in 1977 this technology designed in the 1950's by Professor Silver was the most applied process and represents 60 percent of the total world production capacity. The principle of the MSF technology is based on the fact that a liquid at the boiling temperature can be evaporated effectively through pressure reduction. By reducing the pressure vapor bubbles are readily formed throughout the whole liquid and this process continues till the corresponding equilibrium temperature (the boiling temperature) is reached at the reduced pressure [2.9]. By reducing the pressure the sensible heat of the liquid is also reduced. The difference in heat content is used to flash a portion of the seawater and so reducing the temperature of the flashing seawater. In Figure 2.6 the relation of pressure and boiling temperature is shown.

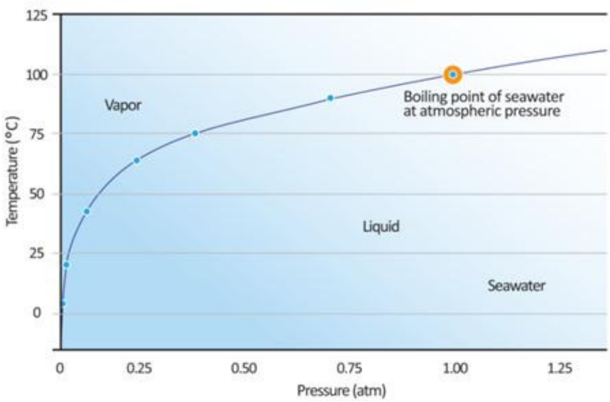


Figure 2.6: The relation of boiling temperature and pressure of seawater [2.4]

In a single stage evaporator the seawater feed is preheated in the condenser section. In Figure 2.7 a schematic of a vessel with a cut away view of an evaporator stage of an Aqua Chem MSF evaporator is illustrated [2.10]. The most important components of a flashing stage are the demister, the brine gates, the preheating section, the distillate gates and the venting compartment.

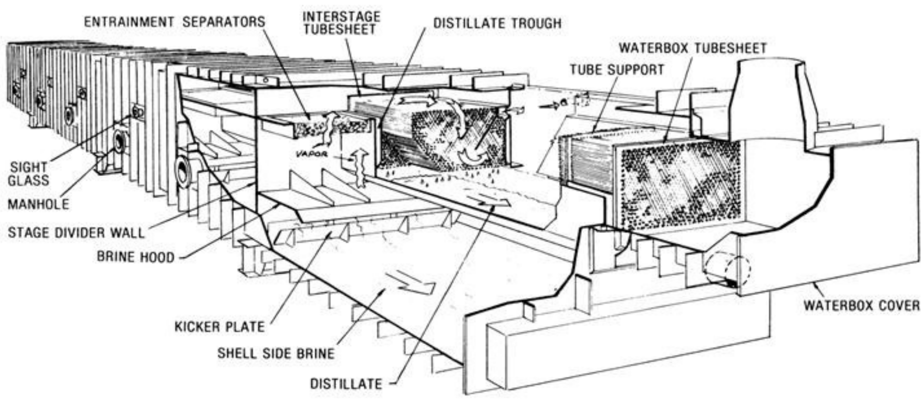


Figure 2.7: A schematic overview of a vessel with a cut away view of the flashing Stage [2.10]

In the brine heater the seawater feed is heated to the boiling temperature by condensing low pressure steam. The seawater feed is kept on sufficient pressure as to avoid flashing in the pipes of the flashing stage. In the flashing stage a lower pressure is maintained through an ejector system. The incoming seawater is at the boiling point at a higher pressure, thus superheated at the lower pressure in the flashing stage.
The seawater has to give up heat to reach the thermodynamic equilibrium in the flashing stage.
The vapor produced passes through a demister to the shell side of the preheating section where it condenses and preheats the seawater feed flowing tube side. A large part of the condensation heat is utilized to bring the seawater to its boiling point [2.9]. The brine flow is then removed from the flashing stage. The Multi Stage Flashing evaporator is in principle a configuration of flashing stages in series where the succeeding stage is at a lower pressure than the preceding stage. The brine from one stage flows through the brine gates to the next stage where the flashing process is repeated. The multi stage principle has improved the efficiency of the single stage considerably. The MSF evaporator with a number of stages in series is known as the *Once Through* configuration. In Figure 2.8 a schematic of the Once Through MSF process is shown together with the corresponding temperature profile.

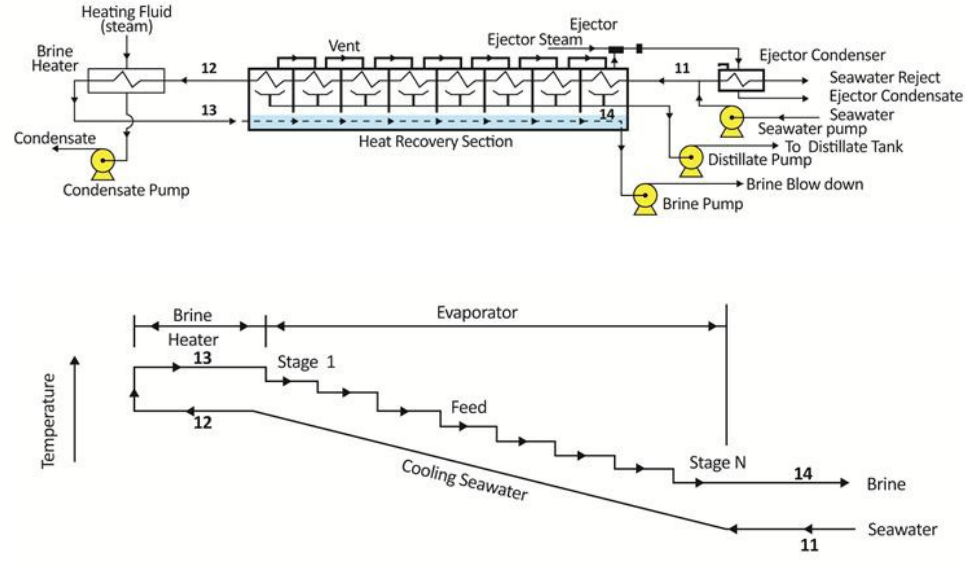


Figure 2.8: A schematic of the Once Through MSF flow diagram with the corresponding temperature profile [2.4]

An improvement of this concept is the MSF evaporator with brine recirculation. In this concept three section are distinguished, namely the heat input section, the heat recovery section and the heat rejection section. A schematic of the MSF evaporator with recirculation brine is illustrated in Figure 2.9.

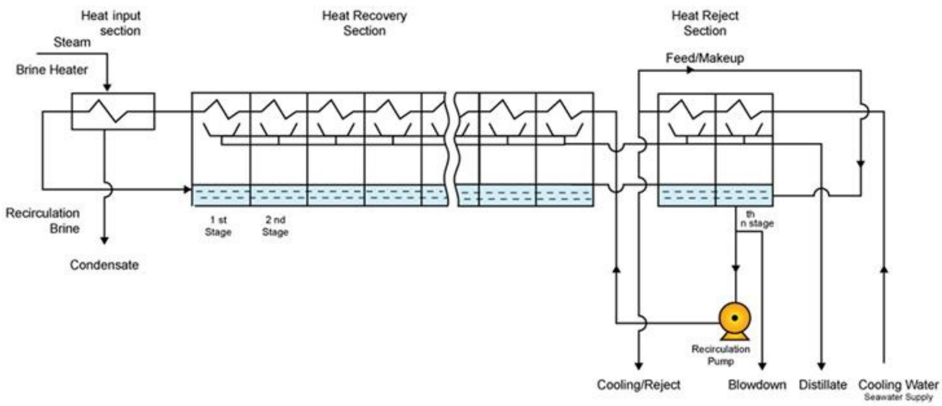


Figure 2.9: A simplified process flow diagram of the MSF evaporator with brine recirculation [2.4]

According to the simplified flow diagram seawater is pumped tube side of the condenser, the heat rejection section, to condense the vapors produced in the last stages. The largest part of the cooling seawater flows back to the sea and a smaller part is used as make up seawater. The makeup seawater is degassed in the deaerator to remove the corrosive gasses such as oxygen, carbon dioxide and non-condensable gasses. The degassed seawater make up flow is than mixed with recirculation brine flow after a portion of it is rejected to the sea as blow down [2.9]. In this way a certain concentration factor of total dissolved salts (TDS) is maintained in the recirculation brine flow. The concentration factor depends on the highest saturated temperature of the recirculation brine flow after the brine heater. At recirculation brine flow temperature of 110 ^{o}C a concentration factor of 1.75 should be maintained. The concentration factor, actually the ratio of the TDS of seawater feed and that of the recirculation brine flow, is an important parameter for the control of calcium carbonate and calcium sulfate scale formation on the heat transfer surfaces especially in the high temperature stages and the brine heater [2.11]. The recirculation brine is pumped tube side of the preheating section of the flashing stages where it is preheated by condensing vapors on the shell side. Hereafter it is heated by condensing low pressure steam in the heat input section, the brine heater. The top brine temperature in the MSF process lies in the range of 90-120 ^{o}C. After the heat input section the recirculation brine flow passes shell side of the flashing stages in the heat recovery section where it is flashed due to continuous pressure reduction in the successive stages. In the stages the produced vapor flows through demisters to the shell side of the pre heating section. The demister removes the in the vapor entrapped seawater droplets, to assure that the condensed vapors are practically free of salts. Concentrated sulfuric acid can be dosed as antiscalant in the makeup flow before the deaerator and a high temperature antiscalant can be dosed in the recirculation brine flow before entering the heat recovery section.
It is well known that the MED process is thermodynamically more favorable than the MSF process. For example the GOR of the MED equals approximately the numbers of stages and with the MSF to attain a certain GOR the number of stages should be about four times the expected GOR. Nevertheless the MSF process 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 these thermal technologies are based on the high energetic phase transition evaporation and condensation. The reverse osmosis technology as will be described in the next section only needs mechanical energy for the fresh water transport through a semi-permeable membrane making it theoretically the most energy efficient technology.

A short description of the Sea Water Reverse Osmosis process

The *Sea Water Reverse Osmosis* (SWRO-) process is a membrane process where fresh water is separated through a semi-permeable membrane from the salt ions in pressurized

seawater. The SWRO process does not require thermal energy and can be operated at ambient temperature. In the thermal process the seawater feed is heated up to 90-120 ^{o}C and phase changes, evaporation and condensation, is required to produce fresh water.
In the SWRO process there is no energy intensive phase change taken place, only mechanical energy for the high working pressure is required for the reverse osmotic fresh water flow through the semi-permeable membranes. It is therefore more energetic favorable then thermal processes. Although the osmosis phenomenon has long been known by men, scientist started not until 1950 for the first time with serious research for the development of osmosis membranes and in 1953 with the development of synthetic reverse osmosis membranes for the desalination of seawater. In 1960 the first successes were obtained with large water flux membranes and desalination membranes in the plate and frame, tubular and spiral wound configurations became available. It last till 1970 that RO membranes were commercially available for the desalination of seawater. The development of the SWRO technology since then grew enormously and in 1984 the seawater market dominating MSF technology lost for the first time in an open bid for MSF and SWRO technology for the construction of a 10 million gallons per day seawater desalination unit in Bahrain [2.4]. The principle of SWRO is based on the phenomenon of osmosis that is known to men already almost two centuries ago. Osmosis is a natural process where water flows through an only for water permeable membrane from a dilute solution to a more concentrated solution. This membrane is called semi-permeable. In Figure 2.10 the principle of osmosis and reverse osmosis is illustrated.

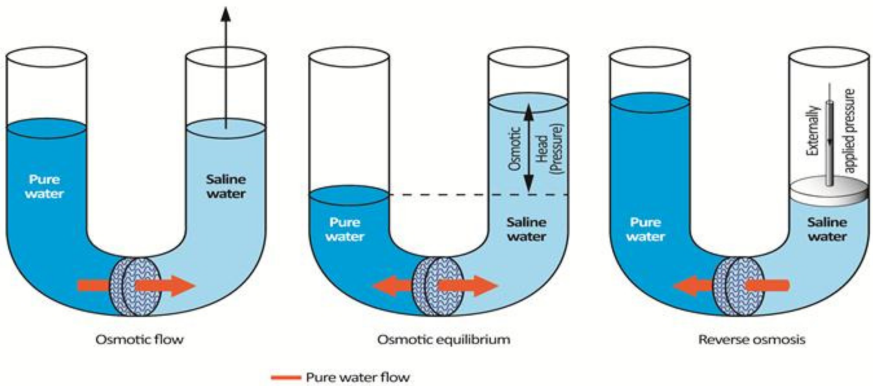


Figure 2.10: The principle of osmosis and reverse osmosis [2.4]

In a U tube, separated in two compartments by a semi-permeable membrane one compartment is filled with fresh water and the other one with seawater. Through the semi-permeable membrane water flows from the compartment containing fresh water to the compartment filled with seawater. The static liquid pressure in the fresh water compartment is lowered and that of the seawater compartment is increased. This process continues till an equilibrium situation is reached where equal amount of water flows on

both sides through the membrane. At equilibrium the liquid level in the seawater compartment is higher than the level in the fresh water compartment, creating a hydrostatic pressure difference over the membrane. This pressure difference is called the osmotic pressure and it depends on the temperature and the concentration of the seawater. If the pressure of the seawater compartment is increased to a pressure higher than this osmotic pressure a water transport in the reversed direction, from the seawater compartment to the fresh water compartment, takes place. This phenomenon is called reverse osmosis and is applied to produce fresh water from saline water. The flow velocity is proportional to the difference of the applied pressure and the osmotic pressure. If this pressure difference is increased, the water flow through the membrane also increases while the salt flow remains practically constant resulting in lower salt concentration in the product water. The salt concentration of the product water depends on the salt concentration of the brine and the salt permeability of the membrane.
The SWRO process consists basically of five components, namely [2.12]:

- The seawater pretreatment
- The high pressure pumps
- The membrane separation process
- The energy recovery device
- The post treatment of the product water.

In Figure 2.11 the basic process flow diagram of the SWRO is shown.

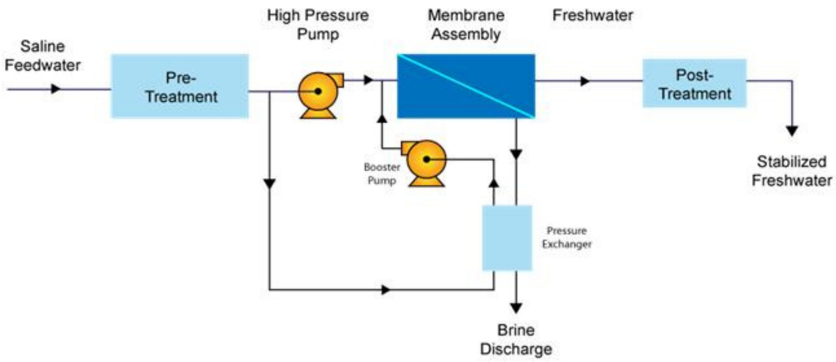


Figure 2.11: The basic process flow diagram of the SWRO [adapted from 2.4]

The seawater pretreatment is of utmost importance because for an effective water separation the membrane surface should be kept clean from: (1) scaling ; and 2) fouling. Scaling is the result of precipitation of supersaturated salts on the membrane surfaces which usually can be prevented with the dosing of acids or antiscalants in the seawater feed. Fouling of the membrane surfaces is mainly caused by: (1) deposition of suspended

particles (*particulate fouling*); (2) deposition of organic materials (*organic fouling*); and (3) settlement of micro-organisms (*biofouling*). Furthermore, membranes can suffer serious damaged by course material. To prevent this kind of fouling and damage the seawater is filtered in *Multi Media filters* (MMF), fine sand filtration, and with cartridge filters to remove fine particles that the MMF could not filtered out. Sometimes a coagulant is also dosed to enhance filtration of suspended particles. Biofouling can be inhibited by the use of a disinfectant such as sodium hypochlorite solution on continuous or intermittent basis. Especially in the case of non-chlorine resistant membranes materials such as polyamide the seawater feed should be dechlorinated with a sodium bisulfite solution.
Sodium hydroxide is also dosed to reduce the boron concentration of 5-6 ppm in the seawater feed to a concentration of 0.3 ppm in the product water according to World Health Organization’s standards for drinking water. The conventional MMF and cartridge filters are nowadays more and more replaced with the more efficient and economical membrane technology consisting of micro- and ultra-membrane filtration, producing a higher quality filtered seawater feed for the membranes.
The high pressure pumps deliver the required pressure for the membrane separation process. The required pressure should be about 25 to 40 bar higher than the osmotic pressure. For brackish water the pressure required for the reverse osmosis separation process is in the range of 25 to 40 bar and for the seawater in the range of 54 to 80 bar.
The membrane separation unit consists of pressure vessels and membranes that should resist the pressure difference across them. They differ in their capacity to permeate water and to retain salts. Nowadays the most used membranes are of the spiral wound configuration and the hollow fine fibers. In Figure 2.12 the components of a spiral wound membrane are illustrated.

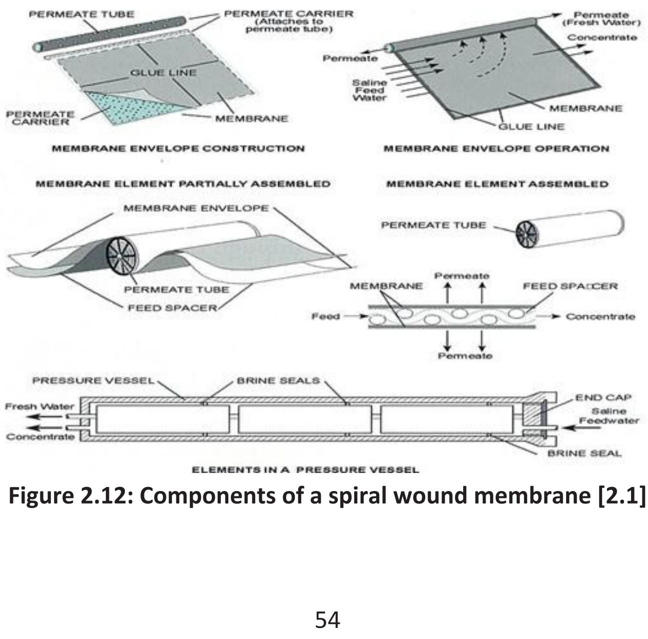


Figure 2.12: Components of a spiral wound membrane [2.1]

In the membrane separation section the seawater feed is separated in a fresh water flow also called permeate and in a concentrated brine flow called the concentrate. The permeate flows through the membrane and the concentrate is rejected through a throttle valve after energy exchange with seawater feed in the energy recovery section. Removing the concentrate is necessary to prevent precipitation of supersaturated chemical components in the concentrate on the membrane surfaces. Precipitation results in plugging the membranes reducing the water flux. If the concentrate is not rejected the pressure should be continuously increased to overcome the increasing osmotic pressure due to the increasing concentration of the salts dissolved in the concentrate. Depending on the concentration of the seawater, the membranes used and process pressure applied 20 to 70% of the seawater feed can be recovered as product water.

In case that the SWRO permeate purity is not the desired quality a second pass, the *Brackish Water Reverse Osmosis* (BWRO), can be applied to further improve the quality of the product water. Ion Exchangers polishers and the new developed *Electro Deionization* (EDI) are also used for the production of high quality boiler feed water [2.13].

The energy recovery device is used to utilize the high pressure of the concentrate flow to pressurize the filtered seawater feed. The concentrate flow has a pressure that is about 1 to 4 bar lower than the pressurized seawater feed. The use of an energy recovery device in combination with a booster pump can drastically reduce the energy consumption of the SWRO. Nowadays energy consumption values of 2.7-4 kWh/m^3 are possible. Commonly applied energy recovery devices are turbines, pumps, work exchangers and the new more efficient pressure exchangers. After the energy recovery section the concentrate is rejected at practically ambient pressure.

The post treatment of the product water is necessary to make it drinkable. The product water of the SWRO is soft and has practically no hardness. Carbon dioxide is dosed in the product water to lower pH especially if sodium hydroxide is dosed for the removal of boron. The acidified product water flows over a bed of lime stones where the product water is mineralized because of calcium carbonate dissolution. Especially in the desalination process of brackish groundwater, as nowadays with the application of beach well seawater feed in Aruba, special attention should be put to remove dissolved gasses as dihydrogen sulfide (H_2S). In Figure 2.13 a schematic flow diagram of the SWRO process is illustrated.

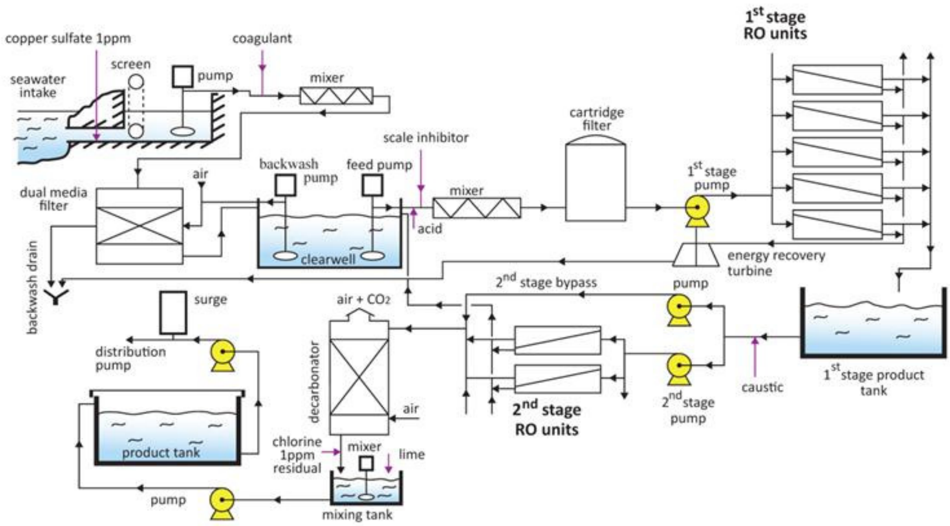


Figure 2.13: A schematic flow diagram of the SWRO process [2.4]

The last 15 years were significant for the SWRO technology. Although there were no fundamental changes in the process concept but improvements particularly in membrane material and efficiency and in the energy recovery section made the technology far more economical than the thermal desalination technology. To finalize this section a summary of the energy requirements of the different desalination processes is shown for comparison in Table 2.1 [2.15].

Table 2.1: Energy consumption of the different seawater desalination technologies [2.15]

Technology	Energy Consumption (kWh/m^3)
Multi Stage Flash	13.5 - 25.5
Multi Effect Distillation/Thermo Vapor Compression	11.0 - 28.0
Mechanical Vapor Compression	7.0 - 11.0
Seawater Reverse Osmosis	3.0 - 7.0

2.3 The history of the drinking water supply of Aruba

Drinking water supply before Seawater Desalination

Aruba is one of the six Dutch Islands in the Caribbean Region. Aruba, Bonaire and Curacao, known as the ABC islands are located only a few miles north of the coast of the continent of

South America. Aruba, the closest to the mainland, is situated at approximately 20 miles off the coast of the Venezuelan Peninsula Paraguana. The Windward Islands Saint Martin, Saba and Saint Eustatius also known as the S-islands are located east south east of the island of Puerto Rico at the boarder of the Atlantic Ocean and The Caribbean Sea. They are very small semi-arid Islands with practically no surface water and insufficient groundwater, therefore no wonder that they were characterized as unworthy islands centuries ago by the Spanish Conquistadores. As a result of the unavailability of natural fresh water resources, for many decades seawater desalination has been for these islands the only reliable source of drinking water supply.

Prior to the period of seawater desalination the source of drinking water for the small population of these Dutch Islands was rainwater collected in the dry riverbeds and natural water catching areas, called by the local people of the Leeward Islands in their native language Papiamento "*rooi*" and "*dam*" [2.15]. Although heavy rain fall in the rain season from August to February, practically most of the rainwater that reaches the ground flows back to the sea through these dry rivers as illustrated in Figure 2.14 [2.16].

Figure 2.14: Rain water flowing back to sea through a "*rooi*" in Aruba [2.16]

As mentioned above some of the rainwater during the flow to the sea are collected in dams as illustrated in Figure 2.15 showing a picture of the well-known dam at Tanki Leendert in Aruba taken around 1930 [2.17].

Figure 2.15: The well-known dam at Tanki Leendert in Aruba [2.17]

The surface water is used in the household and for small-scale husbandry activities. In the rain season the surface water can be abundant as is the case in the previous picture but nevertheless in the dry season, as can be seen in Figure 2.16 showing a picture of the dam at Vader Piet, the available surface water is very little due to evaporation and absorption by the porous ground layers. The rainwater that flows through the porous ground layers are collected in underground aquifers and in underground channels forming the so called underground rivers.

Figure 2.16: Dam at Vader Piet in rain and dry season

At the north east coast of Aruba there is a very small well known creek at Fontein with the whole year a constant stream of clear water. This is in contrast with the dry rivers, where water flows only after days of heavy rain fall. The elder Aruba's inhabitants were very proud of their little river as they used to call it. The water of this creek was used for a long time as water supply by a group of Chinese families for their horticulture growing special Chinese vegetables. In Figure 2.17 this creek, nowadays unfortunately not anymore well maintained is shown.

Figure 2.17: The little creek at Fontein at the north-east coast of Aruba

At different places on the island wells were dug usually by hands using small cold chisels and hammer to collect groundwater. The depth of these wells can vary from some 6 feet near the coast line to more than hundred feet land inward. The groundwater has a high hardness due to dissolution of minerals and calcium carbonates during the absorption process in the porous layers. The Total Dissolved Salts (TDS) concentration of well water of Aruba is in the

range of 1,000- 12,000 ppm. Especially in the coastal area the TDS can be much higher due to seawater infiltration. The well water is pulled up with a wooden bucket tied up to a rope either manually or with wooden winches in bygone days as is illustrated in Figure 2.18. Later on, wind mills of wooden or metal framework were installed to pump the water to the surface [2.17].

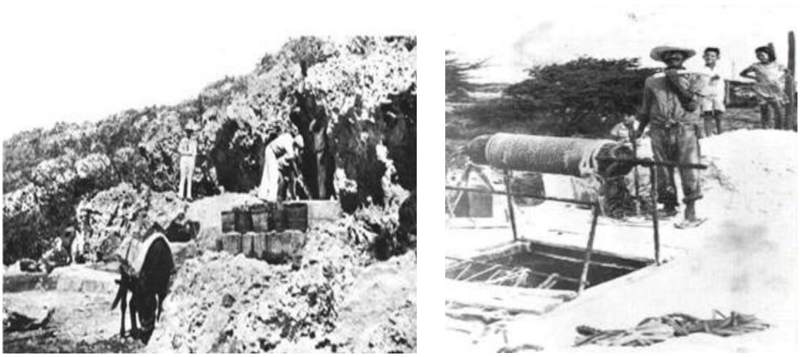


Figure 2.18: Men pulling up water at the wells by hands or with winches [2.17]

As can be seen in Figure 2.19 the common way for water transport in those days was by mules and donkeys [2.17].

Figure 2.19: Buckets filled with well water are transported home with donkeys, [2.17]

The descendants of those donkeys retired after a job very well done, nowadays mainly tourist attractions, live free and wild in the country side of the island.
Wells were so important that a lot of villages are named after these wells; for example "*Pos Chiquito*", "*Mon Pos*" and "*Pos Abow*". Pos is the name for wells in the native language Papiamento. In Figure 2.20 a wooden wind mill is shown together with the well at Pos Chiquito that is still in use today.

Figure 2.20: A wooden wind mill [2.17] and a metal wind mill at the well in Pos Chiquito

The first population of Aruba consisted of Indians (particularly aboriginal emigrants of the mainland of South America) and they were nomads and stayed only for a short period of time at places where enough food and water could be found and after a while they moved on. It is also known that they dig little holes near the beaches and dish up the natural filtered seawater as drinking water. They only build temporary little cabins made of tree branches and leaves. In the later colonial period houses of clay or stones were built with cisterns to collect rainwater fallen from the roofs as shown in Figure 2.21. The rainwater collected in cisterns was mainly used in households and gardening.

Figure 2.21: Typical Aruba country side houses with at the right hand a cistern

The rainwater flowing over the ground end up very contaminated and saturated with suspended sand particles picked up during their transport to the natural catching areas. Large particles settle down after some time on the bottom but smaller particles will stay in colloidal solution given the water a brownish muddy color. In those days already some primitive ways of water treatment were practiced to clear the drinking water. Suspended particles were filtered out of the water in a lime stone jar known by the population as "*Cudi*" [2.18]. Pictures of the "*Cudi*" are illustrated in Figures 2.22. Some form of water cooling was also achieved due to natural evaporation of water in a jar made of clay called the "*Tinashi*" and the larger one known as the "*Purun*". The low heat transfer of the clay further helps to keep the water cool.

Figure 2.22: The Cudi used for filtering out suspended particles

To further clarify surface water, cactus juice or dried cactus pulp was used in a primitive coagulation, flocculation and sedimentation process to remove colloidal particles. Also a little bit of seawater was used. A piece of iron was used to mineralize rainwater in the cisterns [2.19]. It so happened that the soft rainwater was hardened by the leaching out process of the calcite mortar of the cisterns. There is no indication that the piece of iron, heated by the sun or in any other way was used to disinfect the cistern water, a technique already used about 2000 years B.C. in India [2.3]. In Figure 2.23 the "*Tinashi*" is shown in the left picture with cups and plates made of the "*Calabas*" fruit and the "*Purun*" in the right hand picture.

Figure 2.23: The Tinashi with calabas cups and plates and the Purun as natural water cooler

It is also worth to mention that in the time of the Lago Oil Refinery a modern underground rainwater catching basin with water distribution system was constructed for the purpose of gardening water supply for the refinery employee's houses at the Lago Colony located at the east coast of Aruba.

The Desalination History of Aruba

The desalination history of Aruba started more than hundred years ago with the production of process water around 1903 at the Gold Mining Company (1899-1916). Process water is produced for the coal fired steam engines of the Gold Mining Company at Balashi. Already in that period it was obvious that the available groundwater and rainwater to be insufficient for the production of steam and for the high consumption of process water by the physicochemical gold extraction process. Boiling of saline groundwater also causes serious scaling problems in the boilers that resulted in explosions. The decision was then made to desalinate the seawater of the nearby Spanish lagoon [2.20]. In Figure 2.24 a picture taken around 1911 of the Gold Mining Company is illustrated [2.17] and in Figure 2.25 a picture is shown of the construction of single stage evaporators with the so called serpentine heating coils in a construction place of the WEIR Company in Scotland around 1912. This type of evaporators was commonly used for seawater desalination at the end of the nineteenth century and at the beginning of the twentieth century [2.5]. The Gold Mining Company was closed at the beginning of the First World War because the export of chemicals and dynamite to Aruba was stopped.

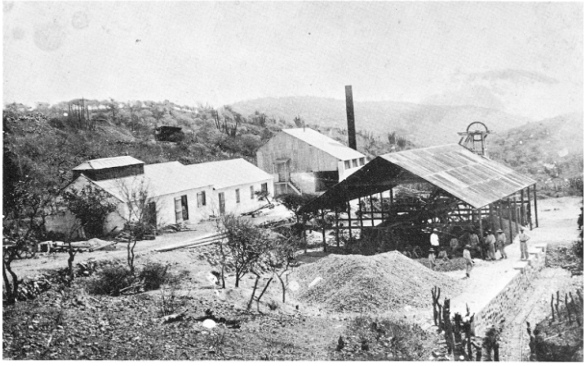
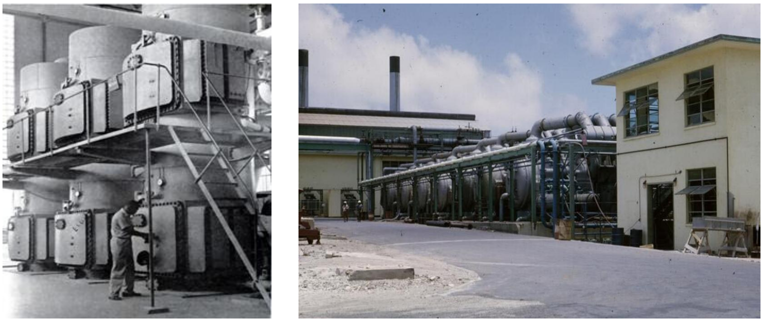


Figure 2.24: The Aruba Gold Mining Company around 1911 [2.17]

Figure 2.25: The construction of single stage evaporators at WEIR Inc. around 1912 [2.5]

W.E.B Aruba N.V. has been producing drinking water for the island of Aruba since 1932 and industrial water since 1958 for boiler water for the Power House and process water for the Oil Refinery. In the period of 1932 to 1983 the WEIR submerged tubes Multi Effect technology was used for thermal desalination to produce drinking water and industrial water. The first installed evaporators had a capacity of 200 cubic meters per day and a gain output ratio (GOR), the ratio of mT produced distillate and mT of steam consumed, of about 2. From 1932 to 1958 ten 200 cubic meter per day evaporators were installed and stayed in production for 13 to 25 years. In 1958, the beginning of combined power and water production was initiated. Five MED evaporators with a capacity of 2,000 cubic meters per day and GOR of about 5 to 6 were installed. Waste steam of the back pressure turbines of the Power House was used as heating steam for the MED evaporators. The evaporators stayed in production for 25 years and were demolished in 1983. In Figure 2.26 the submerged tube Weir MED evaporators are illustrated. The total water produced with the MED technology was about 55.3 million cubic meters (14,607 million gallons) [2.21].



1932 – 1958 1958 - 1983

10 WEIR MED's of 200 m^3/d 5 WEIR MED's of 2000 m^3/d

Figure 2.26: Weir Multi Effect Desalination evaporators from 1932 to 1983

As already mentioned in the introduction of this chapter, in the MED desalination era Aruba was for a short period the largest seawater desalination country in the world in 1959 and lost the desalination crown with the introduction of the large capacity MSF plants in the Middle East, especially Kuwait with the exploitation of the oil fields as illustrated in Table 2.2 [2.11].

Table 2.2: Large Desalination plant in the 1960s [2.11]

Location	Capacity (US gallons/day)	Type	Manufacturer
Aruba (Caribbean)	3,500,000	Submerged tube	G&J Weir, Glasgow, Scotland
Kuwait (Persian Gulf)	3,100,000	Submerged tube	Weir and Westinghouse
	5,100,000	Flash	Weir and Westinghouse
Qatar	1,900,000	Flash	Richardson -Westgarth
Venezuela	1.440,000	Flash	Buckeley & Taylor
Curacao (Caribbean)	1,700,000	Flash	Richardson -Westgarth
Nassau, Bahamas	1,400,000	Flash	G&J Weir
Taranto, Italy	1,200,000	Flash	Aqua-Chem, Inc.
Curacao (Caribbean)	3,400,000	Falsh	G&J Weir
Freeport, Texas, (US Government), OSW demonstration plant,	1,000,000	LTV	Chicago Bridge & Iron
Rowell, N. M, (US Government), OSW demonstration plant	1,000,000	Vapor Compression	Chicago Bridge & Iron

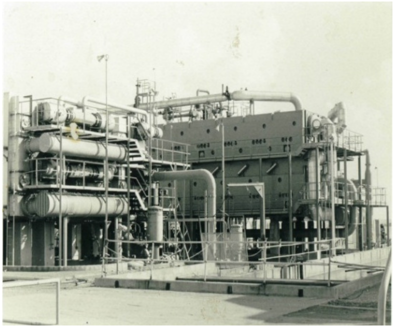
In 1965, the MSF desalination technology was introduced at W.E.B. Aruba N.V. with the installation of a 3,000 cubic meters per day recirculation brine MSF evaporator from Aqua Chem Inc. as illustrated in Figure 2.27 [2.5]. This evaporator had a design GOR of 9.

Figure 2.27: The first MSF desalination unit at W.E.B. Aruba N.V. in 1965 [2.5]

In the 1970s the desalination production capacity was extended with two Aqua Chem evaporators of the second generation with a nominal capacity of 6,000 metric tons per day also with a GOR of 9. These MSF evaporators stayed in operation up to 1985.
In 1983 and 1984 the first two next third generation of 6,000 cubic meters per day Aqua Chem recirculation brine MSF evaporators with a GOR of 10, Aqua Chem #1 and Aqua Chem #2 was installed closing the era of the MED evaporators. From 1978 to 1995 the vertical Multi Stage Controlled Flash Evaporators were used. This revolutionary design with the usage of chlorine gas for the control of marine biofouling in the condensers was intended to increase flash evaporation efficiency and to decrease operational cost. However it turned out to be a failure. These aluminum evaporators had poor performance and were susceptible for corrosion. In this period a disastrous decision was made to replace the part of aluminum pall rings in the deaerator for plastic pall rings without being aware of the fact that these actually function as ion traps inhibiting copper induced aluminum corrosion. The total amount of distillate produced with the MSF technology per December 2011 is about 358.4 million cubic meters from which 21,364,233 cubic meters were produced with the Aquanova Multi Stage Controlled Flash evaporators. With the poor operation experience with the Aquanova evaporators fresh in mind and a short time to evaluate proven new technology the choice was made to continue installing Aqua Chem MSF evaporators to cope with the fast increasing water demand due to fast economic growth in the 1990's. It is worth mentioning that the negative operational experiences with the Aquanova MSF evaporators have for a long time fortified the innovation prohibitive policies of the W.E.B Aruba N.V. as already indicated in Chapter 1.
In Figure 2.28 the pictures of the Aqua Chem and the Aqua Nova MSF evaporators are shown. During the period 1990 to 1998 W.E.B. Aruba N.V. was forced due to rapid economic growth, to increase production capacity with new MSF evaporators each of three successive years: Aqua Chem # 3 in 1990, Aqua Chem # 4 in 1991 and Aqua Chem # 5 in 1993. Two additional MSF evaporators were built in two three-year period namely Aqua Chem # 6 in

1995 and Aqua Chem # 7 in 1998. The total production and the design capacities of the MED- and the MSF evaporators are respectively shown in Table 2.3 and Table 2.4.
As mentioned before, MSF technology was chosen because of reliability, good operation experience and lack of time to evaluate new technology [2.15].

1965 - 1984
1 MSF evaporator of 3300 m^3/d
First generation Aqua Chem evaporators



1970 - 1985
2 MSF evaporators of 6000 m^3/d
Second generation Aqua Chem evaporators

1978- 1995
4 MSF evaporators of 3700-6000 m^3/d Aquanova evaporators

1981-present
7 MSF evaporators of 6000 m^3/d
Third generation Aqua Chem evaporators

Figure 2.28: Multi Stage Flash technology from 1965 to present

In 1982, 1983 and 1990 W.E.B. Aruba N.V. had experienced problems with sufficient water production capacity mainly due to aging of MED evaporators, poor operation of the existing Aquanova evaporators and delay in the installation planning of the new Aquanova evaporators. To cope with the increasing demand, drinking water was imported in 1982, 1983 and 1990 from the United States, Venezuela and Dominica. The quantity of imported water is as follows:

- 1982:   41,918 mT; from Rio Caroni, Venezuela
- 1983: 741,122 mT; from the Hudson River, New York
- 1990: 252,115 mT; from the Hudson River, New York and from the island of Dominica.

The cost of import water was very high and to reduce water cost W.E.B. Aruba N.V. contracted Geveke B.V. to install a 1,000 m^3/day SWRO in 1983 on a *Build Own and Operate* (BOO) contract basis to minimize import of water. This Plate and Frame SWRO production unit stayed in operation from 1983 to 1985. There were a lot of membrane biofouling problems and this SWRO production unit never had an optimal operation. The total amount of water produced with this SWRO production unit was 257,543 cubic meters. In Figure 2.29 pictures of this SWRO production unit are illustrated [2.22].


Membrane Section

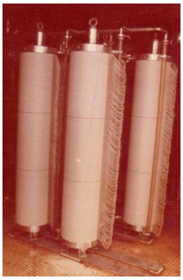


Plate and frame membrane


High pressure pump section

Figure 2.29: The 1,000 cubic meters per day BOO SWRO of Geveke B.V. from 1983-1985 [2.22]

Table 2.3 shows the total amount of water produced in Aruba and the percentage of the total water production with the different technologies from 1933 to 2011.

Table 2.3: Total water produced in Aruba from June 1932 to December 2011, [2.23]

Technology	Year of operation	Total Production [a] (mT)	% total production
MED technology	1933 - 1983	55,288,312	13.06
MSF technology	1965 - present	358,388,269[b]	84.64
RO technology	1983 - 1985	257,543	0.06
	2008 - 2011	9,491,736	2.24
Total production		423,425,860	
Imported water	1982, 1983 and 1990	1,035,155	

[a] *Total production during year of operation*

[b] *25,362,276 mT (7.08%) produced with Aquanova MSF-CFE*

The total amount of water produced from 1932 to December 2011 is 423,425,860 cubic meters from which 2.30% with SWRO (0.06 % in 1983-1985 and 2.24% in 2008-2011) and 13.06% with MED and 84.64% with MSF.
The annual water production has increased from 0.01 million cubic meters to 13.99 million cubic meters per end of December 2011. In the period 1958-1980 and after 1985 the water demand has increased rapidly respectively due to industrial water delivery to the Lago Oil Refinery in 1958, the rapid economic growth and the reopening of the oil refinery in 1985. In Figure 2.30 the annual water production from 1933 to 2011 is shown. The decrease in 2010 is due to the shut-down of the oil refinery.

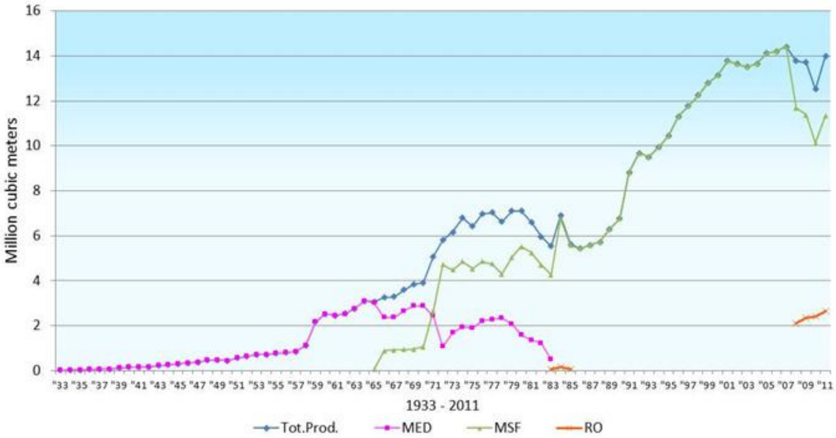


Figure 2.30: Total annual water production from 1933 to 2011 including the production of MED, MSF and SWRO desalination units [2.23]

Since the opening of the Lago oil refinery in 1929 the population of Aruba has increased rapidly with a steep increase in the 1990 due to rapid growth in the tourism industry. As a comparison for the water production trend the population growth of Aruba since 1803 is shown in Figure 2.31 [2.24].

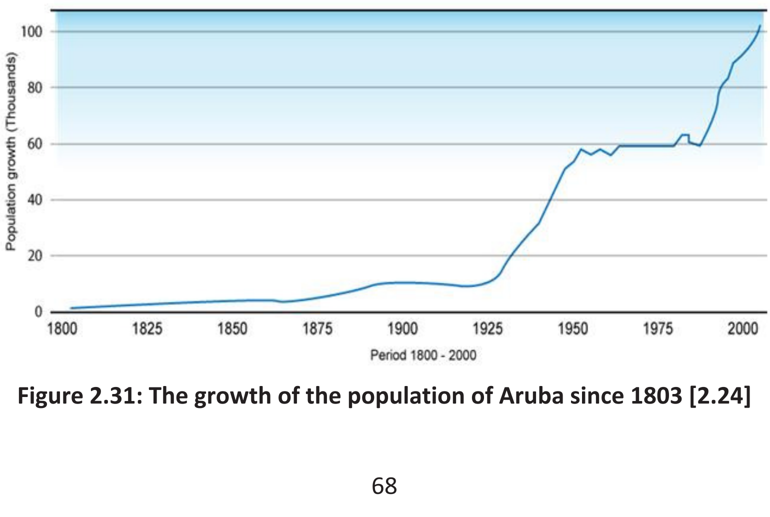


Figure 2.31: The growth of the population of Aruba since 1803 [2.24]

As can be seen the two graphs show a similar trend. To conclude the almost 80 years of thermal desalination history, the chronology of the desalination in Aruba is given in Table 2.4.

Table 2.4: The chronology of seawater desalination in Aruba [2.20]

Desalination unit	Technology	Capacity (mT/day)	Year of startup	Out of Service in	after
10 Weir	Submerged tube MED	200	1933-1945	1958	
5 Weir	Submerged tube MED	2,000	1958	1983	25 years
1 Aqua Chem	Long tube MSF	3,000	1965	1984	19 years
1 Aqua Chem	Long tube MSF	6,000	1970	1984	14 years
1 Aqua Chem	Long tube MSF	6,000	1971	1985	14 years
1 Aquanova	Vertical MSF CFE	4,000	1978	1983	5 years
1 Aquanova	Vertical MSF CFE	4,000	1980	1985	5 years
1 Aqua Chem (AC#1)	Long tube MSF	6,000	1983	2008	25 years
1 Aquanova	Vertical MSF CFE	3,700	1983	1991	8 years
1 Aquanova	Vertical MSF CFE	6,000	1983	1995	11 years
1 Aqua Chem (AC#2)	Long tube MSF	6,000	1984	2012	28 years*
1 Aqua Chem (AC#3)	Long tube MSF	6,000	1990	2012	22 years*
1 Aqua Chem (AC#4)	Long tube MSF	6,000	1991	2012	21 years*
1 Aqua Chem (AC#5)	Long tube MSF	6,000	1992	2013	21 years*
1 Aqua Chem (AC#6)	Long tube MSF	6,000	1995		
1 Aqua Chem (AC#7)	Long tube MSF	6,000	1998		
1 GEIonics (SWRO#1)	2 pass-2 stage SWRO	8,000	2008		
1 Veolia (SWRO#2)	2 pass-2 stage SWRO	24,000	2012		

**According to planning after total taking over of SWRO#2*

Current Water Production and Process of W.E.B. Aruba N.V.

The current thermal water production capacity of W.E.B. Aruba N.V. since the last quarter of 2012 consists of two MSF evaporators, each having a nominal capacity of 6000 m^3/day. They are from the long tubes configuration with brine recirculation. The MSF evaporators have a Top Brine Temperature of 110 ^oC and a Performance Ratio of 10. As scale inhibitor a novel high temperature antiscalant GE Betz HT 15^{TM} has replaced in 2007 concentrated sulfuric acid that was used for more than 40 years. After 43 years of excellent operation with the MSF technology the challenging step toward SWRO has been taken in Aruba indicating the beginning of the closing of the supremacy era of the MSF technology as often remarked in the desalination world. In March 2008 a new 8000 m^3/day SWRO production unit constructed by GE Ionics went in operation. It is a three trains-two pass RO consisting of a SWRO and a two-stage BWRO with an overall design recovery of 39.5% and an energy consumption ratio of 4.00 kWh/m^3. The Aqua Chem #1 constructed in 1983 is taken out of production in June 2008 for economic reasons after more than 25 years in service and still in excellent operation condition. In the last quarter of 2012 the SWRO#2 with a nominal capacity of 24,000 m^3/day constructed by Veolia VWS is put in operation at reduced capacity due to excessive biofouling. It is a two pass RO consisting of four SWRO trains and two trains of a two-stage BWRO unit with an overall recovery rate of 43.2% and an energy consumption ratio of 3.75 kWh/m^3. The two SWRO units produce high quality product water with a TDS of about 15 ppm. In Figure 2.32 the current desalination technologies are illustrated namely the Aqua Chem MSF evaporator and the new SWRO production units.

MSF Technology: 6,000 m^3/d SWRO Technology: 8,000 m^3/d SWRO technology: 24,000 m^3/d

Aqua Chem Inc. GE WPT Veolia VWS

Figure 2.32: The actual desalination technology at W.E.B. Aruba N.V.

As a consequence four of the existing MSF evaporators have been put out of production pending official decommissioning after the SWRO#2 reaches its designed capacity as planned in the first quarter of 2014. In Table 2.5 the actual desalination units with their nominal capacities and year of commissioning is shown.

Table 2.5: The actual desalination units of W.E.B. Aruba N.V.

Desalination Unit	Design capacity (mT)	Type	Year of commissioning
Aqua Chem 5*	6,000	MSF rec. brine	1992
Aqua Chem 6	6,000	MSF rec. brine	1995
Aqua Chem 7	6,000	MSF rec. brine	1998
SWRO 1	8,000	2 pass-2 stage RO	2008
SWRO 2	24,000	2 pass-2 stage RO	2012

** Out of production awaiting official decommissioning in the first quarter of 2014*

The product water of the SWRO and especially the distillate produced with the MSF evaporators are very pure and have practically no hardness. The TDS of the MSF evaporators and the SWRO desalination units are in the ranges of respectively 0.5 to 1 ppm and 10 to 15 ppm. For re-mineralization purposes the SWRO product water is slightly acidified by dosing carbon dioxide to adjust the pH to a value corresponding approximately with the MSF distillate pH value of about 6.3. Since 1932 the distillate of the desalination unit is naturally hardened by flowing over coral stones in the unique coral house.

This coral house re-mineralization system is replaced in 2007 after 75 years for an automated pressurized re-mineralization filter system using lime stones. This is illustrated in Figure 2.33.

Beds of coral stones in the coral house

The new re-mineralization system

Figure 2.33: The re-mineralization techniques applied at W.E.B. Aruba N.V.

After calcium dissolution in the re-mineralization system the drinking water is still very soft and at these conditions very corrosive for the distribution system and is therefore chemically treated by dosing of pyro- and orthophosphate to mitigate corrosion. In Chapter 7 the post treatment will be described more in detail. After the chemical post treatment system the drinking water is pumped to 6 water storage tanks with a capacity of 12,300 m^3 each. The water tanks serve as a buffer for the desalination process.

Further on the island there are water tanks installed with a total capacity of 65,393 m^3. For further quality improvement and to guarantee a biological high quality drinking water Berson in line UV-equipment were installed since 2001 in all of the five distribution pipelines going to the header. The UV dosage is set at 60mJ/cm^2 and the minimum allowed value is set at 25mJ/cm^2. This was never done before because of the high temperature (110 °C) drinking water production at W.E.B. Aruba N.V. It is worth mentioning that the drinking water of Aruba has been tested by BetzDearborn and compared with different bottled drinking water of different natural resources and categorized as one of the world's highest quality drinking water [2.25]. The water quality is also audit by PAHO on a biannual frequency. In their report the drinking water of Aruba is also qualified as one of the best in the world [2.26]. The industrial water is chemically treated with caustic soda at a concentration of 2 ppm to increase the pH from 6.3 to 8.7-8.9. Further sodium hexametaphosphate is dosed at concentration of 3 ppm to inhibit corrosion. After chemical treatment, the industrial water is pumped to two storage tanks both having a capacity of 12,300 m^3. From the storage tanks industrial water is pumped to the Valero Aruba Refinery and to the Power House as boiler make up water. A picture schematic of the desalination process including the post treatment of the drinking water is illustrated in Figure 2.34.

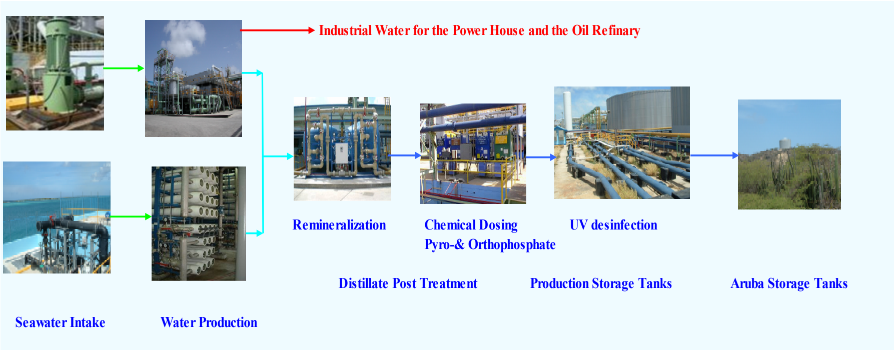


Figure 2.34: A picture schematic of the current seawater desalination process in Aruba

In conclusion of the history of seawater desalination and drinking water supply of Aruba it is noteworthy that the Government of Aruba emphasizing the importance of seawater desalination for the Island of Aruba has honored for the first time worldwide, seawater desalination with a post stamp in 1959 commemorating the extension toward the world's largest desalination capacity and secondly in 2002 for the occasion of celebrating 70 years of seawater desalination. Figure 2.35 illustrates the first day of issue of these post stamps.

First day of issue in 1959 [2.27]

First day of issue 2002

Figure 2.35: First day of issue of post stamps honoring seawater desalination in Aruba [2.28]

To close this section a summary-wise briefly description is given of the desalination development on the other Dutch Islands. Commercial seawater desalination started more than eighty years ago in Curacao in 1928 and on the Island of Bonaire and Saint Martin commercial seawater desalination took place more than thirty five years later, respectively, in 1963 and 1969. The desalination activities especially in Curacao have followed the desalination technology trend in the world, so in consequence the first technology used was thermal evaporation with the famous and robust mechanical vapor compressor and submerged tubes single stage evaporators, followed by the more economical Multi Effect evaporators. In the 1960's, due to the competition in the desalination market, more efficient and reliable Multi Stage Flash evaporators were introduced.
The membrane technology was introduced in 1997 in Saint Martin, Bonaire and Curacao. All these SWRO production units were operated according to a *Build Own and Operate* (BOO) contract, in Curacao and Bonaire by GE Water Process &Technologies and in Saint Martin by Air Fin SXM Holding NV. In 2005 a state of the art SWRO production unit with a capacity of 18,000 cubic meters per day was constructed by Degrémont Enerserve at Santa Barbara in Curacao [2.15]. The post treatment for the conditioning of the produced drinking water on the other island consists of enhanced re-mineralization with carbon dioxide dosing in the distillate to increase calcium carbonate dissolution in the lime stone beds. The current production capacities, the desalination technologies still in use, the post treatment and the percentage Non Revue Water of Aruba, Bonaire, Curacao and Saint Martin are summarized in Figure 2.36.

	Evaporators (mT/d)	SWRO (mT/d)	Tot. Cap. (mT/d)	Drinking water post treatment	% NWR
Aruba	12,000 MSF	32,000	44,000	Lime stone Remin	4.11
Bonaire		3,600	3,600	Lime stone + CO_2 dosing	16.8
Curacao	18,000 MSF, ME, VC	35,000	53,000	Lime stone + CO2 dosing	27.5
St.Martin		14,480	14,480	Lime stone + CO2 dosing	23.2


Curacao


Bonaire


Saint Martin

Figure 2.36: Current desalination processes of Aruba, Curacao, Bonaire and Saint Martin [2.18]

The desalination capacity of Bonaire and Saint Martin consists nowadays for hundred percent of the membrane desalination technology and in Curacao for about 34 percent of the total desalination production capacity. In the last quarter of 2013 this percentage will be 73 for Aruba. The percentage Non Revenue Water for the Island of Aruba, Curacao, Bonaire and Saint Martin are respectively 4.11 %, 27.5%, 16.8% and 23.2%. It is worth mentioning the importance of a well maintained distribution system and an optimal drinking water treatment avoiding leakages in the water distribution system because as in the case of Curacao with a 27.5% Non Revenue Water on a total production of 53,000 m^3/day an amount of approximately 15,000 m^3/day of costly drinking water is lost.
The other two remaining Islands of the Dutch Caribbean Saba and Saint Eustatius still do not have a seawater desalination facility and are fully dependent on their drinking water supply of rain water cisterns and drinking water import from the Island of Saint Martin and some small private own membrane desalination facilities [2.29].
Seawater desalination has supported the economic growth of the Dutch Caribbean Island enormously. The trend of the increasing cumulative contracted production capacity is illustrated in Figure 2.37. It is noteworthy that Aruba had till 1960 a larger capacity than the sister Island Curacao [2.30].

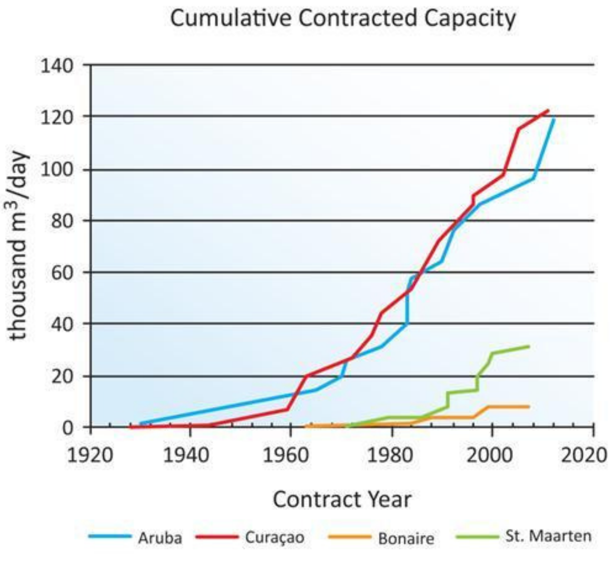


Figure 2.37: The historical trend of the production capacity of the Dutch Caribbean Islands [2.30]

Desalination plans of W.E.B. Aruba N.V. for the near future

Ironically the SWRO technology, which was put out of the picture back in 1983 with commissioning of the supreme MSF technology closing the era of MED technology (the work

horses of the first generation of the desalination technology), is now pushing the MSF technology out of the desalination activities of Aruba.
In the first quarter of 2014 with the SWRO#2 on total design capacity, the SWRO share of the total water production capacity of 44,000 m^3/day will be 72.7% reducing the MSF share to 27.3%. It is the intension to operate the MSF evaporators only with low cost steam produced with the waste heat boilers of the electrical energy producing reciprocating engines from the Power House burning heavy fuel oil to produce mainly industrial water.
It is in planning for the very near future to produce industrial water with the new *Electro Deionization* membrane technology so totally banning the MSF technology from the desalination activities in Aruba.
In conclusion of this chapter it is worth mentioning that Aruba took a long journey from primitive drinking water supply to a sophisticated water production and distribution facility guaranteeing its population hundred percent security of one of the world's highest quality water. In this journey especially the last decades the important part of sustainability, the continuous efficiency improvement of existing desalination units is concentrated on to reduce operation cost and environmental pollution. Further in accordance with the global trend of desalination research concentrating on alternative sustainable energy technology and sustained by the Green Energy vision of the current Government, W.E.B. Aruba N.V. has already taken the challenging steps toward a future with sustainable green seawater desalination. The installation of a pilot plant of the MEM Still, an innovative membrane flash evaporator designed by the institute of applied sciences of the Netherlands, "*Technisch Natuurkundig Onderzoek* " (TNO) [2.32] is already taken into consideration.

2.4 Conclusions

1. The Island of Aruba took a journey from primitive water supply to successful sophisticated water production and distribution and gives its population the security of reliable drinking water of one of the highest chemical and bacteriological quality in the world.
2. Throughout its desalination activities Aruba has gain enormous operation experiences that contributed to the improvements of the desalination technology due to continuously seeking to improved efficiency and application of well proven new technology.
3. Aruba continues to follow the global desalination development trend envisaging the application of innovative green sustainable desalination technologies excelling in efficient and environment friendly operations.

2.5 References

2.1. Buros, O.K., The ABCs of Desalting, 2nd edition, International desalination Association, February 2000, USA.

2.2. http://www.definitivecaribbean.com/caribbean-map

2.3. Handbook of Industrial Water Conditioning, 8th Edition, Betz Laboratories, Inc., USA 1980, 1-2.

2.4. Khan, A. H., Desalination Processes and Multistage Flash Distillation Practice, Elsevier Science Publishers B.V., Amsterdam, 1986.

2.5. Arrindell, E. M., Birkett, J. D., Aruba's Early Experiences in Desalination, Caribbean Desalination Conference, Oranjestad, Aruba, June 2002.

2.6. Spiegler, K. S., El-Sayed, Y. M., A Desalination Primer, Balaban Desalination Publications, ISBN 086689-034-3, Santa Maria Imbaro (Ch), Italy, 1994, 7.

2.7. Choules, P., Personal Communication, 2011.

2.8. Khawaji, A. D., Kutubkhanah, I. K., Wie, J., Advances in Seawater Desalination Technologies, Desalination 221 (2008) 47-69.

2.9. Marchena, F. A., Alberts, V. A., et al., "Strategic Quality Program: Basic Efficiency Control for Brine Recirculating MSF Desalination Units", Caribbean Conference, June 19-21, 2002, Aruba.

2.10. Aqua-Chem, Inc., Field-Assembled Modular seawater Multistage Flash Desalination Plant, Technical Bulletin 750-1122. Wisconsin, USA.

2.11. Spiegler, K. S., Principles of Desalination, 3rd Edition, Academic Press, Inc., USA 1969.

2.12. Fritzmann, C., Lowenberg, J., et al., State-of-the-art of reverse osmosis desalination, Desalination 216 (2007), 1-76.

2.13. Technical Bulletin, GE Water and Process Technologies

2.14. http://www.desware.net/desa4.aspx

2.15. Marchena, F. A., Hodgson, J. W., Experiences and Challenges of Aruba and The Netherlands Antilles in Seawater Desalination, Wetsus Congress, Leeuwarden, The Netherlands, September 22-23, 2008.

2.16. Tromp, J., Personal Communication, 2010.

2.17. Thiel, N., Archivo National di Aruba, Personal Communication, 2009.

2.18. Marchena, F. A., Bulbaai, R. R., Experiences and Challenges of Aruba and The Netherlands Antilles in Seawater Desalination; the Importance of a Water Technology Chair at the University of the Netherlands Antilles, UNESCO Water Education Conference, Asunción, Paraguay, December 11-12, 2008.

2.19. Maduro, J., Larez, A. P., Personal communication.

2.20. http://iclweb01.fsw.leidenuniv.nl/walhain/lesmateriaal/Level_4/lesmateriaal

2.21. Marchena, F. A., Morrell, J. A., et al., The Decision Process to Use Membrane Desalination after 75 Years of Successful Thermal Desalination, International Desalination Conference, Aruba, June 20-22, 2007.
2.22. Arrindell, E. M., Personal Communication, 2009.
2.23. Marchena, F. A., updated unpublished data, 2011.
2.24. Maduro, M., Central Bureau of Statistics Aruba, Personal Communication.
2.25. Post, R. M., BetzDearborn Inc., Personal Communication, 1994.
2.26. Muñoz Elguera, A., Assessment of Water Quality Monitoring and Control in Aruba and Recommendations for Health Risk Reduction, PAHO/OMS Report, June, 2008.
2.27. Solognier Noguera, S. S., Personal Communication, 2011.
2.28. Kock, J., Post Aruba N.V., Personal Communication, 2011.
2.29. Reijtenbagh, R., Consequences of the Constitutional Reformation for the BS-islands' Drinking Water Companies, Internship Report CWA, Saint Martin, August, 2008.
2.30. Birkett, J. D., Marchena, F. A., Early Desalination in the Caribbean and Its Adoption in the Netherlands Antilles, CaribDA 2012 Conference and Exhibition, June 19-22, 2012, Oranjestad, Aruba.
2.31. Marchena, F. A., Efficacy Oriented Operation and Maintenance: An important Step Toward Sustainable Conventional and Green Desalination Technology, Our Future with Green Energy Conference and Trade Fair, September 29th - October 3rd, 2010, Oranjestad , Aruba.
2.32. Hanemaaijer, J., Medevoort van, J., Memstill Membrane Distillation: A near Future Technology for Seawater Desalination, International Desalination Conference, Aruba, June 20-22, 2007.

Chapter 3

Considerations of the human aspect to effectively improve efficiency

Efficacious Motivational Leadership is all about Passion not about Position

Chapter 3

Considerations of the human aspect to effectively improve efficiency

Table of Contents:

Abstract

In the Desalination Department's endeavor reaching out to excellent operation, a socio-technical performance improvement program has been introduced. For efficient production of drinking water especially with the costly seawater desalination technology, the operational work force is considered the determinative improvement factor to enable the transformation into the envisioned high performing department. Motivation and comprehension of human behavior and attitude on the work floor is of imminent importance for the efficaciously deployment of the work force. The Passion and Fear (PF-) motivational and Human Attitude models have been intuitively developed by analogy with acknowledged technological models as supporting metaphoric tools to enhance motivation and comprehension of work floor's human behavior to overcome the always existing resistance for change and personnel dissatisfaction especially induced by company rules and policy. To cope with this fact the employees were giving the opportunity to challenge company rules and policy without violating any of them. This so-called Mahatma Gandhi effect resulted to be a very effective leadership strategy creating the possibility for comprehension of policy and to use negativism as a change agent. This leadership strategy has encouraged the development of the Efficacious Motivational Leadership (EML-) approach as a future improvement perspective. This ergonomically leadership approach is based on the concept of efficacy, efficiency improvement through effective empowerment and involvement of the work floor personnel, inducing self-leadership and self-development. A road map is developed including a plan of action to remediate the most critical human and technical improvement areas distinguished in the initiated socio-technical performance improvement process. This road map is ultimately transformed in a Continuous Desalination Efficiency Improvement Process in analogy with the European Foundation for Quality Management model. In this chapter after a short introduction of the socio-organization theories, the developed metaphoric motivational models, the critical improvement areas of the Desalination Department, the Mahatma Gandhi leadership strategy and the Efficacious Motivational Leadership approach, the road map paving the way to and the achievements realized with the socio-technical performance improvement process are described. Finally an overview is given of the achieved results in coherence with the applied socio-organizational theories.

3.1 Introduction

In the very beginning of the industrial revolution era the process toward more productivity, efficiency and profitability already initiated. Undoubtedly the basis for achieving these goals has been to make the work force more productive. Obviously it was already well understood in those days that motivation plays an important role. Only the concept of motivation and organization management was different along the industrial development path. According to the history of Organization Science, the first profound theories about management were developed at the turn of the nineteenth century throughout the first decades of the twentieth century. Frederic W. Taylor (1856-1915) and Henri Fayol (1841-1925) laid the foundation of the principles respectively for the Classic Management and the Scientific Management [3.1]. According to these principles, the productivity of laborers can be simply optimized by having well defined job descriptions, standardized instructions and taking care of good payment. A basic view in this period was that a worker's motivation to become more productive could be stimulated by satisfying the worker's need of increasing his/her prosperity. A turn in this autocratic approach to organization management came in the 1930's with management concepts highlighting the human aspect of an organization. This Human Relations Movement especially from George Elton Mayo (1880-1949), broadened the management point of view to more democratic and participative methods of management. Based on his studies, Mayo concluded that people's work performance is dependent on both social issues and job content. He suggested a tension between the "logic of sentiment" of workers versus the "logic of cost and efficiency" of managers which could lead to conflict within organizations [3.2]. Further developments based on the fundamental correlation between technical and human aspects of an organization, led after the Second World War to the "Managerial Grid Model" developed by Robert R. Blake and Jane S. Mouton and the Contingency Approach of Fred E. Fiedler. The Managerial Grid Model originally identified five different leadership styles based on the *concern for people* and the *concern for production*. The optimal leadership style in this model is based on Theory Y [3.3]. In theory Y, developed by Douglas M. McGregor, it is believed that employees enjoy their mental and physical work duties. According to this theory, workers possess the ability for creative problem solving, but their talents are usually underestimated and underused in most organizations. Given the proper conditions, employees will learn to seek out and accept responsibility and to exercise self-control and self-direction in accomplishing objectives to which they are committed. Given the right conditions, according to theory Y, most people will want to do well at work. The satisfaction of doing a good job is believed to be a strong motivation.

Fiedler's contingency model postulated that the leader's effectiveness is based on "situational contingency" which is a result of interaction of two factors: *leadership style* and *situational control* [3.4].

Most of modern time management specialists, especially John C. Maxwell, have gained popularity in the last decades accentuating the coaching potential of leadership instead of the managing role through all the aspects of instruction, coaching, motivation, inspiration and delegation of situational management. Creating relationship to attain followers is fundamental for this leadership concept [3.5].

According to the abovementioned, the organizational philosophy transformed since the beginning of the industrial revolution from a pure autocratic approach toward a human oriented perspective. Nowadays the philosophy is based on the consideration of human resources as the most valuable asset of an organization. For excellent operation and efficient production, especially of drinking water with the costly seawater desalination process either by thermal or membrane technology, this point of view is of eminent importance. The operation personnel directly involved with the daily operation of desalination production units are seen as a key efficiency improvement factor. Excellence in operation is direct dependent on their awareness and ability to understand variation in the process and the application of their knowledge to make timely decisions to correct undesired process variations. A thoroughly comprehension of the process, the system units, the components of the installations and their functionality, is the basis for detecting and solving problems and preventing recurrence. It is therefore beyond any doubt that the operational personnel are to be considered as an important aspect, a key performance factor to improve desalination efficiency. From the initial motivation attempts it was directly crystal-clear for the management of the Desalination Department that working together with the operational work force as a team, transforming their operational experiences into measurable useful performance indicators for process efficiency management would render important initial steps toward sequential improvements.

In this context a simple “Passion and Fear (PF-) model” has been developed by analogy with acknowledged technological models as a supporting tool to enhance motivation and to overcome the always existing resistance for change. Fundamental for success in this important human aspect, especially for technical oriented personnel on primary and secondary technical education level, appeared to be the application of understandable technological scientific founded principles, as metaphors, to describe (in the total beauty of their simplicity), human behavior and attitude.

In addition, some basic classic and quantum mechanical chemical reaction models were used as metaphors to describe culture induced human attitude. The “Passion and Fear” model describes the inner human energy of fear promoting performance in the comfort zone and the needed inner energy of passion to overcome the resistance to perform out of the comfort zone. The “Human Attitude” model describes the inner potential energies governing acceptable and unacceptable culture induced human attitudes toward core

values and the in practice experienced fact that personnel with enough passion but even so do not change.
Supported by this “Passion and Fear” and the “Human Attitude” models a quality program has been developed to effectively enhance the empowerment process to fortify this human key performance aspect to increase operational efficiency through promoting strategically small sequential successful steps toward desalination excellence. To effectively involve the work floor in this strategic performance improvement process an effective leadership strategy was invaluable. In this context of efficacy, the effective empowering of the work floor to excel in efficient desalination operation, an “Efficacious Motivational Leadership” (EML-) approach was developed based on the principle of criticizing and challenging but without violating any Company policy and rules. This so called “Mahatma Gandhi effect” resulted to be an effective leadership strategy.

This chapter describes and evaluates three important aspects toward continuous desalination efficiency improvement, namely the: (1) Stimulation of teambuilding; (2) Development and application of the “Passion and Fear (PF-)”, “the Human Attitude (HR-)” and “Efficacious Motivational Leadership (EML-)” models; and (3) the Socio-Technical Performance Improvement program.

3.2 The situation at the Desalination Department as found in 1997

Accepting the management responsibility in 1997, it became a passionate challenge for me directing the Desalination Department to become a role model in the World for the efficient application of seawater desalination for the production of high quality drinking water. Likewise, the intention was also to serve as model for the encouragement of other arid countries to evaluate the implementation of cost effective and innovative sustainable desalination technology as a viable option for the solution of the global water shortage problem. However, it was also directly evident that to realize this ambition, great effort had to be done to create a motivated work environment for the operational work force and to improve work relationship and communication with the supporting departments of Maintenance, Laboratory and Technical Support [3.6]. On different technical and human related operational aspects the inherited Desalination Department had a deficient performance in 1997 and the as found situation can be described as follows.

The operational work force
The operational work force could be characterized as experienced and practical knowledgeable. However, also unmotivated and resistive to company rules and proposed changes and in general they had a distrusting attitude against superiors.
The theoretical and background knowledge about desalination and of desalination processes was very limited. Practically, they knew what to do and when and also how to

react to process changes. However, most of the time they did not know why certain actions had to be taken which is important for trouble shooting purposes.
It was also obvious that the operational work force could be divided into three distinctive groups, a small group with a positive mind set, a large group with neutral attitude, and a small group with a negative resistive attitude. The large group of neutral personnel could further be categorized as a "diffusive" group, consisting of positive oriented personnel, a small neutral group and a group leaning to the negative attitude.
Ownership and accountability among the operational work force was lacking. According to their own perception, this was predominantly induced by the punishing culture of former autocratic management. Workers were in general unsatisfied with their job and usually the communication and relationship with the supporting departments could be characterized as poor.
Mainly due to the occurring job dissatisfaction, the frequent absenteeism was high and consequently also the overtime. Fear to commit mistakes and error while performing their job was evident. This was surely further enhanced by the omission of an adequate desalination course and training program for continuous education. On the job training for new operators was practically nonexistent.

Leadership

The management of the Desalination Department could be characterized by a top down autocratic approach, strictly applying company rules and policy without accepting any objection. The shift lead operators reporting to line management only had work-oriented leadership authority and were not trained in developing leadership skills and competency as front line leaders. They were mostly selected only based on their years of service, not taking into account their practical operational experience and back ground. As a consequence their acceptance by and their communication with the operational work force were deficient. Actually the autocratic leadership style according to the common organization culture, was not promoting relationship building with operational work force. With a distrusted attitude towards superiors as a consequence. Subsequently the communication and relationship with other frontline leaders and line management of the supporting Maintenance, Laboratory and Technical Support departments was also on a low level.

The desalination units

The Multi Stage Flash (MSF-) evaporators were advancing a degrading maintenance and operation condition mainly due to overdue maintenance and inefficient operation. Even the newer MSF evaporators constructed in the beginning of the 1990s, were already experiencing the detrimental effect of the aggressive seawater environment causing internal and external corrosion. The efficiency was frequently below design target value because of lack of effective operational monitoring and control of occurring biofouling and scaling. Due to the commonly experienced production decay at that time and a lack of operation and maintenance planning and effectiveness, the consequently threatening water scarcity forced the “run to kill” (long term operation without execution of the scheduled maintenance) desalination operational and maintenance approach. The common snowy salt deposits on different parts of the desalination units were the visibly results of many leakages promoting external corrosion. This was further worsened, because removed isolation materials after repairing perforation in vessels and piping were usually not reinstalled. Also the necessary painting of the desalination units was not performed as a preventive maintenance measure in a long period of time.

The process monitoring system

The control of the MSF evaporators was performed with a semi-automatic control system applying the old fashioned analog paper recorders. The control and measurement instrumentation were mainly neglected due to the intensive project of the total upgrading of the Power House going on in the first half of the 1990s.

The important chemical dosing for the MSF evaporators and the distillate post treatment including the level control of the Coral House and the water reservoirs were manually controlled by the operational personnel. Process pumps and chemical dosing pumps were adjusted manually with usually overfeed and underfeed of chemicals as a consequence. The condensate return system to the Power House and the distillate processing system were not upgraded to comply with the increased water production capacity in the 1990s. The deteriorating water quality in the period of the Aquanova evaporators producing high salinity drinking water had caused enhanced corrosion in the distillate processing system. Trouble shooting was not a common practice of the operational work force and the monitoring system was further not adequate for this purpose.

Work structure and procedures

Operational work was actually performed without standard operation manuals and standard trouble shooting and problem solving procedures and uniform supervisory performance of the lead operators. The operational work force often complained about inconsistent application of startup and shut down procedures when working with different lead operators. The administrative, operation and maintenance work processes were not structured, nor clearly defined. This caused a lot of confusion and promoted deficiency in ownership and accountability. Process failures and incidents were not documented and practically not well reported.

Maintenance

The relationship with the maintenance departments could in general be characterized as “the unit failed because it was not fixed well” and the counter reaction “the unit failed because it was not well operated”. The desalination units and corresponding process equipment were taken out of production and handed over to maintenance without trouble shooting, without any form of work permit and without any proposal for the expected maintenance work to be performed. Effective communication, relationship or teamwork practically did not exist between the departments. There were no General Inspection or maintenance meetings held between the two departments. The relationship of the Equipment Inspection group of the Engineering Department with the Maintenance Department could also be characterized as very resistive.

Housekeeping, safety and environment
On the water production premises and under the MSF evaporators, regularly used material and maintenance equipment and tools could be found. It was not unusual to find maintenance equipment stored under an MSF evaporator for months awaiting the next shut down for the scheduled maintenance activity. Operation and maintenance was usually performed without the necessary adequate personnel protective gear. Working with sulfuric acid and other chemicals without the prescribed safety measures was a common practice. At the Desalination Department, safety talk and meetings were not commonly held as a standard procedure. There were no housekeeping and safety controls performed either and at the Desalination Department the work force was also not trained to do so.

A first start towards change
Being aware of the fact that motivated personnel is a key efficiency improvement factor, the decision was made to develop a “Socio-Technical Performance Improvement program”. This program was initiated to effectively involve and empower the operational work force to accept the journey toward the covetable goal of desalination excellence. To change the mindset and the consciousness inspiring dominance of the whole spectrum of the desalination efficiency improvement process, intuitively understandable metaphors were developed as guiding principles in the path forward toward the motivational change initiatives. The metaphors, inspired and based on proven technological scientific models, are described in the next section.

3.3 Metaphors as guiding principles to initiate change

Throughout the development of technological science, the art of using representative models for phenomenological description of rather complex processes in nature has always been a very essential foundation for intimate acquirement of theoretical knowledge and comprehension. For example the simplistic description of atoms and molecules as rigid smooth spheres in constant motion and interaction with each other, led to the understanding and postulation of important basic laws in physics excelling to the more in depth description of the behavior of matter as wave functions in quantum mechanics. Still

scientific solutions in modern science are fundamentally based on simplifying the processes of concern in representative models.
The natural habit in physics and chemical technology to search for models that might at least partly explain physical or chemical processes, also led to a search for models that might provide insight on human behavior and motivation on the work floor.
So it seems no wonder, that a technologist without particular psychology background, only with common knowledge of human behavior, seeks for technological models that might be used as metaphors to understand human behavior, motivation and attitude.

The gas-molecular model as a metaphor to understand resistance and motivation to change
Good observation of what really happens in a work environment, trying to motivate to excel in efficient operation in practice, revealed that there were always two energies competing with each other. There is on one side the latent need, a dormant passion to reach for improvements and at the other side the need to stay in the comfort zone of doing things the usual way, the fear for the uncertainty, the unknown and the possibility of losing inducing and enhancing the resistance to change. In the physical chemistry science a well-known similarity of two opposing forces exist for molecules in a gas phase experiencing two competing forces, the gravitational force tending to compose all the molecules in an orderly fashion at a certain reference level of minimal potential energy and the thermodynamic force keeping the molecules in constant motion, the Brownian movement, the thermal or kinetic energy of the molecules spreading them randomly in the available space striving to reach a natural distribution of maximum entropy. The compromise between these two opposing energies is the natural equilibrium resulting in the well-known Boltzmann distribution of molecules [3.7]. In this thermodynamic equilibrium state a well-defined relationship exist for the concentration of the molecules at different height and inherently for the hereto proportional gas pressure. Equation 3.1 gives these relationships for the concentration C and the gas pressure P as a function of the potential and kinetic energies.

$$C = C_o \exp(-mgh/kT) \qquad (3.1\ a)$$

$$P = P_o \exp(-mgh/kT) \qquad (3.1b)$$

In this equation mgh is the potential energy exerting by the gravitational force on the molecules at a certain height h and kT the kinetic energy or thermal energy of the gas molecules. Boltzmann has also proven that the abovementioned relation holds in general for any systems where an external force exists exerting a potential energy U that should compete with the thermal energies of molecules. In analogy with this theorem a simplistic hypothetical psychological model can be developed, without claiming any mathematical correctness only explanatory importance, where the passion to excel can be compared with entropic energy to continuously and randomly seek for innovation, to explore new ways of doing things better and the fear as the potential energy ordering any attempt to change in a comfort zone of minimal energy. A natural sense of prove for this theorem can be obtained by observing a child doing the first steps repeatedly falling and getting up again and cheering sometimes still with tears in the eyes due to the pain from the preceding fall, because of the conquest of a few more small steps indicating that we inherit from birth the entropic passion to achieve the goal we aiming for and to overcome any interference of induced fear.

Analogically the motivation M to change is therefore a natural equilibrium of the competing energies of intrinsic entropic passion energy P and the external force inducing potential fear energy R. In accordance to the molecular concept a relation for the resistance R to change can be written as outlined in equation 3.2.:

$$R= R_0 \exp(- F/P) \qquad (3.2)$$

In the comfort zone the resistance R_0 is the highest. The motivation M needed to overcome the fear to change is proportional to the amount of resistance so therefore the same relationship holds for the motivation M (equation 3.3.):

$$M= M_0 \exp(-F/P) \qquad (3.3)$$

In the reference level of the comfort zone the resistance R_0 to change, to excel to improvements, is maximal due to the fact that the potential energy F of fear is practically zero. In zones away from the comfort zone through the entropic effect of the kinetic energy P of passion the resistance approaches practically to zero. In Figure 3.1 the effects of passion and fear on possible changes together with the motivation and resistance curves are schematically illustrated.

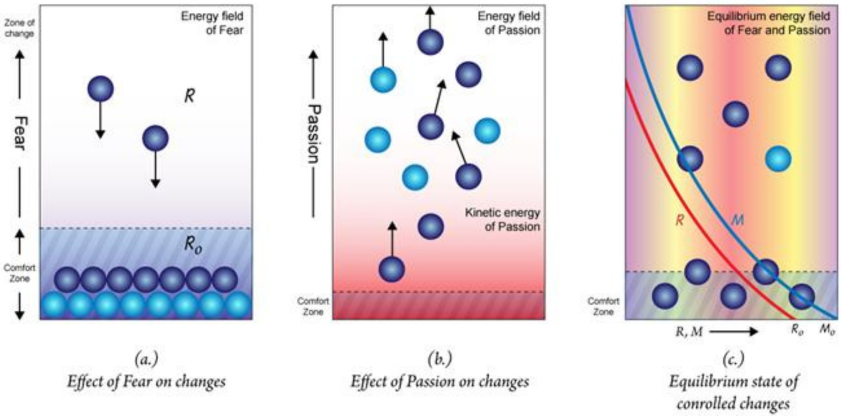


Figure 3.1: The Passion and Fear model to motivate for change

It is worth mentioning that fear besides the negative effect of inducing resistance also has an important positive effect enhancing optimal evaluation of proposed changes before implementation. Thus fear can be used as an effective control mechanism, a regulator for the exclusion of possible implementation of modifications not well thought of.

The chemical reaction model as a metaphor to understand the change process
As indicated above motivation, which can be considered as a motive to take action, is a very important aspect in the process of change. A simple useable model for a basic explanation of this very complex subject in psychology is the basic concept of a simple chemical reaction path where two chemical components for simplicity denoted as A and B reacts to form a different chemical component AB. In this concept the chemical reaction components is considered initially to be in a thermodynamic potential state of a higher energy level then the final state where the two components have formed the new chemical component AB. Before reaching this final state the component form a precursor A…B* in a transition state with an even higher energy than the initial state. The difference between the energies of the transition state and the initial state is called the chemical reaction activation energy [3.8]. It is a well-known phenomenon that even though thermodynamically the conditions are favorable the chemical reactions do not, or take place at a very low rate because of the high activation energy needed. In these circumstances catalysts are used to lower this transition energy to accelerate the chemical reaction. Of importance in catalytic reactions is the fact that the catalyst itself is not consumed, so comparatively a very small amount is necessary and readily available for the next reaction. This chemical reaction path is schematically illustrated in Figure 3.2.

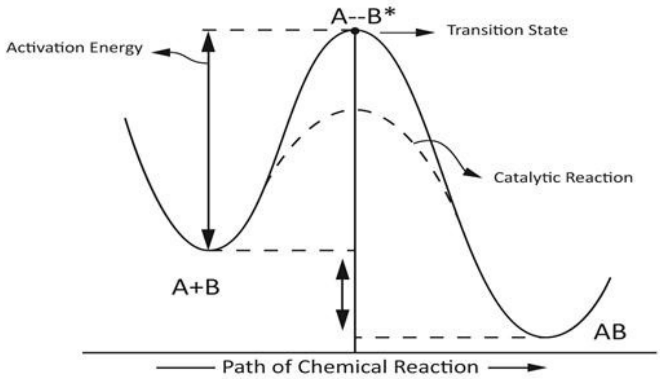


Figure 3.2: A schematic of a simple chemical reaction path

Analogically with the chemical reaction process the path of the process of change can be graphically represented as illustrated in Figure 3.3. In this graph the actual situation, the proposed change and the final situation are denoted for the sake of simplicity as A, I and AI.

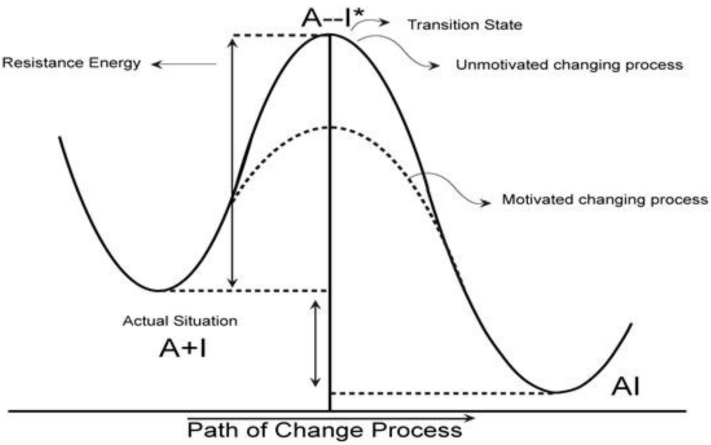


Figure 3.3: A schematic of a simple change process path

Accordingly the process of change initiated from an actual situation A where some kind of modification I is needed always passes through a transition state A…I* with a higher potential activation energy of change, primarily resistance energy induced by fear, to be overcome to reach the modified situation AI. This transition state is most of the time characterized by the desire to keep the situation unchanged, evaluation and re-evaluation of the proposed modification trying to attain a higher possible level of acceptance to effectively make the change. In these situations motivation and passion acts as important catalysts to lower the resistance energy enhancing this change process. This motivation process greatly depends on the very important aspect of human behavior and attitude.

According to the chemical catalytic process the right amount of motivation and passion especially attained after sequential small successful steps of changes should be conserved to keep the desired attitude accepting change with the positive effect of fear as a regulator to manage the implementation of innovative ideas for modification.

A simple quantum mechanical model as a metaphor to understand human attitude
Human behavior is primarily, plausible without a sociological extensive explanation, intensely related to the nation social culture defining rules, standards and core values. These standards and core values will ultimately define the core values and standards of any organization and companies. Nowadays it is generally recognized that organizational culture has a powerful effect on the performance and long term effectiveness of organizations [3.9]. Without an extensive psychological enunciation of human behavior theory (as already illustrated in the two preceding metaphoric explanations) a simple technological model as the physicochemical atomic model can also intuitively be used as a metaphor for a basic explanation of human motivational behavior.
Normal human behavior is a result of a natural inner equilibrium of two competing forces inducing acceptable and unacceptable attitudes towards the core values, rules and standards. In chemical physics an atom in the ground state is described in equilibrium as harmonic vibrations in the ground state and other different excited states so in analogy to this atomic theory human behavior can be explained as harmonic vibration between the acceptable, good attitude and the unacceptable, bad attitude with in the attitude path activation energies to be overcome to change to better attitudes or to worse attitudes as graphically illustrated in Figure 3.4. As normal, overcoming the first energy barrier the successive energy barriers will be less energy intensive indicating that small achieved successes will enhance motivated attitudes toward passionate attitude to reach for excellence in the optimal efficient operations. It is worth mentioning that this theory also predicts successive lower potential energy barriers for the unacceptable attitude enhancing resistance for change not willing to reach out for improvements.

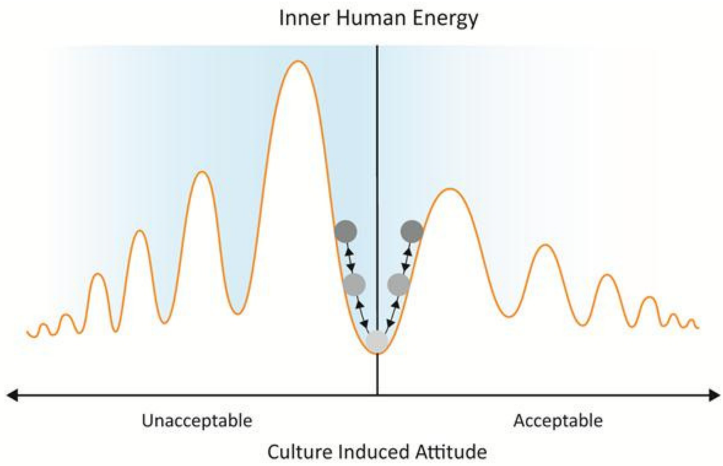


Figure 3.4: A simple schematic of the human attitude path

In practice it is usually observed that already in the initial states of the motivation process the work force can suddenly take an attitude of change toward semi motivated actions and then to fall back to old resistive habits of the comfort zone. This phenomenon can be explained as the well-known tunneling effect in quantum mechanics where particles having less energy than the needed potential energy can break through the potential energy barrier. Being aware of the fact that some personnel always show this attitude, one should immediately grasp these opportunities to catalyze the passionate process. Worth mentioning is also the in practice experienced fact that personnel having enough passion to break through the potential resistance energy but even so do not change. This effect can also be explained analogically with the quantum mechanics theory. This quantum mechanical analogy is schematically shown in Figure 3.5.

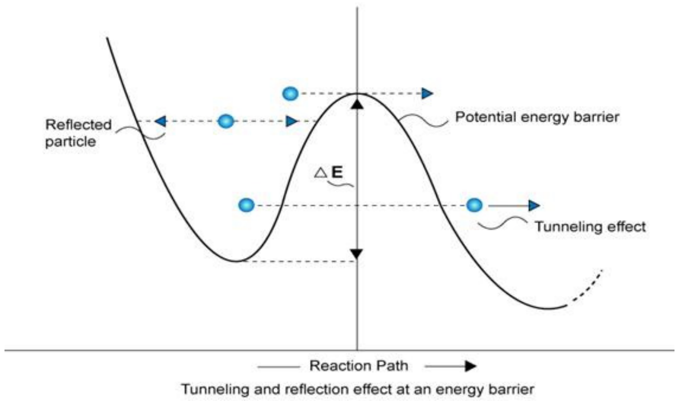


Figure 3.5: Human attitude in analogy with quantum mechanics

On the contrary to classic mechanics predicting that all particles having energy larger than the necessary transitional potential energy should pass the potential barrier, quantum mechanics calculations show that some of these particles may be reflected at the potential barrier [3.10].
The models that were discussed in this section, were used as metaphors and guiding principles to support and sustain an efficiency performance improvement process. The models provided insight, understanding and also commitment among the work floor employees to achieve the desired level of efficiency improvement. The performance improvement process will be explained in more detail in the next section.

3.4 The development of a socio-technical performance improvement process

Envisioning a high performing Desalination Department, initially a Socio-technical performance improvement program was developed. To enhance personnel and technical performance, this program strategically focused on the participative deployment of the human efficiency factor. The human factor was seen as a determinative factor to enable a reach-out from a deficient toward an improved department performance level.
The first draft for a socio-technical performance improvement program was proposed in 1997. This program (as illustrated in Figure 3.6) is primarily based on the evaluation of the management and operation condition of the Desalination Department, the establishment of a collaborative work environment and a plan of action to improve performance and convert department's weaknesses into strengths.

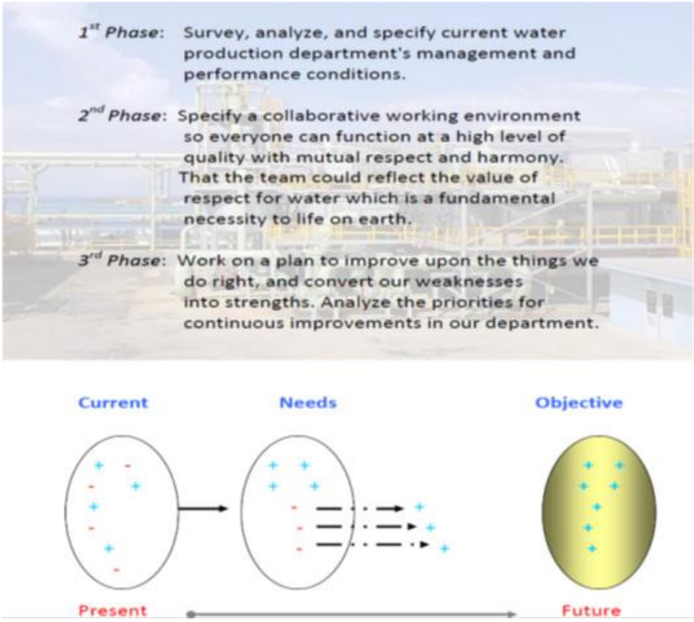


Figure 3.6: A first draft of a socio-technical performance improvement program in 1997

This performance improvement program has been developed in efficaciously cooperation with the operational work floor, with the intention to have by the year 2000 an effective desalination efficiency improvement process continuously focusing on the human and technical aspects. The intended purpose of the phases in the first draft of the socio-technical improvement program was as follows.

The first phase

The main objective in this first phase was to take a critical look at the management and the performance of the Desalination Department. The initial survey performed in cooperation with the work force confirmed the poor communication and poor relationship with and distrust in superiors as a result of former autocratic leadership style of line management, as already indicated in section 3.2. The work force was knowledgeable but also demotivated and unsatisfied with their job. They accentuated the negligence of their involvement by line management for operational improvement as the cause of the perceived deficient operation and maintenance of the desalination units. In this phase the importance of the work force as the key performance improvement factor was constantly accentuated. The development of a participative leadership strategy to promote motivation, involvement and empowerment of the work force to build a firm relationship and stimulation of team building were recognized as critical areas for human performance improvement. The first thoughts to use technological metaphoric models to explain human behavior emerged in this initial phase and the earlier described Passion and Fear motivational model and the Mahatma Gandhi leadership strategy (see section 3.6) took shape to cope with dissatisfaction, as perceived by the operational work force, caused by company rules and policy. The initial concept of the Efficacious Motivational Leadership approach was developed to sustain operational work force participation. The basis for the first crucial steps for the human performance improvement process was set: (1) building a firm line management-work floor relationship; to promote (2) involvement and empowerment to create a motivated, clean and safe desalination work environment.

The second phase

In this second phase the intension was to consolidate the involvement and empowerment of the operational work force to specify and establish a motivated collaborative working environment promoting harmony to enable functioning at a high quality level and of importance with mutual respect. The importance and value of water as a fundamental necessity for life was emphasized to increase job satisfaction and proudness for the operation function. The disunity of the operational work force in three distinctive groups (as indicated in section 3.2) was recognized. The importance of motivational and human attitude models to explain and understand experienced human behavior at the work floor level such as resistance to change, fear and fallen back to the comfort zone after initial shown interest toward improvement was acknowledged. The basics of participative leadership were introduced to enable support of the Efficacious Motivational Leadership (EML-) approach. This approach will be described in further detail in chapter 3.7. Furthermore the importance of a shared vision and mission was acknowledged. In this second phase the subsequent steps for further human performance improvement process were set forth: (3) stimulation of effective internal team building to improve the technical operational performance of the desalination assets and as a condition toward improved communication and interdepartmental team building; and (4) development of a shared department's vision and mission to pave the way forward to the envisioned excellent desalination performance.

The third phase

In the third phase the main objective was to identify desalination operational weaknesses and turn them into strengths through improved human performance. The operational experience of the work force was used to further improve the human and technical performance of the Desalination Department toward a continuous efficiency improvement process. To increase ownership and accountability the work processes needed to be described and documented. The work force was motivated and empowered to support the set-up of a standard operation procedure and to evaluate and to come up with practical solutions for the eventually debottlenecking of the desalination process and monitoring.

Regarding the monitoring system the identified critical improvement areas were the omission of key performance indicators and the inadequate outdated process monitoring equipment. With respect to the desalination process the under capacity of the distillate and condensate processing system, poor maintenance of the desalination assets, omission of standard operation procedures and a quality management system and no work climate for innovation and application of new technology were identified as necessary critical improvement areas. Additionally the proposed desalination performance improvement process were further characterized with the following path forward: (5) to structure and document the work processes; (6) acceptance, evaluation and implementation of a proposed solution to increase desalination efficiency and production; and (7) to improve communication and teambuilding with supporting departments and the desalination equipment manufacturers and chemical supplier.

A roadmap towards continuous desalination efficiency improvement

The critical areas for performance improvement as characterized in the three phases of the initiated socio-technical performance improvement program were prioritized and incorporated to draft the concept of a continuous desalination efficiency improvement process. The initial set-up of the continuous desalination performance improvement process (as indicated in Figure 3.7) is primarily based on the improvement's steps of: (1) leadership efficacy (efficient work force's involvement and empowerment); to strategically (2) deploy the human factor to specify and improve; the (3) Operational Personnel Performance; and the (4) Desalination assets' Performance to reach out from a deficient performing department toward; an (5) improved Desalination Department's performance. The improved Desalination Department's performance is regulated with: (6) targeted Operational Performance Indicators developed in cooperation with the operational work force; to assure a (7) Continuous Desalination Efficiency Improvement Process, achieved targets are specially adapted to reach out to the next higher performance level.

With the most critical improvement areas specified and structured in a first draft of a continuous performance improvement approach, a road map including the plan of action to remediate these distinguished critical areas has been developed (as illustrated in Figure 3.7) to initiate the successively determined steps toward an efficient performing Desalination Department. This roadmap has ultimately been transformed into the Continuous Desalination Efficiency Improvement Process in analogy with the European Foundation for Quality Management (EFQM) model for improvement toward excellence desalination. The basis is leadership strategy in the concept of efficacy, to enable effective involvement and empowering of the operational work force to efficiently take care of the desalination asset in a sound partnership with supporting departments. The ultimate results are an efficient desalination department's performance that are regulated with targeted key performance indicators to guarantee the production of high quality water satisfying all stakeholders in a continuous improving desalination process adding value to the company.

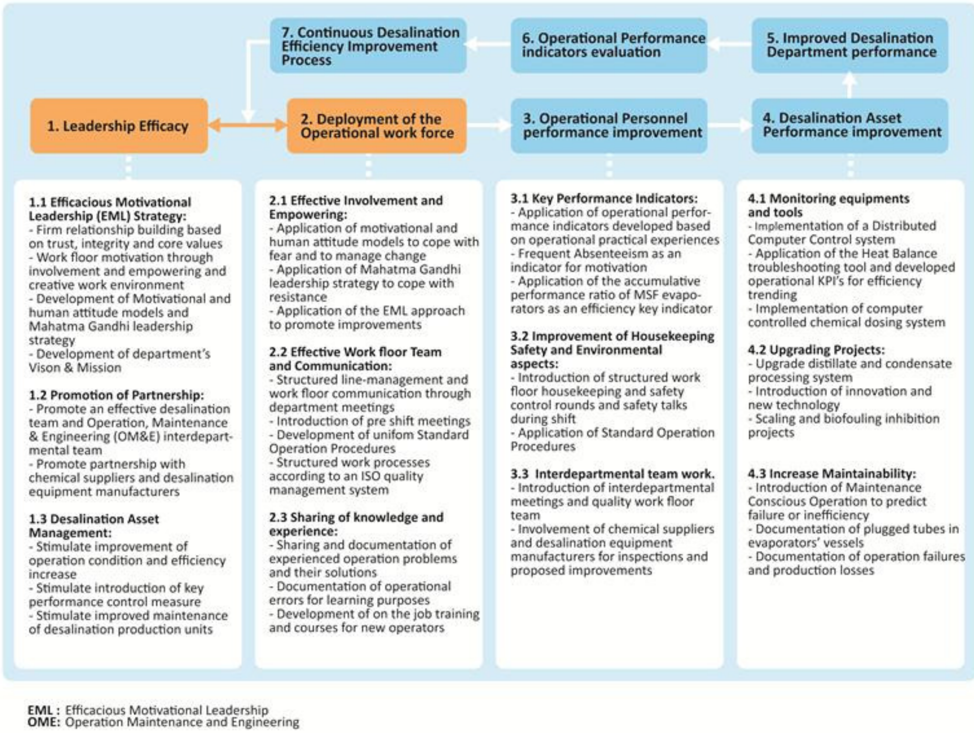


Figure 3.7: The road map toward the Continuous Desalination Efficiency Improvement Process

Figure 3.7 illustrates the introduced road map with the proposed plan of actions in the different improvement steps to reach the envisioned improved Desalination Department performance in the Continuous Desalination Efficiency Improvement Process:

1. Leadership efficacy

In the operational excellence's endeavor of the Desalination Department, leadership efficacy is considered to be the motivational pillar and enabler to continuously drive the operational work force toward motivated effective participation in interdepartmental teams and partnership to increase human performance improving operational processes and the desalination asset's performance. The intended end result is an excellent performing Desalination Department producing high quality drinking and industrial water to the satisfaction of all stakeholders and so adding value to the company. In this context the main points of attention are Efficacious Motivational Leadership strategy to promote partnership to sustain effectively the management of the Desalination asset.

1.1 Efficacious Motivational Leadership (EML) strategy

In this improvement step the leadership strategy is directed to establish a firm relation with the operational work force based on integrity, mutual trust and respect and according to company's core values to primarily eliminate the existing distrust. A firm desalination management-work force relationship is considered determinative to further promote the efficacious motivational concept of effective participative involvement and empowering of the work force to reach out toward an improved performance. In this context socio-technological motivational and human attitude models were developed and applied as metaphors to promote and manage change and to stimulate work floor motivation. A creative and motivated work environment is pursuit and endorsed to improve work floor performance ensuring participation to develop a vivid shared vision and mission toward the envisioned Desalination Excellence. To cope with the experienced work force's resistance to company's rules and policy, the Mahatma Gandhi leadership strategy was developed based on the opportunity to challenge rules but without violation of any of them.

1.2 Promotion of Partnership

The Efficacious Motivational Leadership approach is further applied to consolidate the desalination operational team to lay the foundation for a firm partnership with supporting Maintenance and Engineering Departments to assure a well maintained and engineered desalination asset. The partnership with chemical suppliers and desalination equipment manufacturers is promoted to improve inspections and to facilitate evaluation and introduction of proposed new cost effective chemical and technical applications for desalination operational performance and efficiency improvement.

1.3 Desalination Asset Management

Leadership efficacy acts as enabler stimulating evaluation of operation condition to increase desalination efficiency. The development of trendable operational parameters based on operational experiences is stimulated as control measures for desalination operational performance and efficiency improvement. Furthermore, documentation of process failures and production losses are promoted to assess the maintenance condition of the desalination units and to determine the most critical operation areas needing maintenance attention. The developed key performance indicators are also used to indicate the need of preventative maintenance.

2. Deployment of the Operational work force

The operational and maintenance work force being closest to the desalination units is considered the most important human key performance improvement factor. The main objective of the continuous desalination improvement process is attaining the result of efficient desalination operation through the effective deployment of the operational work force to grow toward a firm Operation Team improving human and desalination asset performance. In this context the main areas of attention are effective involvement and empowering, effective team building and communication and internal sharing of desalination knowledge and experience to enable effective deployment. To reach this goal the following actions are pursuit.

2.1 Effective involvement and empowering

To enable effective participation, the Passion and Fear motivational model and the Human Attitude models are applied with the intension to explain the different experienced habits, behavior and attitudes at the work floor level such as fear for mistakes, negativism, resistance for change, demotivation and the "comfort zone" culture inducing comprehension and a motivated work climate. Especially the so called Mahatma Gandhi leadership strategy is introduced to cope with resistance for the company rules. With the application of the motivational and human attitude models the diminishing of the three partite disunity of the operational work force is enforced and the importance of effective communication and teambuilding endorsed as a condition for performance improvement.

2.2 Effective work floor team and communication

To stimulate effective line management-work floor communication structured department meetings and pre shift meetings are introduced to discuss operational performance, safety and housekeeping and for information of important current organizational issues. To further promote team work the development and application of Standard Operation Procedures is introduced to enable uniform operation. The work force is involved to describe and document the administrative work flow and processes according to the ISO standard to initiate a quality management system to control and assure performance improvement and to increase work satisfaction.

2.3 Sharing of knowledge and experiences

Sharing of desalination operational knowledge and experience is considered as a useful action and promoted as such to enable participation and to enhance deployment of the work force to document experienced operational problems and their solutions. Operational errors are reported and documented for learning purposes to diminish the fear for mistakes and to promote technical operational growth. The setup of a desalination course and the on the job training for new operators and self-education is stimulated.

3. Operational Personnel performance improvement

To improve personnel performance the attention is concentrated to increase awareness for the efficiency control of the desalination production units and to maintain a clean and safe working environment. The importance of interdepartmental team work to achieve performance improvement is emphasized and promoted. The endorsed points of attention for performance improvements in this aspect are key performance indicators, improvement of housekeeping, safety and environmental aspects and interdepartmental team work.

3.1 Key performance indicators

The developed key performance indicators based on operational experiences are applied to monitor biofouling and scaling of the desalination production units and are used to convince maintenance department of the necessary condenser and tube cleaning to increase efficiency. The frequent absenteeism is introduced as a measure and control of motivation and work satisfaction. To trend and control the efficiency of the Multi Stage Flash (MSF-) evaporators the accumulative performance ratio is introduced. The main goal is to increase efficiency awareness by the use of key performance indicators to regulate and improve operational personnel performance.

3.2 Improvement of housekeeping, safety and environmental aspects

To further improve human performance the awareness for maintaining a clean and safe desalination work environment is promoted and constantly identified with the importance and value of the product Water. A thorough cleaning action of the desalination premises is organized including the Desalination Department's line-management to stimulate the introduction of the housekeeping and safety control round of the operational personnel. Safety talks are introduced during the pre-shift meetings. To promote environmental protection, all chemicals used are approved for use in drinking water and environment friendly according to the National Sanitation Foundation (NSF-) standards.

All operational work is performed with the necessary prescribed personnel protective gear. Furthermore, the application of Standard Safety Operation Procedure is introduced as mandatory.

3.3 Interdepartmental team work

To further increase operational personnel performance, interdepartmental teamwork is promoted through biweekly quality meetings with the supporting Maintenance and Engineering departments. Also an interdepartmental work floor quality team headed by the lead operator is introduced to assure the maintenance of a clean and safe desalination work environment. Effective teambuilding training is organized to facilitate team work between Operation and Supporting Departments. The support of the chemical supplier and the desalination equipment manufacturer is introduced for jointly inspection and evaluation of the desalination process if necessary.

4. Desalination asset performance improvement

To enable improvement of the desalination asset the upgrading of the monitoring and control system and the distillate and condensate processing system is proposed. Further the improved maintenance of the desalination asset is stimulated in an interdepartmental team work environment. So, in this aspect the monitoring equipment and tools, upgrading projects and increase of maintainability of the desalination production units are specified as main areas of attention.

4.1 Monitoring equipment and tools

The implementation of a distributed control system is proposed to improve the monitoring system of the MSF evaporators and the distillate processing system and to improve trending of key performance indicators. The application of the heat balance troubleshooting tools developed in cooperation with Engineering Department is promoted. The Pace Setter computer controlled chemical dosing system is introduced to improve the dosing system of the distillate post treatment.

4.2 Upgrading projects

The evaluation of the under capacity of the distillate and condensate processing system is promoted. Proposed upgrading projects are outsourced for engineering and implementation to cope with current and future capacity increase. The aspects of foaming, biofouling and scaling hampering efficient and stable desalination operation are evaluated in cooperation with chemical suppliers and desalination equipment manufacturers. The application of new technology and innovation is promoted to further increase desalination efficiency.

4.3. Increase maintainability

The introduction of the Maintenance Conscious Operation concept (maintaining the production unit by optimal in target operation control) is introduced enabling the prediction of failures and inefficiency. Documentation of plugged tubes is promoted as an indication of the maintenance condition of the MSF evaporators. Visual inspection and vibration check of the rotating equipment is introduced during control rounds. Failures and their effect on production losses are documented to determine the critical areas needing effective maintenance. All outstanding corrective maintenance activities are documented and proposals are made for the maintenance department for planning and execution during the scheduled maintenance program to increase maintainability of the desalination units. The documentations are used to endorse the necessary maintenance activities and to assure their execution.

5. Improved Desalination Department performance
The envisioned results of the improved Desalination Department performance is a motivated work force efficaciously controlling the upgraded desalination processes and well maintained desalination asset in a creative environment of interdepartmental team work under the direction of efficacious motivational leadership to produce efficiently the high quality drinking water and industrial water.

6. Operational Performance Indicators evaluation
Predefined operational performance indicators such as targets for frequent absenteeism and efficiency increase were developed and applied for the evaluation and control of the improved Desalination Department performance. A quarterly efficiency, maintenance and safety report for the work floor is issued as motivation for improving performance.

7. Continuous improvement process
The initiated work floor and desalination asset's operational performance improvement is subjected to continuous evaluation according to targeted key performance indicators (KPI's). If necessary the KPI's are adjusted challenging a next higher performance level.

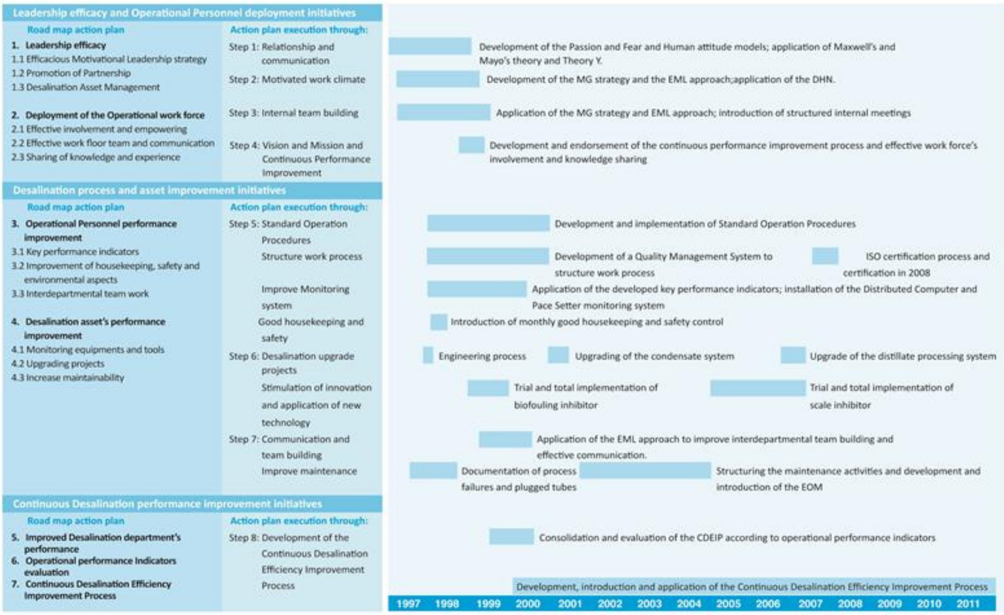
Despite a thoughtful road map as depicted in Figure 3.7 directing the way for implementation, due to unforeseen circumstances and obstacles, the actual steps in practice toward improvement sometimes differed from the planned actions. This is typically the dynamic character of the implementation of an intuitively developed process, usually as a consequence of the often unconscious application of the plan-do-check-act principle. This process toward a straightforward outlined goal is often experienced by the work force and in their synonymous comparatively way expressed as:

> "The sinuous straight line of an Aruban drunken man's walk"

With this in mind the sequentially performed steps in practice at the Desalination Department toward the outlined Desalination Department's improved performance are further described in more details.

The implementation of desalination improvement steps in the period 1997 to 2011
Aware of the resistance of the operational work force for external consultancy, I took

initially the decision as the responsible line manager of the Desalination Department to start the desalination efficiency improvement endeavor accepting the combined role, actually on a trial and error basis, as the initiator, developer, the facilitator, observer and regulator of the continuous improvement process, constantly observing if there are potential work floor personnel interested to take over one of the specific roles. The aspect of leadership efficacy to direct the strategy toward improved personnel and assets management was intuitively based on the personal inner conviction that a work force well-taken care of will be motivated to take care of the asset and processes increasing performance and efficiency to produce value to the company in general and the Desalination Department in particular, according to the Theory Y of Douglas McGregor and the EFQM performance philosophy toward Excellence. The time frame of the implementation of the desalination performance improvement process according to the plan of actions of the road map (as indicated in Figure 3.7) and the applied socio-organizational theories and models is schematically illustrated in Figure 3.8.



DHN:	Desalination Hierarchy of Needs
EML:	Eff. Mot Leadership
MG:	Mahatma Gandhi
EOM:	Efficacy Oriented Maintenance

Figure 3.8: The implementation steps of the Continuous Desalination Efficiency Improvement Process from 1997 to 2011

The steps and the strategies applied at the Desalination Department during the efficiency improvement process, according to the critical areas as specified in the first draft of the socio-technical performance improvement program and in compliance with the planned actions in the road map as illustrated in Figure 3.7 are further described.

Leadership efficacy and Operational Personnel deployment initiatives

1. The first important step to take was establishing a firm relationship with the operational work force based on integrity, respect and mutual trust to end the distrust in superiors
Although initially the well-intended attempts of both sides, by coincidence a big step forward in the relationship building process was attained by the opportunity fortuitously given to the work force to teach me to operate the MSF evaporators and the related desalination processing systems. Comprehending the operational aspects during this period a leading principle was set forth considering operational mistakes and failures as learning opportunities instead of reasons for disciplinary actions to diminish the existing fear to commit mistakes, as mention before practically induced by the autocratic leadership culture, provided that the observed failures and mistakes committed will be well documented as reference for improvement and as a measure of quality. In this stage the omission of Standard Operation Procedures was further classified as a potential source of operational mistakes. The work force's involvement was requested to set up these procedures. According to modern organizational and leadership theories, such as John Maxwell's, the establishment of a good relationship is a key factor for effective leadership [3.5]. Structured department meetings and pre shift meetings are introduced to effectively improve communication. In these meetings operational performance, safety and housekeeping and information of important current organizational issues are constantly discussed.

2. The second step, introduced when the mistrust was diminishing, was the inspiration for involvement of the work force to create a motivated, clean and safe work environment
Firstly the work force was invited to describe the work culture of the Desalination Department taking into consideration the core values, rules and standards of the company. The identification of possible motivators and de-motivators was also requested. As per their description the operational work force was characterized as a three partite group of positive oriented, neutral and negative oriented personnel. Next to autocratic leadership, they also brought forward as a very demotivating aspect that usually their proposals for improvement most of the time was neglected and disapproved or otherwise implemented by superiors as it were their own. The positive group also indicated the desire to understand why some operators do not want to change or some of them sometimes trying but usually after some attempts falling back in the old way of doing work. Especially the negative oriented group often emphasized that they believe in technical theories correctly predicting or explaining practical operational experiences. They disbelieve motivational theories.
These facts had induced the development, description and application of the Passion and Fear model, the motivational change model and the human attitude and behavioral models based on technological scientific models. Surprisingly the explanatory potential of these

models were well accepted.
Further, the implementation of the new household rules proposed by the lead operators, as instructed by Senior Management in 1997, was considered very demotivating for the Desalination Department. This aspect is in accordance with the socio-organizational theory of Frederick I. Herzberg indicating that company policy and rules are the factors leading to the highest employee dissatisfaction [3.11]. In this context, to decrease the resistance the leading principle was set forth to perform strictly according to these rules but the opportunity was also given to criticize and challenge but not to violate any of the company's rules and policy with the intension to get accustom to or improve the existing rules. This was the basis for the development of the Mahatma Gandhi leadership strategy in the course of 1998 leading to the development of the Efficacious Motivational Leadership approach. Adequate personnel protection gears were purchased to increase safety and the Safety Training Observation Program (STOP) of Du Pont is introduced for lead operators to improve safety observation. In team work, including the Desalination Management a hands-on total clean-up of the desalination premises was organized.

3. The third step was effective team building promoting involvement and empowering to identify and solve encountered technical problems and to increase efficiency of the MSF evaporators using operational experiences
As the relation and the motivated work environment was improving the effort concentrated on consolidating the team building to face the technical aspects to be improved. The first technical issue brought forward was poor maintenance and the deficient monitoring system of the MSF evaporators and related distillate processing assets and poor communication with the maintenance departments. Further the physicochemical aspects such as biofouling, scaling, foaming and corrosion were identified as most important technical issues causing efficiency decay. The importance of building a solid internal team was recognized and emphasized as a necessary condition prior to establish an interdepartmental team with supporting departments. Using operational experience, key performance indicators were developed on a trial and error basis and successfully applied to monitor biofouling in the condenser and scaling in the brine heater and heat recovery section of the MSF evaporators. They were also used to convince the maintenance department to perform regular condenser cleaning and tube cleaning of the heat recovery vessels to improve efficiency. This was the first motivational successful step forming the foundation and consolidating an effective team and the confidence in the efficiency improvement process and the conviction of the effectiveness of a culture oriented participative management approach establishing mutual trust and harmony in the Desalination Department.

4. The fourth step was defining a shared vision and mission and a slogan for the Desalination Department and the consolidation of the continuous efficiency improvement
After establishing an improving work relationship, the Vision and Mission of the Desalination Department was developed at the end of 1998 in full cooperation with the operational personnel to define the future envisioned motivational direction toward desalination excellence. The Vision and Mission as developed is illustrated in Figure 3.9.

Vision:

Efficient desalination performance and a model for:

1. Culture Oriented Participative Management and Quality.
2. Sustainable efficient seawater desalination in the World.
3. High quality performance to achieve the vision and goals of W.E.B. Aruba N.V.

Mission:

We produce efficiently high quality water in a creative work environment.

Slogan: ***WE*** *stand for* ***W****ater* ***E****xcellence****!***

Figure 3.9: Vision and mission of the Desalination Department

The vision and mission served to further endorse the deployment of the work floor to improve and fortify the initiated motivated and collaborative work environment and to consolidate the continuous desalination performance improvement process to improve the technical performance aspects. At this stage it is important that the Desalination Department has grown enough in maturity to take a critical look at its management and to look back at the deficient performance without finger pointing to others but only with the shared objective to reach out to be a role model for efficient performance. The first preceding steps are reevaluated and if necessary adjusted to enable effective deployment of the work force and fortify the efficacious motivational leadership approach.

Desalination process and asset's improvements initiatives

5. The fifth step was to structure and document the work processes and procedure
To increase operational personnel performance, the administrative and operational work process and interdepartmental work flow were clearly defined and documented to establish ownership and accountability. Standard Operation Procedures were developed and all the department organizational, administrative work processes were described and documented

as a Quality Management System (QMS) according to the ISO standards in the course of 1999 to 2001. Service Letters Agreements (SLA's) were drafted and approved with the supporting departments. Due to the fact that now everyone knows exactly what to do and what is expected from them the work satisfaction improved.
The developed operational key performance indicators were incorporated in the standard operation procedure and structurally applied to monitor biofouling and scaling and to promote predictive preventive maintenance activities.
With regard to safety and housekeeping monthly control by the work force headed by the lead operator is established and incorporated in the standard operational procedure to guarantee a well-kept desalination environment. This first small success was the cornerstone toward participative involvement and empowering.
In 2007 after acknowledging the achieved Desalination Department's improvements, Senior Management authorized the pursuit of an ISO certification as the only department in a non-certified company. The Quality Management System (QMS) is further improved with external support of BPO Caribbean N.V. and ISO certified by Kiwa Nederland B.V. in 2008.

6. The sixth step was the evaluation, approval, implementation and documentation of proposed technical solution to increase efficiency and production
The desalination process monitoring initiated in step 3 using the developed key performance indicators indicated the necessity of effective chemicals to control foaming, biofouling and scaling to sustain efficient and stable operations of the MSF evaporators. In 1999 and in 2005-2007 in cooperation with the chemical supplier and the MSF evaporator manufacturer respectively the new biofouling and antiscalant additives were thoroughly evaluated and applied. In 1999 extensive studies have been performed with external engineering support to upgrade the condensate system to the Power House and the distillate processing system and to improve the distillate re-mineralization system. The upgrading projects were executed respectively in the period of 2000 to 2001 and in the course of 2006 to 2007. The desalination process monitoring system is upgraded to a new full automatic Distributed Control System, the Citect Scada system and the chemical dosing system of the post treatment of the drinking and industrial water is upgraded with a full automatic computer controlled Pace Setter system in the course of 1999 to 2000.

Interdepartmental team building initiatives

7. The seventh step was to improve work relationship, communication with the supporting Maintenance, Laboratory and Engineering Departments
When the team work in the department was established, the efforts concentrated to improve communication and teamwork with the supporting departments not only at the work floor level but also at the line management levels. General Inspections & Maintenance

(GI) meetings and daily work order meeting were introduced and monthly Operation Maintenance and Engineering (OM&E) quality meetings were organized promoting fast and practical solution for the operational problems. The monitoring and troubleshooting system is further optimized with the Engineering Department and the maintenance activities is structured to implement corrective, preventive and condition based maintenance leading to the development of the new Efficacy Oriented Maintenance approach. Operational coordination for maintenance and inspection activities for the Desalination Department is established. Before a GI, Operations hands over a maintenance proposal document including all maintenance and inspection activities required and the pre GI efficiency and the preceding post GI performance test of the subsequent desalination unit. The interdepartmental creative work environment promoted innovation and the application of new desalination technology facilitating the evaluation of the SWRO technology as a viable option to cope with rapidly increasing energy cost since 2004. Involvement of the work floor personnel in the early stage of the new SWRO desalination projects in 2006 is established for the first time at W.E.B. Aruba N.V. Three patents have been awarded for innovative invention at the Desalination Department, respectively in 2003, 2010 and 2013.

8. The eighth step was the development of the Continuous Desalination Efficiency Improvement Process

Efficacious leadership, in the context of effectively involvement and empowering of the work force, is a servicing process to passionately encourage the personnel to progressively reach out to a higher level of performance continuously seeking to improve the process. The comfort zone should always be overcome to prevent stagnation. It is an inner energetic driven endeavor, in which context Passion, Patience, Persistency and Perseverance are key necessary human characteristics enabling progressively small successful steps toward effective continuous improvement. Key performance indicators such as the frequent absenteeism and the accumulative performance ratio of the MSF evaporators are developed to regulate the continuous performance improvement process. The yearly targets of the key performance indicators are adjusted to encourage performance improvements. This initiated continuous performance improvement process formed (as illustrated in Figure 3.10) the frame work for the Continuous Desalination Efficiency Improvement Process (CDEIP) as described in Chapter 1 to support the quality journey toward the envisioned Excellence in Desalination.

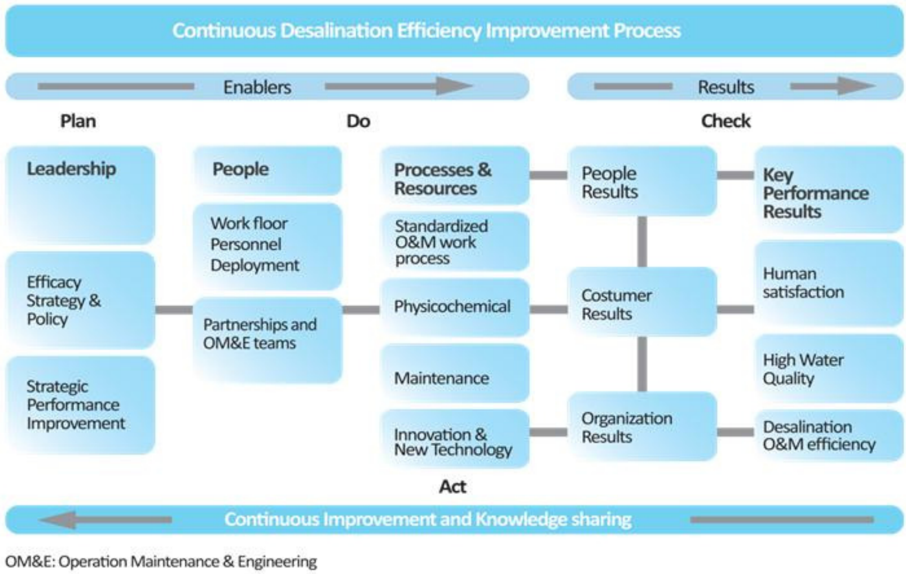


Figure 3.10: The frame work of the Continuous Desalination Efficiency Improvement Process

After the ISO certification, the frame work of this CDEIP is described in analogy with the EFQM model with the human factor, the physicochemical aspect, the maintenance aspect and the aspect of innovation and new technology as the main enablers toward the intended result of people, costumer and organization satisfaction in full compliance with the production of high quality water to create value to the company toward business excellence.

3.5 Achieved results with the socio-technical performance improvement process

For efficacious leadership supporting motivation and creativity, successes are very important. Following the iterative evaluation process based on the Deming PDCA cycle and the Engineering Design process as described in Chapter 1, operational process improvement objectives have been determined, specified and hereto derived projects have been thoroughly evaluated and successfully implemented validating the Continuous Desalination Efficiency Improvement Process as explained in more detail in the subsequent chapters of this dissertation. In this section the trend of the frequent absenteeism, the efficiency of the desalination units and the cost saving as a consequence of this human and technical performance improvement process is illustrated. The frequent absenteeism is considered a useful performance indicator as a measure for motivation and satisfaction of the work floor personnel [3.12]. At the Desalination Department the percentage frequent absenteeism in relation to the total number of employees of the Desalination Department decreased from a value of 53.8% in 1996 to practically 3.7% in 2000 and since then, practically due to the recruitment of new operators needing to be accustomed to the shift work, varying between 14.3 to 6.1% yearly as can be seen in Figure 3.11 [3.13].

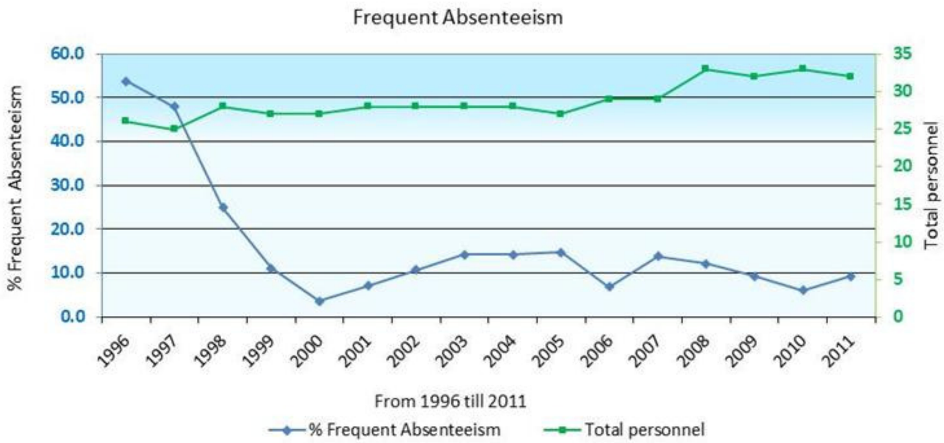


Figure 3.11: The percentage frequent absenteeism and the total number of employees of the Desalination Department from 1996 to 2011

The efficiency of the MSF evaporators (defined as the performance ratio, the ratio of the amount of distillate produced and the amount of low pressure steam consumed) increased steadily since the introduction of the Continuous Desalination Efficiency Improvement Process from the minimal accepted target value of 8.5 to an annual accumulative performance ratio of 9.3. In 2008, as mandated by Senior Management all attention is concentrated to improve the off design efficiency targeted performance of the new commissioned SWRO desalination unit resulting in less maintenance and operation attention on the MSF evaporators consequently leading to efficiency decrease. The efficiency of the MSF evaporators was even more affected with the further decision of Senior Management to increase production capacity with another SWRO unit of 24,000 m^3 per day and decommissioning 4 existing MSF evaporators to reduce increasing operational cost as a consequence of the drastically increasing heavy fuel oil cost. This decreasing effect actually demonstrates the importance of the maintenance aspect for efficiency improvement as illustrated in Figure 3.12. On the other hand the effect of the implementation of more efficient desalination technology to increase efficiency is also clearly seen in this graph showing the calculated total performance ratio including the calculated equivalent performance ratio of the SWRO desalination unit since 2008.

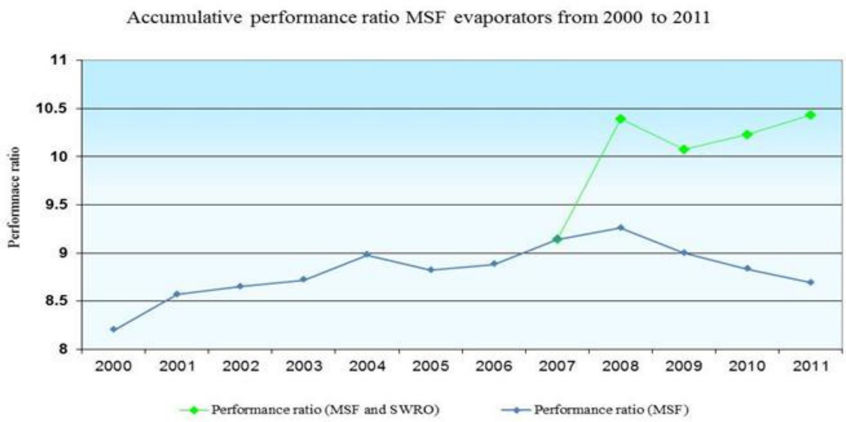


Figure 3.12: The trend of the performance ratio of the desalination units from 2000 to 2011

The contribution of motivated personnel to the financial economic state of the company can be calculated considering the decrease of frequent absenteeism causing overtime, efficiency increase and decrease in operational failure and effective maintenance aspect reducing General Inspection and Maintenance period and increasing its interval. An important contribution of motivated maintenance personnel is aiming to execute the job right and failure free the first time. Due to lack of information found in the literature research up to now, the guidelines for the estimation of the economic aspect of motivation is obtained from the yearly efficiency increase due to effective monitoring and control, yearly decrease in absenteeism and the yearly decrease in process failures as experienced at the Desalination Department assuming validity for the whole company [3.14]. An arbitrarily assumption of 10% yearly savings on the average yearly training cost is made due to increased motivation and leadership effectiveness. Although in 2006 W.E.B. Aruba N.V. increased its training budget to approximately AWG. 1.27 Million on a yearly average training budget of AWG. 0.7 Million in the period of 2003 to 2010 for leadership development and motivation indicating a budget increase of 81.4%. For the sake of simplicity the yearly average increase or decrease is taken for the calculation of the subsequent guidelines. In the period of 2000 to 2008 the desalination efficiency (the ratio of the produced amount of distillate to the consumed amount of low pressure steam) increased from 8.2 to 9.3 indicating a yearly efficiency improvement of 1.6%. As indicated in Figure 3.11, the frequent absenteeism decreased from 53.8% in 1996 to 9.4% of the total desalination personnel in 2009 indicating a yearly average decrease of 6.3%.

The calculation of the costs of absenteeism is related to the average hourly salary. To calculate an estimation of the reduction in maintenance cost due to motivated personnel, the reduction in process failures and pump failures as experienced at the Desalination

Department in the period 1997 to 2009 as will be explained in detail in Chapter 8, is considered. The total cost of production loss due to process and pump failures is reduced from AWG.1.71 million in 1997 to AWG.0.095 million in 2009, indicating a yearly reduction of 7.2% in operations and maintenance cost. The calculated cost benefits accentuating the economic aspect of motivated personnel considering above mentioned items are shown in Table 3.1 and the total annual savings is illustrated in Figure 3.13.

Table 3.1: The cost benefits due to personnel motivation in the period 2000-2011

Year	Absenteeism (kAWG)	Training (kAWG)	Maintenance (kAWG)	Fuel cost (kAWG)	Total annual savings (kAWG)
2000	90.8	70.0	892.3	1,080.5	2,133.6
2001	104.6	70.0	848.0	896.1	1,918.8
2002	91.7	70.0	979.6	1,191.2	2,332.5
2003	95.5	70.0	931.4	1,406.3	2,503.2
2004	89.0	70.0	895.9	1,599.4	2,654.4
2005	95.7	70.0	972.9	2,450.3	3,588.9
2006	103.0	70.0	858.1	3,077.2	4,108.3
2007	93.6	70.0	940.3	3,480.4	4,584.3
2008	93.3	70.0	1,261.3	4,615.5	6,040.1
2009	118.3	70.0	1,351.0	3,102.3	4,641.6
2010	85.0	70.0	1,639.1	3,783.9	5,578.0
2011	74.9	70.0	1,726.5	5,242.0	7,113.4

The trend's decrement in 2009 as shown in Figure 3.13 is due to the fuel oil cost decay, which is the main contributing component to the annual savings.

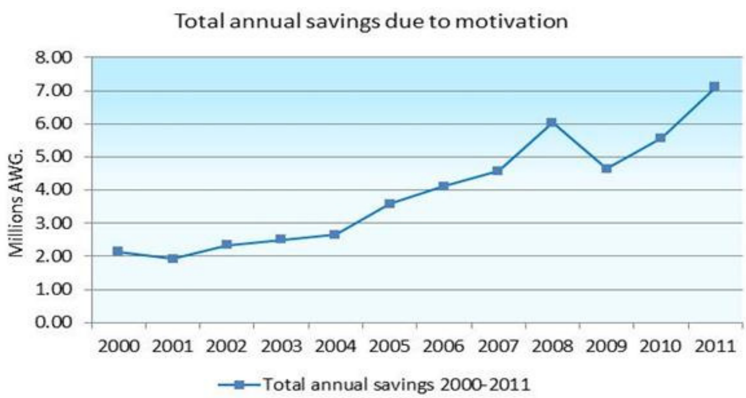


Figure 3.13: The economic aspects of motivated personnel [3.14]

Company-wise savings, in the magnitude of AWG 2-7 million annually, is achievable through motivated personnel indicating the importance for a company to invest in motivating the most valuable asset, the human resource [3.14]. The calculated savings are 0.6 -1.94 percent of the average total annual production and maintenance budget of AWG.360.4 million.

In this context an Efficacious Motivational Leadership approach is developed as will be explained in section 3.7 to continuously motivate the work force creating value to the company.

3.6 An overview of the applied socio-organizational theories and results

The performance improvement approach of the Desalination Department, as explained in the previous sections, was based on (1) the introduction of a socio-technical performance improvement program to determine the most critical management and operational areas for improvement. The identified critical areas for improvement were (2) prioritized and incorporated in a road map with a plan of performance improvement's actions toward an efficient performing Desalination Department. This road map has been transformed in (3) a Continuous Desalination Efficiency Improvement Process based on (4) Leadership Efficacy to enable the work force toward excellence performance. This performance improvement approach resulted (as explained in section 3.5) in clear performance improvements that could be observed over a number of years. For Leadership Efficacy comprehension of human behavior and motivation is of utmost importance. In this context well-known socio-organizational theories have been applied and socio-technological models developed and applied as metaphors to understand human behavior and to explain the process of motivation and change to efficaciously deploy the work force toward performance improvement. The achieved organizational results with the application of these theoretical models are discussed and overviewed in this section.

The applied socio-organizational theories and models and their results

Douglas M. McGregor's *Theory Y*
For the important aspect of leadership's efficacy in the context of effective involvement and empowerment motivating the work force to perform out of the comfort zone, the leading principle is the inner conviction that work force negativism is circumstantially induced by fear for accountability and that given the right motivational condition the work force will outperform the comfort zone and seek responsibility and ownership and will self-promote a creative problem solving attitude and mindset to assure and endorse an excellent performing Desalination Department. This is actually in accordance with the manager's workers perception in *Theory Y of Douglas M. McGregor* [3.3].

George Elton Mayo's Hawthorn effect
After great effort a firm work relationship was built with the work force primarily due to the application of the guiding principle of sincere caring and attention. According to *George Elton Mayo's Hawthorn effect* paying attention to the work floor has demonstrated a performance increasing effect, showing the importance of the social aspect of job

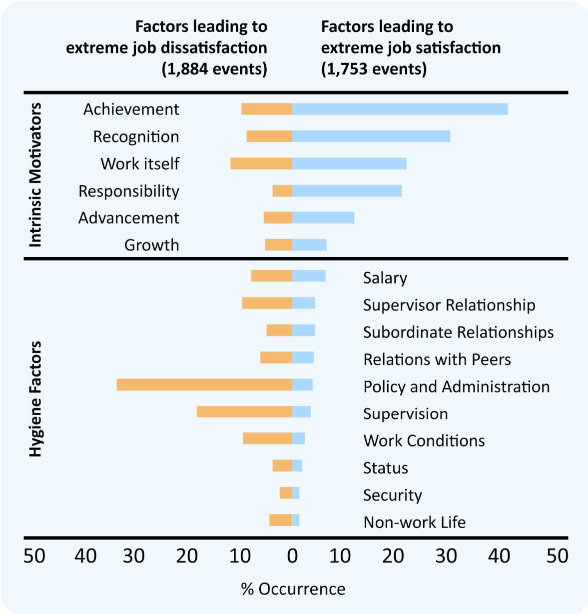
satisfaction [3.2].

Frederick I. Herzberg's Two Factor theory

The relationship was also further consolidated by the opportunity given to the work force in the context of efficacy through effective involvement and empowering to support the establishment of a motivated desalination work environment. The *Two Factor Theory of Frederick I. Herzberg* (as indicated in Table 3.2) distinguished in the context of employee's motivation two factors, the intrinsic motivators and hygiene factors as the principle causes of respectively job satisfaction and job dissatisfaction [3.11].

With respect to the intrinsic motivators, Achievement, Recognition, Work itself, Responsibility, Advancement and Growth are considered the factors that increase job satisfaction. At the Desalination Department, in the process of caring and relationship building with especially the negative oriented group mitigating the distrust in management it became clear that the most dissatisfying factors were lack of rewarding, recognition and acknowledgement for achievements. Aware of this fact a lot of attention is paid to recognize even the smallest successful steps toward personnel and technical performance improvements to increase work satisfaction and motivation. Also great effort is done based on the shared vision and mission to induce proudness for the desalination operation function. The work force was given the responsibility to create a motivated work environment and encouraged to participate in the development of standard operation procedure, to structure the work processes and to develop on the job desalination training, intuitively coping with the abovementioned intrinsic motivators according to the Two Factor Theory. Regarding the most effective job dissatisfying hygiene factors such as Policy and Administration, Supervisor-Subordinate-Peers relationship, Supervision and Work conditions, the introduced "Challenging but no violation of rules" of the Mahatma Gandhi leadership strategy and the established internal and interdepartmental teams and the Quality Management System and improved housekeeping and safety (as explained in the previous sections) had practically diminished these hygiene factors at the Desalination Department. In Table 3.2, the Intrinsic Motivators and the Hygiene Factors of the Two Factors Theory of Frederick I. Herzberg leading to job satisfaction and dissatisfaction are illustrated.

Table 3.2: The Satisfiers and Dissatisfiers of the Two Factor Theory [3.11]



The "Physics' right hand rule" metaphor

In the process of building an effective team to create a motivated work environment it was from the beginning obvious that the Desalination Department consists of very experienced and technical knowledgeable work floor personnel but unmotivated and due the occasion very resistive. It was also obvious that the operational personnel can be divided in three distinctive groups, a small group with a very positive mind set, a large group with neutral attitude and also a small group with a negative resistive attitude. The large group of neutral personnel can further be categorized as a "diffusive "group consisting of positive oriented personnel, a small neutral group and a group leaning to the negative attitude.

The first applied strategy achieving an effective performance team was based on the well-known effect of the "right hand rule" in physics when two forces acting perpendicular on each other in a plane causing a rotation, a resultant force will be created acting perpendicular on the subsequent plane in either upwards or downwards direction depending on the direction of rotation. The attempt to use the positive oriented small group as the motive force to pull the department to an efficient performance team duly failed because of the neglected attractive force and influence of the negative oriented small group, even though it is a common knowledge that peer pressure and the "tough guy" type attitude has initially a somewhat more attractive and influential force than the civilized church going or "good guy" type [3.15]. Realizing this influence of the negative group and the believe that negativism is possibly induced by dissatisfaction and by fear for responsibility and accountability the attention is put on this group to essentially give momentum to an effective performance team. Sincere attention and caring for this group in combination with the opportunity giving to challenge existing rules without violation catalyzed the regain of the mindset of a positive team spirit.

The Mahatma Gandhi leadership strategy

Intuitively the negative group characterized also as resistive, loud mouthed and due the occasion even boycotting rules were given the opportunity to challenge the company's rules and policy but to perform without violating any of them and to propose improvements of the household rules of the department in the frame work of and in compliance with the Company policy. Leadership is very crucial at this point in time for effective communication and caring to establish a firm work relationship with the work floor personnel to monitor and regulate this process of challenging the rules. It is worth mentioning that an important outcome of this strategy is the well desired comprehension of the company rules and policy by the work floor personnel [3.16]. This leadership strategy resulted to be very effective and is named after the historical personage Mahatma Gandhi who succeeded to bring down a whole empire without exerting any violence. The basic concept of *the Mahatma Gandhi leadership strategy* is illustrated in Figure 3.14.

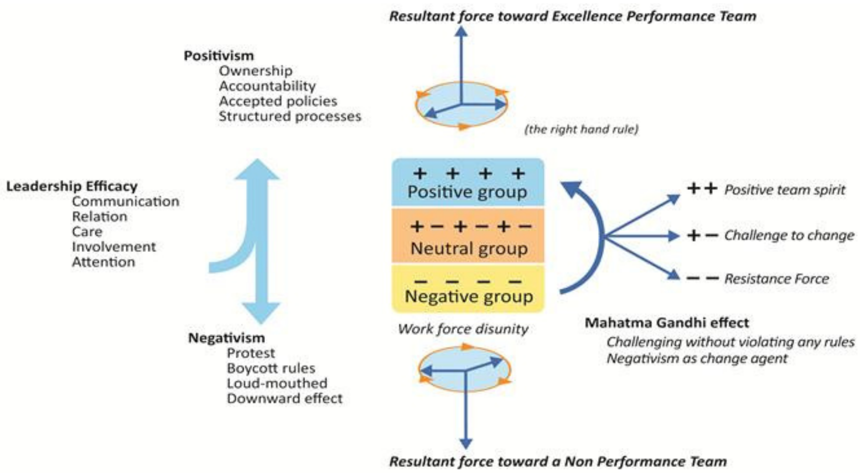


Figure 3.14: The Mahatma Gandhi Leadership strategy

As shown in Figure 3.14, the Mahatma Gandhi effect resulted in transforming the resistance force of the negative group into a positive team spirit to participate actively in the performance improvement process resulting in potential energy that gave the neutral group a spiral effect into an upward momentum toward an excellent performing team. In effect also goal directed well intended attention and caring had helped changing the mindset of the negative group. In this regard it is also worth mentioning the effectiveness of the developed socio-technological models comprehending human behavior, especially for this group that emphasized the importance of technical models and theory instead of socio-organizational and motivation theories.

Abraham H. Maslow's and the Desalination's Hierarchy of Needs

Before developing the socio-technological models, the starting point for motivation initiatives was initially based on the well-known *Hierarchy of Needs* by Abraham H. Maslow. According to this theory the basic psychological survival and safety needs should be first fulfilled before motivation for higher needs such as the social, esteem and self-development and actualization needs can be effective [3.17]. At the Desalination Department the basic needs of this model was interpreted for the work floor environment in the sense of developing a creative work environment and well organized on the job refreshment training and well defined and explained job descriptions for the operators for comprehension of the fundamental basics of seawater desalination and water post treatment. This was also the foundation of the classic scientific organization management theory of Frederick W. Taylor, however in this context only used as a basic motivational need. As already stated in the introduction of this chapter, according to these concepts productivity of laborers is simply optimized by having well defined job descriptions, standardized instructions and good payment. In this context stimulating initial motivation I decided to develop the Desalination's Hierarchy of Needs. In analogy with the Hierarchy of Needs of Abraham W. Maslow, the Desalination's Hierarchy of Needs consists of the need for operational Survival, Safety, Acceptance, Esteem and Desalination Excellence (as indicated in Figure 3.15) which are specified as follows:

The *Need for Survival* is characterized by attaining sound basic desalination knowledge in a motivated supporting and learning work environment directed by job entrancing leadership to endorse relationship and operational aptitude.

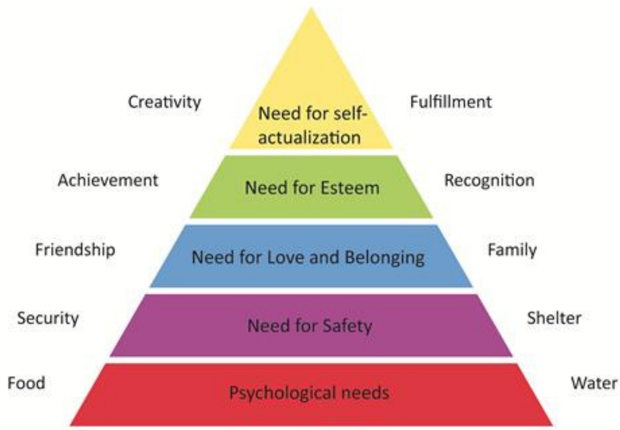
The *Need for Safety* is characterized by well-defined job description and structured work processes and advanced desalination refreshment training to endorse accountability and ownership.

The *Need for Acceptance* is mainly characterized by a firm internal and interdepartmental team to enforce fellowship and partnership.

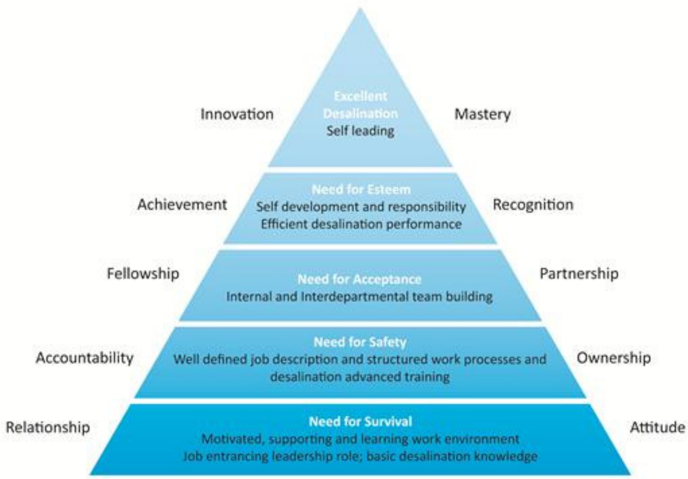
The *Need for Esteem* is characterized by reaching out to the level of self-development and responsibility to achieve the efficient desalination performance to stimulate internal and external recognition.

The *Need for Desalination Excellence* is characterized by personnel fulfillment by the performance level of self-leading to promote innovation and to endorse professionalism, the operational performance on mastery level.

Figure 3.15 illustrates the Hierarchy of Needs motivation model of Abraham H. Maslow [3.18] and the Desalination's Hierarchy of Needs.



a: Maslow's Hierarchy of Needs [3.18]



b: The Desalination's Hierarchy of Needs

Figure 3.15: The Hierarchical Needs motivation models

The Passion and Fear and Human Attitude models

It is worth mentioning that initially the resistance of the operational work force for outsiders to tell them how to perform their job and their conviction that the deficient performance is just a perception of Senior Management not knowing the desalination process and their sound believe in technical theories instead of any socio-organizational theories induced the development of the socio-technological models to enhance comprehension on the work floor level. Especially the positive oriented group was interested in understanding why people resist change and more importantly to understand why people fall back to the comfort zone mindset after initially shown interest to change. After initial doubt but steadily enabling practically simplified explanation of different human behavior and attitude on the work floor, the socio-technological models gained understanding and acceptance.

The Passion and Fear model was applied to explain the motivation and passion needed to perform out of the comfort zone practically dominated by fear and that fear can be considered not only as a negative effect but also as an useful regulator for uncontrolled changes. The chemical and quantum mechanical models enabled simple understanding of the ever experienced resistance for change, the fall back to the comfort zone and the culture oriented human attitude. This was also an important aspect for harmony on the work floor enabling the positive group to basically understand the attitude of the other negative oriented work floor group.

Another aspect of importance of the Passion and Fear model for motivation and the quantum mechanical metaphors describing human attitude is the enormous contribution to the understanding of the value of leadership's awareness of the tunneling effect to continuously motivate the work floor personnel to higher levels of performance especially after the first small successes of the socio-technical performance improvement program preventing falling back to the comfort zone of doing things the usual way.

A Leadership's motivational energy model

The importance of the necessary leadership's passionate energy for motivation can be explained and emphasized in the trend of the technological scientific models using the thermodynamic concept of the necessary amount of energy to change from one thermodynamic state with internal energy U_1, Volume V_1, entropy S_1 to another higher energy thermodynamic state with internal energy U_2, Volume V_2, entropy S_2 both states at the ambient pressure p and temperature T. According to the second law of thermodynamics the amount of energy in the form of heat is equal to the increase of internal energy and the amount of performed work as indicated in equation (3.4):

$$TS_2 - TS_1 = U_2 - U_1 + pV_2 - pV_1 \qquad (3.4)$$

In analogy with this thermodynamic concept the amount of motivational energy ME necessary in a given ambient of creative work environment to encourage the next higher level of performance is equal to the increase of internal passion IP and the passion to take action PA to perform, to exert the necessary work, out of the comfort zone reaching out to excellence performance as illustrated in equation (3.5):

$$ME_2 - ME_1 = IP_2 - IP_1 + PA_2 - PA_1 \tag{3.5}$$

Once again it is emphasized that this socio-technological analogy is only explanatory without the pretention of scientific correctness to emphasize the importance of the necessary leadership energetic perseverance to patiently and persistently passionate the personnel for sequentially small progressive improvements toward the envisioned Excellence Performance.

Awareness of the enormous amount of motivational leadership's energy necessary for personnel deployment toward excellence performance and the positive results of the application of the socio-technologic metaphoric models and the Mahatma Gandhi leadership strategy have laid the foundation for the development of the Efficacious Motivational Leadership approach. In the next section a preview is given of the future perspective of the Quality Management of the continuous performance improvement process in the context of the Efficacious Motivational Leadership approach.

3.7 The Efficacious Motivational Leadership approach; a future perspective

The Mahatma Gandhi effect resulted to be very effective as a leadership strategy for me transforming induced resistance and dissatisfaction characterizing human negativism into a positive team spirit toward an excellent performing team. This culture oriented participative leadership strategy was the cornerstone for the development of a novel leadership approach in the context of efficacious motivation inspiring the effective involvement and empowering of the work floor personnel, the human key pivot to reach out for continuous efficiency improvement in the costly desalination process. The guiding principle of this Efficacious Motivational Leadership (EML-) approach, on the contrary to modern time leadership strategies attaining followers, is inducing self-leadership to promote self-development of the work floor personnel emphasizing the conviction that motivated and knowledgeable work floor personnel, direct involved with the daily operation and maintenance of the desalination units are the imminent key efficiency improvement factor. Based on the desalination improvement steps as described in the previous section and the guiding principles of self-leadership and self-development the main aspects of the generalized EML approach are characterized as indicated in Figure 3.16.

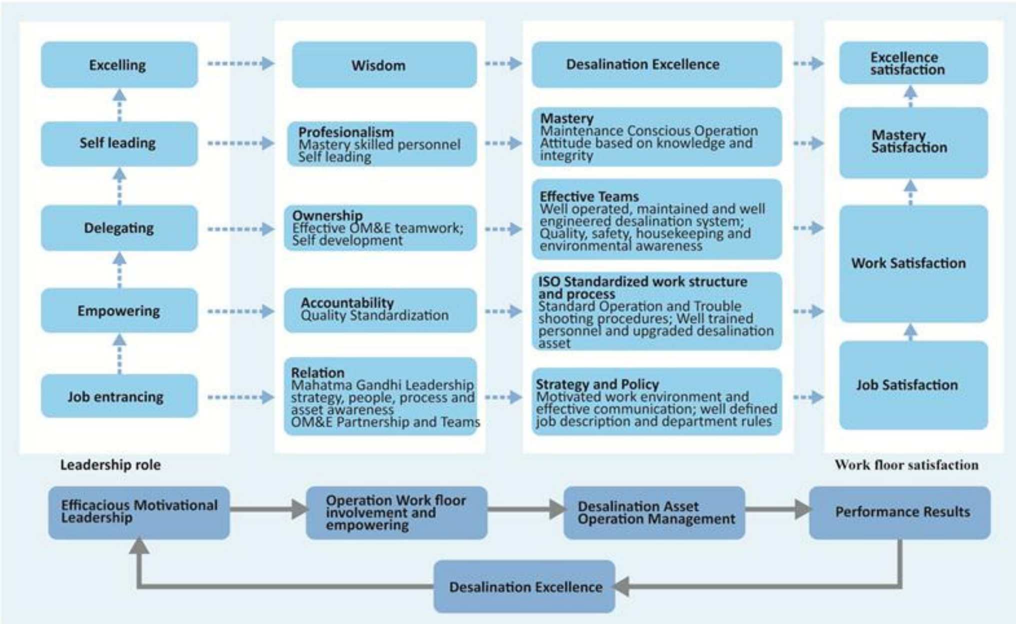


Figure 3.16: The Efficacious Motivational Leadership (EML-) approach

The Efficacious Motivational Leadership (EML-) approach is based, as mentioned before in the previous sections, on motivation in the context of efficacy through effectively involvement and empowerment of the work force to continuously improve the human and desalination assets performance. Toward excellence performance, the human performance transitional states are governed by increased relationship building, accountability, ownership and professionalism supported by the corresponding leadership roles of job entrancing, empowering, delegating, self-leading and excelling. The intended different human performance states are briefly summarized:

Relationship

Culture oriented participative leadership is practiced in the context of the Mahatma Gandhi leadership strategy to establish a firm relationship on work floor level based on caring, effective communication and credibility leading to a motivated creative work environment. With participation of the work floor personnel the efficiency improvement strategy, taking into account people, process and asset awareness, is defined developing the vision, mission of the department. An effective OM&E partnership is emphasized.
In this aspect the main objective is the leadership role of job entrancing, inducing proud toward Job Satisfaction for the operator function producing drinking water the most

important basic need for all living creature on Earth. A good explanation for comprehension of the operations job description is essential in this aspect to fortify that at the Desalination Department we stand for water excellence producing high quality drinking water at an optimal efficiency in a motivated creative work environment.

Accountability
In this aspect the main objective is to structure the whole work process preferably according to international standards such as the ISO 9001 to promote commitment, accountability, safety and good housekeeping. The main goal is that everyone knows exactly and is well trained and capacitated in the desalination process to do efficiently what has to be done attaining the level of Work Satisfaction through the leadership role of empowering. Work floor personnel involvement is crucial in this aspect to formalize the right way to do the job right.

Ownership
In this aspect of the EML-model the main objective is to create an effective team of the Desalination Department and an effective quality team with the supporting departments on line management and work floor level to obtain ownership enhancing Work Satisfaction through the delegating leadership role envisioning and promoting professionalism toward Mastery Satisfaction. The ultimate goal is well operated and maintained desalination units and well-engineered desalination process.

Professionalism
In this aspect of the EML-model the main objective is to reach the self-development level of the personnel to function on a high level of self-respect using and exploring their full potential attaining the level of mastery through the self-leading leadership role toward Mastery Satisfaction envisioning desalination excellence. Knowledge and integrity is the cornerstone of Mastery Satisfaction in this aspect.

Wisdom
In this aspect the main objective is to transform knowledge into wisdom reaching the highly desirable level of excellent operation performance where the necessary motivational energy to a next level of efficiency improvement is practically zero and where the continuous efficiency improvement process is spontaneously induced through the ultimate leadership role of excelling toward Excellence Satisfaction.

The developed EML's Pyramid of Excellence as promoted in the Desalination Department is illustrated in Figure 3.17.

Figure 3.17: The efficacious Motivational Leadership's Pyramid of Excellence

It is worth mentioning that in the EML approach next to the common Job- and Work Satisfaction, the Mastery- and the Excellence Satisfaction have been introduced to extend the essential human performance satisfaction. The situational role models of leadership have also been extended with job entrancing, self-leading and excelling leadership roles.

An introductory evaluation of the effectiveness of the generalized EML approach

The effectiveness of the EML approach has been further evaluated in an introductory study comparing the EML approach with existing and well known socio-organizational motivation theories such as the Hierarchy of Needs theory of Abraham H. Maslow, the ERG Theory of Clayton Alderfer, the Two-Factor theory of Frederick I. Herzberg, Theory of Needs of David McClellands, the Theory X and Y of Douglas M. McGregor, the Situational Leadership theory of Paul Hersey and Ken Blanchard and the Leadership theory of John C. Maxwell [3.16]. The results of this introductory evaluation are summarized in Table 3.3.

Table 3.3: Summary of the introductory comparative study [3.16]

EML comparison with Maslow, ERG, Two Factor and McClelland theories

Criteria	Maslow	ERG	Two Factor	McClelland	EML
Points of Focus	Human aspect (Individual)	Human aspect (Individual)	Individuals	Life expectation of individuals	Leaders and employees
Element of Motivation	Need of individual	Need of individual	Triggers for motivation	Need of individuals	Needs of employee and self-leadership
Element of Leadership					Induce self-leadership and self-development
Relevance to EML	Maslow provided the basis of EML (theory of needs)	ERG provided the basis of EML (theory of needs)	Basis of EML in ways of motivation	Proofs that life experience is crucial to enable self- leadership (the importance of self-knowledge)	
Recommended action	Find out what the needs are of every employee	Find out what the needs are of every employee	Find out the motivators and the de-motivators	Find out what the needs are of every employee	Find out what the needs are of the employee and induce self-leadership

Comparison of EML with X&Y, Maxwell and Situational theories

Criteria	X&Y	Maxwell	Situational	EML
Points of Focus	Believe of the leader	The leader (the key position)	Situation to be lead	Leaders and employees
Element of Motivation	Opinion toward the individual	The leadership skills		Needs of employee and self-leadership
Element of Leadership		Followers	Followers	Induce self- leadership and self- development
Relevance to EML	Provides additional knowledge to explore self-leadership	Basis for self-leadership, the 21 laws are applicable to the self-leadership concept of EML	Leadership style depends on situation, provides knowledge that every situation requires a specific leadership style	
Recommended action	Change the view of the leader	Learn and apply the 21 laws	Find out which leadership style is appropriate for the current situation	Find out what the needs are of the employee and induce self- leadership

The preliminary results of the introductory comparison of the different motivational theories as visualized in table 3.3, can be formulated as follows [3.16]:

- Most of the theories and models have the employees as the same point of focus indicating that the EML approach can be considered a motivational theory finding its validity and credibility in established and respected theories
- Most of the established motivational theories have as main element motivation of employees through satisfying their needs
- The EML has an aspect that the other theories do not address namely self-leadership and self-development instead of focusing on needs satisfaction.
- The EML catalyzes the inner passion of the employees to acknowledge their own needs and to strive to fulfill their own needs through self-leadership and self-knowledge reaching out to excellence
- The EML approach extends the performance satisfaction with Mastery Satisfaction and Excellence satisfaction through support of job entrancing, self-leading and excelling as main leadership roles

The EML approach is based on the Mahatma Gandhi leadership strategy using negativism as a change agent toward a mindset of positivism.

3.8 Conclusions

1. The introduction of a basic strategic socio-technical performance improvement program resulted to be effective in creating a motivated work climate promoting successful progressively stepwise improvements on different desalination operational and maintenance areas reaching out to continuously optimal desalination efficiency.
2. The Mahatma Gandhi leadership strategy based on the opportunity to challenge company rules and policy without violating any of them resulted to be an innovative effective motivation and empowering tool for especially personnel with induced negative attitude.
3. The Passion and Fear motivational change model and the Human Attitude models developed in analogy with technological models resulted to be simple socio-technical models to comprehend human attitude and for effective motivation to perform out of the comfort zone.
4. The Passion and Fear motivational change model has proved an important positive aspect of fear as a regulator next to the negative resistive aspect inhibiting the change process.
5. The Efficacious Motivational Leadership approach with the principle guidelines of inducing self-leadership and self-development resulted to be very effective to lead the work floor personnel to Mastery Satisfaction and Excellence Satisfaction.
6. Excellence, on the contrary with many common heard statements, is a reachable state of self-fulfillment with practically passionate energy approaching zero to reach out for the next level of excellent top operational performance as in accordance with the

spontaneous zero enthalpy transformation of the liquid phase into the gaseous phase at the critical point of a pure substance.

7. Efficacious Motivational Leadership is all about Passion and not about Position.

3.9 References

3.1. Moor de, W., Stress- en conflictmanagement, een constructivistische benadering, ISBN 90 313 1602 4, Bohn StafleuVan Loghum, Houten/Diegem, 1997.

3.2. Moor de, W., Arbeidsmotivatie als management-instrument, ISBN 90 313 1623 7, Bohn StafleuVan Loghum, Houten/Diegem, 1993.

3.3. http://en.wikipedia.org/wiki/Theory_Y

3.4. Fiedler, F. E., A Theory of Leadership Effectiveness, McGraw-Hill, New York, 1967.

3.5. Maxwell, J. C., Developing the Leader within you, Thomas Nelson Inc., Nashville, USA. 1993.

3.6. Marchena, F. A., Alberts, V. A., et al., A Strategic Quality Program: Basic Efficiency control for Brine Recirculating MSF Desalination Units, Caribbean Conference 2002, From Seawater to Drinking Water, Oranjestad Aruba, June 19-21.

3.7. Moore, W. J., Physical Chemistry, ISBN 0 582 44234 6, Lowe & Brydone Ltd., Thetford, Norfolk, UK, 1974.

3.8. Levenspiel, O., Chemical Reaction Engineering, John Wiley & Sons Inc., New York, USA, 1972.

3.9. Cameron, K.S., Quinn, R. E., Diagnosing and Changing Organizational Culture, Jossey-Bass, A Wiley Imprint, San Francisco CA, USA, 2006.

3.10. Alonso, F., Finn, E. J., Quantumfysica, ISBN 90 6674 603 3, Delta Press BV, Oudewater, The Netherlands, 1983.

3.11. Herzberg, F. E., Mausner, B., The Motivation to Work, John Wiley & Sons Inc., New York, 1959.

3.12. Temmink, A., A study concerning the relationship between the level of education of operational personnel employed by Dutch incineration plants and their amount of absence through sickness, dissertation, Southern California University, Santa Ana, Ca. USA, 1999.

3.13. Marchena, F. A., Efficacy Oriented Operation and Maintenance: An Important Step Toward Sustainable Conventional and Green Desalination Technology, Our Future with Green Energy, Oranjestad, Aruba, October 2010.

3.14. Quijada, A. Y., The Economical Contribution of W.E.B. Aruba N.V., Internship Report, University of Aruba, Oranjestad, Aruba, December 22, 2010.

3.15. Jaffe, R., No Bwoy Cyaan Violate: Crime, Alternative Governance and Popular Culture in Urban Jamaica, Presentation at the University of Aruba, May 2010.

3.16. Quintero Molina, C., Scrutinizing the Efficacious Motivational Leadership Model. BSc Thesis, University of Aruba, Oranjestad, Aruba, June 28, 2010.

3.17. Maslow, A. H., A Theory of Human Motivation, Psychological Review, 50, 370-396, 1943.
3.18. http://www.squidoo.com/educational-needs-what-s-really-important?utm_source=google&utm_medium=imgres&utm_campaign=framebuster

Chapter 4

A novel biochemical treatment to control marine biofouling in seawater desalination at W.E.B. Aruba N.V.

Marine ecosystem: a natural elegance, a desalination nuisance

Chapter 4

A novel biochemical treatment to control marine biofouling in seawater desalination at W.E.B. Aruba N.V.

Table of Contents:

Abstract

Throughout the practically eighty years of seawater desalination activities at W.E.B. Aruba N.V. heavy biofouling was always experienced in the intake systems and the condensers of the seawater evaporators. Macro biofouling especially barnacles were obstructing cooling seawater flow through the condenser tubes and marine biofilms on the heat transfer surfaces were reducing heat transfer consequently decaying production and efficiency of the MSF evaporators. Practically every three months an evaporator has to be shut down for condenser cleaning to increase production and efficiency. In 1999 a six month trial has been carried out to evaluate a novel non-oxidizing biofouling treatment based on the quaternary amines technology to control biofouling. Quaternary amines are cationic surfactants with an excellent biocidal efficacy against mollusk bio-organism. The objective of the trial is to prolong stable operation of the evaporators for at least one year without condenser cleaning maintaining at least the nominal production capacity of 6000 m^3/day and a performance ratio above 9. 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. Further on, the subject MSF evaporator, Aqua Chem#5, stayed for 15 months after the initial dosing of the non-oxidizing mulluscicide Spectrus CT 1300™, formerly named Clam Trol CT 2™, in operation without the necessity for condenser cleaning. Different visual inspections during this period showed the condenser in excellent clean condition without any form of macro biofouling. Subsequently the optimal temperature difference of the condenser indicated practically no micro biofouling on the heat transfer surfaces.
Severe membrane biofouling is also experienced with the new SWRO membrane technology affecting production and efficiency. In cooperation with the manufacturer, different membrane cleaning procedures have been applied to mitigate membrane biofouling.
A novel osmotic membrane cleaning and sanitation method is developed and applied effectively increasing production and efficiency above design values.

4.1 Introduction

Thermal and membrane seawater desalination for the production of fresh water is despite all innovations and improvements up to the moment still a very costly process. Efficient operation is therefore an important factor to minimize desalination cost. Besides the human aspect as discussed in detail in Chapter 3 the physicochemical aspect is another very import factor greatly influencing efficiency. It is practically impossible for efficient and effective thermal and membrane seawater desalination without proper chemicals. The main physicochemical based problems encountered in seawater desalination are foaming, scale formation, corrosion and marine biofouling on the heat transfer surfaces in MSF evaporators and on the SWRO membrane surfaces.

This chapter deals with the mere important first chemical process encounter in all desalination processes, the pretreatment of the seawater feed to improve its biological quality mitigating the macro- and micro marine biofouling potential. Especially for the membrane technology inadequate physicochemical pretreatment of the seawater feed is disastrous for stable operation causing fouling or even permanent membrane damage in a very short operation period of time as a consequence [4.1].

Macro biofouling by clams, mussels, barnacles and micro biofouling by film forming micro-organisms of industrial cooling water systems is a global problem of major proportions causing significant loss of unit availability in electrical utilities and desalination units. Various physical and chemical control measures have been employed to cope with macrofouling. These include thermal shocking applying recycling of high temperature cooling water, antifouling coatings, physical scraping and removal, and chlorination. All of these methods have been effective in certain applications, but chlorination and other chemical control measures are more flexible and widely practiced globally.

Chlorine, bromine and other oxidizing agents are the most commonly applied biocides for control of slime-forming microorganisms in industrial cooling systems. However, the effectiveness of oxidizing biocides on mollusks and other macro-fouling organisms is limited because these organisms sense the strong chemical and minimize exposure by closing their shells and reducing siphoning activity. Consequently, continuous or semi-continuous applications of oxidizing biocides for several days of weeks is required to provide effective control of macrofouling organisms [4.5, 4.6].

In 1985, during a screening of established anti-microbial products for efficacy against Asiatic clams, Betz's researchers have by serendipity discovered that low concentrations of certain amines remained substantially undetected by the clams. A comparatively short exposure of only a few hours was hundred percent effective on Asiatic clams. Subsequent testing determined that these amines were equally effective on several species of freshwater and seawater mollusks including zebra mussels, blue mussels, green mussels, barnacles, and other macrofouling organisms.

Additional studies were conducted to determine the most suitable amine based on environmental profile, selectivity to the target fouling organism and cost of use. The best material was determined to be a quaternary amine commonly referred to in the industry as ADBAC*, n-alkyldimethylbenzylammonium chloride*.
At W.E.B. Aruba N.V., as explained in Chapter 2, only in the brief period of the aluminum Aquanova MSF evaporators, dosing of chlorine gas from one ton pressurized liquid chlorine containers, was applied for the control of marine biofouling. At the Aqua Chem MSF evaporators the use of chlorination was discouraged by the manufacturer because of chlorine induced corrosion of metals such as copper nickel alloys and vent side material corrosion. The actual corroding compounds are the bromine compounds formed by the oxidation reaction of chlorine with the bromide ions naturally present in seawater attacking virtually all metals [4.7]. The Desalination Department has experienced a lot of problems with the chlorination application due to frequent leakages of chlorine gas and damaged one ton containers [4.8].
After a successful trial and application of an oxidizing biocide treatment, based on the *dibromo hydantion* technology as proposed in 1996 to control biofouling in the condensers of the steam turbines of the Power Production Facility, W.E.B. Aruba N.V.'s management was convinced to approve a trial with the non-oxidizing biocide technology at the MSF evaporators. The objective of this trial is to extend the three months frequency of condenser cleaning of the MSF evaporators to at least one year maintaining yearly average production of minimum 6,000 m^3/day and a performance ratio, the ratio of the amount of produced distillate and that of the consumed low pressure steam, of above 9. The design performance ratio of the MSF evaporators is 10.
After an introductory elaboration on the biofouling process and its control in section 4.2, an in depth description of the successful trial of the novel non-oxidizing biofouling treatment is given in section 4.3. The application of a surface active non-oxidizing biocicide is most challenging under vacuum condition in an MSF evaporator. It is worth mentioning that this innovative technology was evaluated worldwide for the first time ever in any desalination process for the disinfecting and controlling of marine biological growth in the intake system and condensers of a MSF evaporator at W.E.B. Aruba N.V. in 1999.
Since the first startup of the SWRO technology severe biofouling of the membranes was experienced causing unstable operation and low efficiency and availability not complying with the design operation conditions. Different membrane cleaning procedures have been applied in cooperation with the manufacturer to mitigate membrane biofouling, however with little success.
In the further attempt to solve the biofouling problem a novel osmotic membrane cleaning procedure was developed that resulted to be very effective increasing the SWRO production and efficiency above the design values. In section 4.4 these biofouling mitigating efforts and the preliminary biofouling potential studies using a biofilm monitor and a membrane fouling

monitoring system will be illustrated. The patented novel osmotic membrane cleaning procedure will be further described in details in Chapter 9 of this dissertation.

4.2 The biofouling process in seawater desalination

Biofouling organisms

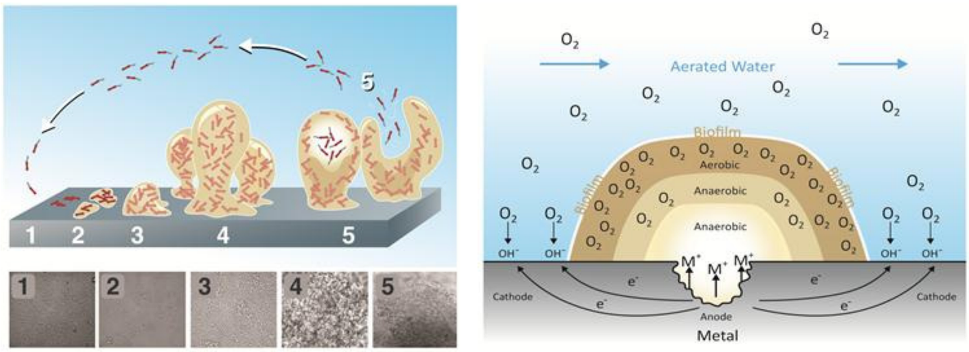
Deposits and corrosion problems resulting from microorganism are common occurrences in the use of seawater or fresh water for industrial purposes especially for process cooling which represents the majority of all industrial uses of water. When deposits are primarily the result of microorganism the problem is referred to as biological fouling or biofouling. When corrosion is primarily the results of microorganism it is referred to as *Microbiologically Induced Corrosion* (MIC). Cooling water systems provide almost an ideal environment for the growth of macro- and microorganism. They offer plenty of water, good aeration and a continuous supply of nutrients such as inorganic and organic compounds added as chemical control agents directly to the system to control corrosion, foaming and scaling. The intake screens also create a predator-free environment. Macro- and micro biofouling of desalination cooling seawater systems by clams, mussels, barnacles and micro biofouling on the membranes of SWRO desalination units are globally a major problem hampering efficiency and availability of thermal and membrane desalination units. Microorganism present in cooling water can be categorized as planktonic which are dispersed in the cooling water and sessile microorganism which are attached on the surfaces forming biofilm layers. These biofilm layers consist of a gelatinous matrix where the sessile microorganisms are embedded together with inorganic substances as clay, silt, precipitated salts and corrosion product [4.9].

The biofouling mechanism

A solid surface exposed to water in an open atmosphere becomes contaminated with microorganism and organic compounds in a relatively short period of time. The development of a biofilm on a surface is considered to be a multistage process involving the following major steps [4.10]:

- Formation of an organic conditioning film on the surface by adsorption of organic molecules
- Transport of microorganism from the water to the solid surface
- Adhesion of microorganism at the surface water interface
- Relocation of the attached cells and production of exopolymers, extra cellular polysaccharides (ECP)
- Detachment of parts of the biofilm as a consequence of shear stress

Once a mature biofilm is formed on a metal surface, Microbiologically Induced Corrosion (MIC) of the metal can be initiated reducing equipment life time. The mechanism of this under deposit corrosion process is primarily differential aeration cells (as indicated in Figure 4.1) formed by non-uniform biofilms where anaerobic areas in the biofilm are depleted of oxygen relative to the surrounding non-colonized areas of the surface, causing a difference in electrical potential inducing corrosion currents [4.12].
Figure 4.1 illustrates a schematically representation of the biofilm formation and biofilm corrosion [4.11, 4.12].



Biofilm formation Microbiological Induced Corrosion

Figure 4.1: The mechanism of biofilm formation on a substrate [4.11, 4.12]

There is considerable EPS formed, such that in mature biofilm less than 10% of its dry weight is in the form of microorganism cells. As a biofilm matures it will have a species-diversity. Some of the physical and chemical aspects that affect the development of the biofilm are the following:

- The ambient and system temperature
- Water flow rate (turbulence) past the solid surface
- Nutrient availability
- Roughness of the solid surface
- pH of the water
- Particulate matter in the water

Planktonic microorganism, while not contributing to deposits or corrosion can pose health problem if pathogenic species are involved (e.g. occurrence of Legionella in the water bulk) or pose odor problem if odor producing microorganisms are present [4.10].
Of course, the problem associated with planktonic microorganism can also occur in biofilms. Most microbiological problems associated with industrial process water systems are caused by a mixed group of microscopic plants or plantlike organism referred to as micro-flora. Very rarely, a single type of microorganism is completely responsible for widespread operational

problems in a system. The type of microorganisms or micro-flora responsible for creating problems in industrial water includes algae, bacteria and fungi. In general bacteria are the greatest biofouling problem in water systems and are most apparent on heat transfer surfaces.
Anaerobic bacteria such as *Sulfur Reducing Bacteria* (SRB) can grow under deposits leading to severe corrosion related problems [4.13].
Macro biofouling is caused primarily by juvenile mollusks and larvae that are small enough to pass through cooling water intake screens. Once inside they settle in low flow areas. They attain adult size within a few months and are then transported further into the cooling system. It is this transport of adult sized mollusks that causes the chronic macro biofouling problems that threaten safety, operation, performance and systems availability [4.2]. In the condenser of the MSF evaporators the most experienced macro biofouling plugging condensers tubes are barnacles as shown in Figure 4.2.

Condenser Aqua Chem #6

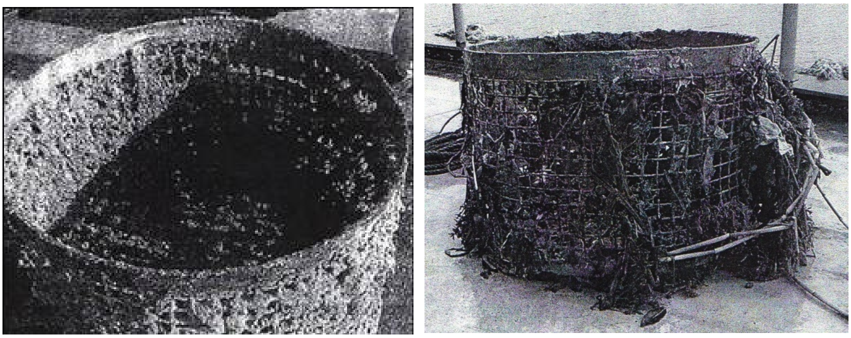
Condenser Aqua Chem #3

Figure 4.2: Barnacles plugging condensers of the MSF evaporators at W.E.B. Aruba N.V. after three months of operation

Physical and mechanical biofouling controlling measures

As already mentioned above many physical and mechanical measures have been applied to control macro- and micro biofouling including physical removal, scraping and mechanical screens with the capability to effectively keeping full sized mollusks outside the intake system. Some large utilities also have the possibility to recycle high temperature cooling water successfully to control biofouling. All these measures have the disadvantage of being corrective and do not actually prevent macro biofouling. Practically all intake systems have stationary or rotating screens to keep fish or full sized macro-organisms outside the intake basin but are inadequate to keep larvae or juvenile mollusks and barnacles to pass through mesh openings of the intake screens. Once inside the intake basin they settle down in low flow areas and proliferate because of an ideal predator-free environment with sufficient oxygen and nutrients.
At W.E.B. Aruba N.V. the mechanical biofouling control measure consist of two stationary screens with mesh sizes of 20 mm and 10 mm installed in front of the basins of the seawater

intake pumps of the MSF evaporators and the SWRO desalination unit. As a further precaution for incoming debris and large macrofouling organisms the bowl assemblies of the intake pumps of the MSF evaporators are equipped with a screening basket with a mesh size of 20 mm [4.14]. In Figure 4.3 the screening basket fouled with seawater macro-organism and course debris is shown.



During normal operation After hurricane Lenny in 1999

Figure 4.3: The screening basket of the intake pumps fouled with microorganism and course debris

The stationary intake screens and the screening baskets are cleaned by hydro blasting. In Figure 4.4 the hydro-blast cleaning process of the stationary screen of a MSF evaporator intake system is shown. The surfaces of the intake structure are vacuum cleaned by divers. The macrofouling, especially barnacles blocking the tube sheet of the condensers as shown in Figure 4.2, are manually removed by maintenance personnel and to remove microfouling on the inner surfaces of the tubes cleaning by bullet shooting or hydro lacing are practiced.

Biofouled intake screen   Hydro blasting intake screen   Cleaned intake screen

Figure 4.4: An intake stationary screen before, during and after hydro blast cleaning

An alternative continuous physical cleaning system is the on line sponge ball cleaning, also known as the Taprogge system, with excellent effect increasing production and performance of MSF evaporators, however the retrofit in existing production units is a big disadvantage [4.15].

Biochemical biofouling controlling systems:

The current practice in controlling microbiological water problems is to use a microbicide, also called a biocide. Microbicides kill microorganism responsible for microbiological problems and are generally classified as oxidizing or non-oxidizing biochemicals. Oxidizing microbicides are capable of undergoing oxidative reactions with organic molecules and include halogens (e.g. chloride, bromide and iodine) and ozone. The latter will not be further discussed in this section.

Oxidizing biocides

Chlorine is by far the most widely used oxidizing biocide, particularly in large volume cooling water systems. Chlorine is so widely used because it has a relatively broad spectrum of activity and is relatively low in cost. For economic reasons chlorine is added to the water as a gas which results in the formation of two acids, hypochlorous (HClO) and hydrochloric (HCl). The hypochlorous acid further dissociates according to the reversible reaction to produce hypochlorite ion (ClO^-) as indicating in the subsequent chemical hydrolysis and dissociation reaction equations:

$$Cl_2 + H_20 \Leftrightarrow HClO + HCl \qquad (4.1)$$

$$HClO + H_20 <=> ClO^- + H_3O^+ \quad (4.2)$$

It is the amount of the hypochlorous acid not the hypochlorite ion that determines the biocidal activity. The ratio of the hypochlorous acid and hypochlorite ion is important because the biocidal effect of hypochlorous acid is 40 to 80% higher than the hypochlorite ion [4.10]. The biocidal activity of hypochlorous acid is very pH sensitive and decrease rapidly for pH value over 7. When chlorine is added to water system it will react with different organic material and inorganic compounds as ammonia, ferrous- and sulfate ions. Under these circumstances chlorine is consumed and is no longer effective as a biocide. For this reasons sufficient chlorine must be added to satisfy this chlorine demand and leave a residual that will perform the biocidal function. In practice, however, even maintaining effective chlorine residual concentration in a water system cannot be relied upon to prevent biofilm formation. Indeed the level of chlorine residual has to be maintained to reasonable low level such as 0.5 ppm, since higher values will increase corrosion rates. Environmental and health issues relating to chlorine have put a lot of constrains on the application of chlorine as a biocide, as will be explained more in details in Chapter 9. There is considerable concern today regarding the long lasting toxicity of compounds such as trihalomethanes that are formed as disinfection byproducts when chlorine reacts with organic compounds typically present in water.

Furthermore mollusks have chemoreceptor giving them the ability to rapidly sense chlorine and avoid consumption of the biocide by closing their shells, making intermittent chlorination ineffective for the biological control of mollusk infestations in water systems. For chlorination to be effective continuous dosing for several days or weeks is necessary to starve these macro-organisms.

Non-oxidizing biocides

Non-oxidizing biocides on the other hand remain undetected by mollusks so making them very effective as a biocide for biological control for seawater intake systems.

The Betz research as described by Post and Marchena [4.3] leading to the development of an innovative non oxidizing barnaclecide for usage in MSF evaporators for the mitigation of macro and micro biofouling will be discussed in this section. With the mounting pressures on the use of chlorine, there are considerable activities in exploring alternative oxidizing microbiocides such as bromine, chlorine dioxide and ozone. In the late 1980s research also concentrated on the evaluation of commonly used non-oxidizing components such as amines and ammonium compounds, organo sulfer compounds, thiocyanates, isothiazoles, organohalogen gluteraldehydes.

In 1985, during a screening of established anti-microbial products for efficacy against Asiatic clams, Betz's researchers observed that low concentrations of certain amines remained substantially undetected by the clams. A comparatively short exposure period of only a few hours was 100% effective on Asiatic Clams. Subsequent testing determined that these amines were equally effective on several other species of freshwater and seawater mollusks including zebra mussels, blue mussels, green mussels, barnacles and other macrofouling organisms. Additional studies were conducted by BetzDearborn researchers to determine the most suitable amine based biocides on environmental profile, selectivity to the target fouling organism and cost of use. The best material was determined to be a quaternary amine commonly referred to as ADBAC, *n-alkyldimethylbenzyl ammonium chloride*. The effectiveness of brief exposures of ADBAC against several common mollusks is shown in Figure 4.5.

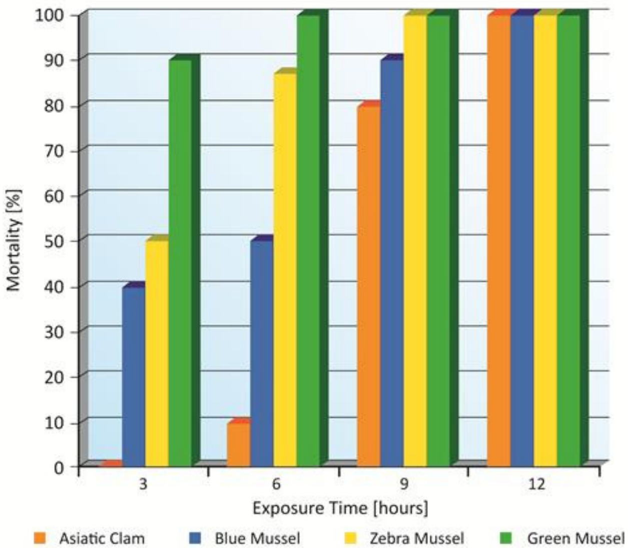


Figure 4.5: Dose-response data for 2 mg/L ADBAC against mollusks at 25 ^{o}C [4.3]

The ability to control mollusks using only short exposure gives rise to a number of advantages over chlorine and other oxidizers.
These include:

- Less chemical is released to the environment
- Chemical delivery and handling are substantially reduced
- Environmental impact is minimized, especially on entrained plankton
- Product concentrations are easily monitored and verified during the entire application
- Costs are lower since far less chemical is required

Cost savings and environmental benefits are particularly significant when the fast-acting characteristics of ADBAC can be used to treat a portion of the system “off line” in a non-flowing condition. This is often the case for power plants and industrial facilities, where one pump can be taken out of service overnight.

Biological mechanism

The physiological effects of these amines on mollusks were examined by Bidwell and his colleagues [4.16]. They found that the amines interfered with mollusks ability to osmoregulate, to control the salt balance between their tissues and the surrounding water. This osmoregulatory disfunction caused the water content of the mollusks tissues to increase sharply after exposure to sublethal concentrations as shown in Figure 4.6.

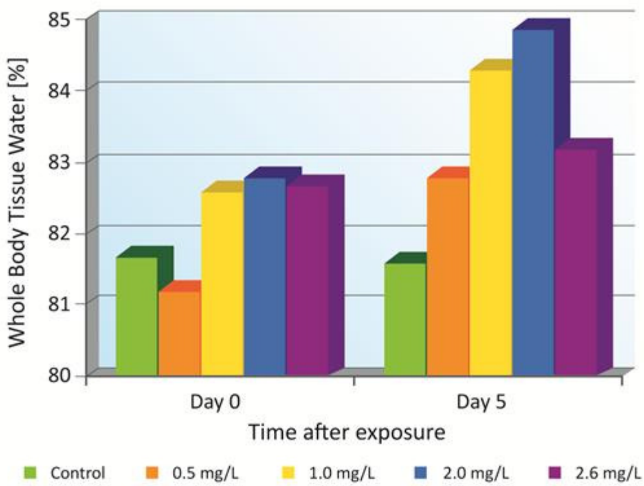


Figure 4.6: Asiatic clam tissue water content following a 24-hr exposure to fatty amine blend at 15 ^{o}C (Day 0 data at end of 24-hr exposure) [4.3]

The amines were also found to cause a reduction in tissue glycogen levels as illustrated in Figure 4.7.

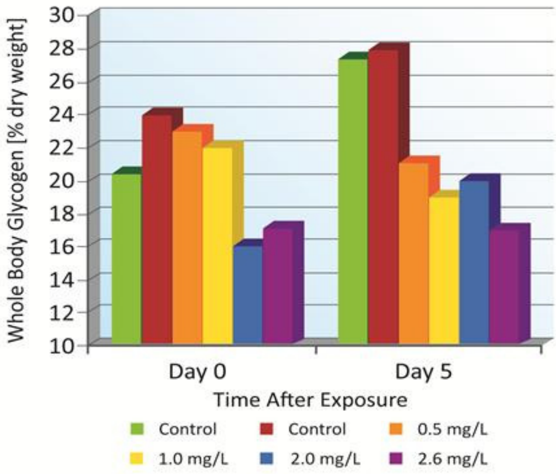


Figure 4.7: Asiatic clam glycogen levels following a 24-hr exposure to fatty amine blend at 15 °C (Day 0 data at end of 24-hr exposure) [4.3]

A decrease in glycogen content corresponds to a reduction in energy stored by the organism. The researchers found similar glycogen and tissue water responses with the zebra mussel. Based on common understanding of the structure of these compounds and their interaction with microbial cells, it is likely that they adsorb onto cell membranes and affect the cells' ability to regulate ion transport across the membrane, which is critical to osmotic balance. The increase in tissue water content causes the soft tissue to swell, making it difficult for the mollusks to close their shells and avoid contact. Observations of exposed Asiatic clams show that their fleshy foot swells to such an extent that it becomes immobilized. Another interesting finding from that study was that the mortality of the mollusks was not increased by pegging their shells open. Pegging the shells open should have caused a sharp increase in effectiveness of non-oxidizing biocides because the mollusks cannot close their shell and avoid contact. Although these amines are not readily detected by the mollusks, pegging their shells open produced no increase in mortality, and in fact decreased mortality by approximately 20%, probably because the peg interfered with normal siphoning.

Selectivity to the target organism

Perhaps the most remarkable aspect of ADBAC is its selectivity to the target organism, as illustrated in the photograph in Figure 4.8. It is possible to place rainbow trout fry and adult zebra mussels in the same aquarium, dose the aquarium with ADBAC, and produce 100% mortality on the zebra mussels without harming the trout. By contrast, chlorine would be lethal to the tout fry at 1/100 the dose that would be effective on the zebra mussel.

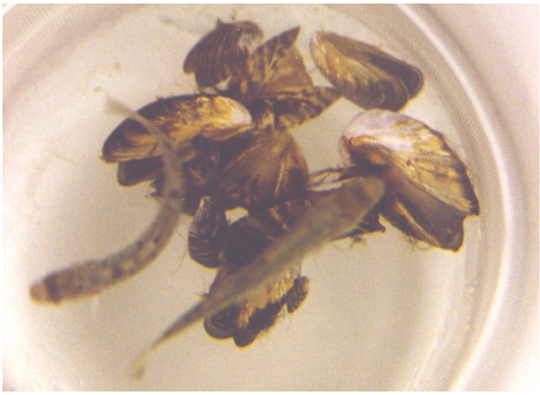
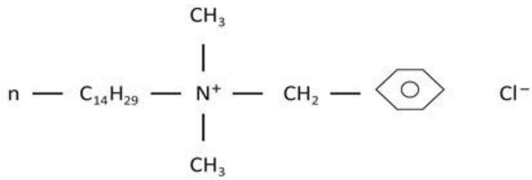


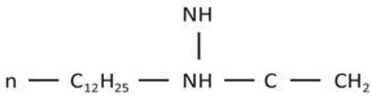
Figure 4.8: Photograph illustrating the selectivity of ADBAC producing 100% mortality on zebra mussels without harming trout fry (0.5 mg/L ADBAC, 96-hr, 65 °F) [4.3]

ADBAC-History and uses

ADBAC is a familiar chemical compound which has been used in broad spectrum of household and industrial applications for more than 50 years, with current annual consumption estimated at 40-50 million pounds in the United States alone. ADBAC is one of a family of compounds known as quaternary amines. In chemistry the term “quaternary” refers to the amine nitrogen being attached to four alkyl groups. ADBAC with an alkyl chain of approximately 18 carbons is often referred to as “stearalkonium” chloride and is the principle ingredient in many hair conditioners and fabric softeners. In these applications the amine’s cationic charge is used to neutralize the naturally occurring negative charges on hair and fabric that are responsible for combing difficulties and “static cling”. ADBAC with an alkyl chain length of predominantly 12-14 carbons is often referred to as “benzylalkonium chloride” and is widely used as a preservative in a variety of personal care products including eye drops and nasal sprays. It is the active ingredient in many household disinfectants and in antiseptics for direct application to cuts and scratches at a concentration approximately 500 times higher than that required for effective macro-fouling control programs. ADBAC with an alkyl chain length of 12-16 carbons has been used to control microbiological slime and algae in cooling towers since the mid-1950s. Today, the largest anti-microbial usage for ADBAC is as a swimming pool algaecide, where the compound has been in use for more than thirty years. Effective dosages in swimming pools are the same as those required for mollusks control, normally in the range of 1 to 3 ppm. The formulation initially introduced for mollusks control was a blend of the two amines ADBAC and *n-dodecylguanidine hydrochloride* (DGH) under the trade name Clam Trol CT 1™ [4.17]. The chemical structures of these cationic surfactants are given in Figure 4.9.



ADBAC (n-alkyl dimethylbenzyl ammonium chloride)



DGH (n-dodecylguanidine hydrochloride)

Figure 4.9: The chemical structure of ADBAC and DGH [4.17]

After conducting exhaustive environmental studies, Betz obtained broad USEPA registrations to use ADBAC for macrofouling control in once through cooling systems and auxiliary water and waste water treatment systems under the registered name of Clam Trol ™ and Spectrus ™ 1300. Betz first commercially applied Clam Trol ™ for macrofouling control is at an electric power station in southern United States in the spring of 1986. Commercial application to control the growth of blue mussels (*Mytilus edulis*) along the Northeast coast of the United States followed in 1989. The product was applied successfully against the green mussel (*Perna viridis*) in 1992, shortly after they were first sighted on Trinidad in North America. As requested, following several additional studies Betz received NSF certification to use Clam Trol CT-2™, consisting of alone ADBAC as the biocide ingredient, in potable water system intakes and desalination facilities producing potable water in 1997. Clam Trol CT-2™ was first applied to control macrofouling in the MSF evaporator Aqua Chem#5 at W.E.B. Aruba N.V. in the summer of 1999. The product was successfully applied against barnacles (*Chtmamalus stellatus*) infestation in the MSF evaporators' condensers.

Environmental studies; biocide effectiveness of Clam Trol CT-2™

The tables 4.1 and 4.2 show the effect of Clam Trol CT-2™ (Spectrus CT 1300 ™) on common target and non-target test organisms. The LC_{50} *concentrations* (the Lethal Concentration with 50% mortality of exposed species) for target and non-target species are in a similar range. However, most standard non-target test species data are conducted using a 96-hour exposure. The contact time required to treat most mussels is much shorter than 96-hours. The Clam Trol CT-2 ™ can usually be applied without risk to fish, taken into consideration: (1) the short exposures required to control macro-fouling species; (2) the dilution from untreated flows from other plant before discharge to the sea; and (3) its short half-life (as indicated in Figure 4. 1) in the seawater environment. By contrast, chlorine and other oxidizing compounds are considerably more toxic to fish than to mussels and require much longer exposure periods.

Table 4.1: Acute Effect (LC_{50}) of Clam Trol CT-2 ™ to Common Target Test Species [4.3]

Common Target Species	Exposure Hours	Clam Trol (LC_{50}-mg/L)
Green mussel *(Perna viridis)*	3-hr	<2.0
Blue mussel *(Mytilus edulis)*	12-hr	<3.0
Zebra mussel *(Dreissena polymorpha)*	6-hr	2.0
Asiatic clam *(Corbicula fluminea)*	12-hr	3.5

Table 4.2: Acute Effect (LC_{50}) of Clam Trol CT-2 ™ to Common Non-Target Test Species [4.3]

Common Non-Target Test Species	Exposure Hours	Clam Trol (LC_{50}-mg/L)
Mysid shrimp *(Mysidopsis bahia)*	6-hr	3.6
Inland silverside *(Menidia beryllina)*	24-hr	1.92
Sheepshead minnow *(Cyprinodon variegatis)*	96-hr	2.9
Rainbow trout *(Oncorhynchus mykis)*	96-hr	1.8
Fathead minnow *(Pimephales promelas)*	96-hr	1.4
Water flea *(Ceriodaphnia dubia)*	48-hr	0.35
Annelid (worm) *(Physa sp.)*	96-hr	1.5

Environmental studies; biodegradability of Clam Trol CT-2™

Clam Trol CT-2 ™ is rapidly adsorbed by naturally occurring silt, suspended solids and removed from the water column. Table 4.3 presents the results of a 1997 study of Betz sponsored by Rohm and Haas showing 91% adsorption of a low level of the active ingredient after a 1 minute exposure to river silt.

Table 4.3: Adsorption of Clam Trol CT-2™ active by various materials [4.3]

Adsorbant	Contact Time (hours)	Initial concentration (mg/L)	Final Concentration (mg/L)	% Adsorbed
River Silt	0.017	0.088	0.007	91
Aquatic Plant *(Azolla aroliniana)*	24	0.070	0.01	86
Alum Floc	0.5	0.118	0.0	100

Figure 4.10 shows that Clam Trol has a half-life of less than four hours when applied to a cooling tower system with the blow down closed.

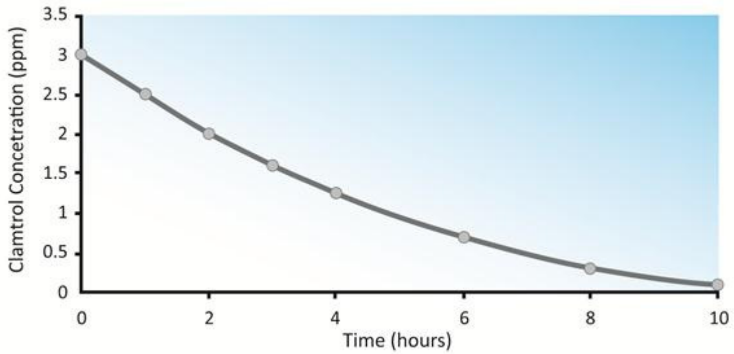


Figure 4.10: Half-life of Clam Trol in a cooling tower with blow down closed [4.3]

In Figure 4.11, the analyses performed on request at the Laboratory of W.E.B. Aruba N.V. of the decay of the Clam Trol CT-2^{TM} in the seawater feed flow, the recirculation brine flow and the blow down flow is shown for an eight hour time elapse. In a cooling tower due to suspended particulates the decay is much faster than in MSF seawater flows.

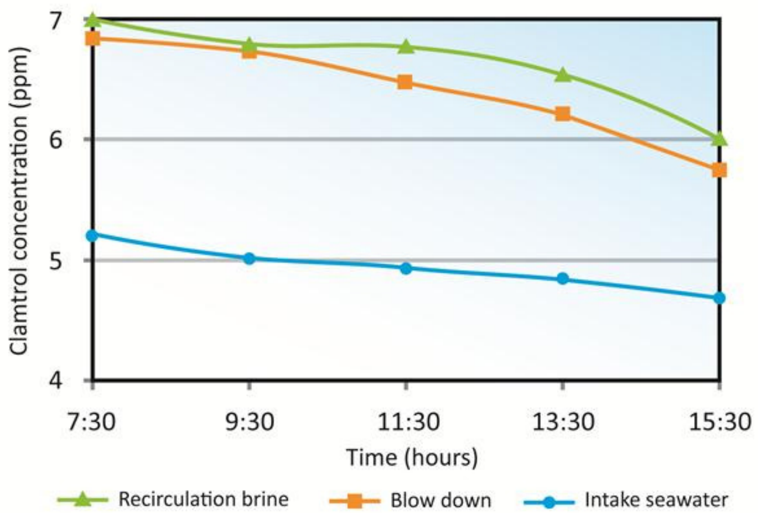


Figure 4.11: Decay of the Clam Trol CT-2 in the seawater feed of the MSF evaporator

Betz ‘s biodegradation studies of Clam Trol CT-2^{TM} sponsored by Continental Oil showed 60% degradation in 24 hours using microorganism that had been acclimated for 20 hours. Un-acclimated microorganism produced 37% degradation after 24 hours and 95% degradation after 48 hours as indicated by disappearance of the parent compound. A standard 7-day Semi Continuous Activated Sludge (SCAS) test sponsored by the ADBAC Product Stewardship Group showed 100% degradation [4.3].

The more stringent biodegradation studies measure the conversion of the compound into carbon dioxide (mineralization) when the test compound is used as the sole source of carbon and energy by un-acclimated microorganisms. Since a portion of carbon in the test material will be converted into cell mass, a result of 60% conversion to carbon dioxide in 28 days has become the international standard according to the *Organization for Economic Cooperation and Development* (OECD) for "ready biodegradable". The inoculum used in such test is also typically several orders of magnitude lower than would be encountered in natural soils, so the test should not be used to directly extrapolate the degradation time in natural environment. Table 4.4 shows the results of a carbon dioxide production test sponsored by ADBAC Product Stewardship Group. In this test greater than 80% of the Clam Trol active ingredient was converted to carbon dioxide indicating that the product was as easily degraded as d-glucose, a common sugar.

Table 4.4: Mineralization of Clam Trol CT-2 active to carbon dioxide [4.3]

Test Substance	Concentration (mg/L)	% of Theoretical CO_2 Production
d-glucose	20	80.6
ADBAC	5	84.0
ADBAC	10	82.6

Results of a similar mineralization study by Betz, shown in Figure 4.12 indicate that after a two day lag, un-acclimated microorganisms metabolized the Clam Trol CT-2™ product as fast as the biodegradable reference compound.

Furthermore, the excellent environmental profile of ADBAC as demonstrated in laboratory studies is supported by the results of field studies. One large study was conducted in 1996 by the Academy of Natural Sciences at a Clam Trol application at a power plant on the Chesapeake Bay. The study included a 3-month assessment of the recruitment and community composition of benthic infauna and attached epifauna, a 3-month study on oyster spat growth and mortality and a 48-hour acute effect study on presettlement oyster larvae.

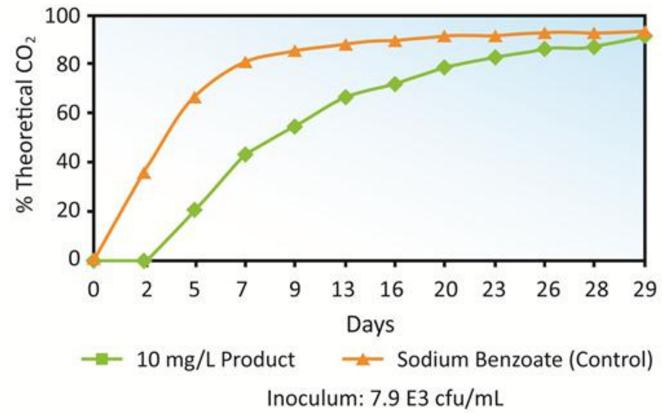


Figure 4.12: Clam Trol CT-2 ™ is mineralized to carbon dioxide as rapidly and to the same extend as the reference compound following a 2-day lag period [4.3]

The study concluded that there were no significant effects on benthic community abundance or composition, no effects on oyster spat growth and mortality and no increase in mortality of oyster larvae.

Application methodology

Application methods for Clam Trol CT-2™ are dependent primarily upon the type of system to be treated as well as on the species of macro-fouling organisms. In all instances the treatment program must be proactive. The objective is to apply the product at a frequency that will prevent the problem organisms from ever growing large enough to cause fouling problems. An effective treatment will cause the organisms to release from the surface and pass through the system in the water column. The required frequency is a function of the growth rate of the fouling organisms and the size of the tubes or passages in the system. For example, zebra mussels and Asiatic clams grow at a rate of approximately 0.5-1.0 inches (13-25 mm) per year; whereas green mussels grow 2-4 inches (50-100 mm) in their first year. Power plant condensers tubes are generally 0.75-1.25 inches in diameter, whereas smaller heat exchangers have typical tube diameters of 0.5-0.75 inches. A power plant with 1 inch diameter tubes can successfully control zebra mussel and Asiatic clam fouling using only one or two application per year. However, an industrial facility with ¾ inch tubes may require dosing every 2 weeks to control green mussel fouling. In any case, the treatment frequency should be such that the maximum size that a fouling organism could grow within the system is limited to the size of other debris which would normally pass through the ¼”-3/8” mesh traveling screens. In general, salt water macro-fouling species grow faster and larger, particular in tropical waters, and require a more frequent dosing schedule than fresh water macro-fouling organisms [4.18]. However warmer water is associated with accelerated metabolism and siphoning rates, permitting the use of lower production

concentrations and shorter exposure times. Due to the comparatively small size of most barnacle species, barnacle fouling is generally not a major concern when other macro-fouling organisms are controlled. However since relic barnacle shell may remain attached for years, application on a 7-14 day frequency may be necessary in systems where it is necessary to limit barnacle shell accumulations.
Cooling systems can be broadly classified as either recirculating cooling tower systems to once-through cooling systems. Cooling tower systems generally suffer the least from macro-fouling and are the easiest to treat successfully. In most case the cooling tower blow down is discontinued while the treatment is in progress. Product residuals are allowed to decay naturally by adsorption onto suspended solids and surfaces within the system. Effective treatments are usually possible with 6-8 hours exposures at the elevated temperatures typical of tower systems. Once through cooling systems are more difficult and expensive to treat due to the approximately 100 times greater intake water requirement. With respect to macro-fouling control, the intake structure is the most critical component of the cooling system. Paradoxically, the intake screens designed to protect the cooling system from debris are the main culprits with respect to promoting growth of macro-fouling organism. Conventional systems cannot screen out microscopic larvae forms.
Yet, the conservative water velocities in the screen pit area designed to prevent fish entrainment are ideal for promoting the settlement and growth of macro-fouling organisms. Once within the protective confines of the screen pit, the mollusks are treated to a constant gentle flow of water and a predator-free environment. In time, the organisms grow shells large enough to block tubes and restrict water cooling passages. It is not unusual to remove cubic yards of mollusks and shells from the intake bays on the "clean" side of the screens. As the mollusks die and break loose, their shells are transported into the cooling system where they lodge against tube sheets and restrict water flow. To be effective, a successful macro-fouling control program must control infestation in the intake bays. Similarly, plants with long inlet tunnels also suffer from severe macro-fouling. Unlike pressurized piping systems which often operate at flow velocities that limit macro-fouling growth, gravity flow intake tunnels operate at lower velocities that are often in the ideal range for macro fouling. In large power plants, these tunnels extend several hundred meters and can support more than 100 cubic meters of micro-fouling growth clinging to their walls. Successful macro-fouling control programs for plants with long intake tunnels require Clam Trol to be injected at the inlet of the intake tunnel. This is generally accomplished by attaching double wall chemical injection tubing to the pipe exterior from the shore to the inlet of the tunnel.

4.3 The control of biofouling in MSF evaporators at W.E.B. Aruba N.V.

The objectives of the Clam Trol CT-2^{TM} biocide trial

After the introductory elaboration in the previous section on the extensive research performed by Betz optimizing the quaternary amine biofouling control program, the

performed research to effectively control marine biofouling hampering effective desalination at W.E.B. Aruba N.V. is in detail discussed in this section. The application of a surface active non-oxidizing biocide is for the first time performed in a vacuum environment in an MSF evaporator.
As discussed in detail in Chapter 3 great effort has been done at the Desalination Department to create a creative working environment and an excellent Quality Team to increase efficiency in operations and management of the thermal desalination process. In the late 1990s the MSF evaporators are routinely taken out of production for a general inspection and maintenance program, normally called a GI, for an average period of 4 weeks. After the initial startup after a GI, with a high production and performance ratio of approximately 6.300m^3/day and 10.3 respectively, always a decay of production and efficiency is experienced in a three month period. In this period production capacity and efficiency normally decrease to approximately 5,800m^3/day and 7.8 especially due to heavy biofouling of the condenser. During this short outage, for which three to four days are

planned, the condenser (vessel V-107) and the inlet of the first vessel of the heat recovery section (vessel V-106) and the screening basket of the intake pump are physically and mechanically cleaned. The fouling consists of mainly marine macro biological organism blocking the inlet of the abovementioned vessels and the screening basket of the intake pump. Observed micro biological fouling on the inner tubes surfaces was impeding optimal heat transfer in the condenser justifying the evaluation of the application of a non-oxidizing microbicide for the control of the experienced macro- and micro biofouling to increase and stabilized high production and efficiency. Aware of the excellent experiences with Clam Trol CT-1™ controlling especially macro biofouling caused by infestation of zebra mussels and Asiatic clams in the cooling water systems at power utilities in the United States, Betz was invited to discuss the evaluation of the Clam Trol program as a potential treatment to control macro- and micro biological fouling in the MSF evaporators. A very important requisite is that the Clam Trol should be NSF approved for the use in thermal desalination to produce drinking water. Because of the difficulty to prove the ready biodegradability of the second active ingredient namely the n-dodecylguanidine hydrochloride (DGH) of the Clam Trol CT-1™ a special blend based on a higher concentration of only the ADBAC active component was formulated on the request of the Desalination Department and after an intensive evaluation the NSF certification was obtained for Clam Trol CT-2 ™ for direct dosing up to a concentration of 3.5 mg/l in potable water systems and to a maximum of 10 mg/l for seawater desalination processes to produce drinking water. The main agreed upon objectives of the trial are as follows:

- The operation run length of the MSF evaporator should be prolonged to at least one year
- The yearly average production capacity should at least be 6,000 m^3/day
- The yearly average performance ratio should be above 9.2

- The MSF evaporator should have a stable and reliable operation during the dosing of the biocide
- The Clam Trol CT-2™ dosage will be 4.5 ppm once a week for 12 hours

This application is innovative due to the fact that it was applied for the first time in a thermal seawater desalination process and very challenging because of the strong foaming tendency of the surface active characteristic of the biocidal active cationic surfactant amine component and evaporation under high vacuum conditions.

The application and evaluation of the Clam Trol CT-2™ biocide trial

The trial for the biocide treatment program started in July 1999 on the Aqua-Chem#5 MSF evaporator for the duration of six month on a “no cure no pay” basis.
Aqua-Chem#5 was chosen as the trial MSF evaporator because of an excellent operation after some adaptation, e.g. adjustment of the brine gates of the MSF evaporator trying to increase efficiency. As base line for this trial the overall performance of the Aqua Chem#5 MSF evaporator after a regular GI up to a condenser cleaning was used.
The available data after a GI was from July 12, 1997 to February 9, 1998. For this period the daily water production and the steam consumption is trended. After February 9, 1998 this MSF evaporator was shut down for condenser cleaning. It is worth mentioning that during this base line period this MSF evaporator had an exceptional performance, nearly six month in operation before a condenser cleaning compare with the normally average period between two condenser cleanings of three months for MSF evaporators [4.19]. As mentioned above the Clam Trol CT-2 ™ will be dosed in the suction of the intake pump at a concentration of 4.5 ppm of active component on a weekly basis. Depending on the results the dosage frequency can be adjusted to a two weekly frequency, a shorter frequency would be unacceptable.

Foaming control

One of the most important aspects dealt with at initial of the trial is the adjustment of the antifoam dosing to cope with the foaming tendency of the biocide. In cooperation with Betz an intensive evaluation is performed to determine the right dosage of the antifoam to address the unstable performance at the startup of the trial. In Figure 4.13 the relation of the dosage of the antifoam and the Clam Trol CT-2 ™ is shown.

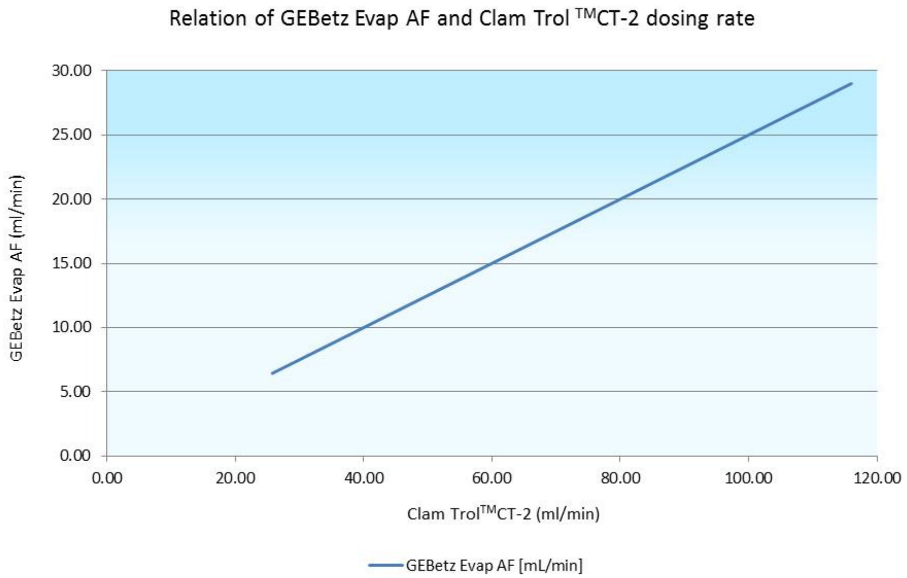


Figure 4.13: The relation of the antifoam feed and the Clam Trol CT-2^{TM} dosage

Sampling and analyses during trial

During the startup phase different streams were sampled in order to determine the concentration of the biocide. The most important samples during the biocide trial dosing were the distillate samples. From all the samples taken the analyzed concentration of the Clam Trol CT-2^{TM} was always below 0.1 ppm indicating no carry over or entrainment with vapor was taken place into the drinking water circuit. The concentration of the biocide in all the samples of the brine blow downstream to the sea has an average value of 0.67 ppm, which is within the acceptable limits and is further diluted by the cooling water streams of the other five MSF evaporators before discharge to the sea. The dosage of the Clam Trol CT-2^{TM} during the trial was verified for correct dosing twice a shift. In Table 4.5 the average concentration of the biocide in the different streams are summarized.

Table 4.5: Clam Trol CT-2^{TM} concentration in the seawater feed, distillate and blow down discharge

Flow	Concentration (ppm)
Seawater feed	4.5
Blow down	0.67
Distillate	<0.1

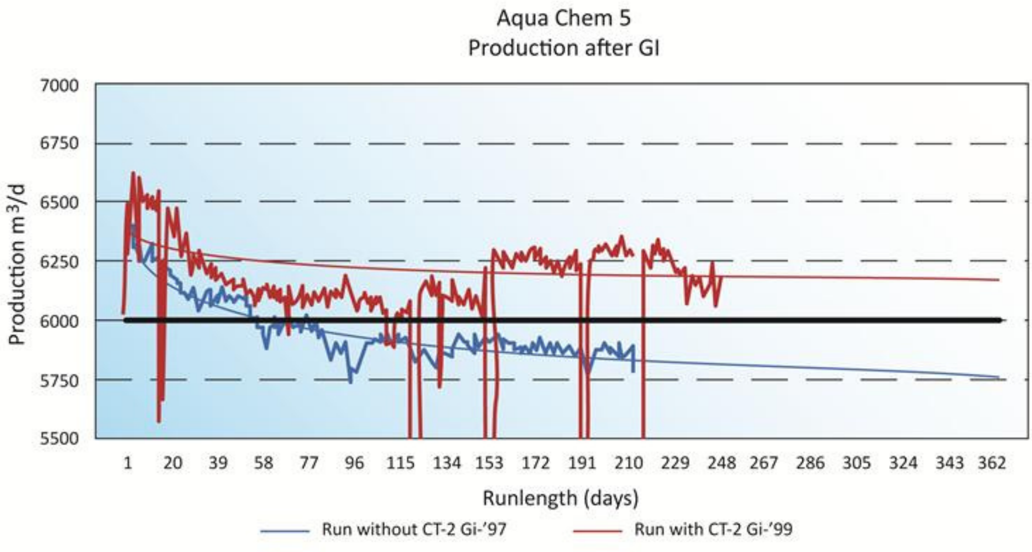
Inspection of the condenser

During the trial the condenser was opened twice for inspection and the intake pump was removed once to inspect the strainer. These two inspections indicate that the biocide treatment is able to maintain the condenser clean and free from micro and macro biological fouling. There is hardly any evidence of marine biological fouling on the suction screening basket of the intake pump. After the first inspection the dosage was optimized from weekly to biweekly and the second inspection also indicates that with the biweekly dosing the cleanliness of the condenser was maintained. In Figure 4.14 the pictures of the as found condition of the condenser during the inspections are shown. At that moment the dosing of the biocide was going on already for 7.5 months. Only non-marine debris, plastic materials that could pass through the intake pump was found in the water box of the condenser.

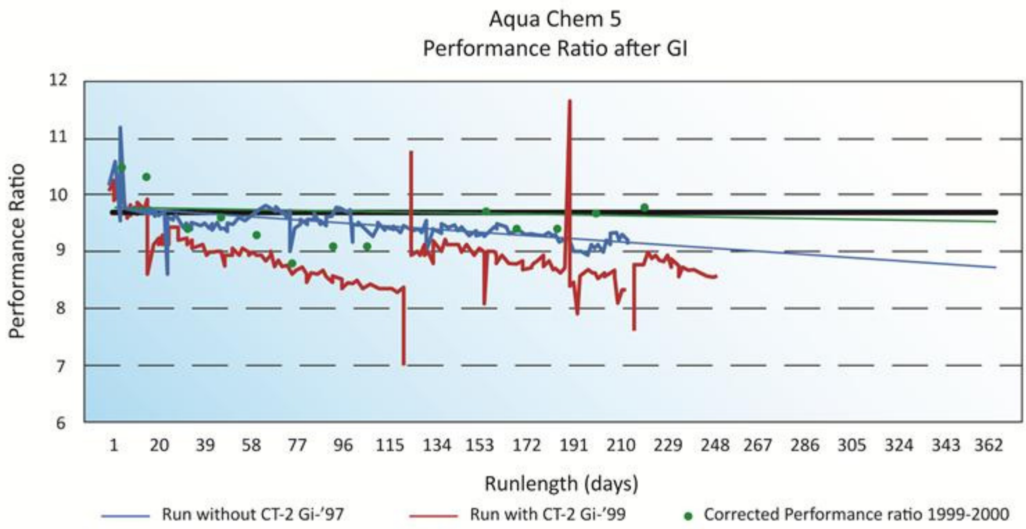
Figure 4.14: Pictures of the as found condition of the condenser during the biocide trial

Performance analysis and data interpretation

In Figure 4.15 a comparison is given between the base line and the trial period where only the production and performance ratio are monitored on a daily basis.



Production of Aqua Chem #5



Performance ratio of Aqua Chem #5

Figure 4.15: Overall performance data of the period July 12, 1997- February 09, 1998 as base line data for the biocide trial

In Table 4.6 the actual production and performance ratio are given from the start to the end and they are extrapolated to 365 days using regression analysis.

Table 4.6: Aqua Chem#5 Biocide trial Performance data

		Base line GI - 1997		Trial - 1999	
Days		213		228	
		Production (m^3/d)	Performance ratio (mT/mT)	Production (m^3/d)	Performance ratio (mT/mT)
	Start	6,353	10.16	6,503	10.22
Actual Production	End	5,770	9.17	6,267	8.83
Regression to one year	End	5,756	8.68	6,169	9.51*

**Corrected Performance Ratio*

As can be seen from Figure 4.15 and Table 4.6 the water production is maintained steady above 6,200m^3/day after a run length of 7.5 months. One of the objectives justifying the biocide quality project is the ability of the biocide application to maintain production above 6000 m^3/day. By regression of the production to 365 days the predicted yearly average production is estimated to be 6169 m^3/day. The production is maintained because the condenser and the suction strainer of the intake pump are kept clean and free from marine biological fouling, maintaining a steady seawater flow to the MSF evaporator, which is essential for a constant high water production.

To calculate the performance ratio of a MSF evaporator the condensate flow, condensed low pressure steam, is measured. During the trial there were a lot of problem experienced with the vortex flow meter. Using the technique developed by the Desalination Department in cooperation with the Engineering Department as explained in Chapter 3 the incorrectness of the flow meter was proven and the correct data correlated. As can be seen in Table 4.6 according to correction made the predicted average yearly performance ratio is 9.51 indicating that the agreed upon objective concerning the performance ratio is met by the dosing of the biocide.

The correlation of the performance ratio was the first proof for the importance and effectiveness of the heat balance trouble shooting tool developed by the Desalination Department. As stated in Chapter 3 to monitor and improve efficiency, key parameters were developed based on operation experiences. This involved correlating many years of operational experience with various data acquisitions that are available for trending. After much experimentation, the *Condenser Fouling Ratio* (CFR) defined as the ratio of the distillate flow to the seawater flow (as indicated in equation 4.3), was determined as key performance indicator to effectively trend biofouling of a MSF desalination unit:

$$\text{CFR} = \frac{\text{Distillate flow}}{\text{Seawater flow}} \qquad (4.3)$$

As shown in Figure 4.16 this novel fouling ratio increases as the fouling of the condenser increases.

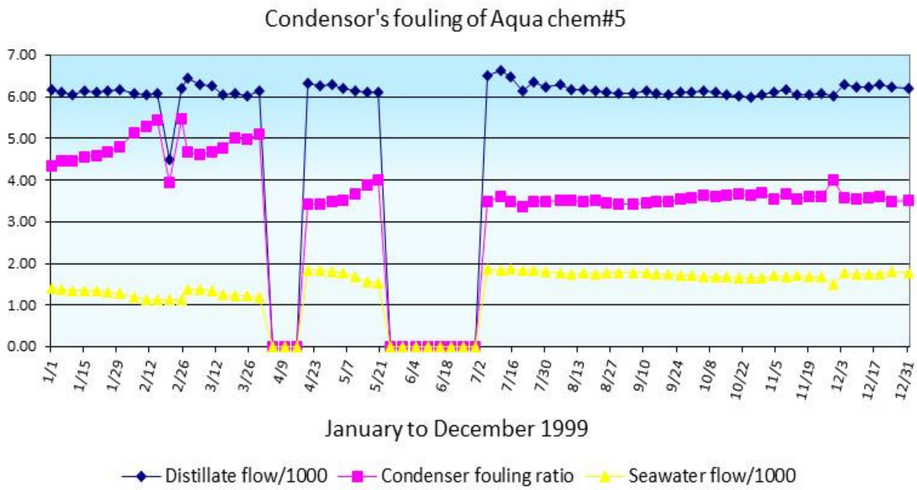


Figure 4.16: Condenser fouling ratio of Aqua Chem#5 in 1999 during trial

This condenser fouling ratio proved to be very useful evaluating the biochemical effectiveness of the Clam Trol CT-2^{TM} dosing during the trial at Aqua Chem#5 to control marine biofouling in the condenser. As show in Figure 4.16 since the start of the trial in July 1999, from this point forward as also shown in Figure 4.17 the condenser fouling ratio remained essentially unchanged, indicating practically no biofouling in the condenser. Aqua Chem#5 stayed in operation for a total of 15 months, nearly 5 times the typical run length, without the need for condenser cleaning after the Clam Trol CT-2^{TM} dosing.

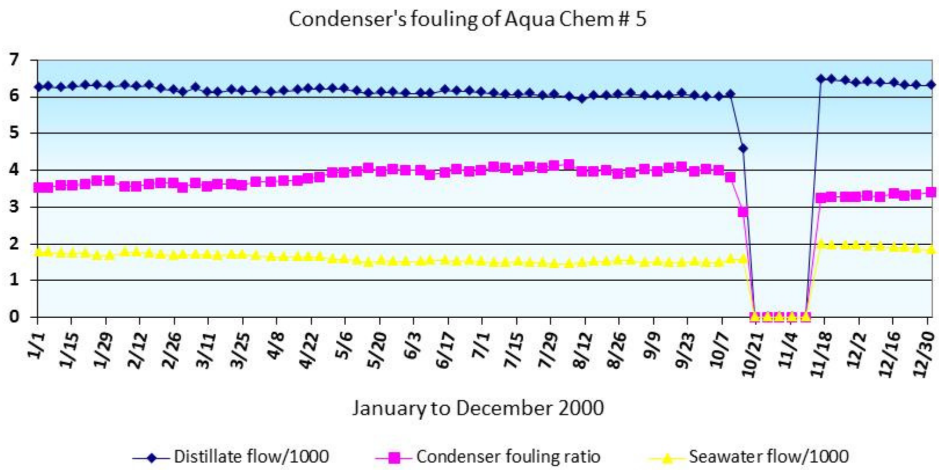


Figure 4.17: Condenser's fouling ratio of Aqua Chem#5 in 2000

By providing effective control of macrofouling, low pressure steam requirements were significantly reduced, resulting in considerable energy savings. Reduced down time, lower maintenance costs and increased water production were also realized. Considering only fuel oil cost of about \$12.00 per barrel in 1999 a yearly saving of \$223,000 is calculated. Based on the successful experience with the biofouling control of the MSF evaporator Aqua Chem#5, W.E.B. Aruba N.V. has expanded the Clam Trol CT-2™ application to all the other MSF evaporators.

4.4 The mitigation of persuasive biofouling in the new SWRO unit

A general introduction and description of the biofouling problem

In March 2008 after seventy five years of successful thermal desalination the more energy-efficient membrane desalination technology was introduced with the commissioning of the 8000 m^3/day SWRO desalination unit manufactured by GE-Ionics. Within days after the initial startup a steady increase of the pressure difference (Δp) across the membranes, high feed pressures and reduced production were experienced indicating higher than expected fouling of the SWRO membranes. Since the beginning of the SWRO project although many times emphasized by the Desalination Department it was omitted to perform a thoroughly analysis of the seawater, a necessity for an optimal design of the most important part of the SWRO technology, the seawater pretreatment to prevent physicochemical and biological fouling of membranes [4.20]. The seawater pretreatment system of this GE Ionics SWRO consists of multimedia filters and cartridge filters with daily intermittent chlorination and antiscalant dosing to control marine biofouling and the scaling potential of the seawater feed entering the plant by means of two dual high volume intake pumps from an open beach intake prior to membrane treatment. Furthermore additional in-line chemical pretreatment include daily multimedia filter backwash chlorination, sodium bisulfite dosing for dechlorination and the dosing of caustic soda for boron removal. This section will describe the complex issues that led to fouling of the SWRO membranes as well as the multi-pronged approach by the W.E.B. Aruba N.V.-GE Ionics Desalination Team to resolve the problem. A combination of process modifications is described as well as investigation into the nature of the foulants. The Toray membranes were at first believed to be irreversibly fouled, however, a combination of various Clean In Place (CIP) chemicals and application methods helped to reduce the high feed pressure and restore the target design flow [4.21].

Description and origin of the problem

By the beginning of the second year of operation, SWRO CIPs were having diminishing effectiveness and consequently little improvement in membrane feed pressure resulted from standard CIPs although production and pressure difference (ΔP) over the membranes nearly always showed moderate improvement. Production of permeate was trending downward on an incremental basis, failing to meet the design target of 8000 m^3/day. Energy consumption for the process was higher than expected because of the higher energy consumption of the high pressure SWRO feed pumps. The CIP solutions did not demonstrate significant color or odor throw from the membranes in the CIP tank solution. The SWRO vessels were also investigated for macro forms of biofoulants showing that the front sides of the lead membrane elements (the first membrane element in the pressure vessel) were not blocked, however, growth and discoloration could be observed. A few lead membrane elements were pulled randomly from some of the SWRO vessels and sent out for analysis to the GE Ionics Watertown Laboratory for inspection and analysis of surface biogrowth and to the Avesta Technologies Inc. laboratories for performance testing and foulant analysis. The analysis results showed the membranes were coated with a uniform, sticky but thin coating composed of extremely fine silt and biofilm indicating severe biofouling to an extent that had not been anticipated and expected [4.22].

General discussion of SWRO membrane scaling and fouling:

There are several general types of SWRO membrane fouling occurring in practical reverse osmosis desalination as will be described below [4.23].

Scaling

This is the deposition of inorganic salts on the membrane surface mainly due to concentration polarization resulting from the water diffusion process 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 [4.24]. Defined 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. The concentration polarization process in the boundary layer adjacent the membrane surface inducing scale formation due to precipitation of supersaturated inorganic chemical components is illustrated in Figure 4.18.

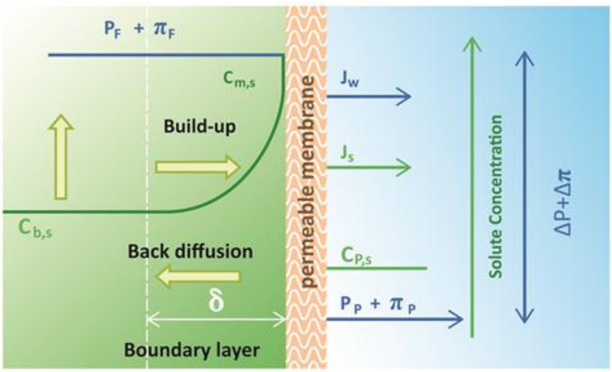
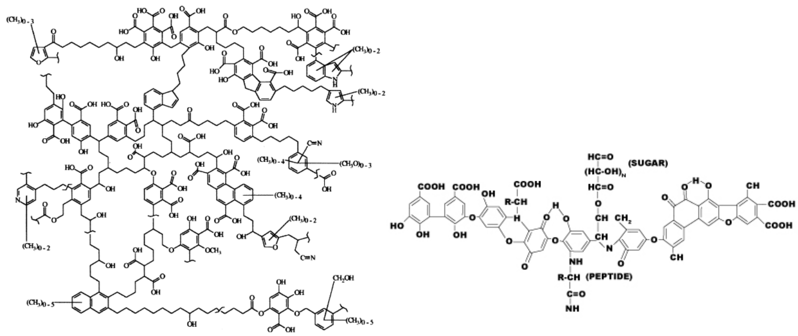


Figure 4.18: The concentration polarization process in the boundary layer adjacent to the membrane surfaces [adapted from 4.24]

Organic Fouling

This 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. In Figure 4.19 the proposed chemical structure of humic acid by Schulten and Schnitzer in 1993 and that of fulvic acid as proposed in 1982 by Stevenson is shown for the purpose of illustration [4.25].



Humic acid molecular structure Fulvic acid molecular structure

Figure 4.19: The chemical structure of humic and fulvic acid [4.25]

Colloidal Fouling

This 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, particulates, and undissolved organic matter such as humic substances. Associative bonding of membrane and foulants by weak surface charge and attraction due to different intermolecular forces is also typical [4.26]. A simple case representing the Van der Waals and electrostatic double layer interaction between a particle and a surface is schematically illustrated in Figure 4.20.

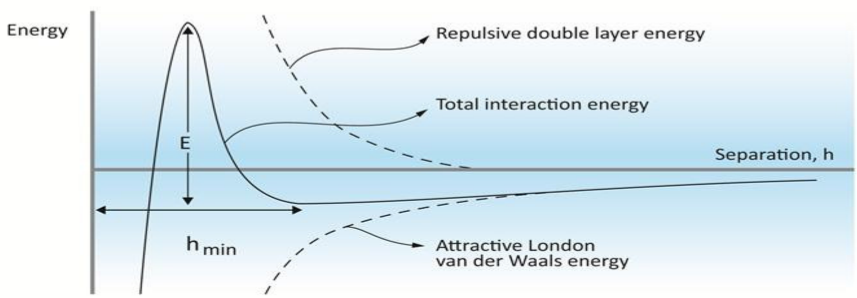
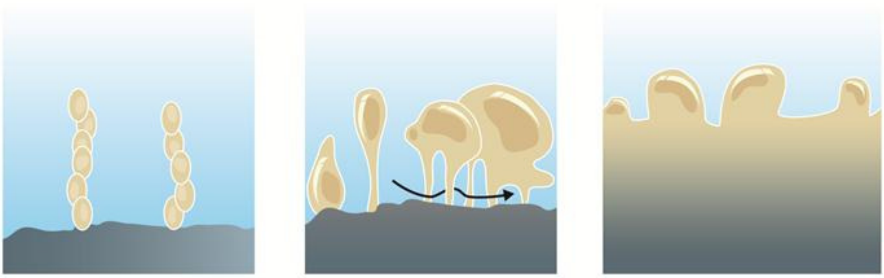


Figure 4.20: The Van der Waals and electrostatic particle-surface double layer molecular interaction [4.26]

Biofouling

This 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 and can develop internal passages. At least three models for biofilm growth have been developed by microbiologist: (1) the heterogeneous mosaic model; (2) the water channel model; and (3) the dense confluent model as is illustrated in Figure 4.21 [4.23].



Heterogeneous mosaic model   Water channel model   Dense confluent model

Figure 4.21: Biofilm growth models proposed by microbiologist [adapted from 4.23]

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. Webb and Paul (1994) describe this as a serious problem for all reverse osmosis systems supplied by surface feed waters [4.27]. Ortega and Rossing (1997) state that biofouling occurs most easily in warm water with organic food sources, and is a function of nutrient source, pH, temperature, and oxygen level [4.28]. Biofilm growth characteristics vary widely with feed source and type of microorganisms present as stated by Prato (2001) [4.29]. A prime indicator of biofilm formation is a decline in membrane flux. Biogrowth on the feed side of the membrane physically inhibits water transport. Carnahan and Bolin (1995) report biofouling-attributable pressure buildup on the first stage elements of an RO system at a plant in Florida [4.30]. Feed pressure is normally increased to maintain constant product flow. Once maximum pump pressure capacity was reached, flow rate will decrease as fouling continues. Reduced product flow means that target production is not achieved. Biofouling usually occurs in concert with other types of fouling, e.g., inorganic scale formation and deposition of suspended solids and non-biological organic foulants. Dunham and Kronmiller (1995) maintain that different foulants form distinct layers on an RO membrane, further complicate treatment of biofouled membrane systems [4.31].

Definition and major characteristics of membrane biofouling

There are different types of membrane foulants, each of which contributes to the biofouling process, either by providing suitable nutrient rich preconditions or by providing a good location for biofilm formation such as fouled surfaces.

Membrane foulants include organic substances such as dissolved humic and fulvic acids, organic particulates such as undissolved agglomerates of decaying vegetables matter and inorganic particulates such as scale particles and colloidal silica.

Knoell and Safarak (1999) describe biofouling potentials of membranes in terms of bacterial attachment [4.32]. Membrane surface roughness, membrane pore size and hydrophilicity of bacteria promote attachment to membrane surfaces and ability to thrive in a porous biofilm. Geometrical irregularities of the membrane surfaces enable bacteria to attach in low flow areas, escaping the sweeping action of flow in the feed compartment. Another strong factor in biofilm formation is the ability of many bacteria to secrete a polysaccharide coating cementing the biofilm layers in place and making them less water-permeable. Many of these factors have combined at W.E.B. Aruba N.V. to create a difficult to manage membrane biofouling condition.

A description of the persuasive biofouling of the SWRO unit

According to the membrane autopsy investigations performed by GE Inonics and Advesta Technologies Inc. at the W.E.B. Aruba N.V.'s SWRO desalination unit the membranes have experienced a significant combination of colloidal fouling and biofilm formation all over the entire surface of the membranes. The deposit is not especially thick, but it appears to be well adhered to the membrane surface. An additional physical factor, the presence of extremely fine silt most likely acting as nucleation sites for biofilm growth, has created in this combination a persuasive biofouling matrix of silt and biofilm. By June 2009, the entire pretreatment and process train was affected by severe biofouling. The extent of biofouling potential had not been anticipated since no intense analyses has been done by the manufacturer because the seawater had appeared to be fairly clean, and preliminary testing had not revealed significant presence of microorganisms. The as-found biofouling in a disassembled membrane of W.E.B. Aruba N.V.'s SWRO desalination unit is illustrated in Figure 4.22.

Disassembled biofouled membrane

Biofouled membrane surface

Figure 4.22: The disassembled W.E.B. Aruba N.V.'s SWRO membrane showing biofilm matrix

The biofilm coating in the left hand picture had a sticky/tacky property with some degree of hydrophobicity making it resistive to being easily rinsed off the membrane surface. Since the relatively thin layer of biofilm could be easily wiped off manually (as is illustrated in the right hand picture of Figure 4.22) this suggested that the right combination of cleaning chemicals should effectively remove the layer, restoring flux and reducing the feed pressure to the membranes [4. 21]. A sample of the material was removed from the membrane surface and examined at the GEBetz Analytical Laboratory in Woodlands, Texas for investigation into the composition of the biofilm layer. In this investigation phase contrast microscope technique is used for microbiological analysis. The sample is examined at various magnifications revealing that it consisted primarily for more than 75% of biological forms including copious amounts of exopolymer-encapsulated bacteria and iron related bacteria e.g., *Leptothrix*. It is a well-known fact that bacteria can over produce exopolymer when their environment contains an abundant biodegradable carbon source. An examination was also made of the marine environment adjacent to and up-current from the shore intake. Microbiological analysis also revealed higher than expected concentration and colony counts of a range of bacteria, but *Leptothrix* was also found to exist in those populations. It is worth mentioning that further process-wise contributing biofouling factors at the SWRO pretreatment include:

- Intake chlorination not optimized as to frequency
- Intake chlorination not optimized as to strength of chlorine addition
- Strong biological and microbiological growth in media filters acting as an incubator for contamination of downstream operations
- Leakage of silt and biofoulants past cartridge filter seals
- Formation on membrane surface of biofilm matrix containing silt, bacteria protected by an extensive polysaccharide coating

Effect of fouling on operating performance

As a result of the heavy fouling of the SWRO pretreatment system and membranes, performance of this membrane desalination unit was significantly off design target. Persistent high feed pressure on all the SWRO trains was not alleviated by a series of standard CIPs. Production had fallen to less than 80% of target flow of 8000 m^3/day and was continuing a downward trend. Axial pressure drop (ΔP), the pressure drop over the membrane feed spacer, demonstrated minor improvement with applied CIPs, but rapidly increased to pre-CIP values within a few days. In the two following set of graphs the performance not in conformance with the design of the subject SWRO is illustrated. In Figure 4.23 the decreasing trends of the normalized permeate flow of one of the SWRO trains is shown. The red line represents the design target flow of 111 m^3/hr.

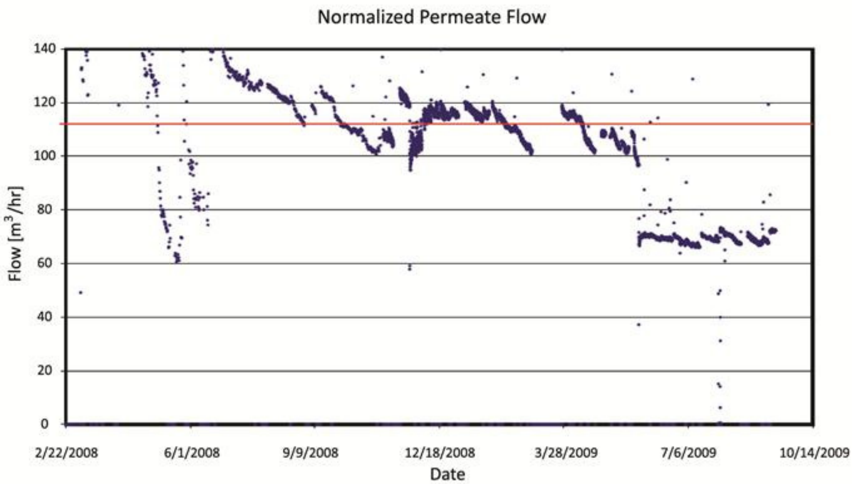


Figure 4.23: The normalized permeate flow of the W.E.B Aruba N.V's SWRO

Figure 4.24 shows the increasing trend of the normalized spacer side differential pressure of the membranes of subsequent SWRO train after the CIPs with practically a 15-20 days frequency.

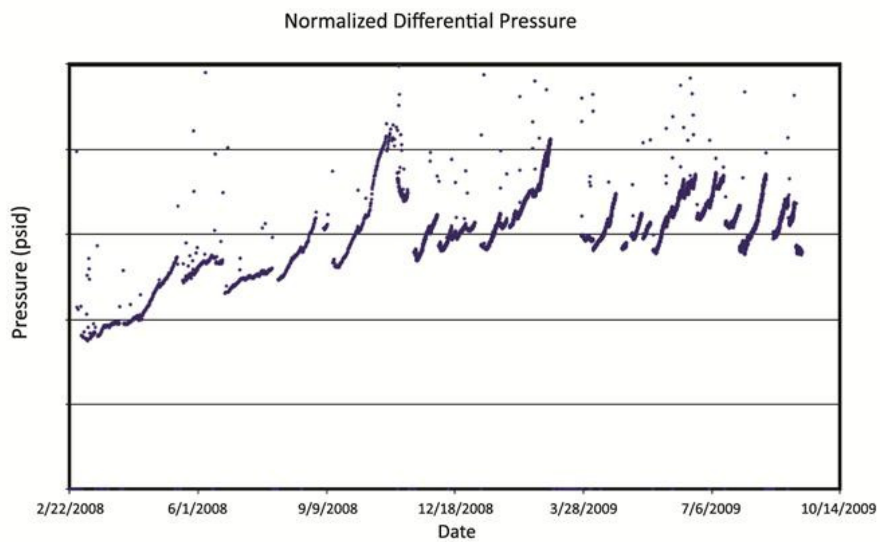


Figure 4.24: The trend of the membrane differential pressure

The upward spikes indicate rapid increase after CIP showing the low effectiveness of the CIP chemicals.

A new CIP approach for W.E.B. Aruba N.V.'s SWRO membranes

As a result of direct information about the nature of the membrane foulants including bacteria type and surface qualities, new CIP chemicals were selected for a series of CIPs. Other actions were also taken to provide conditions for a more successful chemical cleaning such as;

- Correction of the cartridge filters sealing leaks to prevent foulants and silt from getting through to membranes.
- Initiating media filter backwash chlorination. Each filter undergoes backwash once per day. At the slow backwash and one hour soak steps of the backwash cycle, 18-20 ppm of free chlorine is pumped into the filter. After several months of backwashing under these conditions, the macro fouling and high slime conditions within the filters were essentially eliminated.
- Initiating tank and piping sterilization. A procedure was developed for shock sterilization of the piping, tanks, pumps, manifolds and cartridge filter vessels e.g. all of the delivery infrastructure and especially the pressure exchanger (PX) of energy recovery devices which were severely contaminated with slimy biofilms as is shown in Figure 4.25. This is considered a major source for recontamination. Several hundred ppm of free chlorine was pumped through and allowed to soak. The concentration was gradually reduced overnight to 0 ppm levels in order to protect the membranes. Membranes were sealed off from the sanitation solution using valve closure and installation of Teflon blind plates.

Figure 4.25: The pressure exchanger internals contaminated with slimy biofilms

Once these procedures were in place, a series of CIPs were performed to optimize membrane cleaning. A new protocol was also adopted to rinse the energy recovery devices with CIP solution whenever a CIP was done.

Jar testing (test in stirred cells containing different chemical cleaning components) with membrane samples was initiated to observe which set of conditions provoked reaction with or removal of the sticky biofilm. The first dramatically successful CIP dropped the stubbornly high feed pressure from 65 bar down to 59 bar. This was the first time that any significant pressure drop had been observed with a CIP. Finally good color throw was also observed in the CIP solution indicating that material had been removed from the membrane surface. The particular CIP recipe was:

- Soak with Sodium Bisulfite (SBS) to scavenge oxygen out of the water within the elements and piping. This was done to stress aerobic organisms, weakening the metabolism as preparation for attack by following chemicals. Soak with anionic surfactant. The positive anion group would attach to negatively charged organics.
- With surfactant kept in solution, a GE-WPT proprietary cleaner was used. This cleaner was a high pH chemical with a mild oxidizer present.
- The pH was bumped up to a slightly higher level. While presenting some risk to membranes, the slight pH increase was helpful.

Variations in the CIP recipes provided additional benefits including significant drop in axial membrane differential pressure. This Δp went from an average of 1.5 bar down to 0.95 bar. This indicates that pretty much everything was cleaned out of the membrane seawater feed channel. The significance of persistence of high feed pressure versus minimal Δp is an indication of some permanent fouling on the membrane surface. It may also indicate that there are some areas of biofilm that have not been penetrated and may prove to be impervious to the variety of CIP regimes. It is also characteristic of older SWRO membranes that there will be some loss of flux and permanent fouling regardless of operating conditions. The fact that the plant had been operated at maximum pressure of close to 65 bar for an extended period would also contribute to membrane compression, permanent fouling and loss of flux.

The sequences of successful applied CIPs combined with the corollary process improvements enabled the SWRO units to recover design production.

Energy consumption of the SWRO unit was almost 20% over target, and this represents a lot of cost since energy is expensive in Aruba. While the SWRO desalination unit achieved specified energy consumption during the performance testing, it did not meet the specification later in continued operation. The bulk of the extra energy consumption pertained to the constant maximum pressure requirement of the high pressure feed pumps needed to achieve even less than target flow rates. Other factors included non-optimized process flows and recoveries as well as excess extraneous energy for air conditioning.

While energy consumption was improved, it did not bring it down to target energy levels. This is in part due to aging of membranes, but it also pertains to foulants driven deep into the membrane structure, fouling that is not reversible by CIPs.

The following charts show the change in operating parameters after the series of effective CIPs. In Figure 4.26 the two important operating parameters, the high SWRO seawater feed pressure and the permeate flow are illustrated.

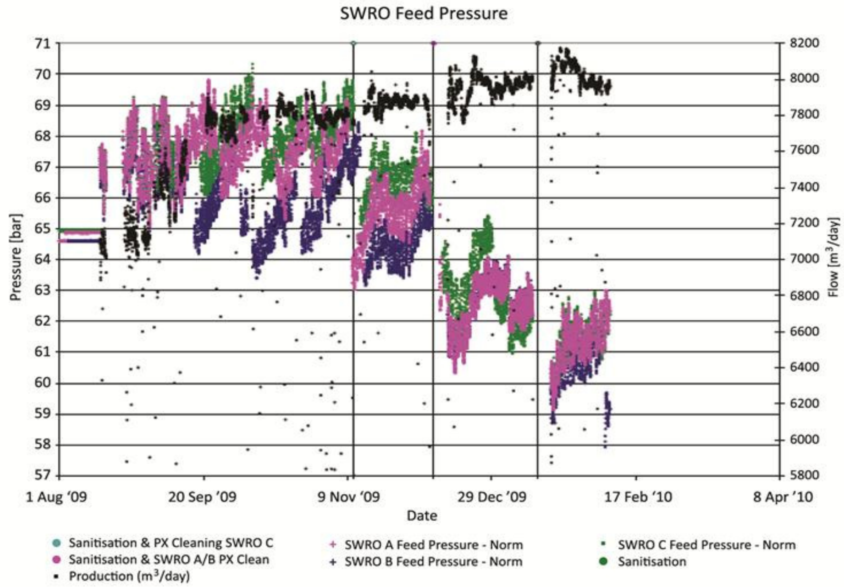


Figure 4.26: The trend of the seawater feed pressure and the permeate flow after the new CIP

The trend in black near the top indicates full recovery of target flow of SWRO permeate. The bulky downward trends are the seawater feed pressures indicating energy efficiency increase of the three units post CIPs.

Multiple CIPs were required to remove successive layers of foulants and biofilm from the membranes. There was a limit to the effectiveness of the cleanings as some of the fouling appears to be irreversible. The scattered points below the trend lines are artifacts of the automatic data logging of the SWRO desalination unit.
The progressive improvement of the axial membrane differential pressure (Δp) over time and after multiple CIPs is illustrated in Figure 4.27.

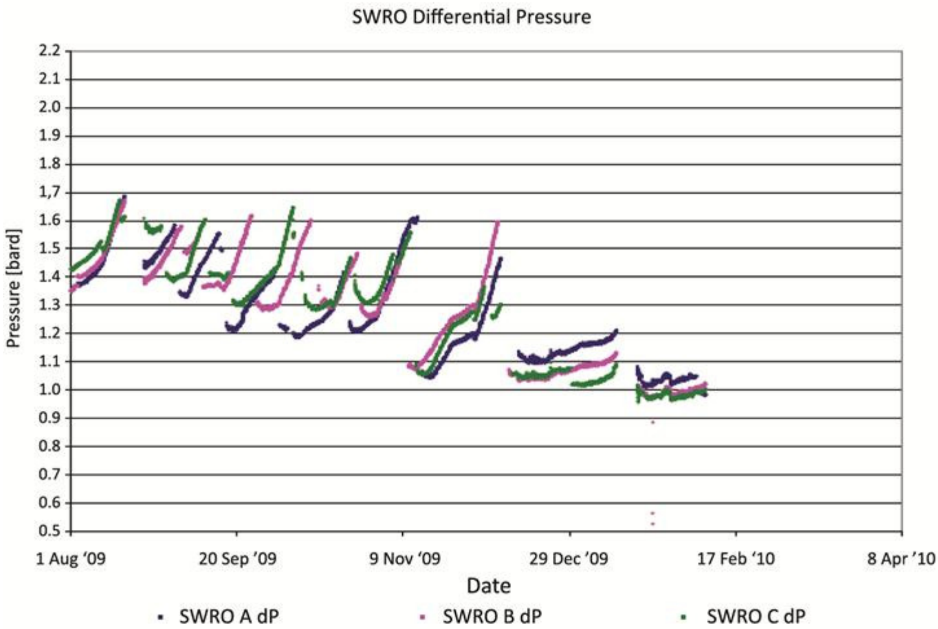


Figure 4.27: The improvements of the axial membrane differential pressure

The increasing horizontal aspect indicates that the ΔP is increasing only slowly over time as demonstrated in Figure 4.28 by plotting the delta delta p representing the change in the slope over time of the pressure curves in Figure 4.27.

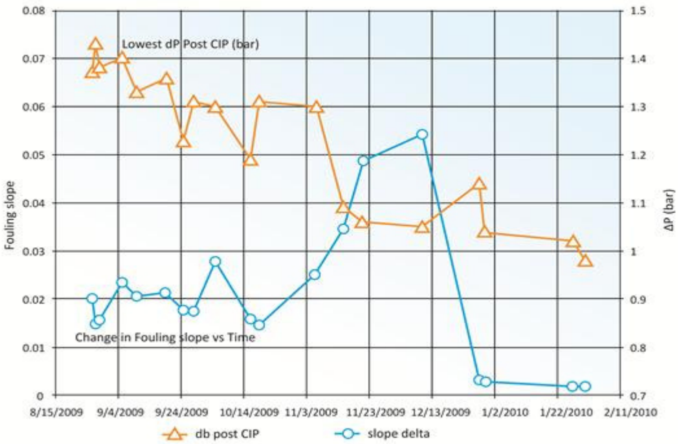


Figure 4.28: The slope of the membrane axial differential pressure [Δ (ΔP)]

The energy consumption as indicated above also showed a minor improvement as a consequence of the new CIPs. This is illustrated in Figure 4.29. It is noticeable that after the application of the CIP the energy consumption goes down to about 4,15 kWh/m^3 and increase readily to values up to 4.45 kWh/m^3 following practically the same trend as the pressure increase of the seawater high pressure feed pumps indicating the major contribution of these pumps to the energy consumption.

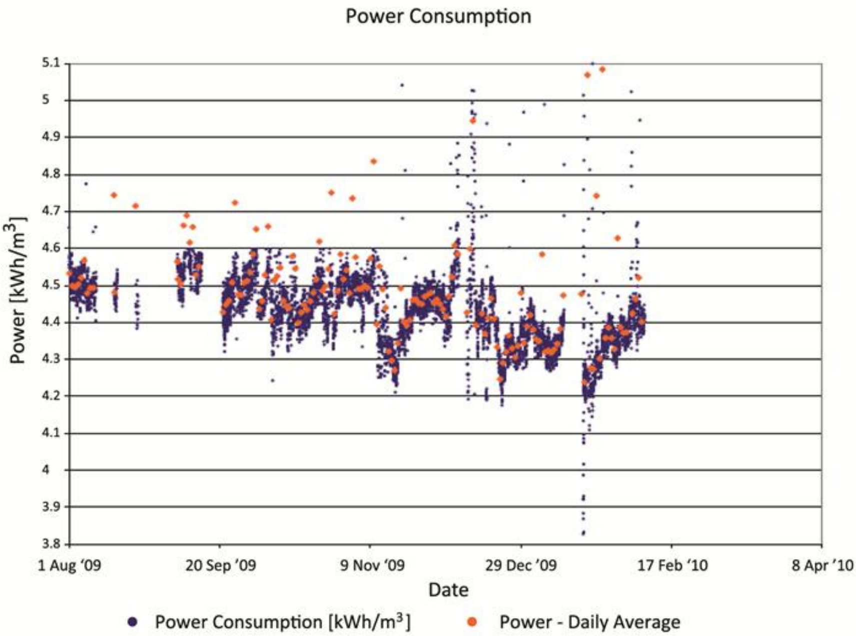


Figure 4.29: The decreasing tendency of the power consumption

The application of an innovative osmotic membrane cleaning process

While it is clear that the correct CIP cocktail helped to improve critical operating parameters of the W.E.B. Aruba N.V.'s SWRO desalination unit 1, the work is on-going to reach the target design energy consumption. Pockets of biofilms continue to exist in sections of the SWRO piping. These have led to rapid recontamination of the seawater membranes in a relatively short period before another CIP is required. As indicated in preceding sections the targeted design production rate has been obtained, however the energy consumption stayed in the range of 4.15-4.45 kWh/m^3 approximately 5-12.5% above the design target of 4.00 kWh/m^3. In the process of continuous desalination efficiency improvement a more effective sanitation procedure has been developed by the Desalination Department and successfully applied in combination with a developed innovative osmotic chemical-free membrane cleaning process. For this osmotic membrane cleaning process a patent has been registered and will be described more in depth in Chapter 9 concerning implementation of innovative desalination concepts to improve efficiency. The sanitation process is practically based on the concept of altering the osmoregulation process of the cells of the micro-organisms with pure distillate and consequently swelling the cell tissues by deregulating the osmotic salt balance of the cell tissues. The sensitivity of the micro-organisms is increased by soaking with different disinfectants as the dibromohydantion, hypochlorite and a proprietary biodispersant of the chemical supplier based on the DBNPA (*2,2-dibromo-3-nitrilopropionamide*).

The applied sanitation process is as follows:

- Overnight soak of the pretreatment system and membranes with pure distillate
- Flush the system and soak the pretreatment system till the SWRO membranes, alternatively with the different disinfectants
- Reduce the recovery rate to lower the high pressure to osmotic-clean the membranes removing or loosening the compressed tenacious scale from the membrane surfaces
- CIP the membranes and flush the membranes and the whole piping system with the biodispersant
- CIP the BWRO membranes with a citric acid based low pH solution after reducing the recovery rate to promote osmotic cleaning
- CIP the BWRO with product water acidified wit carbon dioxide

After the application of this innovative osmotic membrane cleaning process and the intensified sanitation the energy consumption has been dropped for the first time to 3.97 kWh/m^3 below the design target of 4.00 kWh/m^3. After changing the first three lead elements of all the SWRO vessels an energy consumption rate of 3.72 kWh/m^3 was obtained, which is 7 % lower that the target design value. In Figure 4.30 the trend of the energy consumption prior to the application of the novel osmotic membrane cleaning process and post osmotic cleaning is illustrated to demonstrate the effectiveness of the new membrane osmotic-cleaning to increase efficiency. This is a remarkable successful result because of the word wide conviction (especially of the manufacturer) that the SWRO membranes have been affected by the long period of high-pressure operation with foulants on the membrane surfaces as well as the ineffective CIPs. In addition, according to common experience aggressive and frequent chemical CIPs will damage and eventually shorten the life of the membranes [4.1].

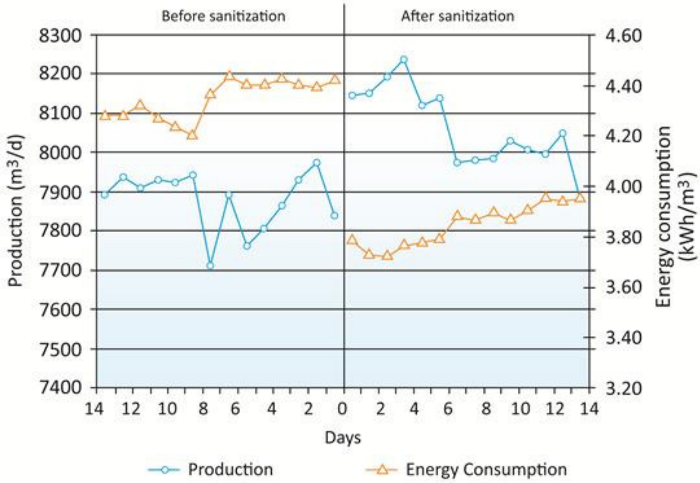


Figure 4.30: The production and energy consumption pre and post osmotic membrane cleaning

It is worth mentioning that GE WPT has granted the Desalination Department the "Proof not Promise" award for this world wide successful result.

Despite the above mentioned success, considering the experienced high biofouling potential of the seawater feed the Management of the Desalination Department proposed to change from open beach seawater intake to beach wells for the existing SWRO desalination unit and for the new SWRO to be constructed. It is a common knowledge that beach wells can deliver high quality natural pre-filtered seawater [4.1]. In the attempt to quantify the biofouling of the seawater, an introductory research has been carried out using for the first time a biofilm monitor [4.33] for the evaluation of the biofouling potential of the seawater and a *Membrane Fouling System* (MFS) as an early warning system characterizing the fouling rate of the membranes [4.34]. This preliminary research will be described in some detail in the next section.

An introductory study quantifying the biofouling of the seawater feed

In April 2009 a research is started to quantify the severe biofouling experienced at the SWRO desalination unit. In this research an innovative evaluation of biofouling is initiated using a biofilm monitor to calculate the biofilm forming potential of the seawater and the filtered seawater. Also an *Early Warning System* (EWS) is installed to monitor the fouling rate of the SWRO membranes indicating the fouling potential of the filtered seawater [4.34]. In this section only some preliminary results are given. It is the intention to further intensify and extend this research to design a pilot plant to intensify the fundamental study of the SWRO biofouling. In Figure 4.31 a picture of the installed biofilm monitor is shown and in Figure 4.32 the graph of the measured *Adenosine Tri Phosphate* (ATP) value of the seawater feed water to the multimedia filters is illustrated. ATP measurement is generally considered a useful measure to quantify biofouling on membranes [4.35, 4.36].

The biofilm monitor   The glass ring column   Glass ring sampling

Figure 4.31: The biofilm monitor installed at the SWRO desalination unit

The biofilm monitor is designed by Kiwa Watercycle Research to evaluate the biofilm forming potential of freshwater in drinking water distribution systems [4.33]. This device consists of a glass column filled with a set of glass rings with a specific outer surface that could capture and hold biofoulant materials. The amount of biomaterial on the glass rings is characterized by ATP measurement. It is the first time that a biofilm monitor is used for the evaluation of the biofilm forming potential of seawater in Aruba.

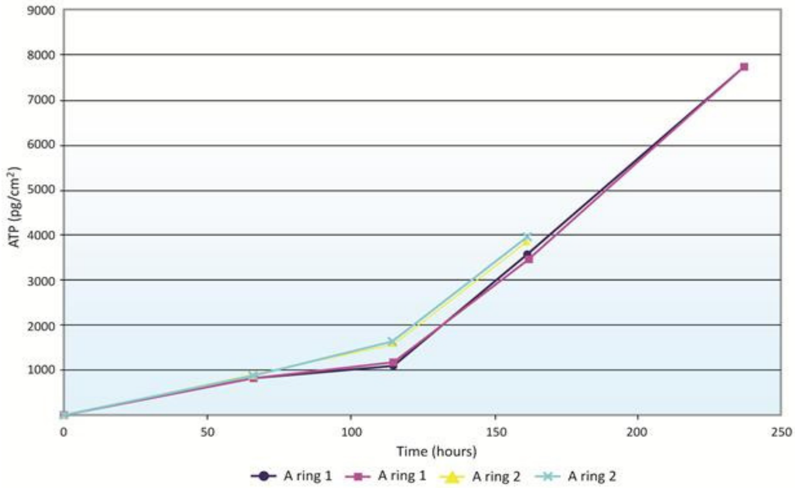


Figure 4.32: Measured ATP values of the Multi Media filters seawater

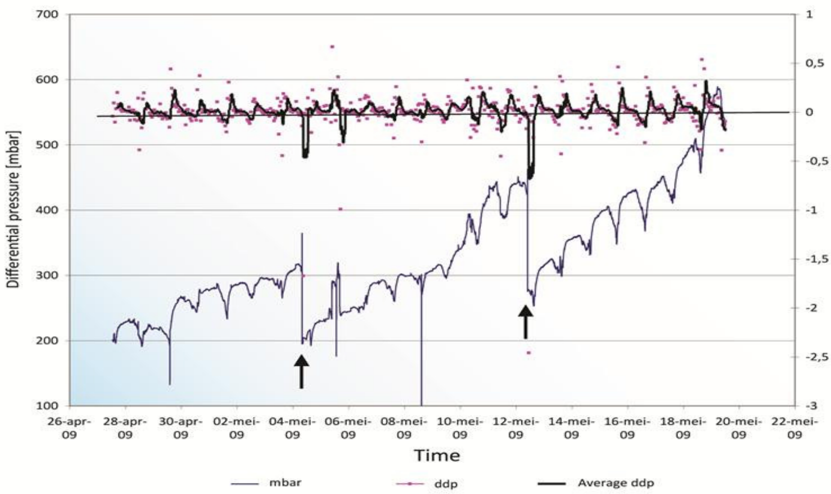
The trend of the seawater's ATP values in Figure 4.32 indicates an increase to 7900 pg/cm2 of ATP within 250 hours, approximately 10 days of operation.

In Figure 4.33 and Figure 4.34, the installed EWS and the trend of the delta p over the spacers of the EWS is respectively illustrated. The Membrane Fouling Simulator is an on line device consisting of a membrane spacer on a support material to simulate the real time axial membrane differential pressure of a SWRO. It is primarily designed to visually show and warn in an early stage for membrane fouling.

Early Warning System Fouled membrane spacer

Figure 4.33: The installed Early Warning System and the visible fouling of the spacer of the MFS

The membrane spacer and the support material of the MFS were found to have a slippery layer on the inside of the piping. This outer slippery layer was over a harder, rubbery biofilm layer. This is a classic representation of mature layers of established biofilms [4.21, 4.23].



***Upwards arrows indicate air bleeding of the MFS**

Figure 4.34: The trend of the delta p over the Early Warning Spacer [4.37]

In Figure 4.34 the rapid increase of the delta p over the spacer is shown. The purple graph is the delta delta p calculated and trended to show the rate of increase of the delta p. These preliminary investigations have undoubtedly proved the high biofouling potential of the very clear and clean Caribbean blue seawater confusing manufacturers not to perform an intensive seawater analysis to design the pretreatment system. Within practically one day already some marine biological attachment is observe on the surfaces of the glass rings in the column of the biofilm monitor. It is also worth mentioning that this introductory research has also proof that the inlet design of the buffer tank is not correct inducing a lot of air in the cartridge filtered seawater feed [4.37]. It is the intention to use the biofilm monitor to further evaluate the Clam Trol CT-2^{TM} biweekly treatment program on the biofilm forming potential on the treated seawater flow to the MSF condensers.

4.5 Conclusions

1. The Clam Trol CT-2 ^{TM} program is able to effectively control macro- and micro biofouling in the condenser of MSF evaporators maintaining high production capacity and high efficiency.
2. The Clam Trol CT-2 ^{TM} dosing has practically reduced down time because of fouled condenser of the MSF evaporators.
3. By proper adjustment of the antifoam feed to Clam Trol CT-2 ^{TM} feed a stable operation of the MSF evaporator is establish during the dosing of this non oxidizing biocide with a high foaming tendency.

4. The Clam Trol CT-2 ™ dosing is in general practicable applicable in all thermal evaporators to effectively control marine biofouling.
5. The biofilm monitor designed for the use in drinking water distribution system is proved to be a viable tool for the calculation and evaluation of the biofilm forming potential of the seawater feed of the SWRO.
6. The Membrane Fouling system is proved to be a very useful visual indicative tool for the evaluation and simulation of biofouling of SWRO membranes that effectively can serve as an early membrane fouling warning system.
7. The Early Warning system is also proved to be an efficient tool to calculate and predict the real time axial differential pressure of the SWRO membranes.

4.6 References

4.1. Wilff, M., The guidebook to Membrane Desalination technology, ISBN 0- 86689-065-3, Balaban Desalination Publications, L'Aquila, Italy, 2007.

4.2. Post, R.M., Marchena, F. A., et al., An Alternative Method for Disinfecting desalination Plant Intake Systems, 2nd Expo/Congress Water 2003, January 29-31, Curacao N.A.

4.3. Post, R. M., Marchena, F. A., et al., A New Method for Controlling Marine Growth in Desalination Plant Intake Systems, Caribbean Desalination Conference 2002, June 21-23, Aruba.

4.4. Lyons, L. A., Davies D. P., et al., Proposed Blue Mussel Fouling Control Technology Using a Non-oxidizing Molluscicide, EPRI Condenser Technology Conference, September 18-20, 1990, USA.

4.5. Morris, D. W., Tackett J. H., et al, "minimizing Chlorine Applications Consistent with Effective Macro fouling Control: A Pilot Study of Continuous, Low Level Chlorination"., Proceedings of the Symposium on Condenser Macro fouling Control Technologies, June 1983 EPRI CS-3343.

4.6. Bidwell, J. R., Cherry, D.S., et al., A comparative Study for the Control of Zebra Mussels Between Chlorine, Bromine and a Non-oxidizing Molluscicide-An onsite Evaluation"., Proceedings of the EPRI Zebra Mussel Control Technology Conference, Itasca, IL, October 23, 1991.

4.7. Gerschke, M., "Chlorination: The Benefits and The Hazards", Aqua facts, technical Publication of Aqua-Chem Inc.

4.8. Marchena, F. A., The safely Processing of Damaged Chlorine one Ton Containers on the Premises of W.E.B. Aruba N.V., Internal Report, 1991.

4.9. Post, R. M., Lyons, L.A., "Evaluation of a New Molluscicide for Alleviating Macro fouling by Asiatic Clams", American Power Conference, April 18-20, 1988, Chicago USA.

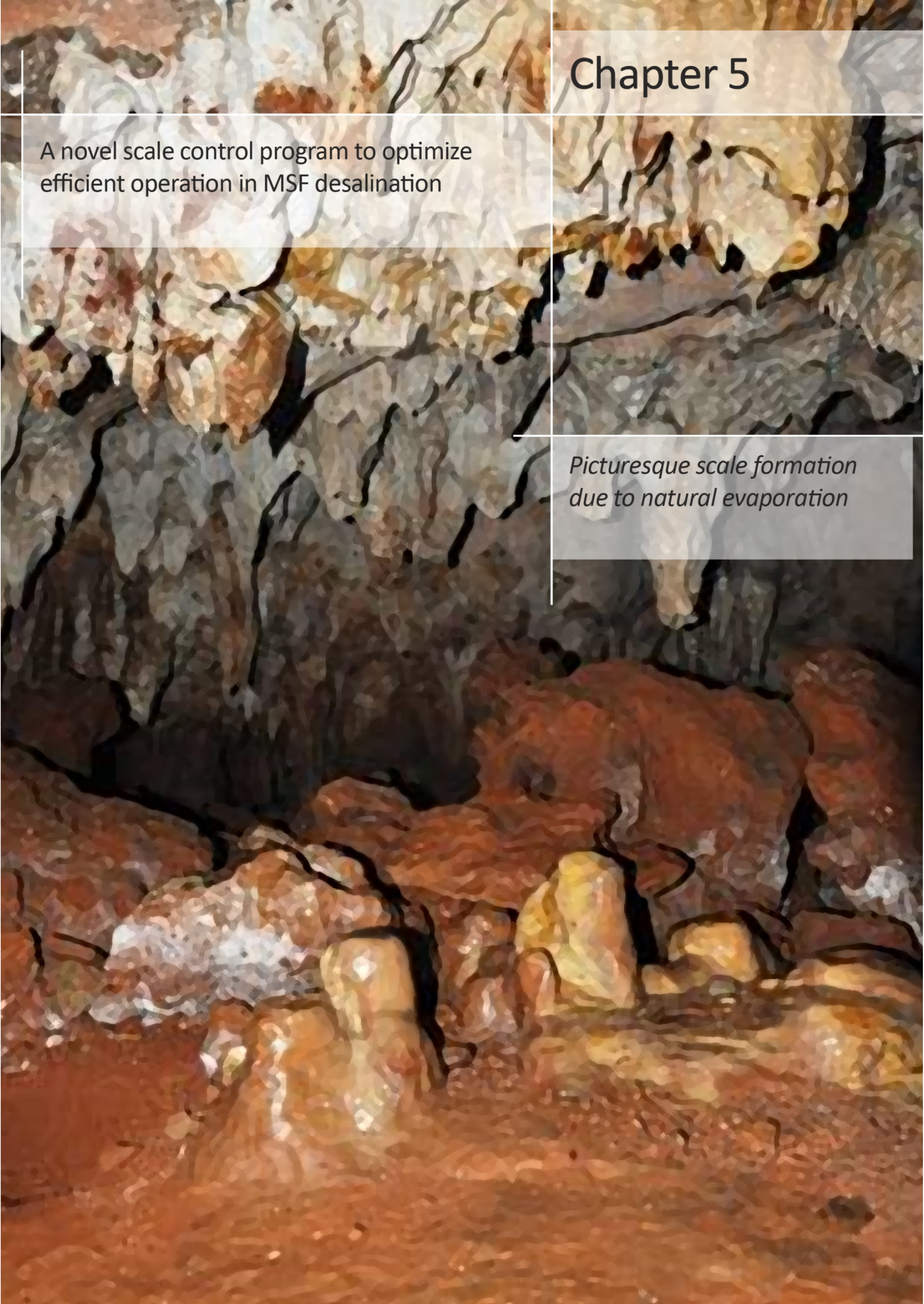
4.10. http://ocw.tudelft.nl/fileadmin/ocw/courses/SanitaryEngineering/res00057/embedded/Waterchemie.pdf

4.11. http://mathbio.colorado.edu/mediawiki/index.php/MBW:Role_of_Biofilm_Matrix_in_Structural_Development
4.12. http://67.53.90.3/Resources.cfm?doc_id=148
4.13. Betz Handbook of Industrial Water Conditioning 8th edition, Betz Laboratories, Inc., Trevose, PA, USA, 1980.
4.14. Marchena, F. A., Alberts, V. A., et al., “Strategic Quality Program: Basic Efficiency Control for Brine Recirculating MSF Desalination Units”, Caribbean Conference, June 19-21, 2002, Aruba.
4.15. Eimer, E., “Energetic Aspects of the Fouling of MSF Desalination Plants with and without the Use of on Load Ball Cleaning System”. Desalination, 40 (1982) 363-372.
4.16. Bidwell, J. R., Cherry, D. S., et al., “Comparative Response of the Zebra Mussel, *Dreissena polymorpha* and the Asiatic clam, *Corbicula flumina*, to the Molluscicide CT-1. Proceedings: Third International Zebra Mussel Conference, 1993, EPRI TR102077, 219-238.
4.17. Post, R. M., Lacey, J. R., “A Decade of Macro fouling Control Using Non-Oxidizing Compounds-An Industry Review”, EPRI Condenser Conference, August 28-30, 1996, Boston Massachusetts.
4.18. Post, R. M., “A review of freshwater Macrobiological Control Methods for the Power Industry”, 20th Annual Electric utility Chemistry Workshop, University of Illinois, Champaign, IL, May, 2000.
4.19. Marchena, F. A., Croes, G. B., Final Evaluation of the Biocide Trial on Aqua Chem Unit No. 5 (AC-5)”, March 09, 2000, W.E.B. Aruba N.V.
4.20. Wes, B., Reverse Osmosis, A Practical Guide for Industrial Users, ISBN 0-927188-03-1, Tall Oaks Publishing, Inc., Littleton, CO, USA, 1995.
4.21. Prato, T., Marchena, F. A., Schoepke, E. J., Resolution of Persuasive Biofouling Issues at W.E.B. Aruba N.V.’s Seawater Reverse Osmosis Plant., IDA Conference, Perth, Australia, 2011.
4.22. Membrane Autopsy Report, Avesta Technologies, Inc., USA, 2008.
4.23. Sheikholeslami, R., Fouling in Membranes and thermal Units, ISBN 0-86689-066-1, Balaban Desalination Publications, L’Aquila, Italy, 2007.
4.24. Meer van der, W. G. J., Mathematical Modeling of NF and RO Membrane Filtration Plants and Modules., PhD Thesis Technological University of Delft, The Netherlands, 2003.
4.25. Helm van der, A.W.C., Integral modeling of ozonation for optimization of drinking water treatment., ISBN 978-90-8957-001-7, Gildeprint Drukkerijen BV, PhD Thesis Technological University Delft, The Netherlands, 2007.
4.26. Prausnitz, J. M., Lichtenthaler, R. N., Gomes de Azevedo, E., Molecular Thermodynamic of Fluid Phase Equilibria., Englewood Cliffs, NJ, Prentice Hall, 1999.

4.27. Webb, W. G., Paul, D.H., Surface Water Reverse Osmosis System Biofouling, Ultrapure Water Magazine, Tall Oaks Publishing, Boulder, CO, November, 1994.
4.28. Ortega, C., Rossing, A., et al., On line Microbiological Control in Reverse Osmosis Systems, Ultrapure Water Magazine, Tall Oaks Publishing, Boulder, CO, October, 1997.
4.29. Prato, T., A Study of Biofouling in Reverse Osmosis: Modeling of Biofilm Growth in RO Cross flow Device Using Natural Organic Materials as Nutrient Source for Bacteria, MSC thesis Tufts University, September,2001.
4.30. Carnahan, R. P., Bolin, L., Suratt, W., Biofouling of PVD-1RO Elements in the Water Treatment Plant of the City of Denedin, Florida, Desalination Journal 102 (1995) 235-244.
4.31. Dunham, S. R., Kronmiller, D. L., Membrane Cleaning Under the Microscope, Water Technology Magazine, September, 1995, 81-83.
4.32. Knoell, T., Safarik, J., et al., Biofouling potentials of microporous polysulfone membranes containing a sulfonated polyether-ethersulfone/ polyethersulfone block copolymer: correlation of membrane surface properties with bacterial attachment, Journal of Membrane Science 157 (1999) 117-138, Elsevier Science B.V. Amsterdam.
4.33. Vrouwenvelder, J. S., et al., Manual Biofilm Monitor, KWR, Nieuwegein, The Netherlands, 2006.
4.34. Vrouwenvelder, J. S., Bakker, S. M., et al, The Membrane Fouling Simulator: a Suitable Tool for Predicting and Characterization of membrane fouling, Water Science & Technology Vol 55 No 8-9, 197-205, IWA Publishing 2007.
4.35. Vrouwenvelder, J. S., Van der Kooij, D., Integral Diagnosis of Fouling Problems by Analyzing Biomass and Inorganic Compounds in Membrane Elements used in Water Treatment, Water Science & Technology Vol 3 No 5-6, 211-215, IWA Publishing 2003.
4.36. Vrouwenvelder, J. S., Schippers J. C., Van der Kooij, D., Tools for Fouling Diagnosis of NF and RO Membranes and Assessment of the Fouling Potential of Feed Water, Desalination 157 (2003) 361-365.
4.37. Gudde, J. C. J., " Quantifying Serious fouling in the SWRO process at W.E.B. Aruba N.V., Internship & Internal Report W.E.B. Aruba N.V., June 10, 2009.

Chapter 5

A novel scale control program to optimize efficient operation in MSF desalination



Picturesque scale formation due to natural evaporation

Chapter 5

A novel scale control program to optimize efficient operation in MSF desalination

Table of Contents:

Abstract

Thermal desalination has been the most important promising and still the largest used technology to solve the increasing threatening water shortage problem in the world. Multi Effect Distillation (MED-) and Multi Stage Flashing (MSF-) desalination are the most used thermal desalination technology, MSF being the most dominant thermal process since the 1960s. To increase system efficiency, the trend in thermal desalination is to operate the systems at as high a temperature and concentration factor as possible to increase production and efficiency. Ever since their application, scale formation is one of the most critical problems affecting efficient and stable operations of both thermal processes. In MSF process the chemical compounds calcium carbonate, magnesium hydroxide and calcium sulfate are the most troublesome scale forming components. Due to the naturally high mineral content in seawater and the relatively high top brine temperature, steps have to be taken to avoid formation of scale on the heat transfer surfaces, including limiting the top brine temperature, controlling the recirculation brine concentration factor and pH. An effective scale inhibitor used since the 1960s in seawater desalination is concentrated sulfuric acid. Due to its corrosive, health and safety hazard characteristics research have concentrated for decades to minimize and replace the use of sulfuric acid as scale inhibitor. In this respect a novel multi component inhibitor program enabling operation of MSF evaporators at higher top brine temperatures and concentration factors without the need of acid feed for pH control has been develop by Betz in cooperation with the Desalination Department of W.E.B. Aruba N.V. Aspects of the experimental testing rig to simulate the MSF process in the laboratory, as well as the physicochemical parameters related to the mechanism of scale formation and prevention and the work done to eliminate the use of sulfuric acid as scale inhibitor leading to the development and the successful application of this novel scale inhibition technology will be discussed in detail in this chapter.

5.1 Introduction

Throughout its seawater desalination history, W.E.B. Aruba N.V. has been a pioneer in the support and the implementation of innovative state of the art technology to cope with the physicochemical aspects to optimize desalination efficiency. The most important physicochemical aspects include the control of the foaming tendency of seawater, the control of biological fouling as elaborated in detail in the preceding chapter and the control of scaling and the physicochemical deposition on the heat transfer surfaces in thermal desalination technology, in particular the MSF brine recirculation evaporator, the main topic of this chapter. This thermal desalination technology, the world's dominant desalination technology since 1960s, represents 100% of the total desalination production technology of Aruba from 1983 to 2008 and since March 2008, 82 % and by the end of 2012 only 27.3 % of the desalination production capacity as referred to in Chapter 2 [5.1].

In this MSF desalination process, recirculation of a portion of the brine mixed together with the seawater make-up flow and operation at a high top brine temperature are essential means to increase water production and efficiency. The brine recirculation results in a higher concentration factor and in combination with higher top brine temperature more distillate can be produced from a given amount of seawater, however, scale formation and fouling has been a limiting factor for higher distillate recovery due to higher chemical saturation of the brine circulation.

Seawater with a higher concentration factor will have higher supersaturation of dissolved salts and higher suspended solids in recirculation acting as useful nucleation sites promoting the precipitation of supersaturated salts forming deposits on heat transfer surfaces.

Deposition on surfaces can be classified as scaling and fouling. Scale formation in seawater desalination is in particular the result of the precipitation from solution from supersaturated salts such as calcium sulfate, calcium carbonate and magnesium hydroxide. Fouling on the other hand is specified as a result of the settling of suspended solids that are present in the seawater such as silt and corrosion by-products on the heat transfer surfaces [5.2].

Precipitation from the seawater of any scale forming salts occurs only if a supersaturation state with respect to that salt is achieved. This state can be reached by increasing temperature, by increasing the pH and by increasing the concentration factor of the seawater in the desalination system. The degree of supersaturation is an excellent indicator for the scaling tendency of the seawater. This can be expressed by the supersaturation ratio which is defined by the ratio of the activity product of the lattice ions of the scale forming salt at supersaturation with respect to the activity of lattice ions at saturation [5.3]. Actually this ratio gives an indication of the effective concentration difference of subsequent ions, the driving force for mass transfer from the liquid phase to the solid phase also know in distillate mineralization process as the *Driving Force Index* (DFI) [5.4].

Scale inhibitors and dispersing agents are normally used to prevent deposition on heat transfer surfaces. Scale inhibitors control precipitation from solution and dispersants

prevent the settling on surfaces of any solid material present in the solution. In the case of an MSF evaporator, deposition is usually prevented by adding an inhibitor to prevent scale formation and either maintaining a low concentration factor and low top temperature than design or combining inhibitor with acid dosing. Acid dosing prevents seawater from becoming supersaturated with respect to calcium carbonate by reacting with bicarbonates to produce carbon dioxide gas that is vented out in the degasification unit and to maintain neutral pH to inhibit magnesium hydroxide precipitation. Temperature and concentration factor is also controlled to ensure that calcium sulfate supersaturation is maintained in the range in which the inhibitor is effective. As already mentioned in Chapter 4 also an online sponge ball cleaning technology is used as a means of physical mechanical control of fouling and scaling [5.5]. For an inhibitor to be effective, a surface-inhibitor structure relationship must exist. Molecular functional groups in the inhibitors as well as the inhibitor molecule size and geometry play an important role on the orientation and adsorption of the inhibitor molecule on the surface active sites. These were the factors that were considered during the development of the new program to control scale on the heat transfer surfaces of the MSF evaporator without the need to use concentrated sulfuric acid [5.6].
For safety, health and environmental reasons elimination of concentrated sulfuric acid dosing has become desirable in MSF application however this increases the potential for calcium carbonate and magnesium hydroxide scale deposition. The conventional scale inhibition technology available in the market place can control scale deposition without acid feed only if the MSF evaporator are run at concentration factor and temperature lower than those experienced with acid feed scale inhibition control. This leads to dramatic reduction of the water production and efficiency of the MSF evaporator. When acid feed is eliminated, magnesium hydroxide and calcium carbonate scale are the main concerns. Available products may inhibit calcium carbonate, however, magnesium hydroxide has been the limiting factor on increasing concentration factor and temperature and pH. In this chapter the development and application of the innovative scale and fouling control program is presented as developed by Betz for the MSF evaporation process in Aruba. This program is also developed to allow MSF evaporators to run at higher concentration factor of 1.75 and higher top brine temperature up to 120 ^{0}C [5.6].

5.2 Toward an effective scale inhibition technology

Scale inhibition history of W.E.B. Aruba N.V.

Scaling in those early pioneering days of thermal desalination due to thermal decomposition of bicarbonates in seawater resulting in reduced availability and unsustainable desalination process was of major concern and a lot of research has been done since then to cope with this problem. In the initial years of thermal desalination removal of scale was done by thermo shock or by hammer and chisel [5.1]. Thermo shock was achieved by alternately permitting hot steam and cold water to flow through the tube bundle. Tube contraction and expansion has the effect of crack-loosening the scales and deposits from the surfaces. This physical mechanical approach of scale control has been practiced in Aruba from 1933 to 1958.

In 1958 the first chemical scale treatment program, the dosing of a solution of ferric chloride ($FeCl_3$) became available after intensive research done by WEIR Inc. in Aruba and Curacao [5.7]. This chemical inhibition technology is based on the predominantly formation of ferrous hydroxide, $Fe(OH)_3$, instead of magnesium hydroxide. Ferrous hydroxide resulted to have the specific property that it stays suspended in the brine flow and does not form a tenacious deposit on the heat transfer surfaces such as magnesium hydroxide and is transported out of the evaporator with the brine blowdown flow. The ferric chloride scale inhibition process proceeds according to the following chemical reactions:

High temperature carbonates reaction:

$$CO_3^{2-} + H_2O \iff CO_2\uparrow + 2OH^- \quad (5.1)$$

High temperature ferric hydroxide formation:

$$FeCL_3 \iff Fe^{3+} + 3Cl^- \quad (5.2)$$

$$2\,OH^- + Mg^{2+} \iff Mg(OH)_2\downarrow \quad (5.3)$$

$$3OH^- + Fe^{3+} \iff Fe(OH)_3\downarrow \quad (5.4)$$

The chemical reaction of ferric hydroxide formation (5.4) is kinetically faster and predominates and prevents the magnesium hydroxide scale formation on the heat transfer surfaces. This technology has been worldwide first applied in Aruba and Curacao in the WEIR MED evaporators [5.8]. In Aruba from 1958 to 1963 ferric chloride was produced on site through an innovative electrochemical process in which a dilute solution of hydrochloric acid and seawater was electrolyzed with iron and carbon electrodes. It seems that using special iron from Scotland as electrode the process was working good but when at the long run the iron was changed with cheaper iron available on the market, poor operation was experienced and also chlorine gas was then produced which caused a poor working environment leading for the search for alternatives [5.1].

This ferric chloride scale control program lasted till 1963 in which year it was replaced by the use of 98% concentrated sulfuric acid as scale inhibitor. First experiments with the dosing of concentrated sulfuric acid were performed on site assisted by secondary technical school internship students [5.9]. The concentrated sulfuric acid dosing was used successfully from 1963 to 2007 and W.E.B. Aruba N.V. was the first commercial desalination facility to use this scale control program [5.10]. Sulfuric acid is very corrosive and a potential health and safety hazard and therefore in 1991 W.E.B. Aruba N.V. started again to look for alternatives. Already in 1983 an attempt was made to eliminate the use of sulfuric acid. The MSF evaporator Aqua Chem#2 was designed in 1983 to operate on 100% high temperature antiscalant. The venting space and vacuum system was adequately designed to handle the additional amount of carbon dioxide generated more intensively without the use of sulfuric acid by thermal decomposition of bicarbonates in the high temperature evaporation compartments. Already in the first week of initial startup unstable operation was experienced due to gas blanketing on the heat transfer tubes and scaling in the long tubes of the high temperature vessels [5.11]. Since then this evaporator went in operation with traditional sulfuric acid dosing. In 1991 to 1994 a combined acid dosing and a high temperature antiscalant, Belgard EV™ from the chemical supplier FMC Corporation Ltd., was used as scale inhibitor. Although decreased corrosion in the evaporators was experienced this combined dosing was terminated due to poor performance as a result of brine heater fouling. It should be mentioned that this scale control program actually required periodically acid cleaning which was not allowed by W.E.B. Aruba N.V. according to the objectives of the trial. This unsuccessful trial with the Belgard EV ™ ultimately induced the conviction that to successfully eliminate sulfuric acid an effective scale inhibitor should have a multi component inhibiting effectiveness to handle not only calcium carbonate scaling but also magnesium hydroxide and calcium sulfate scaling. All existing scale inhibition technologies at that time were based on coping with the formation of calcium carbonate. Adsorption of the antiscalant molecules on the surface of formed calcium carbonate crystals will inhibit the further decomposition to magnesium hydroxide due to steric hindrance. Practical experience with scaling in the MSF evaporators has demonstrated this general accepted theory not to be true. In 1994, unofficially Betz Inc. was asked to develop an innovative antiscalant that can cope with this three scaling forming components. In 1997 Betz Dearborn proposed an antiscalant that can cope with all three scaling component but in a combined dosing with sulfuric acid. As per Betz Dearborn it is practically impossible for 100 percent elimination of sulfuric acid as scale inhibitor. The conviction that it is possible to develop an effective antiscalant for elimination of sulfuric acid using an MSF pilot plant is explained to the representatives of Betz. In 2001 Betz has indeed proposed an innovative HT 20 antiscalant to eliminate sulfuric acid at a dosage of 10 ppm. This proposal was disapproved by Management of W.E.B. Aruba N.V. based on economic reasons. Calculation made, based on received operation data of a once through MSF evaporators in Malaysia [5.12], showed that this antiscalant should work at a break even dosage of 6 ppm which was accepted by the Management of W.E.B. Aruba N.V. after convincing them to change their policy about traditional application of trials that only proven technologies is acceptable, on the term to be willing to accept total accountability and responsibility for possible negative trial results. Eventually, in 2002 a trial was initiated with the HT 20 high temperature antiscalant at a dosage of 6 ppm. According to Betz research the HT 20 based on the poly acrylic technology as scale inhibitor was at that time more effective to cope with magnesium hydroxide than Belgard EV ^{TM} which was based on the poly maleic acid's scale inhibition technology. The experience gained with this trial has promoted the development of an even more effective antiscalant to effectively eliminate the sulfuric acid dosing. Finally in 2004 an alternative was found for the sulfuric acid dosing after an eight month successful trial of 100% high temperature antiscalant resulting in 2007 in the total elimination of the sulfuric acid after approximately forty years of usage as scale inhibitor. Table 5.1 illustrates the scale inhibition history of W.E.B. Aruba N.V. [5.13].

Table 5.1: Scale inhibition techniques used at W.E.B. Aruba N.V. from 1933 to 2007 [5.13]

Period	Scale inhibition technics
1933 - 1958	Thermo shock of the heat transfer coils; removal of scales with hammer and chisel
1958 - 1963	Dosing of $FeCl_3$; on site production of ferric chloride; electrolysis of hydrochloric solution with iron electrodes.
1963 - 2007	Dosing of 98% concentrated sulfuric acid
1991 - 1994	Combined dosing of sulfuric acid and Belgard EV^{TM} (AC#2, AC#3 and AC#4)
2004	Dosing of 100% Betz's HT 15^{TM} antiscalant at AC#5; technical successful trial
2006 - 2007	Elimination of sulfuric acid with 100% HT 15^{TM} antiscalant

The attempts to eliminate the use of sulfuric acid

In 2001 Management was convinced to approve a 6 month trial with the new antiscalant Aqua Max^{TM} HT 20 with a dosing rate of 6 ppm active component to eliminate the use of concentrated sulfuric acid as scale inhibitor. Management also changed their policy about trial, opening the way for testing new non-proven technology and to support further development of an effective technology to eliminate the sulfuric acid use because of safety, health and environmental reasons. The goal of the trial was to achieve an "acid like" performance meaning the same acid operation cost including the same maintenance and energy efficiency performance. A serious accident with concentrated sulfuric acid on March 30, 2000 during unloading at the Aqua Chem#1 further facilitated management approval. In Figure 5.1 two pictures are shown of the serious accident where fortunately no one was seriously injured. During the unloading of sulfuric acid the unloading hose of the truck ruptured causing a serious sulfuric acid leakage.

a: vessels' surface corrosion b: acid spill and corroded vessel

Figure 5.1: Serious accident at AC#1 during sulfuric acid unloading

In this section a short description of the Aqua Max ™ HT 20 trial and the Aqua Max ™ HT 40 trial will be given. These trials were partially successful however experience and understanding and further insight have been acquired enabling the further development of the successful innovative high temperature antiscalant as will be described in section 5.4. Aqua Chem#5 as explained in Chapter 4 had a tremendous performance after the biocide trial and it was agreed upon by W.E.B. Aruba N.V., Betz Inc. and Aqua Chem Inc. to use the performance ratio of the period of November 15, 2000 to October 19, 2001 on sulfuric acid dosing and the biweekly Clam Trol CT-2™ dosing for marine biological control as reference efficiency performance indicator for the trial. Further the following key operational condition and performance indicators were specified and agreed upon.

Key Operation Conditions

Top Brine Temperature	110 ^oC
Aqua Max™ HT 20 dosage	6 ppm
Concentration factor	1.75

In Table 5.2 the key performance indicators to be met after 182 days of operation on additive dosing are illustrated [5.14].

Table 5.2: Key Performance Indicators after 182 day on Aqua Max ™ HT 20

KPI	Method	Target
Efficiency	Performance ratio (moving average)	> 9.2
Distillate Production	Total production from SOR* to EOR**	>1,092,000mT
Plant Corrosion rate	Fe, Cu in total distillate	< 10 ppb Fe < 20 ppb Cu
Acid cleaning	Online	None
Distillate Quality	W.E.B. Aruba N.V. standards	Meet Quality specs
Distillate production cost	W.E.B. Aruba N.V. production cost calculation	Equal to acid

**SOR = Start Of Run; **EOR = End Of Run*

Pre-trial modifications

Although the venting system since the construction of the Aqua Chem# 2 in 1983 was improved for additive dosing, Aqua Chem Inc. was requested to evaluate the venting system for further improvement.

Before the trial in cooperation with Aqua Chem Inc. a modification of the venting system was approved and implemented to improve venting of the higher temperature evaporation stages 1 to 12 to cope with the expected more pronounced carbon dioxide gas liberation due to thermal decomposition of the bicarbonates especially in the stages 1 to 6 [5.15]. With acid dosing most of the bicarbonates react with acid in the make-up seawater flow and the produced carbon dioxide gases are vented out in the degasifying section of the MSF evaporator before entering the evaporation section. In Figure 5.2 the modified vacuum system is illustrated. After stage 6 and stage 12 in the common vacuum system of the MSF evaporator (indicated with the red color in Figure 5.2) additional vent bypass lines with block valves were installed and connected to the vent line from stage 8 directing the non-condensable gasses to the intercondenser of the ejector stages. In Figure 5.2 these vent bypass lines are indicated with the black color.

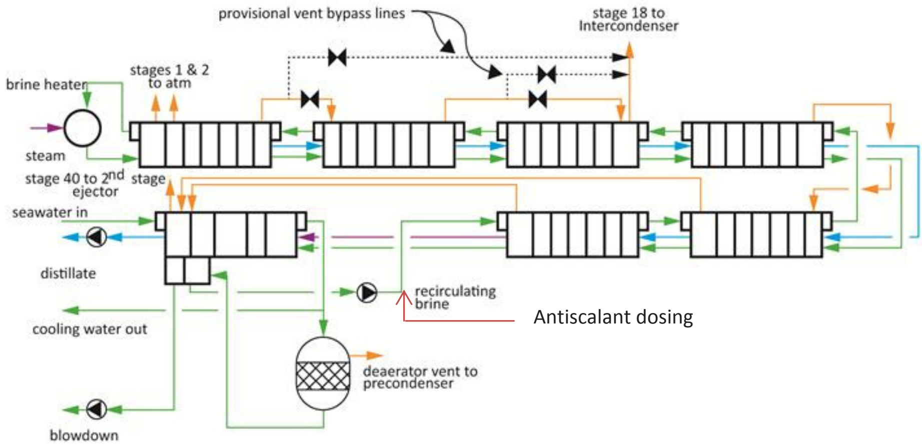


Figure 5.2: The modified vacuum system of the MSF evaporator

The high temperature antiscalant as agreed upon is to be dosed, as indicated in Figure 5.2 in the recirculation brine before entering the heat recovery section of the MSF evaporator. A major problem that had to be resolved before the startup of the trial was a major drawback of the Betz's Pace Setter computer controlled chemical dosing system not being designed with the option for automatically pick in of the redundant pump whenever the operating dosing pump failed which should be detrimental for continuous scale free operation of the evaporator. On perseveringly request and as proposed this problem has been solved and nowadays all Pace Setter systems work with this new feature.

The Aqua Max ™ HT 20 trial performance

With the venting system and the computer controlled chemical dosing system modified the 6 ppm HT 20 trial started on December 05, 2001. During the trial it was evident that this new product has good inhibition control for calcium carbonate, calcium sulfate but a very low inhibition efficacy for magnesium hydroxide. Immediately after startup of the trial the brine heater pressure slowly went up indicating fouling and scaling. Although the brine heater was fouling, the MSF evaporator had a stable operation and a high water production. This was encouraging to continue the trial to further investigate and evaluate the possibility to improve the scale control capability. By switching to acid dosing for 5 days, which actually can be considered as a mild acid cleaning, the high performance was achieved by cleaning the brine heater, a firm indication that high temperature magnesium hydroxide scale was formed and fortunately not the persuasive mild acid-insoluble calcium sulfate. From April 22, 2002 to August 22, 2002 the antiscalant dosage was increased to 8 ppm to evaluate if at this concentration a higher efficacy to control magnesium hydroxide scaling is achievable. Also with the increased dosage the performance was the same. In Figure 5.3 the accumulative performance ratio of the 8 month trial is illustrated.

The accumulative performance ratio was introduced in cooperation with the Engineering Department as an effective tool to evaluate the trial.

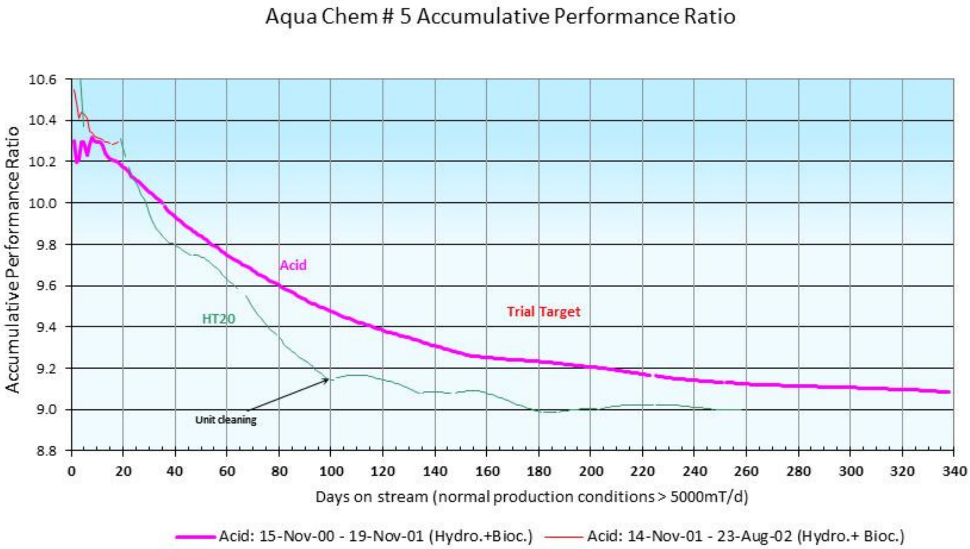


Figure 5.3: The accumulative performance ratio of Aqua Chem#5 on the HT 20 dosing during the trial

The accumulative performance ratio (TPR_t) was defined as the ratio of the total trial-start up -to-date production and low pressure steam consumption at the agreed upon key operational conditions (as indicated in the previous section) and production above 5,000 mT distillate. The reference TPR_t as indicated in Figure 5.3 for Aqua Chem#5 on acid treatment after 6 months of normal operation is TPR_{182} = 9.2. As also can be observed in Figure 5.3, the TPR_{182} for HT 20 dosing is 9.0 which included one off line cleaning, four mild acid cleaning and periods of internal circulation which also had a cleaning effect on the brine heater. In Figure 5.4, the daily performance ratio is given with the different on line mild acid cleanings and off line heater inspection and cleaning. To maintain stable operation and pressure and temperature of the condensing low pressure steam in target, the MSF evaporator was put on acid dosing for 5 to 7 days. By dissolving the magnesium hydroxide scaling with the acid dosing the performance ratio increased back to 10.1-9.6 as can be seen in Figure 5.4.

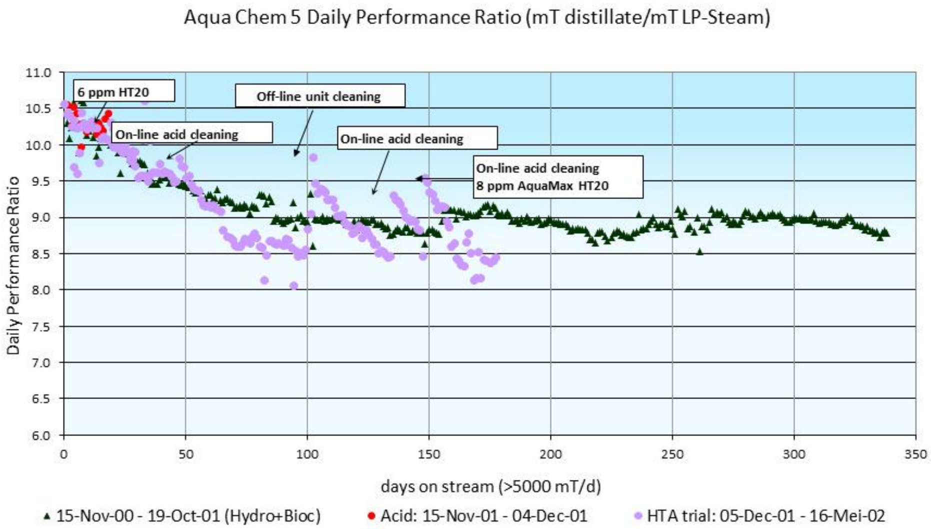


Figure 5.4: The daily performance ratio of Aqua Chem#5 on the HT 20 dosing during the trial

The Aqua Chem#5 trial started after a GI and hydrolase-cleaning of the plant. In the first 20 days after start up baseline corrosion data of vent and distillate were obtained with acid dosing. The TPR_{20} on acid was 10.3 compare to the reference TPR_{20} of 10.2. Since practically fouling in the first 15 days is very important for a MSF evaporator performance together with the Engineering Department a *Performance Decay Indicator* (PDI) is introduced and calculated for every significant change such as product, dosage or cleaning by plotting. The PDI is based on the natural logarithmic regression using the following formula:

$$TPR_t = TPR_{sor} * \exp(-Ct) \tag{5.5}$$

Where TPR_{sor} = the TPR at start of run.

To calculate the PDI the Ln (TPR_t/TPR_{sor}) versus time t is plotted.

In Table 5.3 the PDIs are given for the acid dosing, Aqua Max ™ HT 20 dosing at 6 ppm and at 8 ppm.

Table 5.3: The Performance Decay Indicator for the different treatments

Treatment	Dosage (ppm)	PDI
Acid	110	15
Aqua Max ™ HT 20	6	30
Aqua Max ™ HT 20	8	40

As can be seen in Table 5.3 the performance decay due to fouling of Aqua Max ™ HT 20 at 6 and 8 ppm dosage is 2 to 3 times faster than with acid dosing. This similar trend is confirmed with the temperature and pressure increase of the brine heater as illustrated in Figure 5.5.

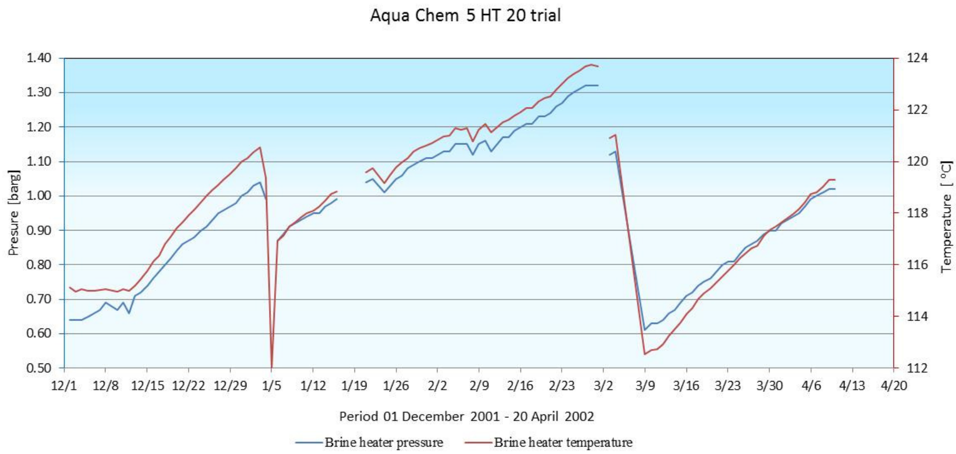


Figure 5.5: The increase of the temperature and pressure of the brine heater

Vent side corrosion

Together with representatives of Aqua Chem Inc. an extensive study has been done to evaluate the vent side corrosion in the MSF evaporator. It was necessary to design special sampling system to take sample from the stages under vacuum. A special corrosion rack and cooler combination has been installed at the venting of the first stage as is illustrated in Figure 5.6.

Figure 5.6: The vent side corrosion monitoring system at Aqua Chem#5

Actually vent side corrosion was always a significant problem in MSF evaporator [5.15]. With additive dosing as already mentioned above this can be more pronounced due to the intensified liberation of carbon dioxide because of thermal decomposition of calcium bicarbonates normally present in seawater [5.16]. The results attained in cooperation with Aqua Chem Inc. are as follows [5.17]:

- Vent condensate is more acidic with a pH of 4.0-4.5 and a concentration of 40-120 ppm CO_2
- Distillate pH measurements show very low level of CO_2, level of iron and copper shows constant reading throughout the trial
- Corrosion coupons test in the vent system indicate corrosion only on carbon steel material in the range of 10 mils per year (1 mpy = 0.001 inch per year). The 90-10 Cu Ni and the 316L SST corrosion coupons show no weight loss

Improvement of the dosing system

Evaluating the MSF evaporator operational performance during the trial more closely, brought up the suggestion to install a second dosing point at the entrance of the highest temperature vessel 101 to cope with heavy deposits on the heat transfer tubes of the brine heater. The second dosing point with the Aqua Max ™ HT 20 product showed a moderate improvement. Practical operational experience directed the conclusion that the Aqua Max ™ HT 20 product has in addition to poor efficacy for inhibiting magnesium hydroxide scaling also a poor dispersing capacity.

The chemical supplier was requested to improve the additive with a component with a higher efficacy for inhibiting magnesium hydroxide scaling and mixed with a better dispersant. This dispersing component should be dosed at the second injection point to cope with precipitation on the heat transfer surfaces in the higher temperature stages and in the brine heater.

Summary of the Aqua Max ™ HT 20 trial

- The plant had throughout the trial a stable operation with only increase in brine heater temperature and pressure
- The Aqua Max ™ HT 20 had a good inhibition efficacy for calcium sulfate and calcium carbonate scaling
- The Aqua Max ™ HT 20 had a poor efficacy for magnesium hydroxide scale control
- The Aqua Max ™ HT 20 had a poor dispersing capacity especially for magnesium hydroxide particles
- The average moving performance ratio was 9.0 and lower that the trial target performance ratio of 9.2
- Overall distillate production was 103.1 % of design

- The availability of the evaporator was 95.7%, which is less compared to acid dosing with a 100.6 % availability, due to the mild acid cleanings and off line cleaning
- The modified venting system has performed well for corrosion and plant stability; operation with the non-modified system resulted in unstable operation

Based on the results of the trail Management was persuasively advised and encouraged to make the important decision to continue research to develop an optimal working additive.

A reformulated additive

Based on the results of the trial the chemical supplier proposed a new formulated acidic additive to cope with the magnesium hydroxide scaling. During practically two week dosage of this new product the dosage was stopped due to poor performance. Betz was requested and recommended to design and to implement a MSF pilot plant for further research because testing in conventional autoclave bomb (lab scale high pressure reactors) even under stringent severe condition do not simulate heat and mass transfer dynamic conditions as in MSF evaporation operational practice. Also the dispersing and magnesium scaling inhibition should be addressed. The recommendations to build a MSF pilot plant and to further improve the magnesium hydroxide inhibition potential of the antiscalant were accepted and new intensified research has led to the development of an effective innovative high temperature additive as will be explained in detail in the following section after an introduction of some theoretical aspects of scale inhibition.
An important step is a thoroughly comprehension of the theoretical and practical aspect of scaling and fouling and the recommendation was a scientific approach considering this process as separate physicochemical adsorption phenomena. This theoretical concept will be further elaborated on in the following section.

5.3 Theoretical aspects of scale formation, fouling and inhibition

The chemical aspects of scale formation in MSF evaporators

The objective of this section is to give an introductory general description of the physical and chemical aspects of scale inhibition, since bulk chemical precipitation, adsorption, dispersants, surfactants, crystal growth, surface thermodynamics are mature technological theoretical sciences on their own. Detail description of these very important broad physicochemical subjects goes beyond the scope of this thesis. As already mentioned above desalination is the process of removing salt from seawater or brackish water to produce fresh water. This process can be accomplished thermally by the sequentially repetitive evaporation and condensation process or by means of the application of the reversed osmotic separation process through membranes. The two most common types of thermal desalination are the MSF and the MED. Both configurations use steam to heat up the influent seawater in sequential chambers to increase the heat transfer efficiency. One important parameter that set these two processes apart is the top brine temperature. In MED evaporators the top brine temperature are in the range of 70 to 90 ^oC while in the MSF evaporators the temperatures are typically from 90 to 115 ^oC. Research is momentarily going on especially in the Middle East to increase the top brine temperature to as high as 130 ^oC by applying nanofiltration membrane technology to reduce the calcium carbonate and sulfate of the seawater feed [5.18].

Scale formation in thermal desalination

Since MED and MSF are both thermally driven processes, increasing the steam temperature within their normal operating range produces more distillate. However, the top brine temperature of any given unit is limited in order to control or avoid formation of scale on the heat transfer surfaces. While most substances are more easily dissolved in higher temperature, the calcium carbonate and magnesium hydroxide naturally contained in seawater exhibit a retrograde solubility, as illustrated in Figure 5.8 [5.19]. As the brine temperature increases the solubility of compounds such as calcium carbonate and magnesium hydroxide decreases. The resulting scale accumulates on heated surfaces and disrupts heat transfer.

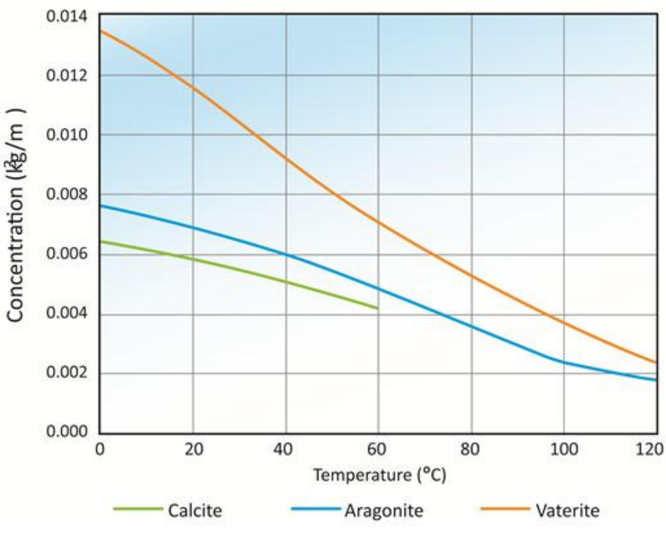


Figure 5.7: The retrograde solubility of calcium carbonate [5.19]

When seawater is distilled, the process produces fresh water and concentrated brine. Similar to the top brine temperature, raising the level of brine concentration increases the distillate yield from the incoming seawater. The cycle of concentration, also known as concentration factor, describe how many times the seawater has been concentrated before

it leaves the evaporator. The concentration factor in some MED units can reach 2.0 while most MSF recirculation units operate below 1.5. In general MED units tend to operate at a higher concentration factor due to the lower brine temperatures in which they run. Bicarbonates present in seawater decompose at high temperature and form carbonates and magnesium hydroxide scale on the heat transfer surfaces in the brine heater and high temperature vessels reducing efficiency. The decomposition and scale formation occurs according to the following chemical reactions [5.1];
At temperature lower than 82°C calcium carbonate formation predominates;

$$2\ HCO_3^- + heat <=> H_2O + CO_2\uparrow + CO_3^{2-} \quad (5.6)$$

$$CO_3^{2-} + Ca^{2+} <=> CaCO_3\downarrow \quad (5.7)$$

At temperature higher than 93°C magnesium hydroxide formation predominates;

$$CO_3^{2-} + H_2O \quad <=> CO_2\uparrow + 2OH^- \quad (5.8)$$

$$2\ OH^- + Mg^{2+} <=> Mg(OH)_2\downarrow \quad (5.9)$$

The chemical reactions of the thermal decomposition of bicarbonates and mass transfer controlling CO_2 desorption in the brine recirculation in MSF evaporators has been described in detail by Glade [5.16]. Calcium carbonate scales is the primary scale formed in MED units where the top brine temperatures are usually below 90°C.
As heat is applied to the brine, bicarbonate alkalinity decomposes to form carbonate ions according to the chemical equation (5.6). The carbonate ions then react with calcium ions present in the seawater to form calcium carbonate according to the above chemical reaction (5.7). At higher brine temperature, such as found in MSF evaporators, the carbonate ions react further with water producing CO_2 and hydroxyl ions according to the chemical equation (5.8). The magnesium ions in seawater can then react with hydroxyl ions, according to the chemical equation (5.9) to form magnesium hydroxide. In Figure 5.8 the scaling diagram of magnesium hydroxide, calcium carbonate and calcium sulfate is illustrated as function of temperature.

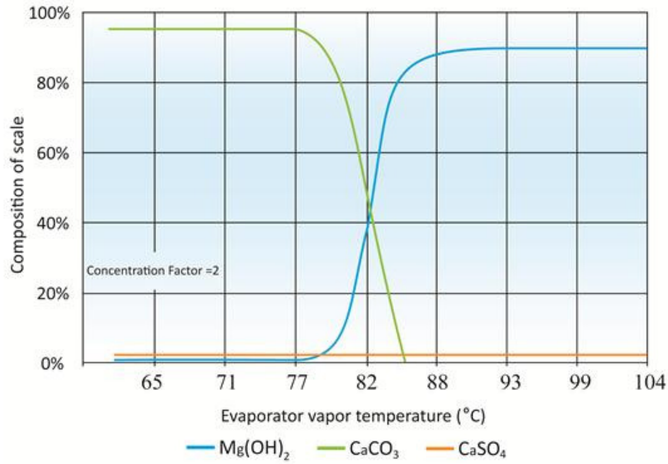


Figure 5.8: The scaling diagram of magnesium hydroxide as function of temperature [5.7, 5.27]

Another type of scale that can be formed in high temperature seawater desalination is calcium sulfate. This is a very complex process in which at least 5 solid forms are involved [5.20]. Already in 1920s, especially by Hall and Partridge [5.21] intensive research has been done to unravel the complex precipitation process of calcium sulfate. Calcium sulfate can precipitate in three different forms which have different rates of formation and can transpose in one form to another even after they have been formed; anhydrate, hemi hydrate and dehydrate or gypsum. In Figure 5.9 the scaling diagram of the different calcium sulfate crystal forms is shown.

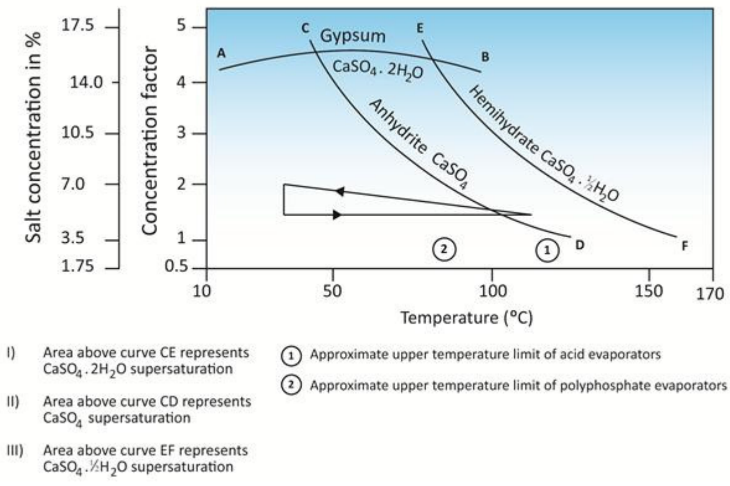


Figure 5.9: The scaling diagram of calcium sulfate forms as function of Concentration Factor and temperature [adapted from 5.10]

The development of scale inhibitors

The first chemical antiscalant developed in the 1950s is the use of Ferric Chloride ($FeCl_3$) as a scale inhibitor based on the fact that ferric ions will react more rapidly with hydroxide ions to form iron hydroxide that is less susceptible to deposit on the heat transfer surfaces and will be transported out of the evaporator with the brine blowdown flow. In the 1960s the use of sulfuric acid and hydrochloric acid became more competitive as economical effective high temperature scale inhibitors in commercial desalination. Large quantities of these inorganic acids were needed because of the stoichiometric characteristic of their inhibition activity.

Guided by the scientific development and comprehension of the threshold activity of dispersive and crystal distorting properties of certain specific organic chemical components further research contributed to the development of high temperature antiscalant such as hydroxyethylidene-1,1-diphosphonic acid (HEDP), 2-phosphonobutane-1,2,4-tricarboxylic acid (PBCTA), polyacrylic and polymaleic acid all of them with a certain potential to control calcium and magnesium carbonate scaling in thermal desalination processes [5.5]. In Figure 5.10 and Figure 5.11 the scale formation tendency of calcium carbonate and magnesium carbonate are illustrated as a function of pH, temperature and cycle of concentration with HEDP as a scale inhibitor. It is obvious that at low pH and low temperature a good scaling control is obtainable with 2 ppm HEDP for calcium and magnesium carbonate. However this graph also indicates that at operation condition as usable in MSF evaporators with a top brine temperature of 110 ^{o}C and the pH of the recirculating in the range of 8.86 -9.1 the solubility of calcium and magnesium are in the red zone indicated problem with excessive scaling and where the antiscalant HEDP is not effective anymore.

S($CaCO_3$) is the supersaturation of $CaCO_3$ and has a value of one when there is enough Ca^{2+} and CO_3^{2-} ions in solution to form a precipitate. At a value of S($CaCO_3$) = 200 the ionic concentrations add up to 200 times the minimum solubility product of 1 and precipitation occurs rapidly not only because of the high ionic concentration but also the increased residence time. The chemical precipitation kinetics depends on both concentration and residence time.

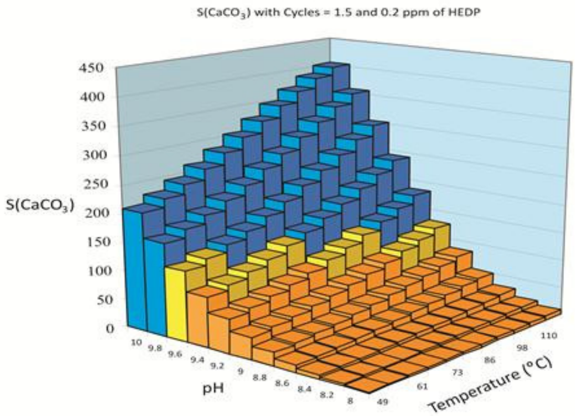


Figure 5.10: The Scaling diagram of Calcium carbonate as function of pH, temperature and cycle of concentration [5.27]

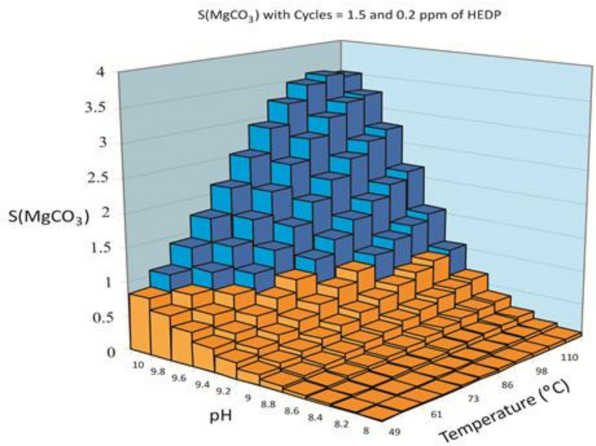


Figure 5.11: The Scaling diagram of Magnesium carbonate as function of pH, temperature and cycle of concentration [5.27]

As mentioned above calcium sulfate scale formation is a very complex phenomenon. In seawater MSF operations the prevalent form that first crystallizes is the hemihydrate because its nucleation time is shorter than the anhydrite form [5.10]. The hemihydrates actually form nuclei for the precipitation of the anhydrite form. Some organic phosphonates have been developed to inhibit this form of calcium sulfate scale [5.22]. Unfortunately it is practically impossible to develop a universal scale inhibitor because all scaling crystallites have different crystal surface lattice structures which are the predominantly geometrical structural characteristic determining scale inhibition effectiveness. Precipitation of supersaturated chemical components occurs especially in the bulk of the liquid and the particles are transported to the heat transfer surfaces where they deposited and form scales reducing heat transfer. In the following section the deposition process of scaling and fouling on heat transfer surfaces is in some detail described.

The physicochemical aspects of the fouling deposition process

The scaling and fouling of heat transfer surfaces can best be describe as a physicochemical deposition process where suspended solids such as silt and precipitated chemical components are transported to the surfaces where they are deposited. In the preceding section a detailed description has been given of the temperature aspects of scaling due to the thermal decomposition of bicarbonates in MSF desalination operation. Another important factor is the concentration aspects of seawater. Seawater evaporators with a higher concentration factor will have higher supersaturation of dissolved salts and higher suspended solids in the recirculation brine. In seawater desalination scale is the result of the precipitation from solution from calcium sulfate, calcium carbonate and magnesium hydroxide. Conversely fouling is a result of the settling of suspended solids that are present in the seawater such as silt, biological growth, dirt, dust, corrosion by-products and water-borne sediments on the heat transfer surfaces [5.5]. Precipitation from the seawater of any scale forming salts occurs only if a supersaturation state with respect to that salt is achieved. This state can be reached by increasing temperature, by increasing the pH and by increasing the concentration factor of the seawater in the desalination system. The degree of supersaturation is an excellent indicator for the scaling tendency of the seawater. This can be expressed by the supersaturation ratio which is defined by the ratio of the activity product of the lattice ions of the forming salt at supersaturation with respect to the activity of lattice ions at saturation [5.3]. In the special case of calcium carbonate scaling potential especially in drinking water corrosion inhibition this ratio is well known as the *Driving Force Index* (DFI) [5.6].

The Crystal growth process

Very important in the precipitation process is the crystal growth process from the initial phase of embryo formation to the nuclei phase reaching a certain critical radius where the thermodynamic potential favors further growth of the crystal as indicated in Figure 5.12.

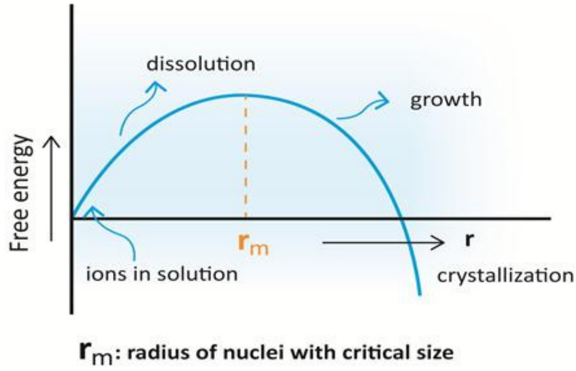


Figure 5.12: The crystal growth process [5.23]

As can be seen from Figure 5.12 supersaturated solutions are meta-stable with respect to nuclei with a critical size. Below this critical size r_m the nuclei, the embryos, will dissolve and beyond this critical size the nuclei will grow to form crystal with larger particle diameters. The critical nuclei size can be calculated by elementary thermodynamic [5.23]. In a thermodynamic system where suspended solids are in equilibrium with their surrounding saturated solution the chemical potential μ_l and μ_s of the saturated solution and solids are equal. A certain state of supersaturation will increase the thermodynamic potential of the solution with an amount $\Delta\mu$. If this super saturation of the solution results in the formation of a nucleus with a radius r the free energy F of the system will be decreased because an amount of substance proportional to r^3 is transformed from the solution to the solid phase. On the other hand the free energy of the system will increase because the crystallite had formed a surface proportional to r^2 with a surface free energy of σ. The change in the free energy ΔF of the system, with C_1 and C_2 as proportional constants is therefore:

$$\Delta F = C_1 r^2 \sigma - C_2 r^3 \Delta\mu \quad (5.10)$$

The maximum increase of the free energy can be found by differentiating
ΔF with respect to r:

$$\frac{dF}{dr} = 2C_1 r\sigma - 3C_2\, r^2\, \Delta\mu \quad (5.11)$$

The maximum radius r_m of the embryos can be obtained when $\frac{dF}{dr}$ equals zero:

$$r_m = \frac{2\ C_1.\sigma}{3\ C2.\Delta\mu} \quad (5.12)$$

Only if the embryos reach this maximum radius, further nuclei growth can take place concomitant with a decreasing free energy and the crystallization process can continue spontaneously.

The scale inhibition process

Scale inhibitors and dispersing agents are normally used to prevent deposition on heat transfer surfaces. Scale inhibitors control precipitation from solution and dispersants prevent the settling on surfaces of any solid material present in the solution. Scale inhibitors can prevent precipitation of supersaturated ions through the chelating action on soluble ions reducing supersaturation and preventing embryo formation. Dispersing inhibitors can adsorb on the high energetic surfaces of embryos and nuclei causing dissolution and inactivation preventing further growth. On larger particles the inhibitor usually adsorb on the active sites of the crystal surfaces causing distortion preventing further growth to larger crystals and adhesion to other substances. This scale inhibition process through the whole crystal growth process is illustrated in Figure 5.13.

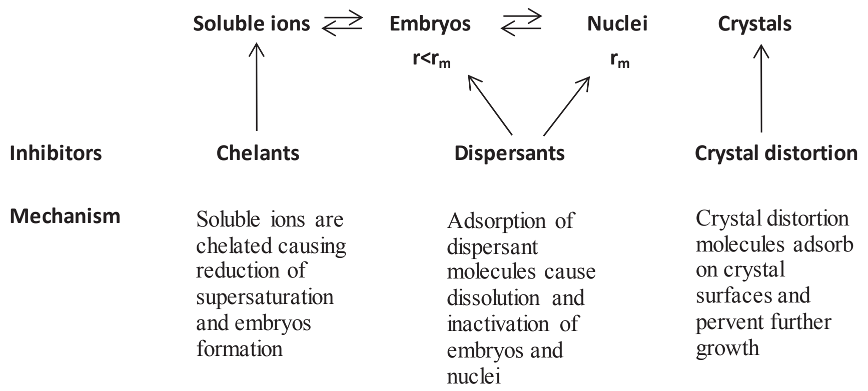


Figure 5.13: The scale inhibition process [5.6]

In the case of MSF desalination, scaling is usually prevented by adding an inhibitor and either maintaining a low concentration factor and temperature than design or combining inhibitor with acid dosing. Acid dosing, to maintain pH close to neutral, prevents seawater from becoming supersaturated with respect to calcium carbonate and magnesium hydroxide.

Temperature and concentration factor are also controlled to ensure that calcium sulfate supersaturation is maintained in the range in which the inhibitor is effective. Online sponge ball cleaning technology is also used to physically and mechanically control fouling and scaling [5.5]. In the scale inhibition process two known technique can be distinguished namely the threshold and the stoichiometric inhibition. In the stoichiometric method the necessary amount according to the subsequent chemical reaction should be dosed to inhibited scale formation and in the threshold method the inhibitor is effective in very low concentration. Typical threshold inhibitors are anionic such as phosphonates and carboxylated polymers. A well-known example of a stoichiometric inhibitor is concentrated sulfuric acid. A large amount of acid is needed with the stoichiometric acid dosing to control alkaline scale. For example for the alkaline scale inhibition in a 6,000 cubic meters per day MSF evaporator an amount of approximately 1,500 kg of sulfuric acid is necessary resulting in a consumption rate of 0.25 kg per cubic meter produced distillate. In the threshold process the inhibitor delay nucleation by dissolution of nuclei and slow crystal growth by distortion as mentioned above. In Figure 5.14 the threshold effect is shown.

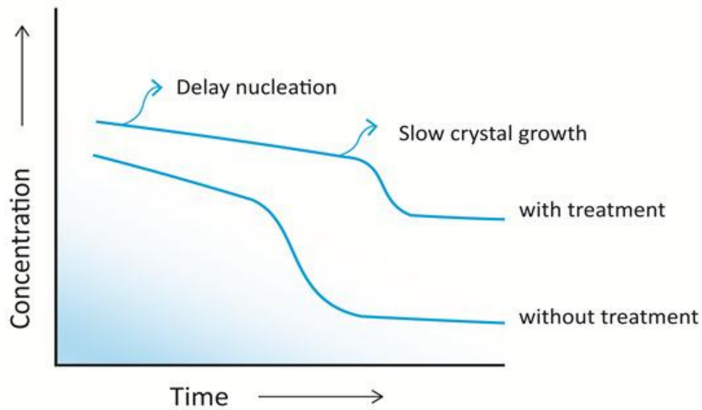


Figure 5.14: The Threshold inhibition effect [5.6]

The deposition process

The deposition process is the physical transport phenomena of particles from the bulk of the liquid to the surface where the particles are attached to the surface by adhesion. The adhesion can be so effectively that all incoming particles stick to the surface.

Adhesion strength, morphology and tenacity of a deposit depend on the physical chemical and the surface variables. Physical chemical variables are related to the chemical composition, supersaturation level, temperature and the flow field. The surface variables are related to the substrate material on which the deposit is attached, through nucleation and adhesion processes and crystal growth mechanisms. The surface roughness also plays an important role. In Figure 5.15 the deposition process is schematically illustrated.

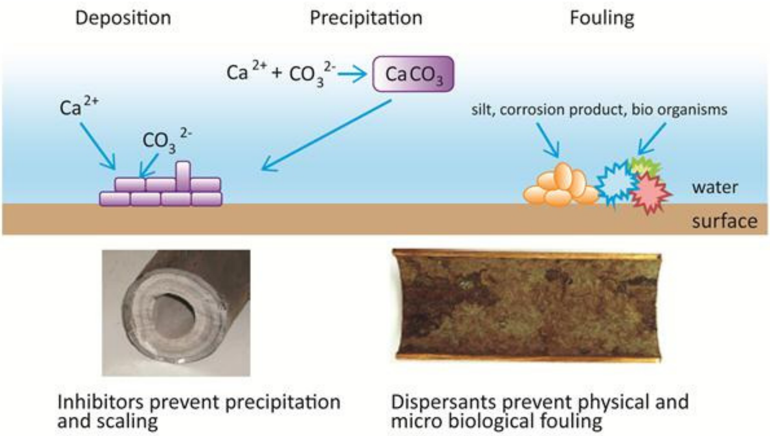


Figure 5.15: A schematic illustration of the deposition process [5.6]

The dispersive process

To inhibit the deposition on the surfaces dispersants are used. Dispersants are surface active chemical components, primarily anionic polymers. They absorb on particles and on the substrate surfaces. The primarily action is to increase the electrostatic repulsion between the particles and between the particles and the substrate. Positive particles are made negative and negative particles are made more negative. Steric hindrance is also a contributive action to the effectiveness of dispersants. Dispersants are not as large a molecule as flocculants that can bridge between two particles promoting particle growth. In Figure 5.16 the dispersive effect is illustrated.

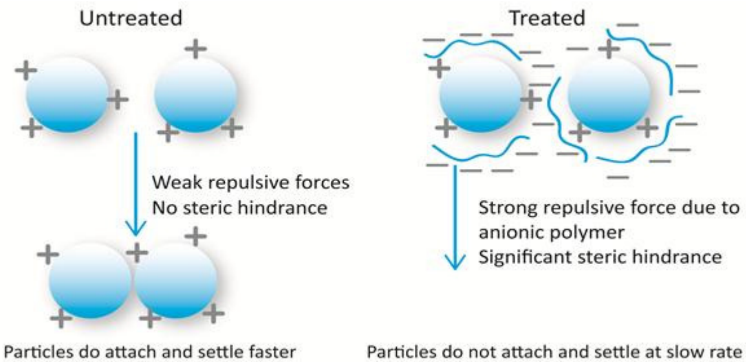


Figure 5.16: The dispersive effect of dispersants [5.6]

Some specific dispersant prevent fouling by modifying the surface properties of the system and reduce and eliminate adhesion of particles to the surface. For an inhibitor or dispersant to be effective a surface-inhibitor/dispersant structural relationship must exist where the molecular functional groups, the molecule size and geometry play an important role on the chemo-sorption on the surface active sites. These were factors that were considered during the development of the novel scale inhibitor as will be discussed in the following section.

5.4 The development of the novel scale control program

Materials and methods used in the development

After the partially successful trial in 2002 with 6 ppm and 8 ppm Aqua Max ™ HT 20 antiscalant dosage experiencing stable operation, although increased brine heater pressure due to scaling on the brine heater tubes as mentioned above, the chemical supplier was requested to perform further research to improve the scale control program with enhanced dispersing efficacy and magnesium hydroxide inhibition efficacy. The effective dispersing agent solution will also be dosed neat at the entrance of the first vessel to cope with scaling in the high temperature vessel and the brine heater of the MSF evaporator. The chemical supplier is also requested to design and construct a MSF pilot plant to simulate the practical dynamic situation as a supplement to the Dynamic Beaker Test (DBT) because these tests even under more severe chemical environment do not represent actual dynamic mass and heat transfer as in a MSF process environment.

The performed research resulting in development of the new antiscalant is described in some detail below and is based on the paper presented by Perez at the International Desalination Association Conference in Singapore in 2005 [5.6].

Throughout the research test were performed with synthetic seawater and was prepared according to standard procedure [5.24]. Physicochemical analyses of the component and deposits are done with the following techniques:

- Calcium and Magnesium ions
  - EDTA colorimetric titrations
  - Inductively Coupled Plasma atomic emission spectroscopy (ICP)
- Silica and other ions
  - Inductively Coupled Plasma atomic emission spectroscopy (ICP)
- Deposits
  - Infrared Spectroscopy (Perkin Elmer System 2000 FTIR):
  - Scanning Electron Microscopy (Amray 1700): deposits
  - Energy Dispersive X ray analysis (Tricor Northen 5500): deposits

Two types of dynamic experimental procedures the *Dynamic Beaker Testing* (DBT) and the *Single Stage Flash Distillation Un*it (SSFDU) were used to evaluate the scale inhibitors tested. The Dynamic Beaker Testing involved the addition of treatment (different mixtures of scale inhibitors as indicated in Table 5.4) to a solution containing lattice ions of the solid to be studied at the required pH and temperature. Coupons of the surfaces to be tested were suspended in the solution. The beakers were incubated in a shaking water bath at the required temperature for a determined period of time. At the conclusion of the experiment, a measured portion was filtered and the concentration of at least one of the ions was determined. Percent inhibition was calculated from the ratio of change with respect to control and stock solutions. Deposition on the suspended non-heated surfaces was evaluated by visual inspection.

In the Single Stage Flash Distillation Unit synthetic seawater was circulated through heat exchanger metal tubes, which were heated by using steam as heating source. After passing the heat exchangers, the synthetic seawater was allowed to flash in a chamber. The concentration factor was controlled by the ratio of seawater feed to blowdown. Temperature, pH and conductivity were monitored and automatically controlled. The amount of deposit formed on the exchanger tubes was determined by rinsing their surfaces first with an acid solution and then with ehylenediaminetetra-acetic acid (EDTA) and analyzing the rinse solutions by ICP. In Figure 5.17 a schematic of the SSFSU is shown.

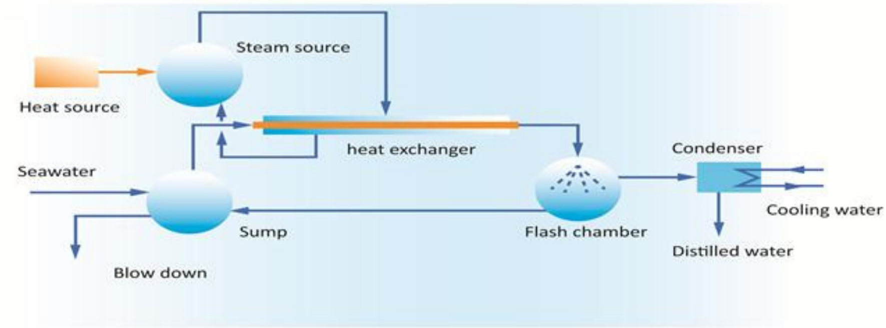


Figure 5.17: The schematic diagram of the SSFDU for dynamic testing [5.6]

A picture of this SSFDU pilot unit is shown in Figure 5.18.

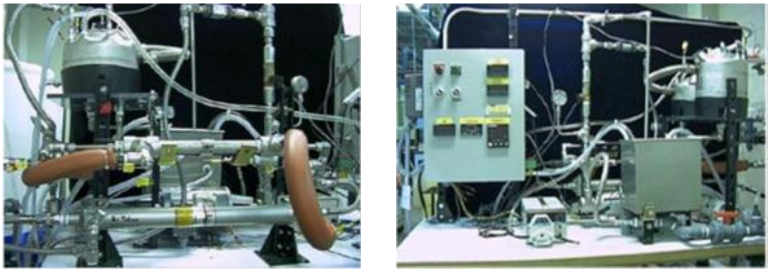


Figure 5.18: Picture of the Single Stage Flash Distillation Unit (SSFDU)

Experimental results and discussion

Under alkaline conditions as that found without acid feed, calcium carbonate, magnesium hydroxide and calcium sulfate are the most common scale found in MSF distillation units operating under conditions of relatively high temperature (112-120 ^oC) and no pH control (pH of 8.8-9.0) at 1.75 concentration factor.

DBT testing was conducted by immersing sealed bottles in a water bath at 93 ^oC and held for 24 hours with shaking to induce scale formation.

At the completion at the hold period the samples were immediately processed through a 0.22 micron filter. The isolated filtrate was cooled to room temperature within a 2-hour period and then analyzed for alkalinity (M-alkalinity). All tests were conducted in duplicate. The M-alkalinity of equal parts of the original solution was measured as control sample and as stock sample. The stock sample is not heated and the control sample is heated so that the filtrate will not have ions that precipitated. The Test sample is the original solution treated with scale inhibition components to be studied and processed as described above. Equation 5.13 was used to calculate the percent inhibition.

$$\% \text{ inhibition} = \frac{(\text{MAlk Sample} - \text{MAlk Control})}{(\text{MAlk Stock} - \text{MAlk Control})} * 100 \qquad (5.13)$$

Commercial available samples as well as new synthesized samples alone or in combinations were screened for efficacy using these tests. Under those conditions, typical scale inhibitors such as hydroxyethylidene-1,1- diphosphonic acid (HEDP), 2-phosphonobutane-1,2,4-tricarboxylic acid (PBCTA), polyacrylic acid and polymaleic acid are not able to control all these potential scale forming salts.

In addition, if these inhibitors are able to prevent one of these scales, their efficacy is greatly reduced by the presence of other scales they are not able to control. The formed scale may serve as a substrate for the heterogeneous nucleation of the otherwise controlled scale. A new polymeric phosphonate was found to be effective in controlling the magnesium hydroxide scale and able to provide better scale control for all potential scale when blended with other inhibitors and dispersants. This new polymeric phosphonate, named DCA 152 is shown in Figure 5.19. Due to commercial sensitivity no further quantitative information of the scale inhibitor blend will be given. The inhibition percentage of different screened samples is illustrated in Table 5.4.

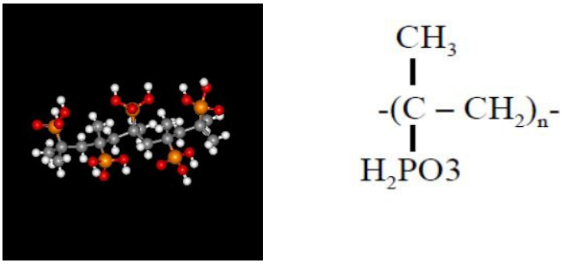


Figure 5.19: The functional groups of the new polymeric phosphonate scale inhibitor [5.6]

In Table 5.4 some of the results obtained during beaker test are illustrated comparing different screened samples at a 20 ppm total active concentration.

Table 5.4: Percentage inhibition of different DBT tested samples [5.6]

Treatment	% Inhibition
Polymaleic Acid (MW~560)	37.0
Polymaleic Acid (MW~2000)	28.0
Copolymer Maleic-Acrylic Acid (MW~3700)	38.0
Polymaleic Anhydride (MW~28000)	24.0
Copolymer Maleic-Acrylic Acid + HEDP	42.0
Copolymer Maleic-Acrylic Acid +New Polymeric Phosphonate	51.0
Polymaleic Acid(MW~560) + Polymaleic Anhydride + New Polymeric Phosphonate	68.0
Polymaleic Acid (MW~560) + HEDP + Polymaleic Anhydride	42.0

The SSFDU was used to determine the efficacy of treatments in preventing scaling forming salts on the heat transfer surfaces under conditions similar to those found in a MSF evaporator. Tests were conducted at the conditions shown in Table 5.5. At the stated conditions, calcium sulfate is perhaps the easiest scale to control and magnesium hydroxide becomes the most predominantly and most difficult to control [5.25, 5.26].

Table 5.5: The experimental conditions [5.6]

Parameter	Experimental conditions
Sump Temperature	56 ^{o}C
Steam Temperature	135 ^{o}C
Top Brine Temperature	105 – 120 ^{o}C
Flash Chamber Temperature	100 – 103 ^{o}C
Concentration Factor	1.75
pH	Not Controlled (Except in control)

A control test was conducted in the absence of any inhibitor. Heavy deposition was observed on the heat exchanger surfaces as well as water turbidity was observed in a 24 hours test. Chemical analysis of the formed deposits showed that it consists primarily of magnesium, calcium and to a lesser extent of sulfate salts. *Fourier Transform Infrared* (FTIR) and *Energy Dispersive X-ray Analysis* (EDXA) showed that the deposit was mainly magnesium hydroxide, calcium sulfate and carbonate and strontium sulfate. Three hundred eighty one milligrams of deposit were formed in the 90/10 copper-nickel tube used at the exit of the heat exchanger that was used for monitoring purposes. In Figure 5.20 a piece of subsequent scaled test tube is illustrated.

Figure 5.20: Heavy deposits on the test tube of the heat transfer surfaces during the control test [5.6]

Some MSF systems operate with acid addition to control pH below 8.0, which allow the systems to run at the temperatures and concentration factors used in the testing. A test was run simulating acid feed conditions. Approximately 14 mgs of deposits formed on the surface of the monitoring tube, which represents a 96% scale reduction with respect to the control run. In Figure 5.21 the surface of the copper-nickel tube after 24 hours test is shown.

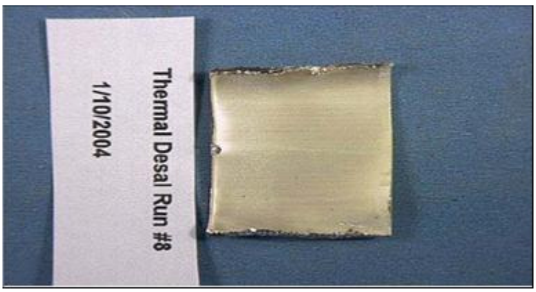


Figure 5.21: The surface at the end of the acid run [5.6]

Test were also conducted by using blends of treatments of commercially available samples of polymaleic acid, copolymer of maleic-acrylic acid, phosphonates and acrylic acids without any success, those runs showed reductions in the 40 to 50 percent range. In addition, relatively high turbidity was observed in the water.

A treatment consisting of a blend of low molecular weight maleic acid (~ 560 MW) blended with a dispersant agent plus the new polymeric phosphonate provided the results with only approximately 5.6 mgs of scale formed, which represents a 98.6 percent reduction on scale formation. Once again it is emphasized that due to commercial sensitivity no further information can be given about the quantitative composition of this scale inhibitor blend. Figure 5.22 illustrates the surface of the monitoring tube at the end of the 24 hours test. No turbidity was observed in the bulk water.

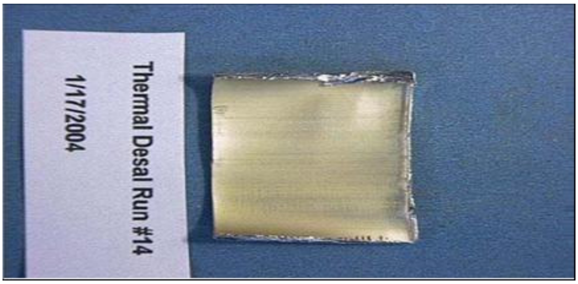


Figure 5.22: Deposits formed with 8 ppm active blend containing the new polymeric Phosphonate [5.6]

Dose response studies were conducted using this new program. As shown in Figure 5.23, seven ppm of the new program was able to control scale at the 98 percent reduction.

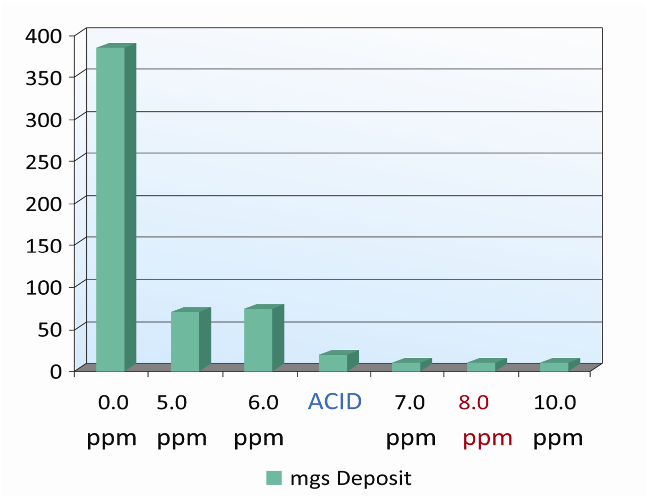


Figure 5.23: New program dose response test [5.6]

These results demonstrates that a program based on the new polymeric phosphonate, is able to control magnesium hydroxide and the other types of scales that may form on the heat transfer surfaces of a MSF units when running at high temperatures (120 ^{0}C), high pH

(~ 9.0) and relatively high concentration factor (1.75). This removes the limitations presently found that prevent running systems at these more stressful conditions.

Static test results, as illustrated in Figure 5.24, also shown the higher scale inhibition efficacy of the new phosphonate polymer compared to the maleic based scale inhibitor and the HT 20 scale inhibitor first applied in the endeavor to eliminate the sulfuric acid dosing.

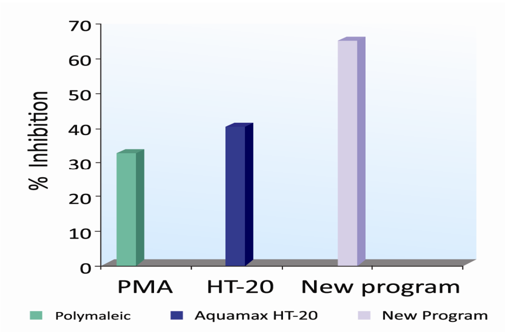


Figure 5.24: Static test to compare the efficacy of the new scale control program, [5.6]

5.5 The evaluation and total application of the novel scale control program

The pre-trial preparation of the novel scale control program

The Desalination Department of W.E.B. Aruba N.V. and Betz Inc. initiated in 2001 a research project to test the efficacy of a new formulation of antiscalants based on a blend of some traditional scale inhibitors and dispersants in an MSF desalination environment in an attempt to eliminate the sulfuric acid dosing. It was determined that the additive chemistry commonly used in high temperature desalination, could not adequately control the mixed scale deposits encountered under the stressful MSF operational conditions [5.19]. This initiated an intensive research in 2003 resulting in the development of a series of new polymers by the Betz synthesis laboratory in Trevose, PA, USA.

As described in the previous section one particular formulation, based on a new developed phosphonate polymer DCA 152 performed significantly better than all conventional scale inhibitors previously studied. This formulation is comprised of GE Betz HT 15 TM as the scale inhibitor and Scaletrol PDC9323 TM as the dispersant for practical application and is intensively evaluated in a MSF evaporation pilot plant to ensure efficacy of the new program and to estimate required dosages for efficient application in the MSF evaporator. The objectives and operational results of this new scale inhibition program efficacy trial at the MSF evaporator Aqua Chem#5 will be further discussed in this section.

Technical trial objectives

The primary demonstration purpose of this MSF operational scale control program was to confirm the scale inhibition efficacy of the new treatment program to ultimately efficiently eliminate sulfuric acid dosing. The criteria for success set forth based on acid like performance included the following technical objectives:

- Control scale without acid addition
- Control scale at TBT of 110 ^{o}C
- Control scale at 1.5 cycles of concentration
- Maintain or improve distillate production
- Maintain or reduce low pressure steam consumption
- Maintain or improve Performance Ratio
- Maintain or reduce MSF evaporator corrosion

A detailed Engineering Package and Trial Protocol was set up and approved by all parties for a 180 days demonstration of this novel scale inhibition program at the Aqua Chem#5 MSF evaporator of W.E.B. Aruba N.V. describing the pre-trial preparation activities and the whole evaluation process as described below.

The antiscalant dosing and monitoring

Extensive MSF evaporation pilot plant testing performed at the Betz Laboratory has revealed 8 ppm dosing of GEBetz HT 15^{TM} and 0.8 ppm dosing of the Scaletrol PDC 9323 ^{TM} as the optimal dosage for efficacy scale inhibition control with a scale formation reduction of 98.6% under the severe MSF desalination conditions.

Under normal conditions, sulfuric acid is injected to the seawater makeup line prior to the degasifying section of the MSF evaporator. As proposed by the Desalination Department the new scale inhibitor GE Betz HT 15 ^{TM} is added downstream of the brine recirculation pumps and the dispersant Scaletrol PDC9323 ^{TM} is dosed at a second injection point at the entrance of the high temperature stages of the first vessel as indicated schematically in Figure 5.25. An automatic computer controlled chemical dosing system, BetzDearborn Pace Setter ^{TM} Platinum Plus, communicating with the Distributed Control System accurately controls the antiscalant injections. The BetzDearborn Pace Setter system as mentioned earlier is upgraded for effectively dosing pump redundancy operation, guaranteeing operational safeguards to ensure safe and smooth operation of the evaporator. During the sulfuric acid-GE Betz HT 15 ^{TM} program transition period, chemical feed system calibration, brine pH and alkalinity, brine heater temperature profile and distillate quality were closely monitored.

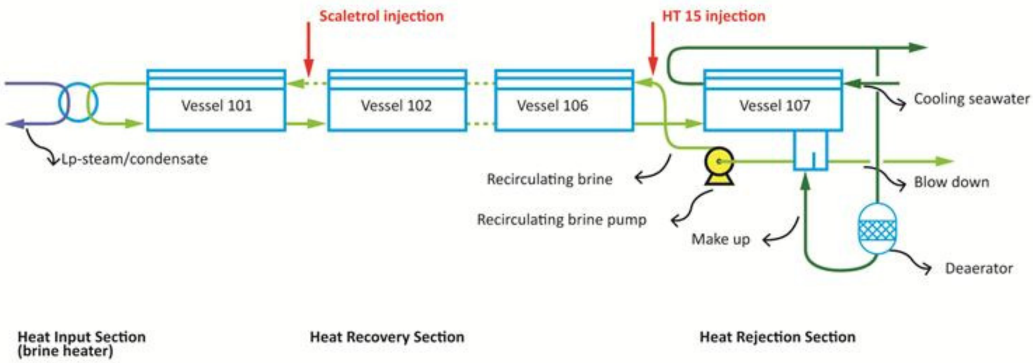


Figure 5.25: The scale inhibition dosing points

Prior to the trial the MSF evaporator Aqua Chem#5 was taken off-line for general inspection and maintenance and initially it was started up on acid dosing and once the operation was stabilized the GE Betz HT 15 TM and Scaletrol PDC9323TM antiscalant dosing was started, reducing slowly the acid dosing, in sequentially 25% decrements of normal dose in a 16-hour period. The step changes were designed to minimize system upsets by allowing the brine alkalinity to rise slowly. The pH increase from approximately 8.1 to slightly above 9 in the transitional period is shown in Figure 5.26.

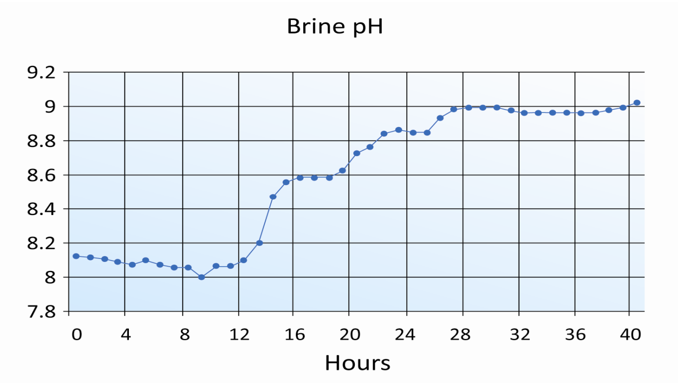


Figure 5.26: The pH increase in the transition period

As agreed upon the trial started at the moment the evaporator was stabilized on 100% dosing of the high temperature antiscalant with the pH and the alkalinity of the brine circulation in specified ranges of respectively 8.86 - 9.1 and 180 - 205 ppm. The trial performance evaluation is discussed in some detail in the following section.

The novel GEBetz HT 15 TM trial performance evaluation

Already from the first days of the trial after obtained stable operation it was obvious, especially taken into account the constant brine heater initially observed operational condition, that the new scale inhibition program may be successful. During the 180 day's demonstration period the MSF evaporator had maintained very stable efficient operation with practically a constant brine heater pressure indicating practically no fouling and scaling on heat transfer tubes in the brine heater and the heat recovery section. The average distillate production during the trial was 6285 m^3/day and had a slightly decreasing trend as shown in Figure 5.27.

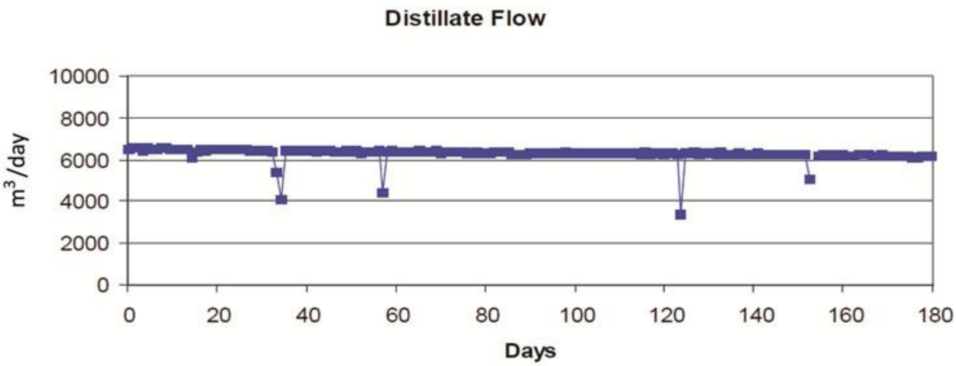


Figure 5.27: The distillate flow during the 180 days trial period

The condensate flow also showed a slightly increasing trend and had an average flow of 636 m^3/day, indicating practically negligible high temperature fouling and scaling in the high temperature vessels and the brine heater. The trend of the condensate flow is shown in Figure 5.28.

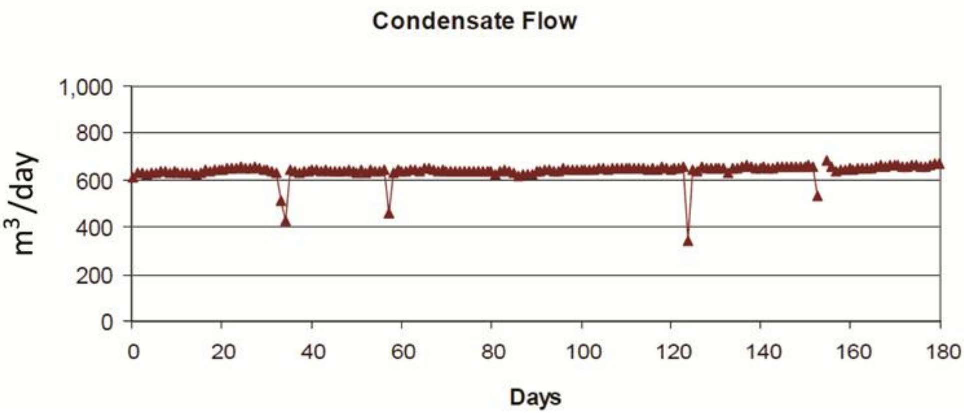


Figure 5.28: The condensate flow during the 180 days trial period

At W.E.B. Aruba N.V. the commonly used terminology for the GOR, the ratio of the distillate production in mT/day and the condensate flow in mT/day representing the low pressure steam consumption, is the Performance Ratio. In accordance with the two graphs above, the Performance Ratio during the trial period had a slightly decreasing trend as shown in Figure 5.29. The performance ratio had an average value of 9.88 during the 180 trial period.

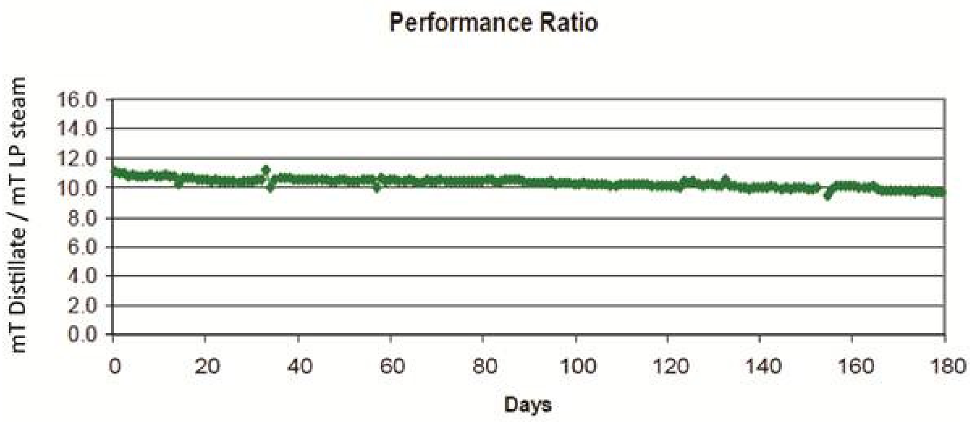


Figure 5.29: The Performance Ratio during the 180 days trial period

The key trial operational parameters

As mentioned before the scale inhibition program should have for successful trial conclusion an acid like performance and the same approved targeted performance baseline and key operation parameters as with the prior Aqua Max^{TM} HT 20 trial were maintained as evaluation criteria. In Figure 5.30 the accumulative performance ratio (defined as the ratio of the accumulative distillate production and the accumulative low pressure steam consumption) acquired during the demonstration period for the new scale inhibition program is illustrated in comparison with the former trial results.

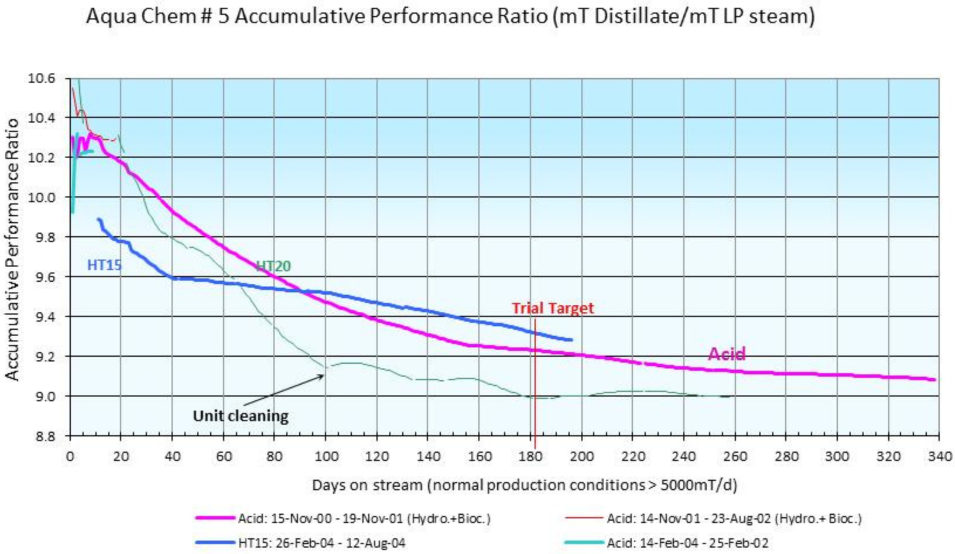


Figure 5.30: The accumulative performance ratio of the GEBetz HT15 ™

It is worth mentioning that one of the benefits of using the accumulative performance ratio is the immediate indication of the trial performance status. As soon as the actual trial performance ratio line intersects the target line this indicates that an acid like performance is met and if it stays above the target line as is the case in Figure 5.30 the trial has exceed acid like performance and can be successful concluded.

The introduced *Performance Decay Indicator* (PDI) is calculated as explained previously in section 5.2 by plotting Ln (TPR_t/TPR_{sor}) versus time t (equation 5.5 gives the relation of TPR_t and TPR_{sor}) and compared with the former trial of HT 20 and acid dosing. In Table 5.6 the PDI is shown for the three scale inhibitors.

Table 5.6: The PDI for GEBetz HT 15 ™, Aqua Max ™ HT 20 and sulfuric Acid

Treatment	Dosage (ppm)	PDI
GEBetz HT 15 ™	8	10
Acid	110	15
Aqua Max ™ HT 20	6	30
Aqua Max ™ HT 20	8	40

In conformance with the MSF pilot plant testing at the Betz Laboratory in Trevose, the HT 15 ™ antiscalant had a PDI of 10 compared with a PDI of 15 for sulfuric acid during the trial indicating a slightly lower fouling potential than sulfuric acid. As mentioned above during a trial run in the MSF pilot plant with the novel scale inhibitor an amount of 5.6 mgs of scale deposits was formed on the test tubes compared with 14 mgs deposits with sulfuric acid dosing indicating a scale inhibition capability difference of 60 % compared to the 50% difference calculated with the PDI, practically in quite good agreement. In Figure 5.31 the graphical calculation of the PDI's is illustrated.

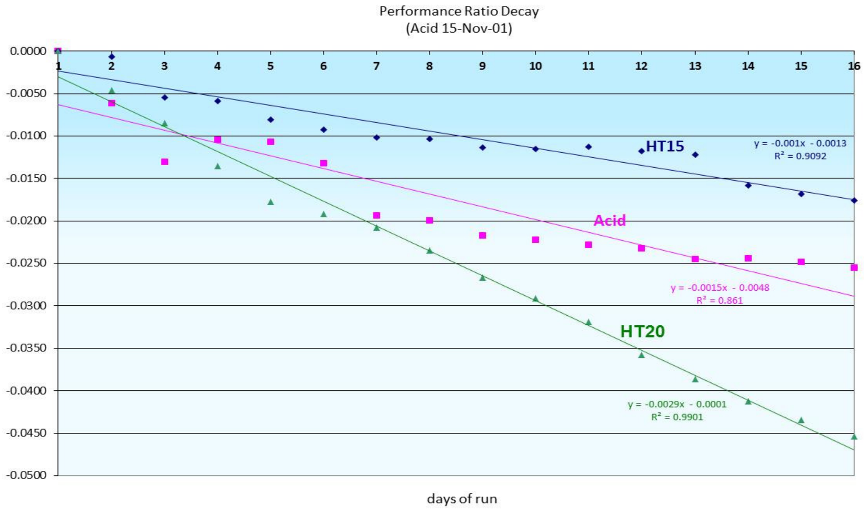


Figure 5.31: The graphical calculation of the PDI

Corrosion monitoring

During the earlier antiscalant evaluation at W.E.B. Aruba N.V. in 2001, it was determined that the upgraded existing vacuum system had adequate capacity to remove any CO_2 that may have evolved in the high temperature flashing stages as a result of the higher alkalinity. To insure that CO_2 induced acidic corrosion did not increase as a result of the new treatment program, iron and copper content in the distillate was closely monitored.

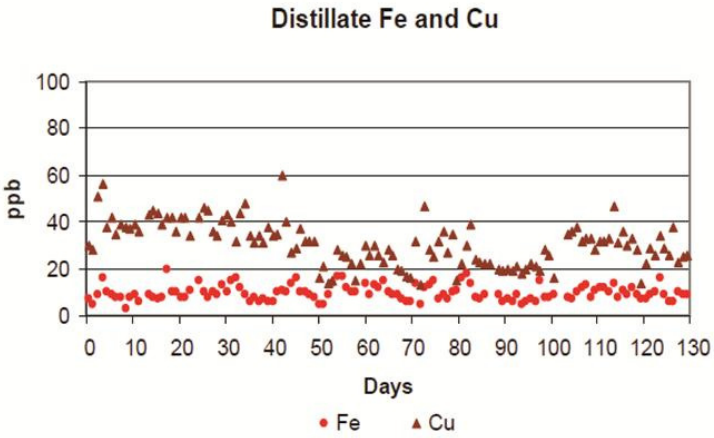


Figure 5.32: The distillate iron and copper concentration during the trial period

Based on the iron and copper levels that were measured during the first four months, it can be deduced that corrosion in the vapor phase did not increase. The data actually suggest a noticeable decrease in copper levels in the distillate as is illustrated in Figure 5.32. Copper and iron concentration were in the range of respectively 20-40 ppb and 0-20 ppb. In an effort to better gauge conditions in the vapor section of the evaporator, a corrosion probe was installed in the vent piping after stage 6.

The initial readings ranged from 2.3 to 2.6 mils per year (0.0023-0.0026 inch per year) for carbon steel. In Figure 5.33 the results of the on line corrosion monitoring in cooperation with the Engineering Department is shown.

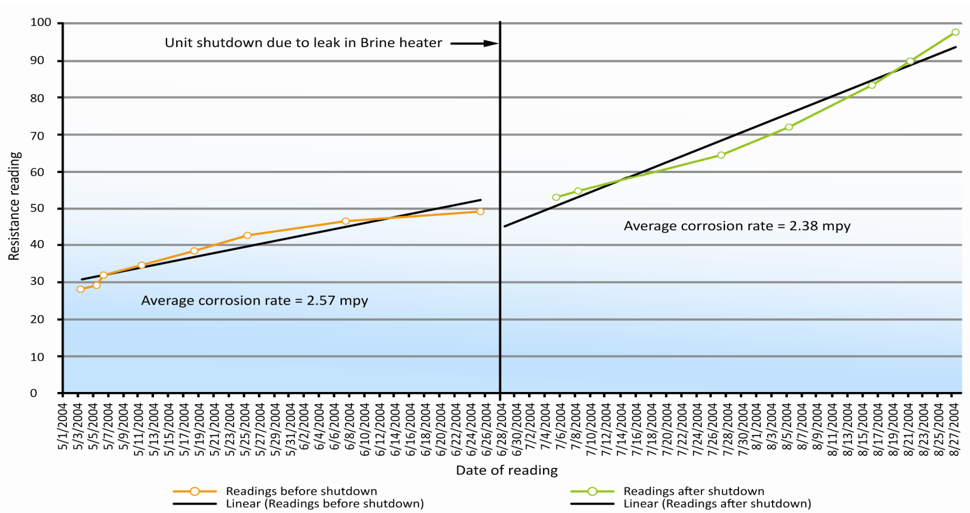


Figure 5.33: Carbon steel corrosion monitoring at Aqua Chem#5

Brine heater and flash chambers inspection

The MSF evaporator was taken off-line after 8 months of continuous operation on high temperature antiscalant dosing for general inspection of the brine heater and the flash chambers. During this inspection, the brine heater tubes were found extremely shiningly clean as is shown in Figure 5.34.

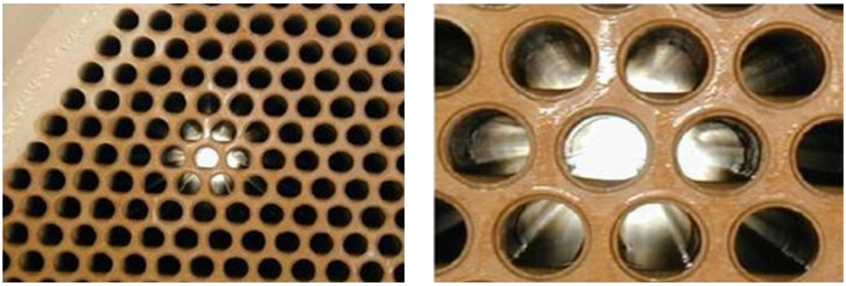


Figure 5.34: Pictures of the brine heater after 8 month on additive operation

The loose white deposits typically found during normal operation on sulfuric acid dosing, as shown in Figure 5.35, were not evident.

Figure 5.35: Brine heater when on acid dosed operation

As expected (as shown in Figure 5.36) the increased alkalinity of the brine resulted in moderate scaling in the lower portions of the stage walls. Almost all of the deposits in the flash chambers formed on non-heat transfer surfaces. A slight dusting alkaline deposit on the exposed lower surface of the demisters was evident. Closer investigation of the mesh demister material revealed superficial deposits only**.**

Figure 5.36: Slight dusting deposits in the flashing chamber and on demisters

Immediately after the 8-month inspection of Aqua Chem#5, the demonstration was declared a success. All performance objectives of the GEBetz HT15™/ Scaletrol PDC9323™ program established by W.E.B. Aruba N.V. and the chemical supplier were met and can be summarized as follows:

- Effective control of scale without acid addition
- Effective control of scale at TBT of 110 ^oC
- Effective control of scale at a concentration factor of 1.75 cycles.
- Performance Ratio above acid like performance
- Little or no adverse effect on plant corrosion

The total conversion to antiscalant dosing

The chemical supplier further proposed a superior scale inhibitor with the dispersant and the scale inhibitor blended in one solution compiled as GEBetz HT 45™ instead of the two injection points system. Senior Management agreed with this proposal because of the economics of one product solution for the total application of the additive dosing for the elimination of the sulfuric acid. According to the objection brought forward by the Desalination Department founded on the theoretical and practical MSF operational knowledge this application failed within two months. Already at the start of this application at Aqua Chem#1 and Aqua Chem#5 it was noticeable that the one product blend does not have the same scale control efficacy as the GEBetz HT15™/ Scaletrol PDC9323™ program based on the two injection points system. The venting system had to be adjusted more than during the GEBetz HT15™/ Scaletrol PDC9323™ program and the brine heater pressure started to increase directly after the application of the GEBetzHT 45™. The main reason is that the dispersing capacity of the one product blend needed in the high temperature flashing compartments is already diminished in the low temperature flashing compartments due to the high suspended particles content normally present in the recirculation brine and more excessively in increased alkalinity environment.

In Figure 5.37 the trend of the brine heater pressure during the GEBetz HT 45™ dosing and the GEBetz HT15 ™ dosing is shown.

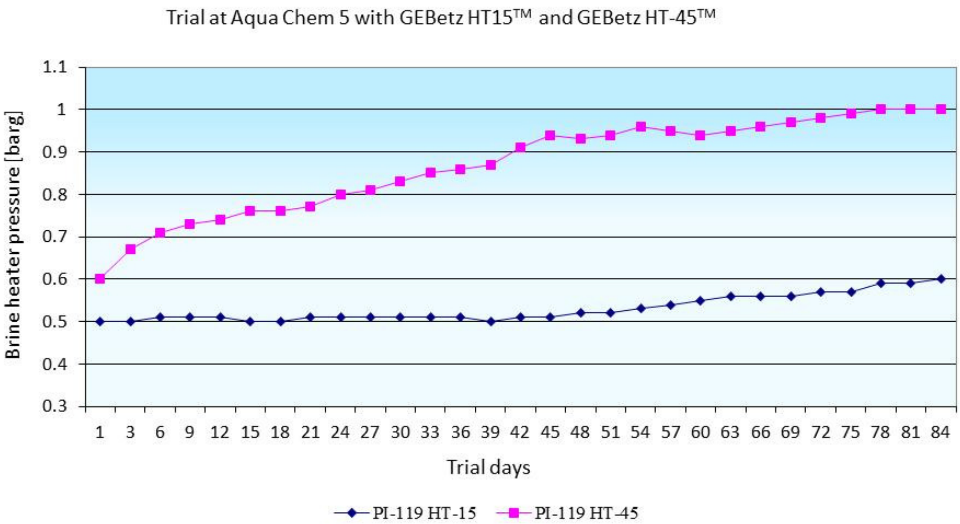


Figure 5.37: The increase of the brine heater pressure of Aqua Chem#5 with the GEBetz HT 45 ™ and GEBetz HT 15 ™ dosing

After this adventure with this GEBetz HT 45™ product, negotiations started to achieve an optimal cost effective total elimination of the sulfuric acid dosing with the GEBetz HT 15™ /Scaletrol PDC9323™ two dosing points scale control program. In 2007 all MSF evaporator were successfully converted to 100% anticalant dosing and the first worldwide transition with effectively increase in annual accumulative efficiency increase from 8.86 in 2006 to 9.3 in 2008 is achieved as indicated in Figure 5.38.

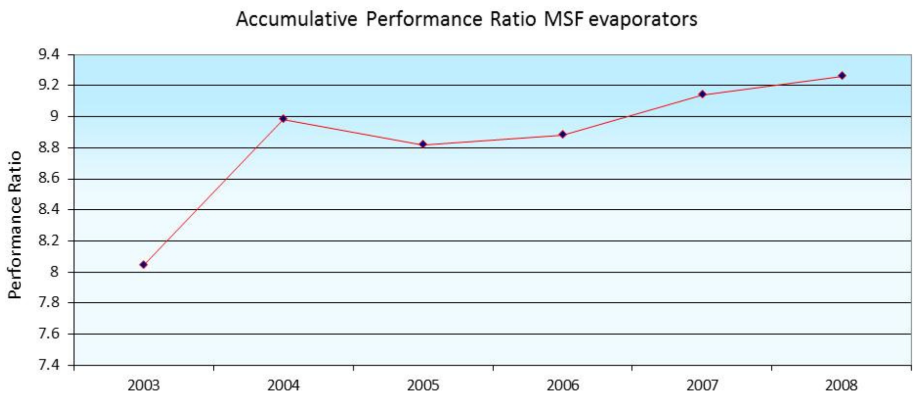


Figure 5.38: The annual accumulative performance ratio in the period of 2003 to 2008

5.6 Conclusions

1. The GEBetz HT 15™/Scaletrol PDC9323™ scale control program proved to be very effective complying with all performance objectives and key performance targets set forth.
2. The GEBetz HT 15™/Scaletrol PDC9323™ scale control program is only effective with the two dosing points. The second dosing point for the dispersing agent Scaletrol PDC 9323™ is necessary for the amount of particles in the recirculation brine and the high transport to the surface in the high temperature vessels.
3. The change in the Pace Setter operation to guarantee redundant operation of the dosing pumps is crucial for the successful operation on additive dosing.
4. The successful GEBetz HT 15™/Scaletrol PDC9323™ scale control program is the first worldwide application for the elimination of 100 percent sulfuric acid scale inhibition technology maintaining a higher annual accumulative performance ratio compare to acid dosing.
5. Vent side corrosion is comparable with acid dosing due to the designed high venting capacity of the Aqua Chem evaporators. The modification done by the Desalination Department and Aqua Chem Inc. was necessary for stable operation of the MSF evaporator.
6. The effort of the Desalination Department convincing Senior Management to change the policy for the application of new technology and the decision to go forth with the support of the development of a new additive to eliminate acid was crucial for the success of the trial.

5.7 References

5.1. Marchena, F. A., Alberts, V. A., et al., Strategic Quality Program: Basic Efficiency Control for Brine Recirculating MSF Desalination Units, Caribbean Conference, June 19-21, 2002, Aruba.

5.2. Al-Ahmad, M., Aleen, F. A., Desalination, 93 (1993) 287

5.3. Perez, L., Polizzotti, D., NACE 99, presented at NACE 99.

5.4. Margaritha, R. E., Product Water Mineralization and Water Distribution Systems, IDEA Desalination Operation Course, 1975, U.S. Virgin Islands.

5.5. Eimer, E., Energetic Aspects of the Fouling of MSF Desalination Plants with and without the Use of on Load Ball Cleaning System., Desalination, 40 (1982) 363-372.

5.6. Perez, L. A., Carey, W. S., et al., Development of a New Scale Control Program for Seawater Thermal Desalination Processes, IDA World Congress, SP05-211, September 2005, Singapore.

5.7. Hillier, H., Scale Formation in Seawater Distilling Plants and its Prevention., Proceeding of Industrial Mechanical Engineering (A) vol.167, 42, 1953.

5.8. Stewart, J. M., Desalination in Curacao-The First Phase, CaribDA Conference, Willemstad Curacao, June, 2008.
5.9. De Lannoy, E., Personnel Communication, W.E.B. Aruba N.V. 2002.
5.10. Khan, A. H., Desalination Processes and Multistage Flash Distillation Practice, Elsevier Science Publishers B.V., Amsterdam, 1986.
5.11. Arrindell, M. E., Croes, O., Performance test of Aqua Chem#2, Internal Report W.E.B. Aruba N.V., 1983.
5.12. Pereira, E., Personal Communication, 2004.
5.13. Marchena, F. A., Maria, D. R., Successful Novel Antiscalant technology to replace Sulfuric Acid Dosing in MSF Evaporators in W.E.B. Aruba N.V., International Desalination Conference, Oranjestad, Aruba, June 2007.
5.14. Marchena, F. A., Angela, A. E., Aqua Chem#5: AquaMax ™ HT 20 Trial Evaluation, Internal Report W.E.B. Aruba N.V., Aruba, 2002.
5.15. Al-Mutaz, A. S., Alodan, M. A., et al., Experimental Investigation of Vapor Side Corrosion in Multistage Flash Desalination Plants, IDA World Congress, Maspalomas-Gran Canaria, 2007.
5.16. Glade, H., Genthner, K., Chemical Reaction Kinetics and Mass Transfer Phenomena Controlling the Release of CO2 in MSF Distillers, Proceedings of the IDA World Congress on Desalination and Water reuse, San Diego, CA, 1999.
5.17. Minnich, K., Neu, D., Impact of HTA Dosing on Vent Stream Acidity of an Acid Dosed MSF Plant, Caribbean Conference, June 19-21, 2002, Oranjestad, Aruba.
5.18. Hamed, O. A., Operational Performance of an Integrated NF/MSF Desalination Pilot Plant, IDA World Congress on Desalination and Water Reuse, October, 2003, Bahamas.
5.19. Helalizadeh, A., Muller-Steinhagen, H., Jamialahmadi, M., Mixed salt crystallization fouling, Chemical Engineering and Processing 39 (2000) 29-43.
5.20. Logan, D. P., Walker, J. L., Development of Treatment additives for Desalination of Seawater in high Temperature Multiple Stage Flash (MSF) Evaporators, The International Congress on technology and Technology Exchange Pittsburgh, Pennsylvania, May, 1982.
5.21. Partridge, E. P., White, A. H., Journal of American Chemical Society, 51 360, 1929.
5.22. Logan, D. P., Walker, J. L., Calcium Sulfate Scale Formation Lab Studies lead to Development of New Inhibitors for High Temperature MSF Operations, Calgon Corporation, Pittsburgh, PA, USA.
5.23. Dijkgraaf, L. L., Physical Chemistry, Delftse Uitgevers Maatschappij, The Netherlands, 1980.
5.24. Standard Methods for the Examination of Water and Wastewater, ed. Greenberg, A. E., et al., 18th edition (1992).
5.25. Porteous, A., Saline Water Distillation Processes, Longman (1984) 25.

5.26. Knudsen, J. G., Fouling in Heat Exchangers, Hemisphere Handbook of Heat Exchangers Design, ed. G. F. Hewitt, Hemispere (1990).
5.27. Marchena, F. A., Uytiepo, B. A., et al., Plant Experience on New Antiscalant Technology for MSF plants, IDA World Congress-Maspalomas, Gran Canaria, Spain, October, 2007.

Chapter 6

A novel method to optimize foam control in MSF evaporators

Foaming tendency of seawater: a natural beauty, a desalination inadequacy

Chapter 6

A novel method to optimize foam control in MSF evaporators

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Abstract

The foaming tendency of seawater is next to the marine biofouling and inorganic scaling another physicochemical aspect of importance hampering stable evaporation in thermal seawater desalination for the production of high quality water. This foaming process is further enhanced and stabilized due to the presence of natural bio-organic surface active components in seawater. Dosing of an effective antifoam is due necessary to control violent evaporation inducing excessive foaming in the MSF evaporation process to eliminate distillate contamination and production decrease. The biofouling and scale control chemical additives also have surface active properties enhancing the foaming tendency of the recirculating brine so adjustment of the antifoam dosage is inevitable. While most operating parameters were relatively unchanged, subtle changes in the hydrodynamic behavior of the MSF evaporators was observed and by the trial and error method the correct dosage of antifoam was determined. A novel approach for determining the optimum operating antifoam dosing range was developed by characterizing the MSF evaporator’s tendency to foam by profiling the recirculating brine's interfacial surface tension. This chapter gives a detailed description of this novel approach based on the surface energy concept to optimize the dosing of the antifoam. The theory is based on the surface tension effect on evaporation due to the curved interfacial surface of the bubbles formed during flashing, on the contrary to the usual misconception assuming a flat evaporation surface. Furthermore, an explanation is given for the effect of under- and overdosing of the antifoam on distillate conductivity and production. Up to now there is no acceptable explanation for this effect. The Gibbs-Marangoni foam stabilization mechanism actually permits liquid to flow from a low energy level to a high energy level. In this chapter an explanation in accordance with the natural flow from a high energy level to a low energy level is given. Measurements of the surface tension of different concentrations of the antifoam and the biofouling and scale control additives and the resulting optimal antifoam concentration are illustrated in this chapter.

6.1 Introduction

In the process of desalination efficiency improvement, as explained in detail in the preceding chapters the physicochemical aspect next to the human factor plays an important role. Chemical additives are due necessary to control the experienced biofouling and scaling in thermal evaporation, however both the bio-disinfectant and the antiscalant are surface active agent drastically enhancing the foaming tendency of the flashing seawater in the MSF evaporation process. As a consequence foam control is another important aspect in sustainable evaporation to eliminate distillate contamination and efficiency reduction. The control of the foaming tendency of seawater in MSF evaporation is not always possible by mechanical means (such as stationary or rotating breaker bars) so additives are required to control excessive foaming. In MSF evaporation variation in process variables such as pressure, temperature, flow and alkalinity can initiate this foaming process in the recirculating brine and the small amount of surface active bio-organic components naturally present in seawater stabilizes this foaming. The applied antifoaming additive should be stable at the high temperature MSF operating conditions and compatible with the bio-disinfectant and the antiscalant and should not contain volatile components to exclude the possibility of diminishing distillate quality [6.1].
The theoretical aspects of the surface chemistry of foam stabilization and antifoaming are extremely complex and go beyond the scope of this thesis and consequently only a basic introduction is given in this chapter just for explanatory purposes of the foaming and defoaming processes occurring in MSF evaporators. Foam is actually an unstable vapor-liquid disperse system trying to minimize its thermodynamic free energy by returning to the homogenous liquid state at environmental physical conditions. Inasmuch foaming characteristics are surface physicochemical phenomena, the presence of a small amount of surfactants in the interfacial boundary layer between the vapor phase and the liquid phase will stabilize the foam. The different foam stabilization mechanisms and the inherently foam destabilization methods will be in short described in section 6.2. The particular properties of the interfacial surface layer characterized by the surface tension or surface energy and the influence of the surface curvature on evaporation is also explained. Hereto, the influence of the surface tension on MSF evaporation is explained and related to the curved surfaces of the vapor bubbles spontaneously formed during flashing, on the contrary to the common misconception assuming no relationship because of the consideration of flat interfacial surface evaporation.
The common practical method to adjust the antifoam dosing to stabilize the flashing process is by means of trial and error. In practice underfeeding of the antifoam always causes contamination of the produced distillate giving rise to production waste and inefficiency. On the other hand, overfeeding always causes the MSF evaporator to react as it were fouled reducing production and efficiency. A theoretical point of view is given for a simple explanation of this effect. Up to now there is no satisfactory explanation for this effect [6.2].

The foam stabilization theory especially the Gibbs-Marangoni actually permits surfactant molecule to flow from an interfacial surface segment with lower surface energy to an interfacial surface segment with higher energy level, actually in contradiction with the natural thermodynamic convection from a high energy level to a lower energy level. A simple theoretical model is illustrated to demonstrate the surfactant stabilization in which surfactant flows from higher to lower energy level in the interfacial surface.
Based on the surface tension dependence of evaporation in the flashing process an innovative method is developed to optimize the antifoam dosage in MSF evaporators eliminating the adjustment by trial and error. To establish a firm basis for this new method, surface tension measurements have been performed for the different additives in pure water and seawater at different concentrations. Also the effect on the surface tension of different mixtures of additives in pure water and seawater solutions is measured. For all these measurement a bubble type surface tension meter is used as will be explained in section 6.3.

6.2 Some theoretical interfacial surface aspects in thermal evaporation

The effect of the interfacial surface curvature on evaporation
In the desalination evaporation process water molecules are transported from the bulk of the seawater flow to the vapor phase through the boundary layer, the interfacial surface between the liquid phase and the vapor phase. In this transitional boundary layer a characteristic dynamic molecular interaction condition exists between the surface layer molecules with the bulk liquid molecules and the vapor phase molecules resulting in the well-known interfacial surface tension given the surface an elastic membrane like property [6.3]. In the thermodynamic science it is know that the saturated vapor pressure of a liquid in dynamic equilibrium with its vapor phase only in the situation of a flat interfacial surface is not depended on the surface tension. In thermal desalination, the general misconception is that surface tension has no significant influence especially considering the assumption of a flat surface of the evaporating seawater. However, in the multi stage flashing desalination process, evaporation proceeds by spontaneous vapor bubbles formation in the bulk of the evaporating liquid at reduced pressure. Figure 6.1 illustrates the complex vapor bubble matrix of the evaporating brine entering a flashing stage through the brine gates of an MSF evaporator.

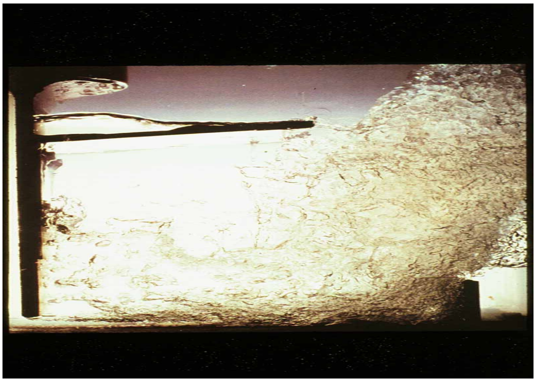


Figure 6.1: Flashing brine in an MSF evaporating stage [6.4]

Theoretically, for the sake of simplicity the vapor bubbles formed can be considered to have approximately a spherical curved interfacial surface. Despite the complex thermodynamic theoretical nature of the physicochemical interfacial science, the objective of this section is to illustrate a point of view from which the complex physical and chemical interfacial aspects of the flash evaporation, foaming and defoaming appear in its greatest simplicity toward a simple scientific based explanation of some phenomenon experienced in the desalination process relating to the surface tension of seawater.

The molecular interactions responsible for interfacial surface curvature

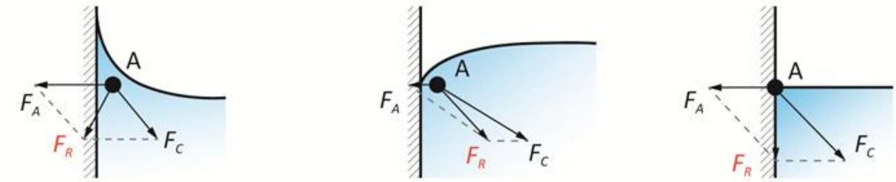
The saturated vapor pressure of a substance above its liquid surface depends on the curvature of the surface. This phenomenon is best explained considering a liquid molecule in the liquid-solid interface L,S. The molecule in question experienced the following forces [6.5]:

- F_A, the adhesion force as a consequence of the integrated London-van der Waals interaction between the molecules of the solid phase and the liquid phase in the boundary layer.
- F_C, the cohesion force of the liquid molecules present in its surrounding molecular attraction environment.

The net force acting on this molecule is the resultant force F_R of these two adhesion and cohesion forces. Now three different situations can be distinguished:

- The cohesion force F_C is of such a magnitude that the resultant F_R is directed toward the surface of the solid phase
- The cohesion force F_C is of such a magnitude that the resultant F_R is directed parallel to the solid surface in the interfacial surface L,S
- The cohesion force F_C is of such magnitude that the resultant F_R is directed toward the bulk of the liquid phase

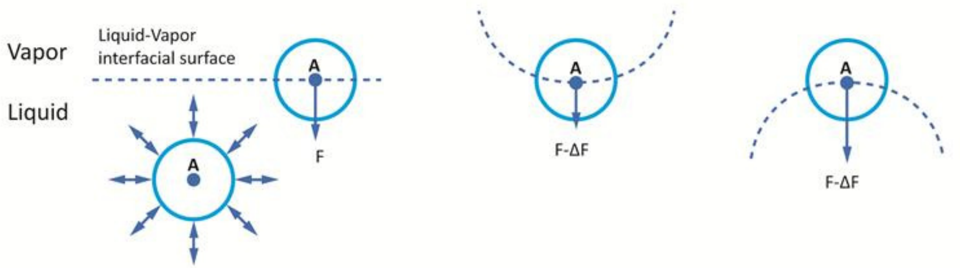
The liquid surface in stationary condition, minimizing its thermodynamic free energy, always positioned itself perpendicular toward the resultant force F_R consequently forming a flat-, a convex- and a concave surface as is indicated in Figure 6.2.



a: concave liquid surface b: convex liquid surface c: flat liquid surface

Figure 6.2: Curvature of the liquid surface dependence on the London-van der Waals molecular interactions in the boundary layer [6.5]

As mentioned above the saturated vapor pressure of a liquid in equilibrium with is vapor depends on the curvature of the liquid surface. This can again simply be visualized considering the London-Van der Waals cohesion interaction of a molecule in the liquid-vapor interfacial surface L,V with neighboring molecules of the less dense vapor phase and the liquid phase in the direct vicinity of its molecular attraction atmosphere.
As schematically illustrated in Figure 6.3 the resultant cohesion force F_C is different in the case of a flat surface and a curved surface.

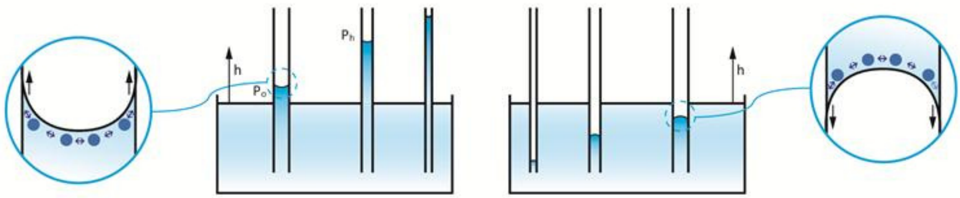


a: flat liquid surface b: concave liquid surface c: convex liquid surface

Figure 6.3: The resultant cohesion force of a molecule in a flat-, convex- and concave interfacial surface [6.5]

In the situation (a) of a flat surface, a molecule A in the interfacial surface has practically half of its molecular attraction atmosphere occupied by vapor molecules. In the vapor phase the molecules have larger intermolecular distances and the cohesion intermolecular forces are lower compared to the liquid phase. Consequently, the molecule A experienced a resultant force directed to the bulk of the liquid. In the liquid phase as in the vapor phase the resultant force F_C is zero due to the statistically equal neighboring molecules in all direction of a subsequent molecule. Therefore this molecule A has a higher potential energy than the bulk molecules. However, the same molecule A will experienced a smaller resultant force (F_C-ΔF) in a concave surface because the part of the molecular attraction atmosphere of molecule A in the interfacial surface occupied by vapor molecules is now smaller as indicated in situation (b). In situation (c) representing molecule A in a convex interfacial surface having more of its molecular attraction atmosphere occupied by vapor molecules the resultant force (F_C+ΔF) is now larger as compared with the flat surface situation. As a consequence the liquid with a concave and convex surface has respectively a lower and higher saturated vapor pressure as compared with a flat surface. The surface tension dependency of the saturated vapor pressure of a liquid is best demonstrated with the well-known capillary rising and depression effects of liquids.

The surface tension influence on capillary effects
In a capillary tube immersed in a liquid contained for example in a beaker glass large enough to consider the liquid surface as flat, the capillary behavior of the liquid depends on the curvature of the interfacial surface L,V. As mentioned above the saturated vapor pressure above a concave surface is lower that saturated vapor pressure in an equilibrium situation above a flat surface. Consequently a liquid exhibiting a concave surface due to the pressure difference will rise in the capillary tube and in the case of a convex surface having a higher saturation pressure than a flat surface will exhibit capillary depression as illustrated in Figure 6.4.



a: capillary rise b: capillary depression

Figure 6.4: The capillary behavior of a liquid exhibiting a concave and convex Interfacial surface L,V [6.5]

This capillary phenomenon can also be deduced thermodynamically [6.5]. In the situation of a flat liquid surface in equilibrium with its vapor the thermodynamic potential (μ) of the

liquid phase (l) and that of the vapor phase (v) are equal;

$$\mu(v) = \mu(l) \tag{6.1}$$

If the pressure (*p)* of the liquid phase for any reason increases with $dp(l)$ than the thermodynamic potential of the liquid phase will increase with an amount equal to $d\mu(l) = V_m(l)\, dp(l)$ and correspondingly the thermodynamic potential of the vapor phase should increase with an amount of $d\mu(v) = V_m(v)dp(v)$, with $V_m(l)$ and $V_m(v)$ the molar volume of respectively the liquid phase and the vapor phase. In the equilibrium condition the following should hold according to equation 6.1;

$$V_m(l)dp(l) = V_m(v)dp(v) \tag{6.2}$$

In the case the vapor phase behaves as an ideal gas, $V_m(v) = \frac{RT}{p(v)}$ and equation 6.2 can be rearranged as;

$$\frac{dp(v)}{p(v)} = \frac{V_m(l)dp(l)}{RT} \tag{6.3}$$

If there is no additional pressure on the liquid phase then $p(l) = p(v) = p*$, with $p*$ representing the normal saturated vapor pressure. Considering the increase in pressure of the liquid phase from $p* = p* + \Delta p$ and the vapor phase pressure increasing from p^* to *p*, the integration of equation 6.3 leads to:

$$p = p^* \exp\left[\frac{V_m(l)\Delta p}{RT}\right] \tag{6.4}$$

The increase in liquid pressure can be assumed to be the result of curvature of the liquid surface as in the case of a spherical liquid drop with radius r and a surface energy γ_{lv}, in thermodynamic equilibrium with its vapor at ambient pressure p(v) and temperature T as is schematically illustrated in Figure 6.5. The required energy to increase the liquid volume V with an infinitesimal spherical liquid volume $dV = 4\pi r^2 dr$ is equal to $(pl - pg)4\pi r^2 dr$.

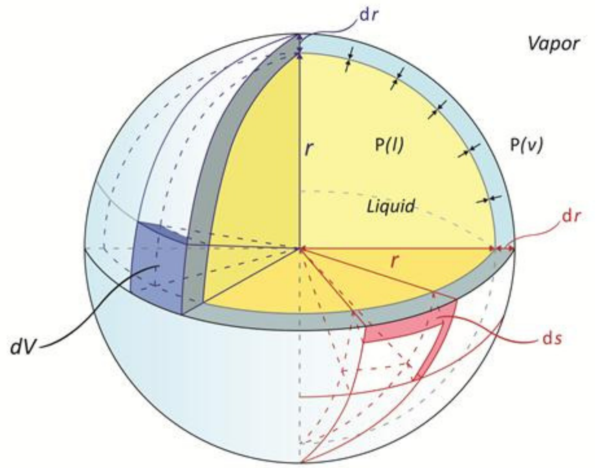


Figure 6.5: A spherical segment of a liquid drop with internal pressure p_l in thermodynamic equilibrium with its vapor at pressure p_g

This increase in liquid volume results in an increase of the interfacial surface $dS = 8\pi r dr$ and in the thermodynamic equilibrium situation the energy to increase the liquid volume should be equal to the energy, $\gamma lv\ dS = \gamma lv\ 8\pi r dr$, required for the infinitesimal increment *dS* of the interfacial surface. The equality of the volume and surface incremental energies gives the following equation:

$$\left(p_l - p_g\right) = \Delta p = \frac{2\gamma_{lv}}{r} \qquad (6.5)$$

This equation is known as the Laplace equation. Substitution of equation 6.5 in equation 6.4 results in the equation describing the surface tension dependence of the vapor pressure of a curved liquid phase:

$$p = p^* \exp\left[\frac{V_m(l) 2\gamma_{lv}}{RTr}\right] \qquad (6.6)$$

Equation 6.6 clearly indicates that for a spherical convex and concave curved surface respectively with a positive and negative curvature radius r the respective vapor pressure is lower and higher than the saturated vapor pressure above a flat liquid phase in equilibrium with its vapor.

Figure 6.6 illustrates schematically a capillary with a diameter of *2r* and liquid surface with spherical curvature $R = \frac{r}{cos\theta}$. For the capillary rise in hydrostatic equilibrium, the vapor pressure $p(g) = p(l) - mgh = p(l) - \rho g h V_m$ resulting in

$\Delta p = (p(l) - p(g)) \; = \; \rho g h V m$. Substitution of this expression for Δp in equation 6.5 gives the equation for capillary rise relating the surface tension to the density of the liquid:

$$\gamma_{lv} \; = \frac{\rho g h r}{2 cos\theta} \qquad (6.7)$$

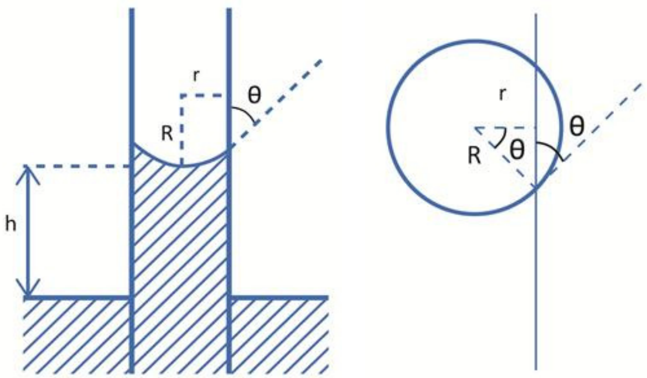


Figure 6.6: The capillary rise at hydrostatic equilibrium [6.6]

As will be explained in the next sections, the relation of the surface tension and the viscosity of a liquid phase in the interfacial surface is important in the stabilization process of foams. A basic relationship can be derived considering the dynamics of a laminar flow in a capillary with length x and a diameter *2r* as illustrated in Figure 6.7. According to Hagen-Poiseuille the laminar flow velocity in the capillary can be described as:

$$v = \frac{dx}{dt} = \frac{r^2 \Delta p}{8 \eta x} \qquad (6.8)$$

As a first approximation neglecting the gravity force the capillary pressure difference Δp is equal to:

$$\Delta p = \; \frac{2 \gamma_{lv} cos\theta}{r} + \; \Delta p_{external} \qquad (6.9)$$

Substitution of 6.9 in 6.8 gives equation 6.10

$$\Delta p_{external} + \frac{2 \gamma_{lv} cos\theta}{r} = \frac{8 \pi \eta x}{r^2} \frac{dx}{dt} \qquad (6.10)$$

Further, integration of equation 6.10 with the boundary condition L=0 for t=0 gives the following equation:

$$x^2 = \frac{r^2}{4\eta}\left(\frac{2\gamma_{lv}cos\theta}{r} + \Delta p_{external}\right)t \tag{6.11}$$

This equation is derived by Washburn in 1921 and is extensively used in the mercury porosimetry for the characterization of the internal structure of porous materials, such as catalyst support materials [6.5].

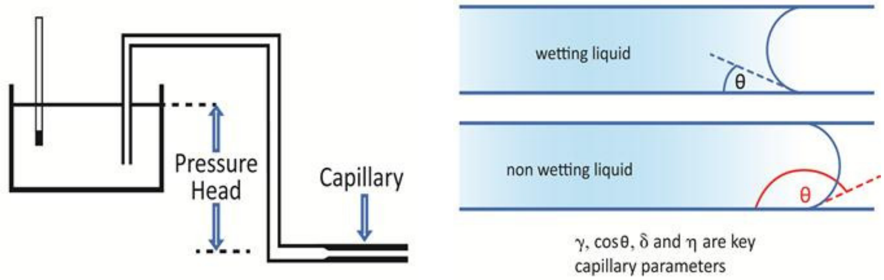


Figure 6.7: The dynamic situation of flow in a horizontal capillary [6.7]

Taken into consideration the gravitational inertial forces the general equation for the capillary flow dynamics, the extended Washburn relation, can be written as in equation 6.12;

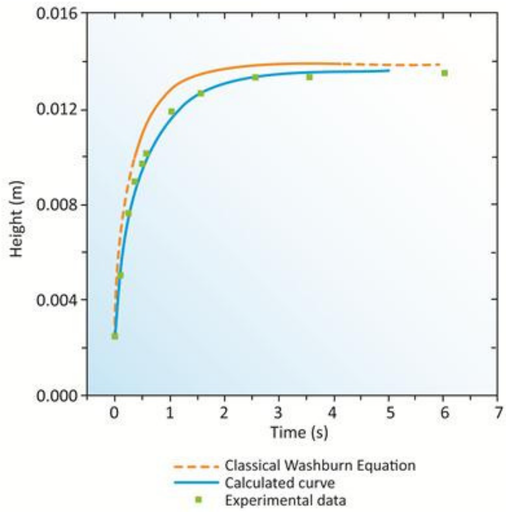
$$\Delta P_{external} + \frac{2}{R}\,\gamma_{lv}\,cos\theta = \frac{8}{R^2}\,\eta x\frac{dx}{dt} + \rho\left[x\frac{d^2x}{dt^2} + \left(\frac{dx}{dt}\right)^2\right] \tag{6.12}$$

Where,

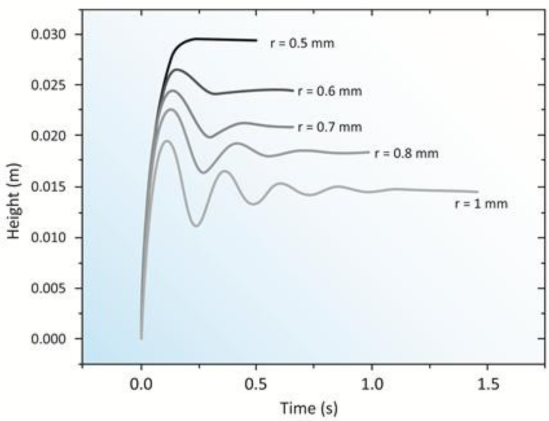
The factor $\frac{8}{R^2}\,\eta x\frac{dx}{dt}$ represents the viscous dissipation and

the factor $\rho\left[x\frac{d^2x}{dt^2} + \left(\frac{dx}{dt}\right)^2\right]$ represents the gravitational inertial effects.

The complexity of the capillary dynamics can be simply demonstrated with the analytical solution for a vertical capillary showing gravitational inertia induced capillary oscillation of the meniscus as a function of capillary radius in comparison of the Washburn capillary behavior as illustrated in Figure 6.8 [6.8; 6.9]. This oscillation phenomenon is important in the case of the possible use of the capillary relationship as a surface tension on line measurement as will be explained in the following sections.



a: the classical Washburn equation



b: the extended Washburn equation

Figure 6.8: The dynamic flow behavior in a vertical capillary [6.8; 6.9]

The particular molecular interactions in the interfacial surface liquid and vapor boundary governs the characteristic hydrodynamic properties of foams and vapor bubbles in the flashing evaporation process as will be explained in the next section.

Theoretical aspect of foams, foam stabilization and foam destruction

In the MSF seawater desalination efficiency improvement process, mitigation of excessive foam formation is crucial to guarantee sustainable efficient drinking water production eliminating product waste due to decreased distillate quality.

Foam is a natural occurring surface phenomenon originating from a dispersing process of a vapor phase in a liquid phase. In a pure liquid and vapor disperse system occurred foams are unstable, however in the case of natural seawater containing about 3-4% dissolved inorganic salts and traces of natural bio-organic surface active components excessive stable foaming can be produced and especially enhanced in the concentrated recirculating brine in a MSF evaporator [6.10].

In MSF evaporation practice next to foaming two other different phenomena can be distinguished that drastically degrade distillate quality, namely priming which is defined as liquid droplets dispersed in the vapor phase and entrainment of solids with the vapor phase. These three phenomena are closely associated and usually confusingly and interchangeably used as foaming to describe contamination of the distillate. Priming originates from the violently evaporation throwing slugs of seawater into the vapor and carryover is entrained fine seawater droplets and solids in the vapor and foaming is the result of stable bubbles formation at the surface of the evaporating seawater [6.11]. In Figure 6.9 the natural occurrence of priming and entrainment and foaming in coastal seawater can be visualized.

Figure 6.9: Foaming, entrainment and priming of seawater in natural windy situations

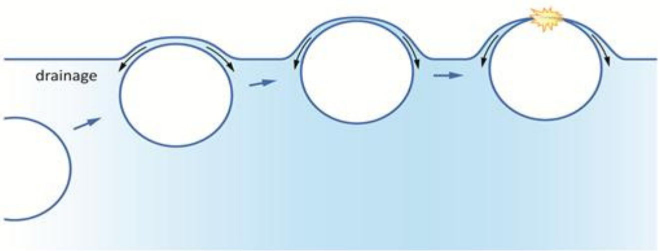
Despite the complexity of the physicochemical aspects of the interfacial surface science, in this section an introductory explanation is given of some basic principles and theoretical mechanisms of aqueous foam formation, foam stabilization and the destabilization role of the foam controlling additive in MSF evaporators. It is also the intension to give a simple acceptable theoretical explanation of some phenomena experienced in MSF evaporation practice related to antifoaming effect.

Aqueous foam formation and stabilization

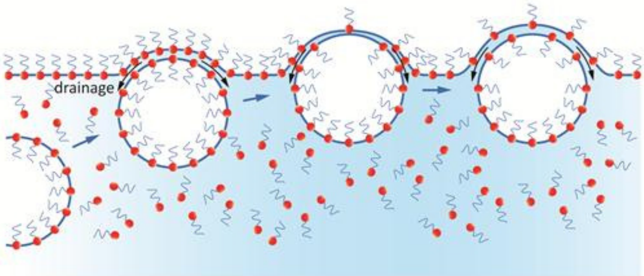
Naturally, pure water in thermodynamic equilibrium with its vapor phase is in a state of minimum free energy at a given ambient temperature and pressure. Under influence of gravitational forces exerted on the water molecules the water-vapor interfacial surface is flat at large distance of the solid surfaces of any containment. Vapor bubbles formed in the bulk of the water by flashing or boiling will eventually accumulate at the interfacial surface increasing the interfacial surface consequently increasing the free energy disturbing the equilibrium state of the water-vapor system.

Water molecules in the thin liquid film of the bubbles will flow to the bulk of the water under influence of gravity, resulting in thinning of the water film and eventually leading to rupture of the bubbles releasing the excess vapor contained in the water phase. This drainage process is the primarily cause of the actually thermodynamic inherently instability of pure liquid foams retaining again the equilibrium state of minimum free energy. A surface active component is due necessary to concentrate in the surface film of the bubbles to mitigate this drainage process stabilizing the vapor bubbles at the interfacial surface.

Surfactants are organic molecules with a hydrophilic polar part and a hydrophobic tail that usually oriented itself in an aqueous interfacial surface with the polar head facing the water molecules and the hydrophobic part oriented away from the water phase in the direction of the vapor phase. Figure 6.10 illustrates the foam drainage and the surfactant stabilization process. In practice surfactants are classified as anionic, cationic and nonpolar polymers.



a: foam formations in pure liquid



b: surfactant stabilized foam formations in pure liquid

Figure 6.10: Foam instability and the surfactant's stabilization process

Small concentration of surfactants in the interfacial surface layer opposes drainage by several mechanisms, most importantly by increasing viscosity, elasticity, electric repulsion and reduction of gas diffusivity through the interfacial surfaces as shortly describe as follows:

- Film viscosity:
  Intermolecular hydrogen bonding of the surfactant molecules form a semi polymeric molecular network increasing viscosity and lowering the drainage of surface layer water molecules toward to bulk
- Surface elasticity:
  Thinning of the surface layer or thin spots are repaired by the Gibbs-Marangoni effect, the accelerated diffusion form the bulk water and surfactant molecules to the affected surface areas of the bubbles
- Electrical repulsion:
  In the case of anionic or cationic surfactants, electrical repulsion at close approximation of equal charged molecules adsorbed on opposite interfacial layers reduces further thinning of the interfacial surface film
- Interlayer gas diffusion:
  Surfactants molecules absorbed on the interfacial layer reduce the diffusion of vapor or gas from smaller bubbles with a higher internal pressure into larger bubbles preventing breakage of the smaller bubbles.

In practice three different foam structures are usually distinguished during foam formation with different resistance to drainage, subsequently increased stabilization potential as indicated in Figure 6.11 [6.12].

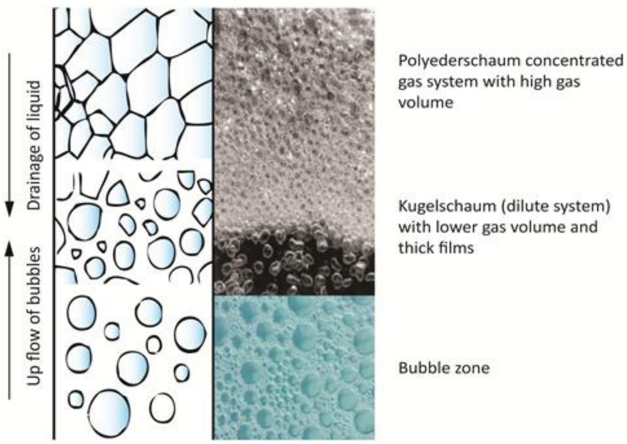


Figure 6.11: Foam structure during formation and drainage [6.12]

Aware of the fact that the common theories explaining the foam stabilization mechanism of Gibbs and Marangoni preventing drainage of the surface interfacial liquid film of foam bubbles actually permits liquid to flow from a low energy level to a high energy level actually in contradictory with the natural thermodynamic principles a new theorem is introduced based on the pressure in the bubble liquid film, as indicated in Figure 6.12 [6.13].
In the initial formation stage of a foam bubble at the liquid surface, liquid in the surface interfacial layer and surfactants molecules will flow toward the liquid bulk. Consequently, creating a situation with uneven distribution of surfactant molecule over the interfacial bubble film where in the direct vicinity of the bulk more surfactant molecules are present as in the intersection A. Due to the lower surface tension and consequently a lower attraction force left to the intersection A, a molecule in this intersection will experience a resultant force to the right of intersection A containing less surfactant molecules resulting in a higher attraction force to the right of intersection A. In intersection B in the upper interfacial surface film the resultant force is practically zero due to the same surfactant concentration or less concentration difference on both sides of intersection B. As a consequence the intersection pressure P_A is higher than the P_B permitting a flow from a hydrodynamic higher energy level to lower hydrodynamic energy level to inhibit drainage stabilizing the foam bubble.

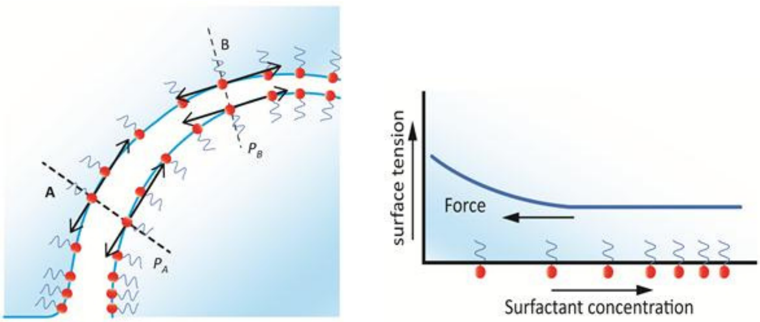


Figure 6.12: The foam stabilization process based on the surface interfacial liquid pressure [6.13]

Next to surface active organic polymers, finely divided solid particulates such as silt, corrosion products or precipitated inorganics salts such as calcium carbonates, commonly found in the MSF distillation process adsorb onto the vapor-liquid interface providing a stabilizing film around the foam bubbles. In summary in the MSF seawater evaporation process with the presence of the two major foam stabilizing contaminants e.g., natural bio-organic surfactants and finely divided particulates practically an ideal foam promoting circumstance exists, needing effective additives to control excessive foaming.

Foam destabilization and destruction

As indicated above stabilized foams is a surface phenomenon deriving its stability from the particular electrical, viscous, elastic or self-healing and gas diffusivity properties as a result of the characteristic intermolecular interactions of the surfactants in the vapor-liquid interfacial surfaces. The physicochemical foam destabilization process is based on foam control additives that are able to displace the stabilizing surfactant from the interfacial boundary layer enhancing bubble film drainage or locally enabling surface tension increment promoting rupture of the thin liquid film of the bubbles. As indicated in Figure 6.13, in the interfacial thin liquid film of surfactant stabilized foams the charged hydrophilic end of the surfactant is oriented in the water phase and the hydrophobic tail in the vapor phase with the charged parts facing the two opposing boundary layers.

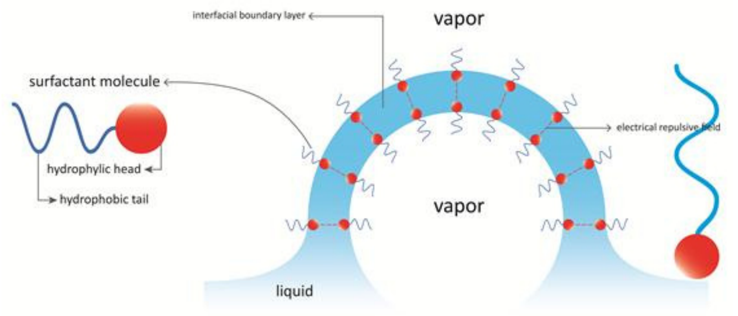


Figure 6.13: Foam stability by electrical property of the bubble's interface double layer

Foam stability is primarily due to electrical properties of anionic and cationic surfactants and the polar character of nonionic surfactants. The different theoretical stabilization mechanisms can simply be explained without the pretention of a sound scientific enunciation laying the basis of the defoaming and antifoaming process. Once oriented in the interfacial thin layer of the foam bubble as indicated in Figure 6.13, the equal charged molecules in both gas-liquid interfaces will hold themself in place because of the electrical repulsion field and steric hindrances experienced from neighboring molecules in the same layer or in the opposite layer, realizing a thermoelectric equilibrium of the thin film with maximized free energy. Any attempt to bring them in a smaller space, as caused by the drainage process, they will resist because of the high concentration and the like electrical charges giving the interfacial the self-healing property. The high concentration of the surfactant polymer molecules in the surface layer also increases the viscosity and markedly decreases the liquid drainage to liquid bulk. Another important property is the fact that in the presence of surfactant smaller vapor bubbles are stabilized lowering the rising velocity to the water surface. Larger bubbles have a large breakage tendency than smaller bubbles.

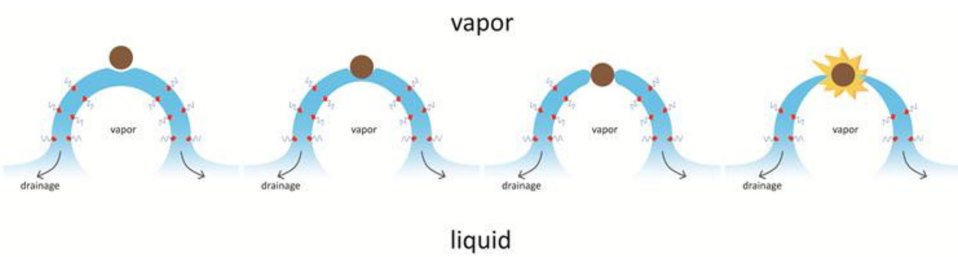
Foam control or the foam destabilization process is based on the disruption of these several aqueous surface properties to produce stable foams. In any process, two kinds of foams can in general be distinguished namely the surface foams which is more obvious and easily detected and eliminated and the entrained air/vapor dispersed in the liquid bulk, actually foam beneath the liquid surface. These kinds of internal foams are more difficult to control and practically a more severe problem than surface foams. There are a variety of mechanical and chemical foam controlling methods, however in this section the main attention is on chemical antifoaming because of their importance for application in MSF evaporation. Chemical foam control can be accomplished in two different ways as follows [6.14]:

- Antifoaming:
  The physicochemical process of a chemical additive to prevent foam from forming or reduces the foam level
- Defoaming:
  The physicochemical process of a chemical additive to destruct foams on occurrence

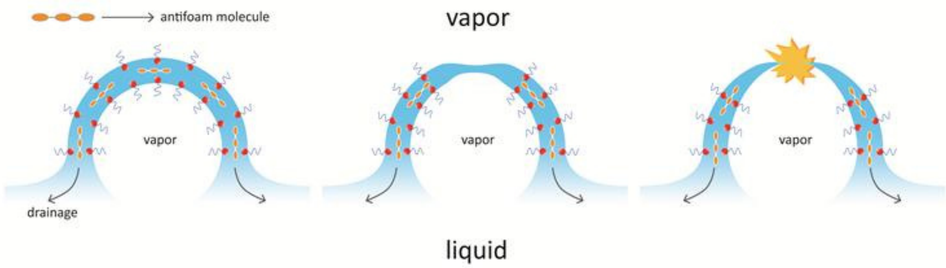
Although differences between these processes, in practice they usually are used synonymously. The foam control additives of both processes generally perform by both of the following mechanisms to disrupt the stabilization process [6.15; 6.16]:

- Particulate interference:
  The surfactant molecules arrangement in the bubble interfacial surface is interrupted by the interposing of hydrophobic particulates producing locally weak points. This bubble thin film interruption permits coalescence of entrained bubble foam in the bulk liquid and collapsing of surface foam bubbles [6.15].
- Preferential surfactant displacement:
  The non-foam stabilizing antifoam surface active components replace the undesirable foam stabilizing surfactants from the interfacial surface of the bubble. The unstable bubble double layer now permits easy coalescence and collapse of entrained or surface foams.

The foam destabilization mechanisms are schematically illustrated in Figure 6.14.



a: antifoam particles mechanism



b: Surfactant removal mechanism

Figure 6.14: The foam destabilization mechanism of antifoam additives [6.15]

Antifoams depend on some major properties to qualify as an effective foam control additive. To be effective the antifoam should be insoluble but dispersible in the foaming medium and should be effective on both entrained and surface foams [6.17]. Especially in the case of the efficient seawater desalination it should eliminate foams quickly and retain its effectiveness throughout the process residence time and should in no circumstances interfere with the product quality. In the MSF seawater desalination process underfeeding of the antifoam always reduces distillate quality increasing the dissolved salt content and overfeeding of the antifoam decreases production and consequently desalination efficiency. In the next section a plausible explanation is given for this experienced phenomenon of underfeeding of antifoam. It is noteworthy that up to now there is no acceptable explanation for this phenomenon [6.2].

Theoretical aspects of antifoam performance in MSF evaporation

Inherently to the flashing process, foam initiates in the first evaporating stages of the MSF evaporator due to pressure reduction of the superheated recirculating brine. Large volume of carbon dioxide gas resulting from high temperature decomposition of bicarbonates, and non-condensable gasses and water vapor are hereby released from the turbulent brine flow and if not properly vented and if the condensing capacity is inadequate increased stage pressure will reduce gas diffusion and consequently promote foam stabilization. In the lower temperature evaporating stages, formed foams may be stabilized due to the increased salt concentration of the recirculating brine in combination with increased interfacial surface viscosity as a result of the lower stage temperatures. Furthermore the biofouling and high temperature scale inhibiting additives are surface active chemical component that enhance foam formation. Foam control is an inevitably important physicochemical aspect for desalination sustainability and efficiency and should comply with the following criteria for antifoaming effectiveness:

- The antifoam should be compatible (no adverse inference with intended function) with both the biochemical and antiscalant and should not reduce heat transfer
- The antifoam should be stable at the high operating temperature of the MSF evaporator and retain stability during the residence time in the evaporator
- The antifoam must not contain any vapor volatile components to contaminate the distillate

Many antifoam are on the market for use in MSF evaporators, however research have demonstrated the chemical component class of nonionic polyethylene glycol mono alkyl ethers with an hydrophobic and hydrophilic portion as most effective [6.1]. The antifoam GEBetz Evap AF ™ used at the Desalination Department of W.E.B. Aruba N.V. is such an antifoam.

The Antifoam GE Betz Evap AF™

The high temperature antifoam GEBetz Evap AF ™ used at W.E.B. Aruba N.V. to inhibit foaming in the MSF evaporators is an ethylene oxide-propylene oxide (EO-PO) block copolymer. It is a nonionic surface active component with the ethylene oxide as the relatively hydrophilic portion and the propylene oxide portion of the copolymer is relatively more hydrophobic. Actually ethylene oxide-propylene oxide copolymers are similar to surfactants and the function of this copolymer as a surfactant or an antifoam is related to the amounts of the ethylene oxide and propylene oxide components and the lengths of blocks of these components in the copolymer chain [6.18]. This nonionic antifoam functions by interacting with the cationic surfactant in the interfacial surface layer of the foam bubble. The hydrophobic propylene region of the antifoam molecule interacts with the hydrophobic tail of the surfactant molecule making it less hydrophobic and helping to draw it away from the interfacial layer of the bubble into the water phase. On the other hand the relatively more hydrophilic ethylene oxide portion of the antifoam interact with the cationic charges of the surfactant molecules reducing their electrical repulsive interaction with other cationic surfactant molecules [6.19]. In essence, the antifoam disrupts the orientation of the cationic surfactant molecules in the water-vapor interface and in the water phase. This reduces the thickness of the bubble’s water film and allowing the film to drain away from the top surface and the water to evaporate normally. Figure 6.15 illustrates the molecular structure and the destabilization function of the antifoam in MSF evaporation.

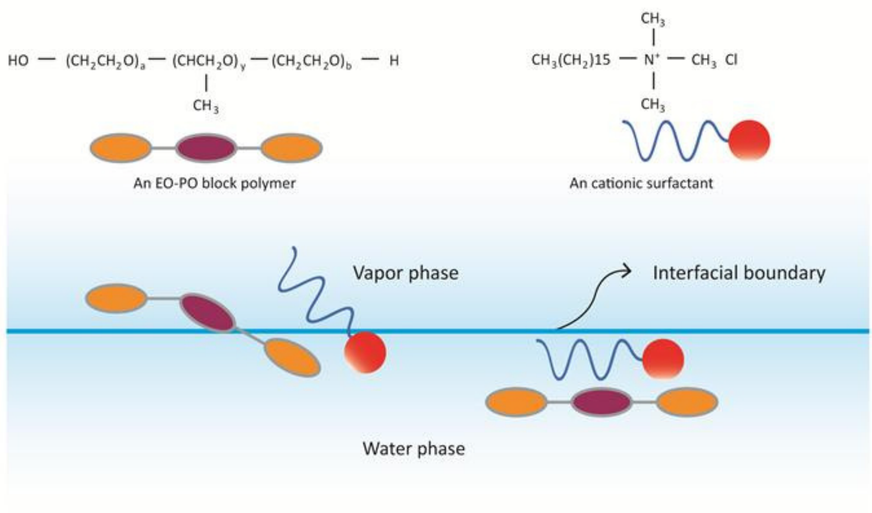


Figure 6.15: The GEBetz Evap AF™ destabilization function and molecular structure [6.19]

Foam destabilization is an interfacial phenomenon, the nonionic ethylene oxide and propylene oxide copolymer antifoams are effective at extreme low dosage in the range of 0.4-0.6 ppm based on the seawater make up flow in the MSF evaporator. Insufficient dosage especially due to pump failure causes distillate high salt concentration due to high foaming and priming. Over feed of the antifoam always causes the MSF evaporator to behave as it is fouled decreasing production and efficiency. A sound explanation for this practically unexplained effect of overfeed is further elaborated on.

The effect of antifoam overfeeding on MSF evaporation

The lack of an acceptable explanation of the behavior of an MSF evaporator in the case of overfeeding of the antifoam is possibly the negation or omission of two important aspects. In the first place the surface tension effect on evaporation. In the flashing process evaporation process proceeds by spontaneous vapor bubbles formation with practically a spherical curved surface flowing through the bulk liquid toward the liquid surface, increasing in volume due to vapor-liquid mass transfer forming unstable foam bubbles matrix with an effective foam control. An effect that is observable in a glass of bubbling water, champagne or beer where carbon dioxide bubbles rapidly flow toward the surface increasing in volume because of carbon dioxide transfer from the liquid phase to the gas phase [6.20]. Effective drainage permits normal evaporation through bubble film rupture without priming and carryover.

In the second place, as mentioned above in the foaming process two different form of foaming can be distinguished namely the surface foam and the entrained foam. The latter being most difficult to observe and is practically most difficult to control. The entrained foaming process is practically inherent to the flashing process due to spontaneous vapor bubbles formation in the bulk. In the presence of a higher concentration of antifoam due to higher surface energy of the tiny bubbles the nonionic surfactant molecules of the antifoam are adsorbed on the surface of the bubbles. The hydrophobic tail of the absorbed antifoam molecules and the cationic surfactants hinder vapor transfer from the bulk liquid to the vapor phase of the bubble decreasing the tendency of the dispersed internal foam bubbles to rise. This situation is illustrated in Figure 6.16.

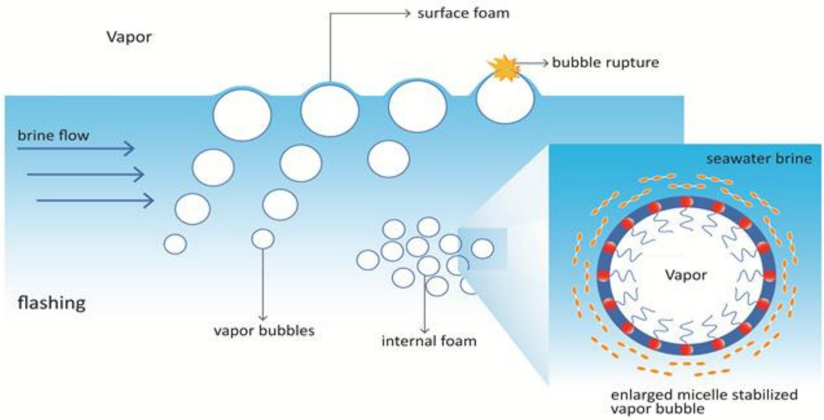


Figure 6.16: Entrained foam stabilization due to increased antifoam concentration

The stabilization of entrained foam will increase the volume of the gas phase of the recirculating brine decreasing the effective pumping capacity of the recirculating brine pumps. The two phase flow will also decrease the heat transfer of the heat recovery section and the heat input section of the MSF evaporator. The result is more steam consumption to maintain the top brine temperature at reduced production drastically decreasing efficiency. The operational personnel noticing this effect explain this phenomenon erroneously as a cooling effect of the antifoam. A similar situation had occurred with an Aqua Chem MSF evaporator during commissioning in Malaysia where the recirculating brine pumps could only reach total rated capacity after dosing of minute concentration of an antifoaming agent even when no foaming was observed [6.21]. The start-up engineers involved thought the solution is the extra energy of the antifoam, actually the main reason was that the pumps where pumping a seawater-air/vapor two phase flow. The air/vapor entrained internal foam effect was stabilized by a higher concentration of natural bio-organic surface active components of the seawater feed. Acknowledging the importance of antifoam dosing and the surface tension in MSF evaporation, a novel approach is developed based on the surface tension to optimize the antifoam dosing. An introductory research is set up to measure the surface tension of different combination of the additives. The results are given in the next section.

6.3 A novel surface tension method to optimize foam control in MSF evaporators

On the contrary to boiling, flashing is an efficient process for evaporating a liquid by means of pressure reduction, however inherently to this process the violently production of vapor bubbles results in the possibility of initiating the most problematic vapor entrained foam formation. Foam stabilization and antifoaming are processes that particularly take place in the interfacial surface of the vapor-water dispersed system. As described in the previous section evaporation from a curved surface and interfacial surface phenomena as foam formation and antifoaming are primarily all related to the surface tension of liquid in question. Acknowledging this imminent importance of the influence of the surface tension on evaporation in MSF evaporators due to curved surfaces of the spontaneous vapor bubbles formed during flashing and the interfacial surface tension governing the foam control processes, a novel method is developed for the optimization of the additives dosing based on the surface tension of the recirculating brine. Effective control of the antifoam dosage by measuring the surface tension of the recirculating brine will ultimately solve the problems experienced with underfeeding causing product quality dissemination and overfeeding resulting in product loss. The guiding principle behind this method is the fact that an optimal foam controlled recirculating brine should have a specific surface tension, high enough to promote the foam destabilization process mitigating the surface tension reducing properties of surfactants, the natural bio-organic surface active seawater components, the bio chemical disinfectant and antiscalant both having surfactant properties promoting foaming and evaporation instability. Surface tension measurements have been performed with a bubble type tensiometer in an introductory research to prove the feasibility of the surface tension foam control concept.

The surface tension measurement

The surface tension measurements of the different chemical additives used in the MSF evaporator at different concentrations in seawater are performed with a Kruss PocketDyne BP 2100 bubble type tensiometer. The surface tension measuring technique of this bubble type tensiometer is based on the generation of air bubbles in the liquid phase by means of a constant air flow through a capillary of certain radius. The pressure of the air flow changes during the bubble generation process depending on the radius of the growing bubble as indicated in Figure 6.17 [6.22].

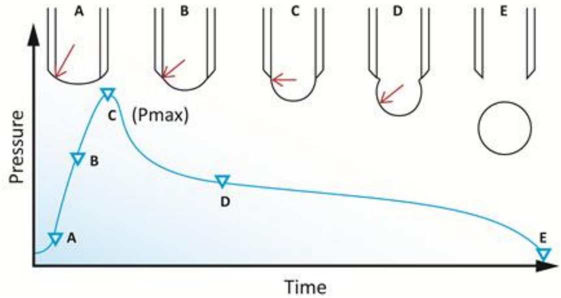


Figure 6.17: The pressure of the air flow during the bubble generation [6.22]

The pressure reached its maximum value when the generated spherical bubble attain a radius equal to that of the capillary as indicated in the situation C in Figure 6.17. At this maximum pressure, the bubble reach the dimension of a half a sphere and the dynamic surface tension can be calculated using the following equation.

$$\gamma_{lv} = \frac{(\Delta p_{max} * r_{cap})}{2} \tag{6.13}$$

In equation 6.13, γlv is the dynamic surface tension and Δp_{max} and r_{cap} represent respectively the maximum air pressure and the capillary radius. The pressure is measured with a sensitive pressure sensor connected to a computer. The air pressure successively decreases after the maximum pressure till the air bubble separates from the capillary. The air generating cycle A-E is known as the surface aging. Figure 6.18 illustrates the bubble type tensiometer.


Figure 6.18: The Kruss PocketDyne BP 2100 bubble type tensiometer [6.22]

The dynamic surface tension is measured of the commonly used chemical additives in the MSF evaporators at W.E.B. Aruba N.V. at different concentrations in seawater and pure distillate to evaluate the effect of concentration of the different surfactants on the surface tension of seawater and pure water [6.13; 6.23]. The measurement results of the Clam Trol CT-2 TM are presented in Figure 6.19.

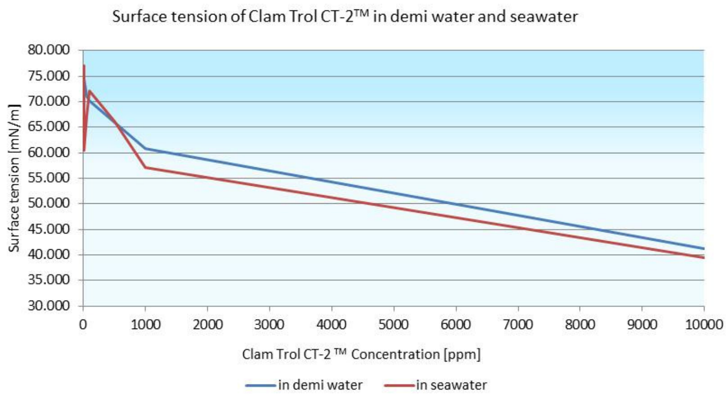


Figure 6.19: The surface tension as a function of the Clam Trol CT-2 TM concentration [6.23]

As shown in Figure 6.19, the Clam Trol CT-2 TM has a surface tension reducing effect indicating the foaming potential of Clam Trol CT-2 TM as also experienced in practice. The measurement results of the surface tension as a function of the Scaletrol PDC 9323 TM concentration is illustrated in Figure 6.20.

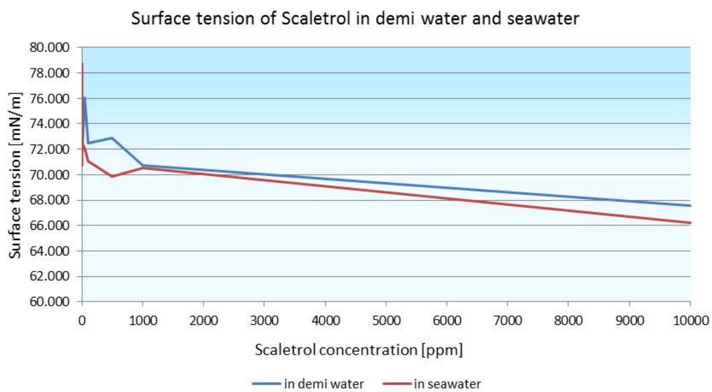


Figure 6.20: The surface tension as a function of the Scaletrol PDC 9323 TM concentration [6.23]

The Scaletrol PDC 9323 TM is also known as a high temperature antiscalant component with a high foaming potential as also indicated by the measurements.
Figure 6.21 illustrates the effect of the GEBetz HT 15 TM on the surface tension of seawater and pure water.

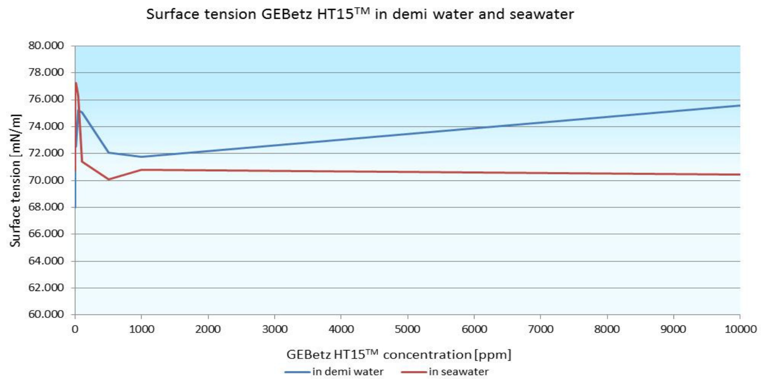


Figure 6.21: The influence of GEBetz HT 15 ™ on the surface tension of demi water and seawater [6.23]

As expected the GEBetz HT 15 ™ component is more a crystal distortion and dispersant product with less surface activity as the two former products. Figure 6.22 shows the effect of the antifoam GEBetz Evap AF ™.

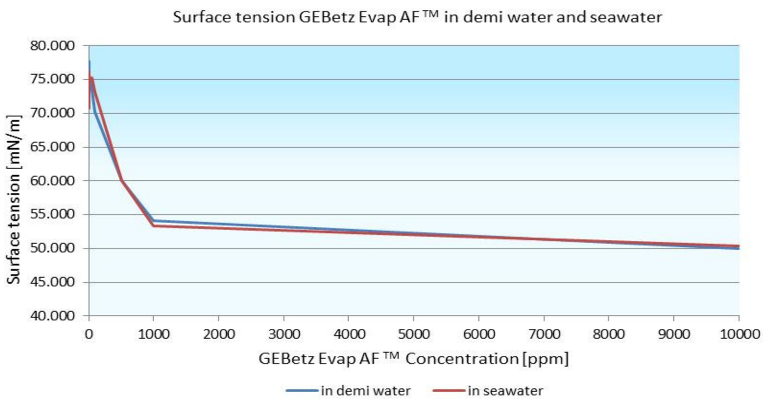
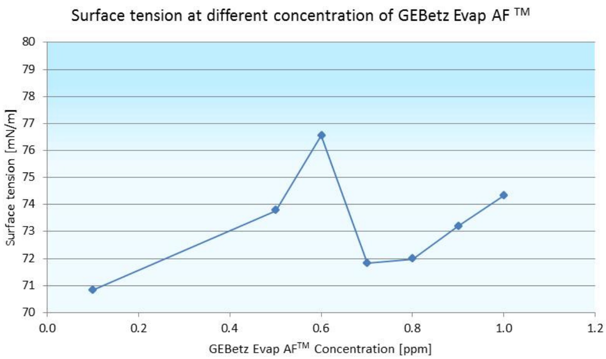
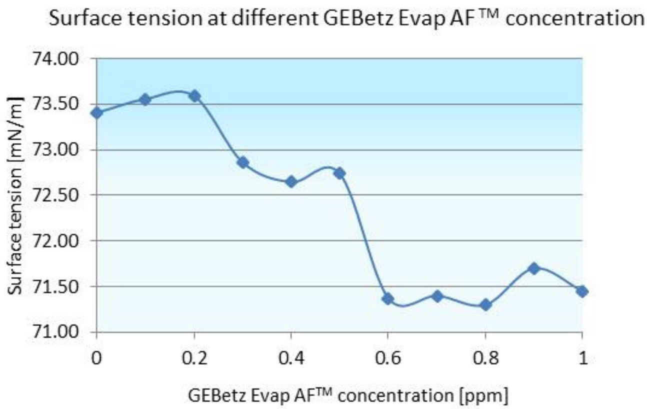


Figure 6.22: The antifoam effect on the surface tension of seawater and demi water [6.23]

As Figure 6.22 indicates, the antifoam has the highest effect on the surface tension lowering both the dynamic surface tension of seawater and pure water from 73 mN/m to about 50 mN/m. The surface tension of pure water consists of dispersive forces of 23 mN/m and of the hydrogen bonding forces of 50 mN/m [6.25]. This means that at higher concentration of antifoam the surface is practically a monolayer of antifoam molecules and the dominating force is the hydrogen bounding. The dynamic surface tension is also measured of the seawater with the common operation concentration of the bio-disinfectant and antiscalant namely 4 ppm Clam Trol CT-2 TM , 8 ppm GEBetz HT 15 TM and 0.8 ppm Scaletrol PDC 9323TM as function of the antifoam concentration. This is an important measurement proving the feasibility to use the concept of surface tension of the recirculating brine as method to optimize the chemical additives dosing in MSF evaporators. Figure 6.23 shows the results of the measurements during two independent internship researches with respectively no temperature and with temperature control by means of a water bath.



a: Results of the first investigation without temperature control [6.23]



b: Results of the second investigations with temperature control [6.24]

Figure 6.23: The influence of the antifoam on the surface tension of seawater at normal operation condition

The results in Figure 6.23 indicate the very important decrease of the surface tension and a surface tension in the range of approximately 71-72 mN/m at an antifoam concentration of about 0.6-0.8 ppm indicating the foam destabilization effect. The dosing of the antifoam for stable operation of the MSF evaporators is set by trial and error at a concentration of 0.6 ppm. This also indicates that the developed novel surface tension method to optimize foam control in MSF evaporator is a feasible method.

For effective foam control an online surface tensiometer should be developed and the measured surface tension of the recirculating brine should be automatically compared with a preset target value in the computer controlled chemical dosing system to adjust the antifoam dosing. A conceptual design of such an online surface tensiometer measuring system is illustrated in Figure 6.24.

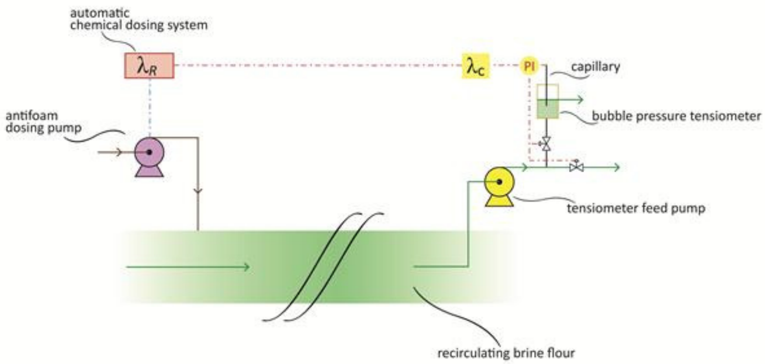


Figure 6.24: A conceptual design for a possible on line surface tensiometer

This conceptual design and the possibility to use the bubble type tensiometer on line and the membrane integrity testing method [6.26] are subject for further research. In the membrane integrity testing the pressure at which air will pass through defects is related to the pore diameter of the defects and the surface tension of the liquid as indicated in equation 6.14.

$$\Delta p_{max} = \frac{4k\gamma_{lv}\,cos\theta}{d} \qquad (6.14)$$

6.4 Conclusions

1. In the flashing evaporation process, the surface tension of the evaporating liquid plays an important role due to the spherical curved interfacial surface of the vapor bubbles.
2. In the seawater flashing evaporation due to the violent vapor bubbles formation and the turbulent flow, distillate contamination is not only caused by foaming though also because of priming and entrainment.
3. In practice two forms of foam can be distinguished, the surface polyhedral foam which is easily detected and controlled and the troublesome vapor entrained bubble type foam that is more difficult to detect and controlled. The latter is inherently to the flashing evaporation process.
4. In MSF seawater evaporation, initiated foam is stabilized by the bio-organic surfactants naturally present in seawater.

5. Surfactants stabilize foam by mitigating the drainage process in the interfacial film by the mechanism of molecular electrical repulsion, by increasing the interfacial film viscosity through hydrogen bonding, by lowering the surface tension enhancing the self-healing effect or increasing the elasticity of the interfacial surface layer. The destabilization process of nonionic EO-PO antifoams is based on displacement of the surfactant from the interfacial surface eliminating the abovementioned effects.
6. Production loss experienced with overfeeding of the antifoam is caused primarily due to stabilization of the entrained vapor bubbles enhancing internal foams.
7. The surface tension of the recirculating brine is a feasible novel control measure to optimize the antifoam dosing in additive dosed MSF evaporators.
8. The surface tension measurement with the bubble type tensiometer has proven the feasibility of the novel surface tension additive dosing optimizing method.

6.5 References

6.1. Auerbach, M. H., O'Neill, J. J., Reimer, R. A., Walinsky, S. W., Foam Control in MSF Desalination, Desalination, 38 (1981) 159-168, Elsevier Scientific Publishing Company, The Netherlands.

6.2. Hamed, O. A., United Arab University, Personnel Communication, International Desalination Conference, 2007.

6.3. www.engr.uconn.edu/eviron/envphys/pdf/capillarity_revised01.pdf

6.4. Arrindell, E. M., Birkett, J. D., Aruba's Early Experiences in Desalination, Caribbean Desalination Conference, Oranjestad, Aruba, PowerPoint presentation, June 2002.

6.5. Marchena, F. A., Theoretical Aspects of the Mercury Porosimetry, MSc thesis, Delft University of Technology, The Netherlands, 1985.

6.6. Moore, W. J., Physical Chemistry, Longman Group Limited, ISBN 0 582 444234 6, London, 1974.

6.7. http//crmm.umh.ac.be, Modeling of micro-fluidics: inside a micro-pore, Centre de Recherche en Modélisation Moléculaire.

6.8. Hamraoui, A., Nylander, T., Analytical Approach for the Lucas-Washburn Equation, Journal of Colloid and Interface Science 250, 415-421, (2002).

6.9. Or, D., Tuller, M., Capillarity, University of Connecticut, http://www.engr.uconn.edu/environ/envphys/pdf/vadose_pdf/Capillarity_revised01.pdf

6.10. Imam, M., Al-Raheed, R., Al-Tisan, I., et al., Studies on a polyoxypropylene glycol-based antifoaming agent in MSF plants, Desalination 129 (2000) 187-196.

6.11. Betz Handbook of Industrial Water Conditioning, Betz Laboratories, Inc., USA, 1967.

6.12. Pugh, R. J., Foaming, foam films, antifoaming and defoaming, Advances in Colloid and Interface science 64 (1996) 67-142

6.13. Fernandez Segrera, F. S., Optimizing Chemical dosage in MSF evaporators, BSC-thesis University of the Netherlands Antilles, Curacao, June, 2010

6.14. Betz Paper Chem. Inc., Foam Training Course, Jacksonville Florida, USA, 1994.

6.15. Dippenaar, A., The Destabilization of Foam by Solids. I. The Mechanism of Film Rupture, International Journal of Mineral Processing, 9 (1982) 1-14, Elsevier Scientific Publishing Company, Amsterdam, The Netherlands.

6.16. Betz laboratories Inc., Mechanism of Foam Formation and Control, training course.

6.17. Otrhalek, J. V., Gomes, G. S., TAPPI Papermakers Conference Proceedings; Boston, Massachusetts, USA, April 1979, 183-189.

6.18. Rosen, M. J., Surfactants and Interfacial Phenomena, 2nd Edition, John Wiley & Sons, ISBN 0-471-83651-6, 1989, USA.

6.19. Post, R. M., Personnel Communication, 2010.

6.20. Wesselingh, J. A., Separation Processes, Lectures University of Technology Delft, 1981

6.21. Tonner, J., Personnel Communication, Aruba, 2010.

6.22. Krűss PocketDyne Mobile Bubble Pressure Tensiometer, Instruction Manual, V01.16-02, Krűss GmbH, Hamburg 2003-2008.

6.23. Albus, S. J., Optimizing the Chemical dosing by means of the surface tension, BSc Internship Report, W.E.B. Aruba N.V. and Avans Hogeschool Breda, February 2011.

6.24. Peterson, I. , Optimizing the chemical dosing of MSF evaporators by the surface tension method, Bsc Internship Report, W.E.B. Aruba N.V. and Hogeschool Utrecht, July 2012.

6.25. Takamura, K., Surface Tension and Surfactant, RBU Functional Polymers-NAFTA, BASF Corporation, Charlotte Technical Center, takamuk@basf.com.

6.26. Wilff, M., The guidebook to Membrane Desalination technology, ISBN 0- 86689-065-3, Balaban Desalination Publications, L'Aquila, Italy, 2007.

Chapter 7

Corrosion and red water inhibition technology applied in drinking water systems of W.E.B. Aruba N.V.

The Coral house, a worldwide unique natural drinking water mineralization system

Chapter 7

Corrosion and red water inhibition technology applied in drinking water systems of W.E.B. Aruba N.V.

Table of Contents:

Abstract

The post treatment of the drinking water produced by means of the seawater desalination technology is the last essential physicochemical aspect in the desalination efficiency improvement process. Seawater desalination either by thermal or a two pass membrane technology can purify the seawater to such an extent that it contains practically no dissolved minerals. The produced product water is very soft and so not potable and corrosive for the distribution network. Red water (iron corrosion) and blue water (copper corrosion) is caused if the post treatment is not optimized. Corrosion can on his turn cause leakages due to perforation of the distribution pipes. Since the introduction of seawater desalination in Aruba for the production of drinking water natural coral stones were used in the worldwide unique Coral House for the natural mineralization process in the post treatment of the produced distillate. The effluent of the "Coral House" was still very soft and so sodium hexametaphosphate was used as a corrosion inhibitor to mitigate iron corrosion. Especially during the period of the Aqua Nova MSF evaporators producing less quality water, iron corrosion was enhanced by the increased concentration of chloride ions in the distillate. W.E.B Aruba N.V. had thoroughly evaluated the brown water problem in the distribution system in cooperation with Betz Inc. in 1990 and the pyrophosphate/orthophosphate technology is introduced to inhibit iron corrosion increasing the drinking water quality. Enhanced lime stone filtration as practiced in many other Caribbean Islands with carbon dioxide acidified distillate, although increasing the buffer capacity of the drinking water still causes brown water. The use of the corrosion inhibitors pyrophosphate and zinc orthophosphate has eliminated the red water problem in Aruba since the application in 1990. The American Water Works Association considers this technology as an economical effective treatment for soft water. Due to good maintenance and operation of the distribution system, good water quality and client services W.E.B. Aruba N.V. has managed to have the lowest percentage Non Revenue Water in the region, of about 2.6 to 4.11 % comparing with 15 to 70% in the neighboring islands. In an introductory study a low Infrastructure Leakage Index indicating the well-maintained condition of a distribution system is calculated and compared with the other Dutch Caribbean Islands. In this chapter the post treatment of the drinking water in Aruba is described in details.

7.1 Introduction

Thermal distillation and membrane desalination plants produce potable water of the very highest purity and quality. In particular the distillation process eliminates all of the many contaminants which commonly occur at low levels in potable water taken from surface water and well water supplies. For example, *U.S. Environmental Protection Agency* (USEPA) regulations list 87 contaminants in their primary drinking water standards [7.1], none of which are found in distilled seawater. Although distilled and membrane treated water is pure, it is also 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. Distilled water represents a special challenge; the distillation and the membrane process removes natural corrosion inhibiting minerals such as calcium and bicarbonate along with sea salts and other contaminants. Special care is also required in the selection of corrosion inhibitors since many commonly used inhibitors do not work well in highly desalinated water. Moreover, due to the large size of modern desalination facilities, the treatment must not add significantly to the cost of the finished water.

Since the very beginning of the thermal desalination activities at W.E.B. Aruba N.V., the hot distillate has been cascaded over a bed of natural coral stones in the “Coral House”. The Coral House imparts an average of 12 mg/L total hardness and 12 mg/L of total alkalinity and lightly buffers the water to a pH of 9.3, and aerates the water in the process. From the Coral House, the finished water is pumped to storage tanks and distribution piping system. From the late 1980s until 1990, the community of Aruba experienced brown water problems throughout the island due to corrosion in the distribution system, with the iron content far beyond *World Health Organization* (WHO) standards. During that period, sodium hexametaphosphate (SHMP) was used as a corrosion inhibitor. In 1990, a comprehensive corrosion survey of the Aruba’s Potable Water Distribution System was performed by W.E.B. Aruba N.V. in combination with Betz Laboratories, Inc. Following the survey and careful consideration of many treatment options, the SHMP program was replaced with a 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 “red 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 and elimination of iron production in the system. In 1996, the zinc product was replaced by an orthophosphate/zinc blend, and the pyrophosphate dosage was reduced.

The current treatment consists of low level of both zinc orthophosphate, and pyrophosphate. W.E.B. Aruba N.V. has occasionally observed blue water in the distribution system caused by corrosion of smaller copper distribution lines. A study was conducted to identify and assesses treatment alternatives. This chapter provides a detailed description of the corrosion process and the water treatment technology applied to thermal and membrane desalination potable water systems of Aruba. This optimal conditioning of the potable water has effectively mitigated corrosion in the water distribution network eliminating the occurrence of red water, blue water and corrosion induced perforations of distribution pipes. The water losses are significantly reduced and the lowest percentage *Non Revenue Water* (NRW) in the region of about 2.6 to 4.11 % comparing with 15 to 70% in the neighboring islands and a low *Infrastructure Leakage Index* (ILI) is achieved indicating the well-maintained condition of the distribution network. For this reason, some aspects of the drinking water distribution network of Aruba related to corrosion and drinking water quality is highlighted in section 7.5.

7.2 Corrosion in Potable water Distribution Systems

An introductory iron and copper corrosion theory

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. In the steel and copper production mills, these metals are refined to their pure state. Corrosion is simply an electrochemical reaction of the refined metal with its environment that returns the metal to its natural oxidized state [7.2]. For example, iron ore is composed principally of iron oxide. The ore is refined to steel using energy from coal or other sources. 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 take more volume 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. The color causes the water to stain surfaces it comes in contact with and imparts unpleasant tastes. Over the long term, corrosion causes a loss of pipe wall thickness and eventual perforation, resulting in water leaks. The pictures in Figures 7.1 are vivid examples of corrosion in steel and copper used in potable water systems [7.3]

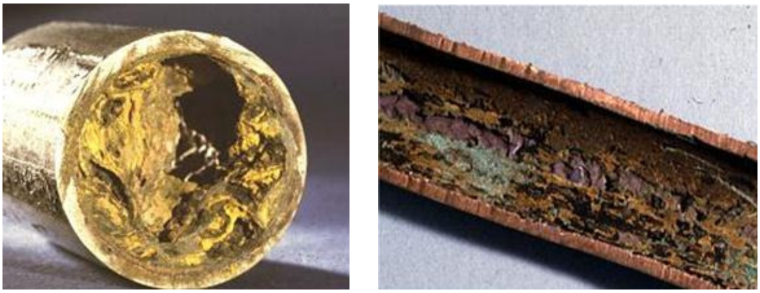


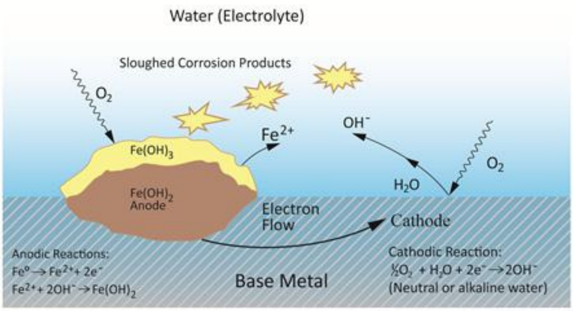
Figure 7.1: Iron and copper corrosion in distribution pipes [7.3]

In more scientific terms, corrosion can be understood as an electrochemical process, essentially a battery operating under uncontrolled conditions.

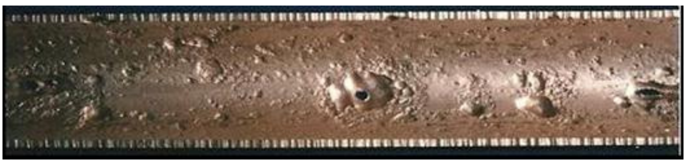
There are four basic elements to the corrosion cell:

- Anode, where the metal gives up electrons and dissolves into solution
- Cathode, where the electrons given up at the cathode are released to solution
- Conductor (base metal), which conducts the flow of electrons
- Electrolyte (water solution), where the flow of ions in solution completes the circuit

Figure 7.2 illustrates schematically the electrochemical aspects of the corrosion cell for steel in a water system [7.3].



a: theoretical steel corrosion mechanism



b: practical occurrence of steel corrosion causing red water and perforation

Figure 7.2: The electrochemical iron corrosion cell in water systems [7.3]

Metal oxidation and loss occurs at the anode of the corrosion cell. Often, when localized corrosion occurs, the anode is separated by a physical distance from the cathode, where a reduction reaction takes place. An electrical potential difference (voltage) exists between these sites, and there is an actual flow of electrical current and a counterbalancing flow of the ions in solution between anodic and cathodic sites.

For steel, the anodic oxidation reaction is the iron base metal dissolving into solution with the release of two electrons [7.2, 7.3]:

$$Fe^0 \rightarrow Fe^{2+} + 2e^- \qquad (7.1)$$

The iron entering solution reaction typically reacts with free hydroxide ions according to the following chemical reaction:

$$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2 \qquad (7.2)$$

In the presence of oxygen, the ferrous hydroxide then further oxidizes to produce insoluble gelatinous red ferric hydroxide, $Fe(OH)_3$ and the familiar red iron oxide, Fe_2O_3, known as hematite, or simply rust.

The primary cathodic reaction in neutral or alkaline water is the reduction of oxygen:

$$½\ O_2 + H_2O + 2e^- \rightarrow 2OH^- \qquad (7.3)$$

The production of hydroxide ions (OH^-) creates a localized high pH at the cathode, often 1 to 2 pH units above the bulk water pH.

In acidic water, where the concentration of free hydrogen ions is greater, hydrogen ion becomes the predominant electron acceptor as shown in the equations below:

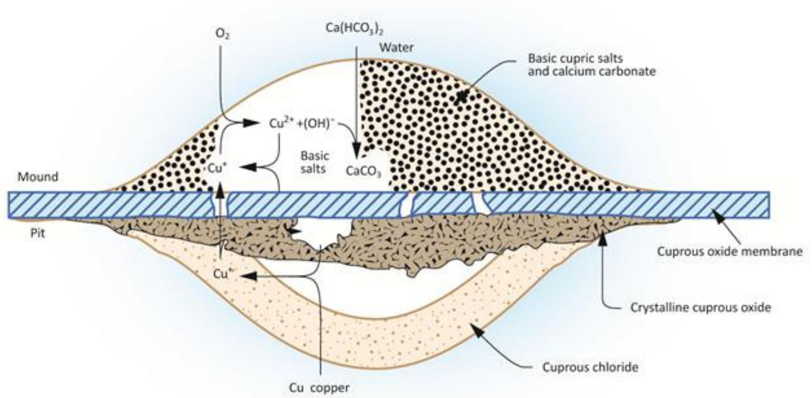
$$2H^+ + 2e^- \rightarrow H_2\uparrow \text{ (hydrogen evolution)} \qquad (7.4.a)$$

$$½\ O_2 + 2H^+ + 2e^- \rightarrow H_2O \qquad (7.4.b)$$

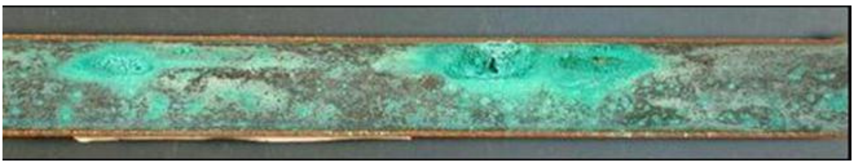
At neutral or higher pH, the concentration of H^+ ions is too low for this reaction to contribute significantly to the overall corrosion rate. However, as pH decreases, this reaction becomes more important until, at a pH of about 4, it becomes the predominant cathodic reaction, which is one reason why metals corrode much faster under acidic conditions. The reduction of hydrogen ion in acidic solution (7.4a) is much faster than the diffusion controlled reduction reaction of dissolved oxygen as indicated in equation 7.4b. In this acidic environment the anodic reaction is the dissolution of the iron base metal as indicated in equation 7.1 followed by the reaction of the iron cation with water as indicated in equation 7.4.c [7.2].

$$Fe^{2+} + 2H_2O \rightarrow Fe(OH)_2 + 2H^+ \qquad (7.4.c)$$

The overall corrosion process for most metals is similar to that for steel. It is worth noting that for steel at neutral or alkaline pH, the rate of oxygen diffusion to the surface and the oxygen reduction are the rate-limiting steps. This form of corrosion is well known as diffusion controlled corrosion [7.4]. 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 7.3, a diagrammatic representation of the flow accelerated pitting corrosion of copper producing blue water in drinking water distribution pipe lines is illustrated. The mechanism of copper pitting corrosion is very complex. Different oxidation-reduction reactions (as shown in Figure 7.3) take place forming different copper oxides and salts deposits.



a: theoretical copper corrosion mechanism



b: practical occurrence of copper corrosion causing blue water

Figure 7.3: Chloride induced copper corrosion in aqueous systems [7.4]

A simplified description is given considering the self-passivation mechanism of copper alloys through the reaction of the copper metal with dissolved oxygen forming a cuprous oxide (Cu_2O) membrane layer on the copper metal surface. Further oxidation of the cuprous oxide layer by dissolved oxygen or chloride ions followed by reaction with bicarbonate and hydroxide ions leads to the formation of a second blue green layer of $CuCO_3.Cu(OH)_2$ (malachite) on the cuprous oxide layer.

The overall chemical reaction involved in the initial corrosion of copper (as indicated in the mound above the pit in Figure 7.3) is as follows [7.4]:

$$4CuCl + Ca(HCO_3)_2 + O_2 \rightarrow CuCO_3.Cu(OH)_2 + CaCO_3 + 2CuCl_2 \quad (7.5)$$

Pitting can develop very fast under the damaged protective layer due to the anodic dissolution reaction of copper base metal in the pit and the cathodic reduction of dissolved oxygen above the pit. The anodic and the cathodic reactions are as follows:

$$Cu \rightarrow Cu^{2+} + e \quad (7.6a)$$

$$½\ O_2 + H_2O + 2e^- \rightarrow 2OH^- \quad (7.6b)$$

In the pit the cupric ions further react with water forming an acidic environment in the pit accelerating the copper corrosion according to the following reaction:

$$Cu^{2+} + H_2O \rightarrow Cu(OH)^+ + H^+ \quad (7.7)$$

It is also known that in stagnant oxygen depleted water the corrosion in the pit can continue due to the reduction of the cupric oxide by the bare copper metal according to the Kuch mechanism [7.5]. This reduction-oxidation reaction is as follows:

$$Cu + Cu^{2+} \rightarrow 2Cu^+ \quad (7.8)$$

Copper tubes are very susceptible for localized corrosion known as pitting due to erosion-corrosion and diffusion controlled corrosion. Erosion-corrosion is primarily caused by destruction of the protective oxide film layer at the metal surface by flow turbulence or impingement of particulates present in the water. Once the protective film is damaged or removed the electrochemically corrosion of the unprotected metal surface started rapidly and is predominantly controlled by diffusion of the corroding components (such as oxygen and chloride ions) to the metal surface.

Due to this diffusion process the pitting corrosion is also called diffusion controlled corrosion [7.6]. In stationary water the corrosion pit has practically a half spherical form. In situation with high velocity of the water flow a peculiar corrosion pattern of the corrosion pits is formed typified in most literature as “horseshoe pattern of a horse walking upstream” [7.7]. This horseshoe type copper corrosion is illustrated in Figure 7.4.

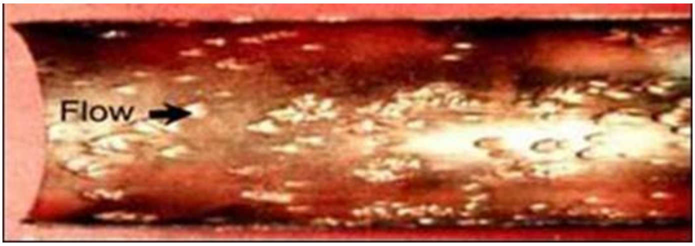


Figure 7.4: The horseshoe type corrosion in drinking water copper pipes, (7.7)

Corrosion tendency of desalination water as compared to natural waters:
Corrosion in potable water distribution systems has been studied for many years. However, almost all of this research has focused on naturally occurring well water and surface waters. The characteristics of thermal and membrane desalination water are significantly different from naturally occurring water and require a different treatment methodology.

Corrosion in natural waters and common corrosion indices
The steel corrosion inhibiting properties of natural water arise from an abundance of calcium and magnesium minerals, commonly known as hardness, in combination with bicarbonate ions, commonly referred to as alkalinity. With the right balance of hardness, alkalinity, and pH, a thin, protective film of calcium carbonate will form at the locally high pH cathode on the metal surface. Water with too high a concentration of these ions, or too high a pH, will tend to form hard calcium scales or “hardness deposits”, especially on heated surfaces. The origin of the calcium carbonate film theory is often credited to the German chemist, J. Tillmans [7.8], with many references by J. R. Baylis [7.9]. W. F. Langelier published the seminal work with respect to corrosion of steel in natural waters in 1936, in which he provided a simple and practical computational method for determining the pH at which calcium carbonate is in equilibrium in solution, which he referred to as pH_s [7.10]. His equation expresses the relationship of pH, calcium, total alkalinity, dissolved solids, and temperature as they relate to the solubility of calcium carbonate in waters with a pH of 6.5-9.5:

$$pH_s = \log K_s - \{\log[Alk] + \log[Ca^{2+}] + \log K_2\} \qquad (7.9)$$

where:

pH_s : the pH at which water with a given calcium content and alkalinity is in equilibrium with calcium carbonate

K_2 : the second dissociation constant for carbonic acid (H_2CO_3)

K_s : the solubility product constant for calcium carbonate

$[Ca^{2+}]$: the molar calcium concentration

[Alk] : alkalinity, the molar equivalent of acid required to titrate the solution to pH 4.3, which is approximately equal to the bicarbonate concentration for most natural waters.

K_s and K_2 are functions of the temperature and the total mineral content. Their values for any given condition can be computed from known thermodynamics constants.

The Langelier Saturation Index (LSI) is the difference between the actual pH of the water and pH_s. It is approximately equal to the log10 of the calcium carbonate super-saturation ratio:

$$LSI = pH - pH_s \qquad (7.10)$$

LSI values greater than 0.0 are considered to be oversaturated and have a tendency to lay down a protective coating of calcium carbonate in the pipe, while values less than 0.0 are considered to be under-saturated and have a tendency to dissolve a protective calcium carbonate coating. The LSI for most natural waters falls within the range of -2.0 to +2.0 with -2 being extremely corrosive and +2.0 extremely scale forming. The calculation of pH_s has been simplified by the preparation of various tables and nomographs. With the availability of computers and programmable calculators, several numerical expressions which fit the tables have appeared. One such equation is shown below [7.11]:

$$LSI = pH - pH_s$$

$$pH_s = 16.58 + \log(CaH) + \log(Alk) – 0.1 * \log(TDS) + 2.6 * \log(T) \qquad (7.10.a)$$

where:

CaH : Calcium hardness concentration, mg/L, as calcium carbonate equivalent

Alk : total (methyl orange) alkalinity, mg/L, as calcium carbonate equivalent

TDS : Total dissolved solids, mg/L

T : temperature of water in degrees F

In 1944, Ryzner proposed a stability index in which he arbitrarily doubled the Langelier's value of pH_s and substracted the pH [7.12]. This index has since become known as the Ryzner Stability Index or RSI.

$$RSI = 2(pH_s) - pH \tag{7.11}$$

Ryzner then conducted a survey of several waters which he fits to the RSI expressions as shown in Figure 7.5.

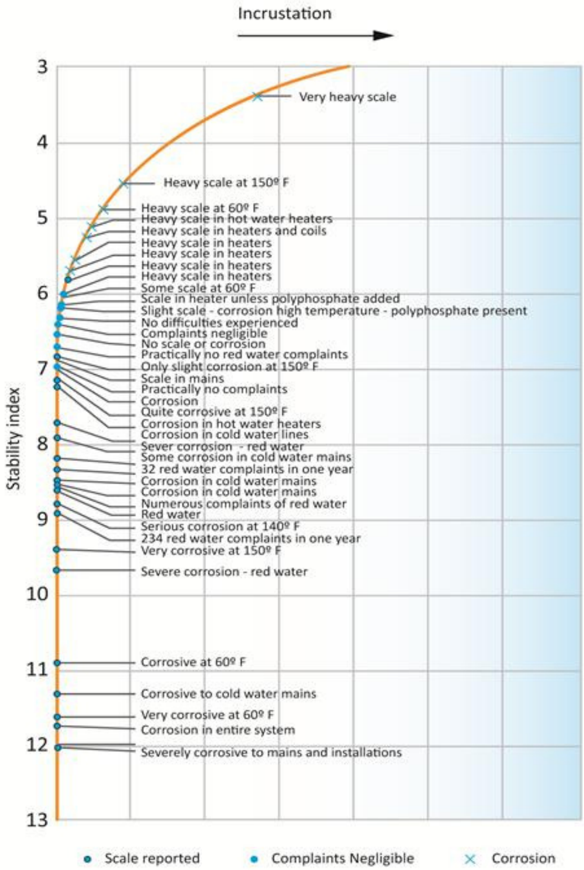


Figure 7.5: The Ryzner Stability Index [adapted from 7.13]

According to Figure 7.5, an RSI of approximately 6.5 produces no significant scale or corrosion. RSI values greater than 7.0 are considered corrosive, while values greater than 8.0 are severely corrosive and produce complaints of red water. On the other side of the spectrum, RSI values between 6 and 7 produce some calcium carbonate scale without chemical inhibitors and values less than 5.0 are associated with heavy scale.

As noted earlier, the desalination process removes all ions including calcium and bicarbonate ions that can have a beneficial effect on steel corrosion as indicated by the RSI. In principle it is possible to nearly eliminate the corrosivity of the desalination water to steel by re-introducing sufficient quantities of calcium and bicarbonate ions to the distillate, and in practice like in Aruba some calcium and bicarbonate are added to the distillate in the Coral House, reducing the RSI to approximately 10.5. However, complete reliance on calcium and bicarbonate for corrosion control in desalination water is undesirable for several reasons:

- Large amounts of calcium and bicarbonate (>100mg/L) are required to reduce the RSI of desalination water to the neutral value of 6.5
- In waters with naturally high calcium and bicarbonate which are typical of Europe and the Midwestern U.S., adjusting the pH slightly to bring the water in balance is an economical treatment practice. However, in desalination water, where all calcium and bicarbonate must be purchased, this practice is not very economical.
- Calcium carbonate has an inverse solubility with respect to temperature. Raising the calcium carbonate to the saturation point to protect cold water piping systems will result in some calcium carbonate scale in water heating equipment.
- Although a film of calcium carbonate will limit oxygen reduction at the cathode, calcium carbonate films are not free of cracks and defects, and are not as efficient as many other materials inhibiting corrosion.
- Calcium carbonate films do little to protect copper alloys where the anodic process is rate limiting, and may accelerate corrosion on stainless steels, which are prone to under-deposit pitting.
- Calcium ions in the water can produce undesirable aesthetic effects including formation of soap sups, reduced detergent efficiency, spotting on glass and polished surfaces, and can leave the skin with a prickly feeling and hair less manageable.

Factors influencing corrosion [7.14, 7.15]:

The principal factors affecting the corrosion of steel and copper in water are oxygen concentration, temperature, dissolved solids, pH, and water velocity. In poorly buffered water, free carbon dioxide (carbonic acid) can also significantly accelerate corrosion. The general effect of each of these constituents is shown schematically in Figures 7.6 through 7.11 and will be discussed with relationship to desalination water [7.3, 7.14, 7.15].

The effect of oxygen

The cathodic reaction as shown in Figure 7.2 is dependent on oxygen reduction. The reaction rate can be slowed by decreasing the oxygen concentration in the water or by decreasing the transport (flux) of oxygen to the metal surface. In closed systems, such as boiler feed water, it is practical and desirable to limit corrosion by maintaining the oxygen concentration at very low levels. However, in large potable water distribution systems, with many storage tanks and branches, it is impractical to maintain very low oxygen levels. Further, the process of adding hardness and cooling the water in the Coral House exposes the distillate to air and oxygenates it. The rate of oxygen transport can also be limited by the formation of films that lower the rate of oxygen reduction or interfere with oxygen transport to the surface. In many cases, the corrosion of iron is limited only by the diffusion of oxygen through a thick rust coating. In that instance, the corrosion rate of iron is proportional to the oxygen concentration as shown in Figure 7.6.

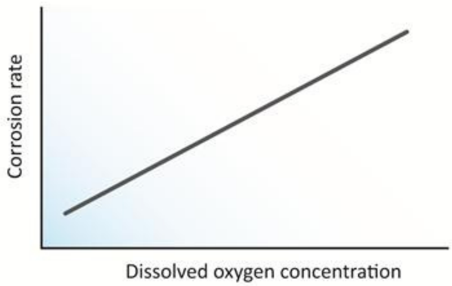


Figure 7.6 Effect of dissolved oxygen [7.3, 7.14]

However, in some cases in which metal is easily passivated, generally at higher pH and with low levels of aggressive ions such as chloride and sulfate, increasing the oxygen level past a certain point may assist in the formation of a passive film, and actually begin to decrease corrosion. WHO has no health-based guideline for dissolved oxygen.

The effect of temperature

Temperature can have a very significant influence on corrosion rate as shown in Figure 7.7. The rates of most chemical and electrochemical processes increase with temperature. The common rule of thumb is that the rate of chemical processes approximately doubles for each 10 ^{o}C increase in temperature. Equilibrium constants, the hydrolysis constant for water, solubility of oxygen and other dissolved gases, the transport properties of water (viscosity and diffusivity), and the solubility of many dissolved substances all depend heavily on temperature. All of these factors play a role in the corrosion process and consequently, the overall impact of temperature is the net result of a number of component processes, some of which act in different directions. However, the overall effect is for corrosion to increase with increasing temperature as shown in Figure 7.7.

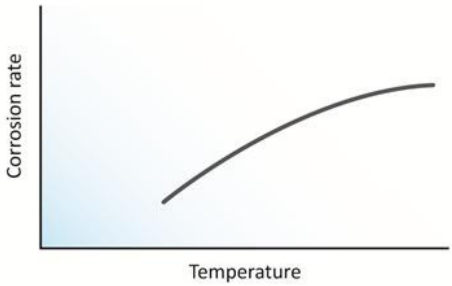


Figure 7.7: The effect of temperature on corrosion [7.3, 7.14]

For steel at a near-neutral pH, the dependence is roughly linear, but the corrosion rate is very much system dependent. Compared to potable water distribution systems in much of the world, thermal desalination plants have higher temperatures. This is both a consequence of the hot distilled water leaving the desalination unit and the fact that most of the world's desalination facilities are located in hot, arid regions. WHO has no health-based guideline for temperature.

The effect of dissolved solids

As illustrated in Figure 7.8, corrosion rate increases with an increase in dissolved solids. Dissolved solids increase the conductivity of the solution and improve the efficiency of the electrolyte (water) portion of the corrosion cell. Very pure water such as distillate is nearly non-conductive but easily becomes conductive due to its strong tendency to dissolve minerals from the surfaces it contacts and dissolve gases such as carbon dioxide from the air. Some dissolved ions are more corrosive than others. The dissolved ions having the greatest impact on corrosion are the aggressive anions, chloride and sulfate. The corrosiveness of water containing these anions is best calculated with the *Corrosion Index* (CI) which is defined as the sum of the chloride concentration and twice the sulfate concentration divided by the *Total Inorganic Carbon* (TIC) [7.16]. The CI is shown in the following equations 7.12a and 7.12b:

$$CI = [Cl^-] + 2[SO_4^{2-}]/TIC \qquad (7.12a)$$

The TIC is defined as;

$$TIC = [CO_3^{2-}] + [HCO_3-] + [CO_2] \qquad (7.12b)$$

The TIC is defined as the sum of the concentration of the carbonate- and the bicarbonate ion and the concentration of carbon dioxide. Chlorides in particular are small ions that tend to diffuse through protective films as coatings and cause severe localized attack, generally referred to as ”pitting”. Seawater is very corrosive primarily because of its chloride concentration, approximately 19,000 mg/L. Fortunately, the thermal desalination process reduces chlorides to well under 10 mg/L and sulfates to less than 5 mg/L.

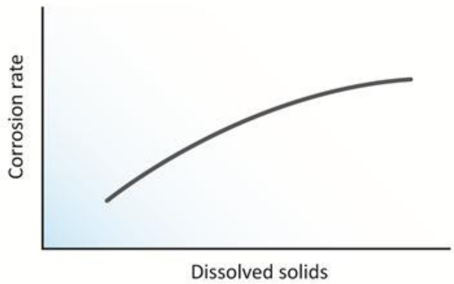


Figure 7.8: The effect of dissolved solids on corrosion [7.3, 7.14]

At some desalination facilities, a small amount of seawater is added back to the distillate to provide hardness and alkalinity, and taste, as well as increasing the total potable water output of the plant. This practice has the very undesirable consequence of adding high concentrations of corrosive chlorides to the finished water. Another issue with increased chloride concentration in the drinking water is the iron corrosion enhancement by the catalytic reaction with chloride ions increasing the occurrence of brown water. As indicated in Figure 7.9, the small chloride ions diffuse easily through the porous deposit and react with iron to form ferric chloride anions. The ferric chloride ions diffuse back through the deposit and react further with oxygen in bulk to form iron oxide consequently producing brown water [7.17].

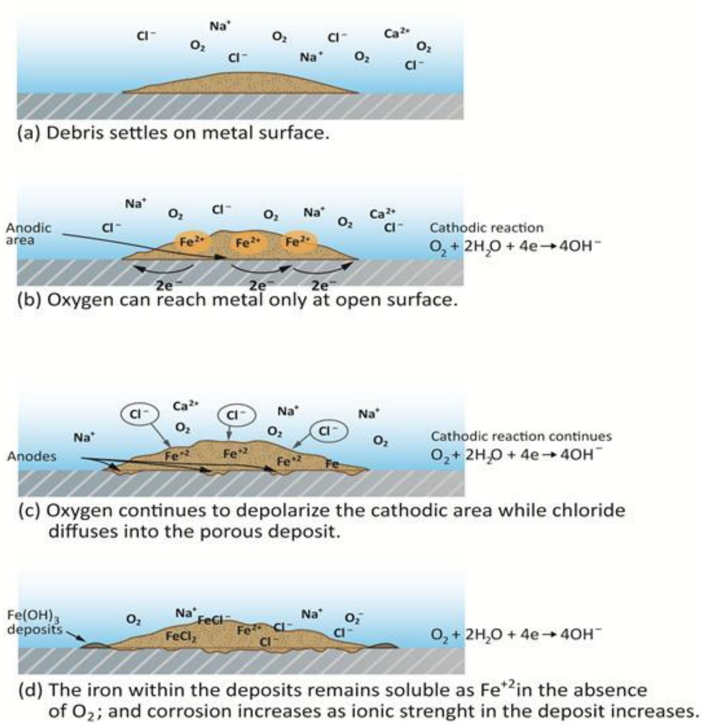


Figure 7.9: Chloride catalytic enhancement of iron corrosion [7.17]

Although WHO has no health based guidelines for dissolved solids, most consumers consider water with total dissolved salts of less than 1,000 mg/L to have an acceptable taste and waters with a low salt content typical of desalination facilities is often considered to have a “flat” taste.

The effect of pH on corrosion

As shown in Figure 7.10, the corrosion rate for steel, copper, and most metals increases sharply below a pH of 4. Two factors are responsible for this: at low pH, the iron and copper oxides and other corrosion products are completely soluble; and the concentration of hydrogen ions increases with lower pH to the point where hydrogen evolution replaces oxygen reduction as the rate limiting step at the cathode.

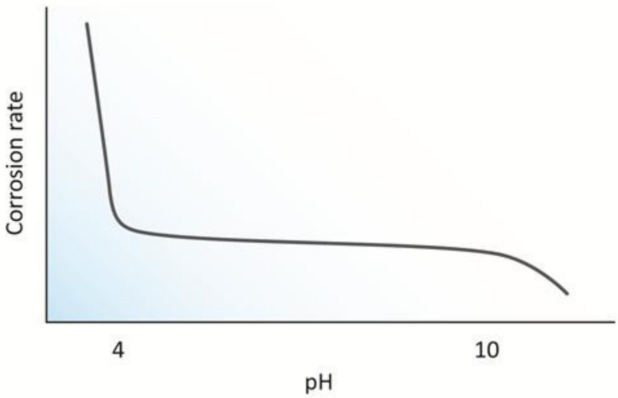


Figure 7.10: The effect of pH on corrosion [7.3, 7.14]

In the pH 4 to 10 range, oxygen reduction becomes the predominant cathodic reaction and the corrosion products which form at the anode are less soluble. At pH>10, the corrosion rate for steel and copper drops to very low values due to the formation of passive metal oxides films, although copper corrosion begins to increase above pH 11 due to formation of the soluble cuprate species. At a pH above 12 (or less than 6) lead also starts to become soluble, and water with a pH above 10.5 will dissolve galvanized (zinc) coatings used in some plumbing materials. In natural waters containing calcium and bicarbonate ions, a pH above 8.0 often leads to the formation of excessive calcium carbonate scale. As discussed previously, thermal desalination water has very low concentrations of calcium and is not prone to scale formation. However, the water must have a pH within the acceptable range for potable water. The WHO recommendations for potable water have changed several times since they were originally issued in 1958. Although WHO no longer has any health-based guideline value for pH, eye irritation and exacerbation of skin disorders have been associated with pH values greater than 11 [7.18]. WHO guidelines for drinking water note:

”*The optimum pH required will vary in different supplies according to the composition of the water and nature of the construction materials used in the distribution system, but is often in the range of 6.5-9.5*”

Canadian and U.S. drinking water guidelines recommend that pH not exceed 8.5, although that is primarily due to concerns over calcium carbonate scale, as well as a decrease in the effectiveness of chlorine and an increase in harmful chlorinated byproducts trihalomethanes (THM’s) at high pH especially if natural organic constituents are present in the water. Additionally, in highly buffered waters, a very high pH can result in a bitter taste and soapy feel to the water. A study of the potable water at the 100 largest U.S. cities in 1962 showed that the pH ranged from 5 to 10.5, with the average pH being 7.5. At W.E.B. Aruba N.V. the pH of the water entering the distribution system is carefully maintained in the range of 8.8-9.5.

The effect of water velocity

In uninhibited water, increasing water velocity in the piping system increases the mass transport of oxygen to the surface and tends to increase the corrosion rate as shown in Figure 7.11.

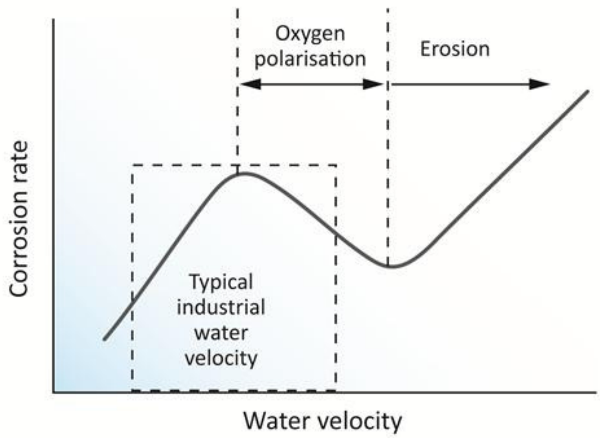


Figure 7.11: The effect of water velocity [7.3, 7.14]

Above a certain threshold, approximately 1 m/s enough oxygen may reach the surface to cause partial passivation of the metal, and the corrosion rate often declines. At very high velocities, erosion-corrosion of the pipe surface may occur. Although the water velocity required to produce erosion-corrosion (localized corrosion due to destruction of the protective film by flow turbulence or particulates) in steel pipes corresponds to a pressure drop well above economical pumping costs, erosion-corrosion can be a concern for softer metals such as copper, particularly in smaller service pipes at the ends of the distribution system or in the consumer's building. Practical methodology to prevent corrosion will be discussed in the next section.

Corrosion inhibitors

Corrosion control requires a change in either the metal or the environment. The first approach, changing the metal, is expensive. In addition, highly alloyed materials such as stainless steel, which are very resistant to general corrosion, are more prone to failure by localized corrosion mechanism such as pitting. The second approach, changing the environment, is a widely used practical method of preventing corrosion. In aqueous systems, there are three ways to effect a change in environment to inhibit corrosion:

- The formation of a protective film of calcium carbonate on the metal surface (less effective for copper) using the natural calcium and alkalinity in the water, as previously discussed
- The removal of the corrosive oxygen from the water, either by mechanical or chemical deaeration, which is not practical for a large potable system
- The addition of corrosion inhibitors

The preferred method in most cases is to add corrosion inhibitors, many of which are also referred to as passivating agents. These materials function by slowing the rate of the electrochemical reactions at the cathodic and anodic sites as discussed above. Corrosion inhibitors are often classified as either cathodic inhibitors or anodic inhibitors based on whether they inhibit primarily the cathodic or anodic reactions. This concept is illustrated by the Evans diagram of polarization resistance curves in Figure 7.12 [7.14, 7.19].

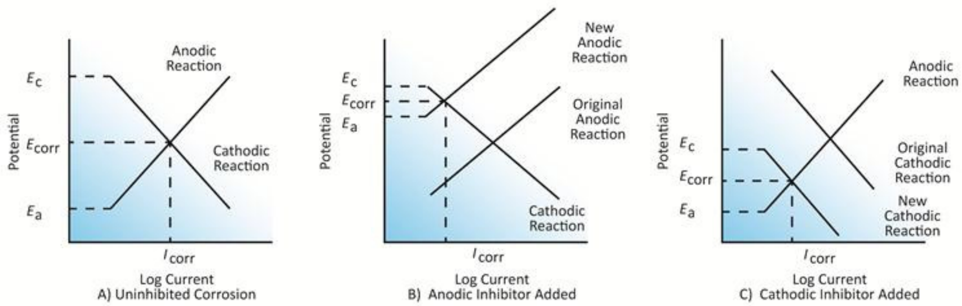


Figure 7.12: Polarization resistance curves showing electrochemical potential versus log current density [7.3, 7.14]

By applying and varying external voltages to the corrosion cell (as described in Figure 7.2) it is possible to determine the rates of the anodic and cathodic reactions individually. In these curves, the electrochemical potential or voltage (E) is shown on the vertical axis, and the log of the current density (I) is shown on the horizontal axis. These lines are called *polarization resistance curves* and represent the electrochemical potential change as a function of the amount of current applied [7.20]. Although other factors such as oxygen diffusion may affect the shape of the curves, pure electrochemically controlled corrosion will form a straight line on a plot of E versus log I. The current flow (I) is directly proportional to the loss of electrons by the parent metal, and therefore directly proportional to the corrosion rate. It is essential to understand that in the absence of an applied potential, the steady state anodic and cathodic reactions must proceed at exactly the same rate. In other words, the oxidation and loss of electrons by the base metal at the anode must exactly equal the rate of electron withdrawal and oxygen reduction at the cathode. Consequently, it is possible to stifle the corrosion cell by shutting down either the anodic or cathodic reaction.

Figure 7.12 A, illustrates the uninhibited corrosion cell. The intersection of the anodic and the cathodic polarization resistance curves occurs at the steady state potential E_{corr}, corresponding to the steady state corrosion current I_{corr}. The corrosion inhibition process based on reducing the corrosion rate I_{corr} is as follows:
1) Anodic corrosion inhibitors function by polarizing the surface in the anodic or oxidative direction. Many metals, including iron and copper, form thin, protective passive oxide films when polarized sufficiently in the anodic direction. Care must be exercised to ensure that sufficient anodic inhibitor is present to reach the critical passivation potential required for the protective oxide to form. Anodic films are formed rapidly, are tenacious, self-limiting in thickness, and reform quickly if damaged. Addition of an anodic inhibitor decreases (as illustrated in Figure 7.12 B) the rate of the anodic oxidation reaction. This causes a reduction of the corrosion current I_{corr} and the original anodic reaction curve is shifted to a higher steady state potential E_{corr}.

2) Cathodic inhibitors typically function by forming a microscopic precipitated coating at the localized elevated pH cathodic portion of the corrosion cell. This thin coating is thought to reduce the cathodic reaction by providing a barrier to oxygen diffusion. Care must be exercised to ensure that the proper balance of cathodic inhibitors are applied, otherwise the intended microscopic film can become a thick coating that impedes heat transfer and actually stimulates under deposit corrosion. Precipitated films are less tenacious than anodic passive films and take longer to repair after a system upset. The effect of cathodic inhibitors on polarization is illustrated in Figure 7.12 C where the original cathodic curve is shifted downward and to the left, reducing both the corrosion potential and the corrosion current, on the contrary with the anodic inhibitor shifting the polarization curve upward increasing the corrosion potential and reducing the corrosion current.

3) Another class of corrosion inhibitors is referred to as adsorption inhibitors. These inhibitors function by adsorbing directly onto the metal surface, creating an often-hydrophobic film that limits oxygen diffusion and iron transport reactions between the base metal and the water.
Although it is clear from the preceding discussion that all three types of corrosion inhibitors can be used independently, the most effective treatment methodology is to use a combination of anodic, cathodic, and adsorption inhibitors. The number of available corrosion inhibitors suitable for drinking water is very limited due to health and safety standards, taste, aesthetics and the cost of completing the rigorous potable water certification requirements imposed by the National Sanitation Foundation (NSF) and KIWA, the two international certification agencies. Organic inhibitors, although commonly used in the treatment of industrial water systems are seldom used in drinking water systems since they tend to break down in the long time in the water distribution system and the organic

carbon may contribute to microbiological growth. Corrosion inhibitors for potable water systems are generally inorganic compounds. The principal inhibitors and their properties are shown in Table 7.1.

Table 7.1: Corrosion inhibitors suitable for potable water [7.3]

Anodic Inhibitors	Cathodic Inhibitors	Film formers
Orthophosphate (polyphosphates) (silicate)	Zinc Polyphosphates Pyrophosphate Tripolyphosphate Hexametaphosphate	Polysilicate
	(orthophosphate)	

Potable Anodic Inhibitors:

Orthophosphate

The primary anodic inhibitor in potable water systems is orthophosphate $(PO_4)^{3-}$, which can be supplied in liquid acid form, as a liquid potassium salt solution, or as dry sodium salts. As stated earlier, classic anodic inhibitors such as chromate and nitrite function by oxidizing the surface of the metal to form a passive metal oxide film. Orthophosphate is not really an oxidizer per se, but it facilitates oxide formation in the presence of oxygen. If steel is placed in an orthophosphate solution without oxygen present, the corrosion potential remains active and the corrosion rate is not reduced. However, if oxygen is present, a passive film develops over a period of 1-2 days, the corrosion potential increases in the noble direction, and the corrosion rate decreases markedly. Orthophosphate is not regulated in drinking water, and many beverages contain orthophosphate at concentrations at thousands of times higher than would be practical for addition to potable water. Silicates, particularly monomeric silicates, are often classified as anodic inhibitors because they adsorb onto the iron oxides at the anode and impede the anodic current flow. However, since they have negligible oxidizing power even in the presence of oxygen and function by adsorption rather than oxidation, it is more useful to consider silicates and polysilicates in particular, to be part of a third class of inhibitors, adsorption inhibitors. Polyphosphates are generally considered to be cathodic inhibitors in natural water systems, but display anodic character in distilled water due to the near absence of calcium and the presence of oxygen. Neither orthophosphate nor polyphosphate provide any significant benefit in reducing copper corrosion.

Potable cathodic inhibitors:

Zinc

Zinc is an excellent cathodic inhibitor. Its solubility as the hydroxide, $Zn(OH)_2$, is very sensitive to pH, decreasing 100-fold for each 1.0 unit increase in pH. As such, it very efficiently precipitates a thin film at the locally high pH cathodic site. Zinc rich films also provide some protection against under deposit attack. Zinc is very effective at low concentration (0.1-2.0 mg/L) on steel surfaces, but is also effective to some extent on copper alloys. Zinc is the only inorganic cathodic inhibitor that does not require the presence of calcium ions in solution. Consequently, it is a critical component of corrosion inhibitor programs for low calcium natural waters and for desalination water which have essentially no calcium aside from that which is deliberately added. Zinc is approved for use in potable waters up to a concentration of 5.0 mg/L as Zn. However, WHO advises that the taste threshold for zinc is 4 mg/L as zinc sulfate, or approximately 1.6 mg/L expressed as Zn. At W.E.B. Aruba N.V., the concentration of zinc leaving the desalination plant is maintained at 0.5 mg/L, well below the taste threshold. Zinc is commonly supplied as a concentrated sulfate or chloride salt solution. At W.E.B. Aruba N.V. it is supplied as orthophosphate solution.

Polyphosphate

The term polyphosphate, refers to a family of compounds derived from phosphoric acid which has been molecularly dehydrated, such that it forms a polymeric $[-P-O-]_n$ structure. Pyrophosphate is the common name given to the simplest polyphosphate, where n=2. Sodium tripolyphosphate refers to a polyphosphate where n=3, and hexametaphosphate is actually a polymeric ring structure of n=6. These materials all function as cathodic inhibitors by reacting with excess calcium in the water to form an insoluble calcium polyphosphate film preferentially at high pH cathodic sites on the metal surface. Since they are similar in that regard, they are considered in many texts to be essentially equivalent. However, there are several important distinctions between the individual compounds which are critical in many situations, including waters with very low or high hardness, piping systems which have pre-existing rust deposits, and systems which suffer from red water due to existing corrosion deposits or due to iron contamination in the source water.

Pyrophosphate

Prevention of red water in potable distribution systems is a key objective for systems with low hardness waters (low LSI, high RSI) such as desalination water. Pyrophosphate plays a dual role in that process. As a corrosion inhibitor, pyrophosphate inhibits corrosion and the formation of corrosion products that cause red water. More importantly, pyrophosphate is an excellent sequestrant for both ferric and ferrous forms of iron. Pyrophosphate’s affinity for iron is completely separate and distinct from its corrosion inhibiting properties and distinguishes it from hexametaphosphate. A pyrophosphate (as PO_4) to ferrous (Fe^{2+}) iron ratio of approximately 2:1 is required to stabilize the iron corrosion and substantially reduce its tendency to form gelatinous red oxides and hydroxides. With aeration over time, some of the ferrous complex will further oxidize to ferric (Fe^{3+}), however, the ferric-pyrophosphate complex that forms is a fine white particulate which again prevents red water complaints. Pyrophosphate is also commonly used in paper mill water supplies where even the slightest tinge of red will affect sheet brightness and reduce the value of the paper. In addition to controlling rust and red water, pyrophosphate's iron sequestering capability slowly removes old rust accumulations, restoring the pipe's flow carrying capacity. Figures 7.13 and 7.14 illustrate the superior ferric iron sequestering ability of sodium pyrophosphate relative to sodium hexametaphosphate [7.3]. In the pH range of 5 to 8 sodium pyro phosphate has practically a constant sequestering capacity of 16 gram of Fe^{3+} ions per 100 gram of sodium pyrophosphate compare to a decreasing sequestering capacity of 12 gram of Fe^{3+} ions to practically 0 gram per 100 gram of sodium hexametaphosphate.

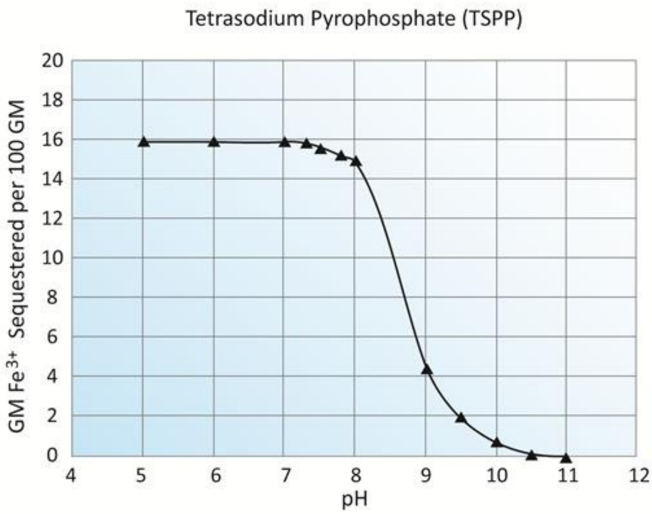


Figure 7.13: Pyrophosphate is a strong iron sequestrant [7.3]

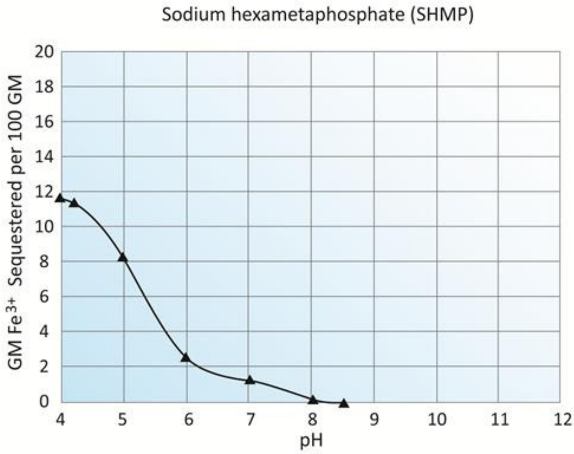


Figure 7.14 : Hexametaphosphate is a weak iron sequestrant [7.3]

Hexametaphosphate

In natural waters high in calcium and bicarbonate, protection from excessive calcium carbonate scale (hardness deposits) is of greater importance. Occurrence of red water is less probable because waters that have a tendency to deposit calcium carbonate are less corrosive. Such water is typical of Europe and Midwestern U.S. In fact, many water treatment practitioners advocate maintaining the water slightly supersaturated condition and using a scale inhibitor or stabilizing treatment. Hexametaphosphate is superior to pyrophosphate as a calcium carbonate sequestrant for use in calcium carbonate supersaturated conditions as shown in Figures 7.15 and 7.16 [7.3].

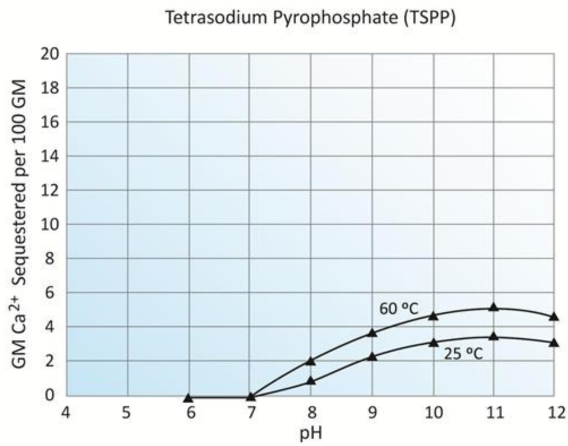


Figure 7.15: Pyrophosphate is a weak calcium sequestrant [7.3]

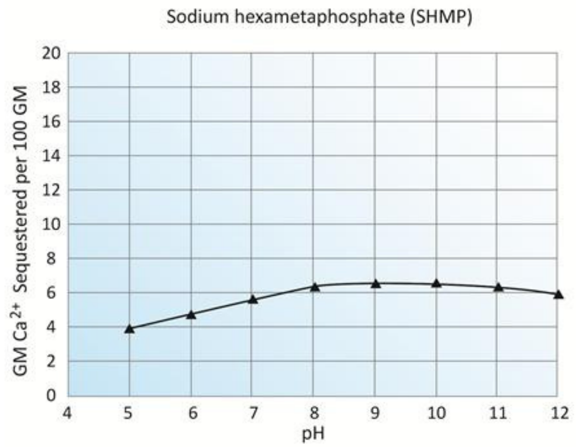


Figure 7.16: Hexametaphosphate is a strong calcium sequestrant [7.3]

In low hardness waters hexametaphosphate can sequester beneficial calcium ions and reduce the tendency to form a protective calcium carbonate film as is the case of the drinking water in Aruba.

Orthophosphate
Although orthophosphate is often thought of as an anodic inhibitor, low levels of orthophosphate react with calcium or zinc in the water to form a protective film at locally high pH cathodic site. Both calcium and zinc phosphate have an inverse solubility relationship with pH, making orthophosphate a very effective cathodic inhibitor in the presence of sufficient quantities of either ion.

Adsorptive film forming cathodic inhibitors:

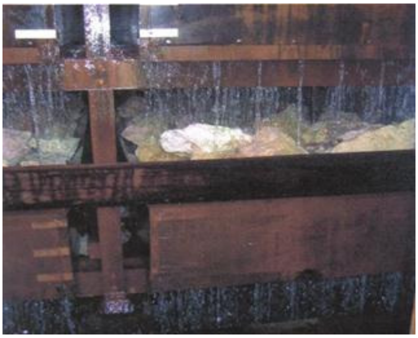
Polysilicate
Polysilicates have been used for many years to inhibit both steel and copper corrosion, particularly in potable water systems. Silicates are non-oxidizing and appear to inhibit by an adsorption mechanism. The exact mechanism is not clear, but it is now thought that the polysilicate ions or colloidal silica are the active species. There are formed very slowly on the surface of the metal from monosilicic acid, which is the predominant species in the pH range of potable water. Silicates are very slow film formers, and this film is easily disrupted by high concentrations of corrosive chloride and sulfate ions. However, desalination water and many potable waters are comparatively low in chloride and sulfate, and in those situations, silicates can be very effective. Since copper corrodes at much slower rate than steel, cathodic corrosion inhibitors are of limited value because at low corrosion rate, there is only minimal pH elevation at the cathode. For this reason, inhibitors of the adsorption type such

as polysilicates tend to be the most effective inhibitors for copper alloys. Polysilicates are also effective inhibitors for aluminum, lead, and galvanized surfaces. Polysilicates can sequester and solubilize iron, although not as effectively as pyrophosphate. Polysilicates require higher dosages than the phosphates or zinc to be effective, and therefore tend to be more costly and less widely used. Early work with polysilicates by Speller [7.21] and Texler [7.22] suggests a minimum initial polysilicate dose of 8 mg/L for 3-4 weeks to establish an initial film, and a minimum of 4 mg/l silica to maintain the protective film. However, in relatively low conductivity desalination water, with minimal concentrations of chloride and sulfate ions, lower concentrations of silicate may prove effective, especially in combination with cathodic and anodic inhibitors.

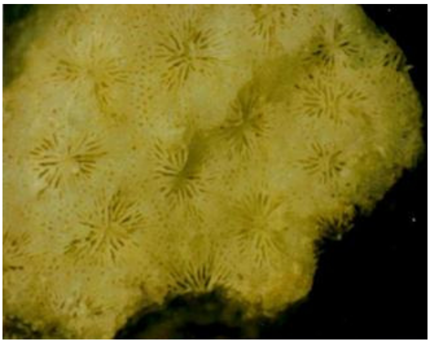
7.3 Distillate post-treatment at W.E.B. Aruba N.V.

Addition of calcium and alkalinity at the Coral House

Since the start of the desalination activities in 1932 in Aruba till mid-2007, W.E.B. Aruba N.V. produces distilled water, which is adjusted to approximately 12 mg/L total hardness, 12 mg/L alkalinity, and pH 8.8-9.3 by cascading it down over a bed of natural crushed coral, as shown in Figure 7.17. The coral serves as an economical source of calcium carbonate (lime stone) which dissolves at a controlled rate, raising the pH above neutral and imparting some calcium (hardness) and carbonate/bicarbonate buffering (alkalinity) to the water before it enters the distribution piping.



A: Bed with coral stones



B: Fragment of coral stone

Figure 7.17: Distillate passing over bed of natural coral stones to impart calcium and alkalinity

Elemental analysis by Betz Laboratories in 1990s of a fragment of used coral stones, as shown in Figure 7.17, indicate that it contains about 96.2% calcium (Ca), 1.4% magnesium (Mg) and minor amounts of sulfur (S), aluminum (Al) and Iron (Fe). The analyses were performed with *Scanning Electron Microscopy* (SEM) and *Energy Dispersive X-ray Analysis* (EDXA) [7.23].

In 2007 the Coral House is replaced by a modern automated re-mineralization pressurized lime stone fixed bed system especially to increase the biologically integrity of the re-mineralization process eliminating the free aeration process of the distillate in the Coral House. This reduces the possibility to induce air-born *Legionella Pneumophila* bacteria contamination of the drinking water. Especially warm water in sub-tropical distribution systems might enhance legionella growth increasing potential health risks [7.24].
Both the MSF distillate and the SWRO product water although acidic with a pH in the range of 6.3 to 6.7 contains low concentrations of carbon dioxide (CO_2). Thus the natural dissolution of calcium carbonate enhanced by carbon dioxide remains very low. Compared to natural surface water and well waters in most areas of the world and hard water, hardened distilled with CO_2 enhanced lime stone re-mineralization as in the neighboring Dutch Caribbean Islands, the resulting water as it leaves the coral bed is still relatively soft with a comparatively low alkalinity and an alkaline pH.

Chemical treatment before 1990

Although the calcium, alkalinity and pH elevation provided by the Coral House reduced corrosivity of the water, it was still relatively aggressive to the piping, so corrosion inhibitors were used to further reduce corrosion. Prior to 1990, sodium hexametaphosphate alone was used to inhibit corrosion. As discussed previously hexametaphosphate is a cathodic inhibitor that forms a protective film on the steel surface. Hexametaphosphate has some iron sequestering capabilities which help it to reduce red water complaints, but not as strong as other polyphosphates. Further it has also the capability to sequester calcium ions reducing the film forming potential for corrosion inhibition. The concentration of iron in the drinking water exceeded 0.5 mg/l, which is above the WHO guidelines for iron of 0.3 mg/L. Alternative treatment programs were evaluated to further reduce corrosion and iron concentration.

Chemical treatment from 1990-1995

In 1990, W.E.B. Aruba N.V. replaced the hexametaphosphate-based program with a multifunctional program. Pyrophosphate replaced hexametaphosphate to take advantage of its superior iron sequestering capabilities to slowly clean up the piping system and eliminate the red water complaints. A very low level of zinc, an excellent corrosion inhibitor for low hardness water, also supplemented the pyrophosphate. As shown in Figure 7.18, the change in treatment program significantly reduced iron levels from 0.7 mg/L in 1990 to 0.05 mg/L in 1995 well within WHO guidelines for iron. The point was reached when the bulk of the iron corrosion products had been removed from the system and the treatment was shifted toward eliminating the production of the iron in the system. A portion of the pyrophosphate was replaced with orthophosphate, which both anodic and cathodic inhibitor and more cost-effective. This was done by replacing the single component zinc product with a blended liquid product containing zinc and orthophosphate.

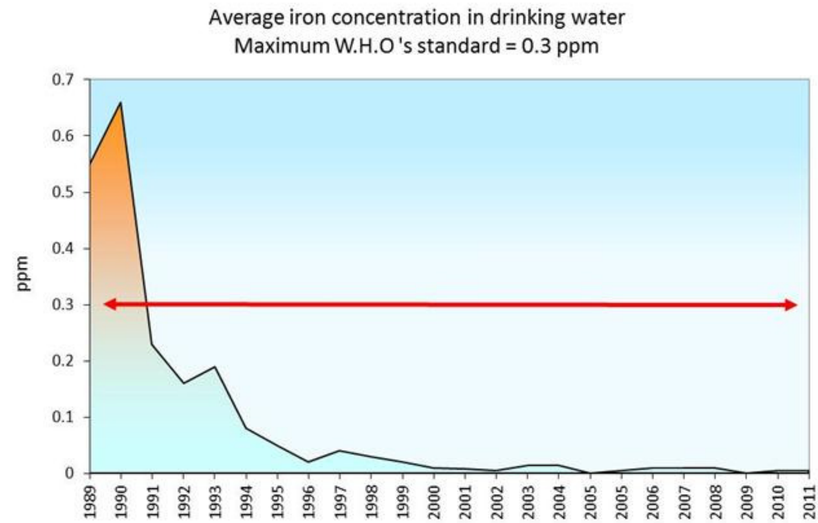


Figure 7.18: Changes to the corrosion inhibitor program effectively reduced the concentration of iron corrosion products in the drinking water

Chemical treatment from 1996 to date

The current treatment program consisting of 0.2 mg/L of zinc (as Zn), 0.6 mg/L of orthophosphate (as PO_4) and 0.5 mg/L of pyrophosphate (as PO_4) has reduced the iron levels to approximately 0.01 ppm, a reduction of nearly 99% from levels prior to the changes in the treatment program. Since the introduction of the pyrophosphate/zinc orthophosphate corrosion inhibition program in 1990 no occurrence of brown water in the distribution system has been reported.

7.4 Evaluation of high pH and copper corrosion in the distribution network

The aspects of soft and low alkalinity desalination water

Relative to natural well and surface waters, desalination water is comparatively soft and low in alkalinity.

The low alkalinity water provides little pH buffering, which allows the pH to change readily with aeration, corrosion, or contamination. Thermal distilled water and membrane product water is under-saturated with respect to most materials that it contacts and therefore has the tendency to dissolve those substances into solution. The desalinated water then becomes contaminated by small amounts of these substances, which can easily alter its properties. The potable water system at W.E.B. Aruba N.V. occasionally experiences two problems which appear to be related to these properties:

1. When left standing in cement-lined pipe during periods of low flow, the desalinated water leaches out a small amount of free lime of the cement, causing the pH of the water to rise above W.E.B. Aruba N.V.'s targeted upper limit of 9.5. The leaching reaction can be summarized in the equation below:

$$Ca(OH)_2 \rightarrow Ca^{2+} + 2\ OH^- \quad (7.13)$$

Since pH approximately equal to log [OH^-] +14, the pH will increase as a result. In water which is well-buffered, the excess hydroxide ions are simply adsorbed with little change in pH:

$$OH^- + HCO_3^- \rightarrow CO_3^{2-} + H_2O \quad (7.14)$$

2. When left standing in copper pipes, during periods of low flow, excessive corrosion sometimes occurs, releasing blue-green copper corrosion products. This occurred on an irregular and infrequent basis, but was often associated with physical disturbance of the copper line near the point of use. Initially, the presence of blue copper oxides was confusing, since this form of corrosion is associated with low pH waters (pH<7.0), generally with an excess of dissolved carbon dioxide. The water leaves the desalination plant at pH of 8.8 – 9.2. At a pH of 8.3 and above, the concentration of carbon dioxide is essentially zero and copper corrosion rates are generally very low. Further sampling showed that the waters containing the blue oxides were generally low in pH, in the range of 5.0 to 7.0. Two possible causes for the low pH have been identified:

    1. Metal hydroxides

$$Cu + 2\ H_2O \rightarrow Cu(OH)_2 + 2H^+ \quad (7.15)$$

    2. Carbon dioxide adsorption from air:

$$CO_2 + H_2O \rightarrow HCO_3^- + H^+ \quad (7.16)$$

Cement-lined pipe investigation

Cement-lined ductile iron pipe has become the most commonly used pipe for use in potable water systems. The American standard for the manufacture of this type of pipe are published in ANSI/AWWA C104/A21.4-90 [7.25]. Similar standards exist in other countries. The cement lining is applied to the interior of the pipe section prior to installation using a centrifugal casting process, in which the pipe is spun at a controlled speed while the mortar is injected. When properly performed, the process produces a dense and uniform cement coating. When expose to water, free lime encapsulated in the cement matrix maintains a very high pH (>12) at the pipe wall ensuring that it remains passive as illustrated earlier in Figure 7.10. In waters that are under-saturated with respect to calcium carbonate, or in improperly cured mortar, some leaching of free lime out of the cement paste has been known to occur, producing similar pH elevation in stagnant lines as observed on Aruba. The observation that leaching was occurring raised three issues:

1. Was the rate of leaching so great that the lining would deteriorate and fail to protect the iron pipe wall?
2. Was the quality of the water being significantly and adversely affected?
3. What actions would be appropriate to reduce current and future leaching issues?

With respect to the deterioration of the pipe, our research indicated that the first installation of cement-mortar linings in cast-iron pipe was in 1922 in Charleston, South Carolina, U.S.A. The natural water in Charleston is very under-saturated with respect to calcium carbonate to approximately the same degree as the Aruba water. Sections of this original Charleston pipe, which has been examined after more than 70 years of service showed the pipe and mortar to be in excellent condition. Chemical analysis was conducted on a sample of the cement lining from a section of pipe which had been in service for several years on Aruba. Initial chemical analysis of ground-up lining showed a very slightly lower calcium to silica ratio in a sample of exposed pipe as compared to a sample of lining from unexposed new pipe as shown in Table 7.2. This raised the possibility that some lime was leaching from the cement matrix (lime is CaO).

Table 7.2: Chemical analysis of new versus exposed lining indicating possible lime leaching [7.3]

Element	New Lining [Weight %]	Old Lining [Weight %]
Silica	63	67
Calcium (CaO)	25	17
Alumina	3	1
Zinc (ZnO)	0	1
$CaO:SiO_2$ ratio	0.397	0.254

Based on this result, a more comprehensive evaluation was conducted on additional lining samples, and using more sensitive cross-sectional analytical techniques. These included phenolphthalein staining (similar to the technique used for concrete structures), SEM (scanning electron microscope) photomicrographs, and SEM/EDXA (Energy Dispersive X-ray Analysis) line scans for calcium, silica, and iron along the cross section of the mortar to determine the depth of lime leaching.

A review of the AWWA standard for cement-lined pipe and discussions with an expert in the manufacture of cement-lined pipe indicated that there are three general types of lining in use [7.3]. In the United States, which has a variety of water types ranging from very under-saturated to very over-saturated with respect to calcium carbonate, the AWWA standard states:
"Unless otherwise specified, the cement lining shall be given a seal coat of asphaltic material."

This seal coat is centrifugally applied on top of the mortar coating and provides resistance to leaching as well as simplifying the curing process. In Europe, the mortar is left uncoated unless otherwise specified by the purchaser, perhaps because most European waters are heavily supersaturated with respect to calcium carbonate. The third common mortar specification is for double thickness. Most of the double thickness mortar is supplied without the seal coat and is commonly specified for the Middle Eastern desalination facilities to provide increased corrosion resistance. Apparently, it is common practice in Middle East desalination facilities to add back some seawater or first pass RO water after the desalination process, resulting in extremely aggressive water [7.26].
The AWWA standard for cement lined pipe contains Leaching resistance standards, but these are only required for seal-coated pipe. In essence, the leaching resistance test involves placing a sample of the pipe in distilled water at room temperature on three successive days. To pass, the specimen must impart no more than 25 mg/L of hardness or alkalinity to the water in any 24-hour period. Although this leaching test is not an AWWA standard for non-seal-coated linings, it is useful procedure for comparing the suitability of various pipe linings for potable thermal desalination water.
There are three types of cement-lined pipes in service on Aruba:

1. German pipe : All pipe > 4 in. and less than three years old.
2. Canadian pipe: All pipe up less than 9 years old, except for the German pipe.
3. American pipe: All pipe greater than 9 years old and more recent 4 in. pipe.

Although there were significant variations in the physical appearance of the linings, including thickness, color, and surface roughness, none of the linings were seal-coated with an asphaltic coating.
Casual observations did not reveal any relationship between the type of pipe and the occurrence of high pH in the distribution network.
Chemical analyses for calcium, silica, iron were conducted using EDXA on sample of each of the three types of lining which had been in service for several years. Each lining was analyzed at three points; the side in contact with water, the side immediately in contact with the pipe wall, and a point in the center of the lining cross-section. A lower calcium to silica ratio at the water surface would indicate lime leaching. The presence of iron at the

surface and throughout the lining might indicate corrosion, or iron leaching through the cement liner. Results of the tests are shown in Table 7.3.

Table 7.3: Elemental analysis of the linings as a function of the cross sectional depth [7.3]

Source	Elements	Water Side [Weight %]	Middle [Weight %]	Pipe Side [Weight %]
European	Calcium	74	35	39
	Silicon	13	62	45
	Iron	4	2	10
American	Calcium	72	68	71
	Silicon	14	26	18
	Iron	5	2	5
Canadian	Calcium	72	43	75
	Silicon	11	49	15
	Iron	2	3	5

Photomicrographs showing cross-sections of the three exposed lining materials after mounting and polishing are shown in Figure 7.19. The left face was exposed to distribution system water. The right face was against the ductile iron pipe wall.

European **American** **Canadian**

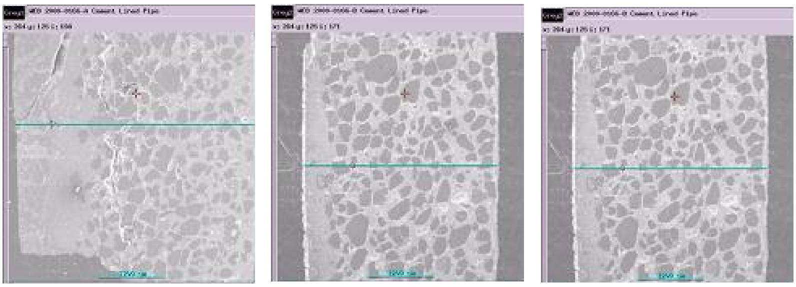


Figure 7.19: Photomicrographs showing the 3 linings in cross-section [7.3]

The scale bar barely visible at the bottom of each photo is 1200 microns long. The line across the approximate middle of each photo shows the path of the SEM/EDX line scan. Figure 7.20 shows the elemental line scans for silica (yellow), calcium (green), and iron (red) for European, American, and Canadian linings, respectively. The left side of each specimen was in contact with the water, the right side of each was in contact with the iron pipe wall.

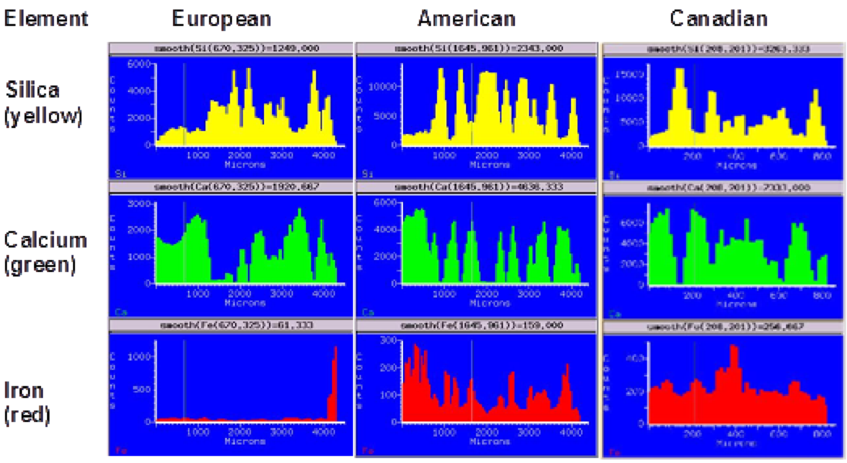


Figure 7.20: SEM/EDX elemental line scans of the three cement linings [7.3]

It should be noted that in Figure 7.20, each element scan was normalized to 199% of scale on both the horizontal and the vertical axes so the absolute value of each scale is different. For reference, since the scales are not legible at the above resolution, the horizontal axis is 4,500 microns for the European liner, 4,400 microns for the American, and 860 microns for the Canadian. The vertical axes are also in a relative scale and do not relate directly to the percentage of each element. For example the average iron content in the European liner is similar to that in the American and Canadian liners. However, the European liner had a higher concentration of iron in the cross-section at the pipe surface, 10% versus 5% for the American and Canadian, as illustrated in Table 7.3.

The presence of aggregate, which is relatively high in silicate and low in calcium, added more scatter to the scans than we had hoped. However, the line scans clearly show no evidence of lime (calcium) leaching from the liner at the water interface and certainly not to any measurable depth. There is also no iron gradient evident in the American and Canadian samples. However, the European liner had comparatively high iron content at the surface of the pipe, possibly the result of corrosion during fabrication or in service. As shown in Table 7.3, the calcium concentration of the liner at the pipe wall for the European specimen, which relates to the lime and alkalinity of the cement, is also comparatively low, 39% as compared to 71% in the American and 75% in the Canadian. Although the line scans shows that the relative lack of corrosion-retardant lime at the pipe wall did not result from leaching, it may nevertheless result in lower corrosion resistance than the American and Canadian linings. Overall, it would appear that although some leaching is occurring, as evidenced by the increase calcium and alkalinity at some points in the distribution piping, the amount of calcium being removed is insignificant with respect to service life of the pipe and lining.

With respect to the effect of leaching on the quality of the potable water, it is important to realize that WHO no longer has health-based guideline for pH, although W.E.B. Aruba N.V. strives to maintain the pH consistently below pH 9.5 at all points in the distribution system for aesthetic reasons.

Copper corrosion investigation

A systematic sampling program determined that the sporadic occurrences of turbid, blue-colored water were associated with blue particles and sediments comprised of copper corrosion products. The elemental analysis, 61% Cu, 29% O, and 6% C is consistent with the basic copper carbonate/chloride salts commonly referred to as malachite and azurite. The pH of the solution containing the particles was low, in the range of 5.0-7.0, which is consistent with the formation of these copper corrosion compounds. It has been theorized that the low pH may arise from carbon dioxide entering the top of the water storage tanks on the island. The tanks are configured so that water enters and exits the tanks at the bottom. Normal operating practice is to keep the tanks nearly full in order to maintain an adequate reservoir of water. Carbon dioxide entering the vent at the top of the tank may cause the inactive area at the top of the tank to develop a low pH. This theory is in the currently being investigated. Another theory for the low pH is that the corrosion reaction itself is sufficient to cause the low pH when the water is allowed to remain nearly stagnant in the lines for some time. Possibly, both factors are involved to some extent.

One potential solution to copper corrosion is to supplement the existing corrosion inhibitor program with polysilicate. As discussed in the previous section, polysilicates are the most effective potable water corrosion inhibitors for copper. To evaluate the effectiveness of silicate in reducing copper corrosion, a series of laboratory experiments was conducted in simulated W.E.B. Aruba N.V. water adjusted to pH 6-7 to simulate the low pH condition. As a matter of practicality, the exposure duration was kept short, only 40 hours. As noted earlier, silicate films may take several weeks to fully develop, so the data may underestimate the beneficial impact of polysilicate. Four combinations of inhibitors were evaluated in the study for their ability to reduce copper corrosion:

- Zinc and orthophosphate (similar to the current program)
- Polysilicate alone
- Zinc and polysilicate
- Zinc, orthophosphate, and polysilicate

Since the laboratory study was conducted in a closed cell, it was possible to make measurements of both the copper concentration in the water and the corrosion rates measured by coupon weight loss and linear polarization resistance. There was excellent agreement between the three methods. The results of the study are shown in Figure 7.21 and Figure 7.22. The data are plotted as copper corrosion rate in mpy (mils per year which is equal to 0.001 inch per year) or copper ion concentration (mg/L) versus zinc dose concentration (mg/L) on the horizontal axis. Where phosphate is used in the treatment, the phosphate concentration as PO_4^{3-} is three times the zinc concentration.

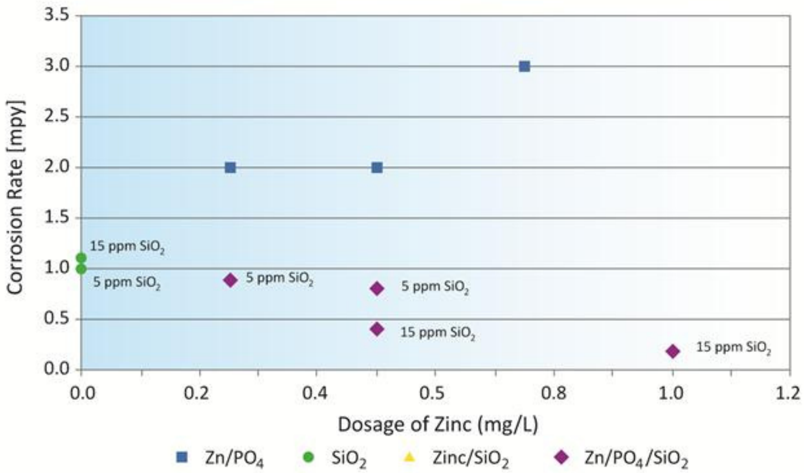


Figure 7.21: Corrosion rate for several treatments [7.3]

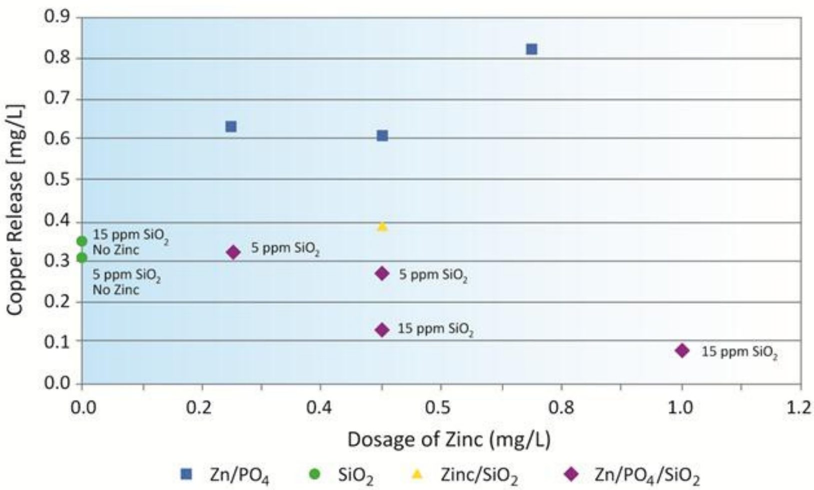


Figure 7.22: Copper released with several treatments [7.3]

Figure 7.21 and Figure 7.22 illustrate that 5-15 mg/L of polysilicate, either alone or in combination with other inhibitors, substantially reduced copper corrosion and copper release to the water. The most effective treatment was a combination of all the inhibitors with a polysilicate concentration of 15 mg/L. This combination reduced copper corrosion by approximately a factor of 5 as compared to the baseline program without silicate. Silicates are also added to some types of cement to reduce porosity. One potential benefit of polysilicate is to adsorb onto the surface of the cement-lined thereby reducing free lime leaching from the cement lining. This has not yet been investigated.

The expense of 5-15 mg/L of polysilicate would be considerable, so an additional study was conducted to evaluate lower concentrations of polysilicate in the range of 0-5 mg/L. Additionally, the study was run both with and without the pyrophosphate. Results of the 40-hour low level polysilicate are shown in Figures 7.23 and 7.24.

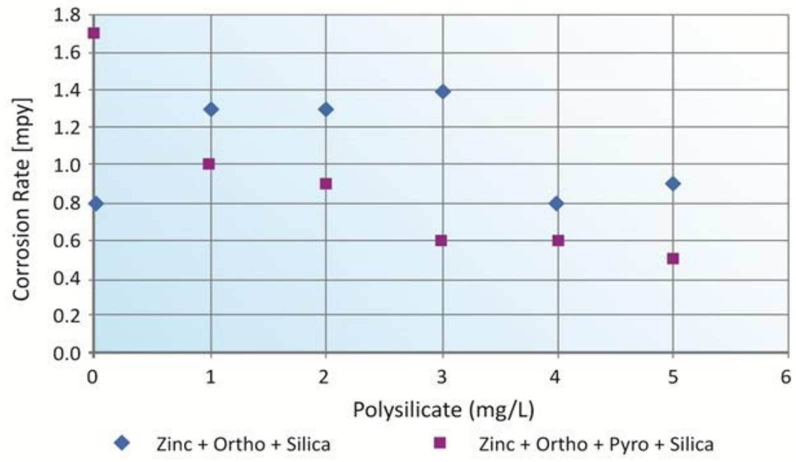


Figure 7.23: Effectiveness of polysilicate-based corrosion inhibitors on copper corrosion [7.3]

In the pyrophosphate system polysilicate was shown to produce a nearly 71% decrease in copper corrosion rate from 1.7 mpy to 0.5 mpy as the silicate concentration increased from 1 to 5 mg/L (as SiO_2).

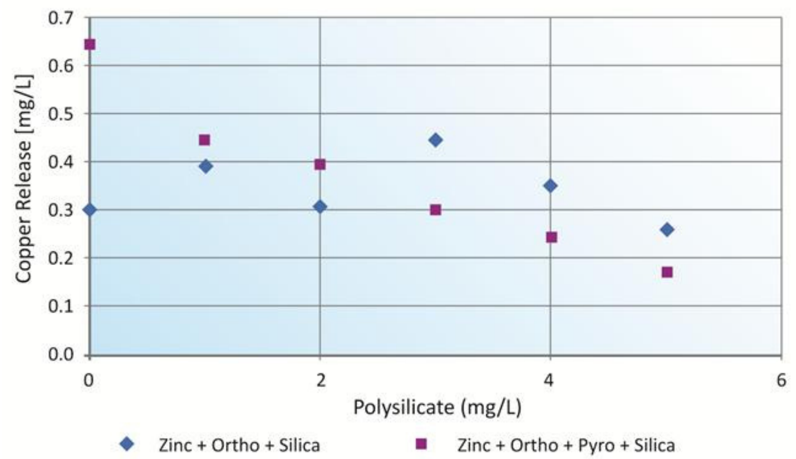


Figure 7.24: Effectiveness of polysilicate-based corrosion inhibitors on copper release [7.3]

Copper release was reduced by 73% from 0.64 mg/L to 0.17 mg/L. Pyrophosphate slightly reduced copper corrosion under these conditions, as least for silica concentration above 3 mg/L.

7.5 Some aspects of the distribution network related to drinking water quality

The water distribution network of Aruba

W.E.B Aruba N.V. is responsible for the production and distribution of high quality and safe drinking water for the population, the trade and industrial sector of Aruba and the delivery of industrial water for the Valero Aruba Oil Refinery. The distributed drinking water in Aruba is of the very highest chemical and bacteriological quality. Chemical and bacteriological quality control and assurance is performed by respectively the laboratory of W.E.B. Aruba N.V. and the laboratory of the Aruban Government Health Department. Since the privatization of the Water Company in 1992 major investments have been done to upgrade the water distribution network. A large part of the old distribution piping system has been renewed [7.27].

In 2000 after the Legionella incident in Bovenkarpsel in the Netherlands, W.E.B Aruba N.V. has taken proactively actions to guarantee the bacteriological quality of the drinking water [7.28]. Aruba with a population of about 110 thousand inhabitants has a high living standard and a high developed tourism industry with more than 800 thousand yearly overnight tourists [7.29]. Especially for the tourism industry, the most important economical pillar of Aruba, the hundred percent operational and delivery assurance of this high quality drinking water is of utmost importance. Due to the high cost of this high quality conditioned desalinated water the main objective of the Desalination and the Water Distribution Departments of W.E.B Aruba N.V. is to optimally minimize the loss of drinking water. A Client Service Department is set up with a strict encashment policy resulting in a very low percentage in default of drinking water payment. The production of well-conditioned drinking water, good operation and maintenance of the distribution network and a strict water control program objectively resulted in a very low leakage percentage due to corrosion, breakages and flushing of the dead ends. Water theft is practically non-occurring [7.30]. In this section a short description of the water supply network is given.

The pumping station of the Desalination Department

The pumping station of the Desalination Department for the water supply to the distribution network, as schematically indicated in Figure 7.25, consists of six drinking water tanks and two industrial water tanks with a total storage capacity of 96,800 m^3. The drinking water tanks are connected to the suction header of the five drinking water pumps. These drinking water pumps are further connected to the Aruba drinking water header that delivers the water at a working pressure of 8-10 bar to the Aruba distribution network by means of four main transport pipe-lines. In each of the high-pressure pipe lines to the Aruba header a

Berson in-line Ultra Violet disinfection apparatus is installed to guarantee the bacteriological quality of the drinking water [7.31].

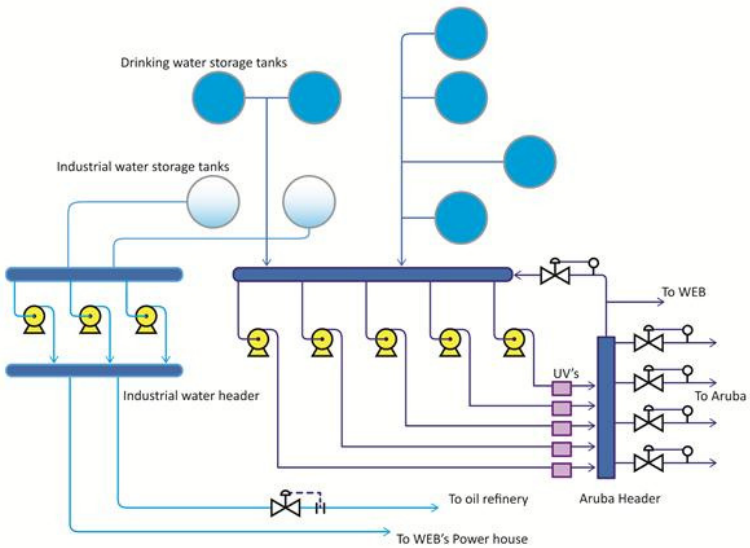
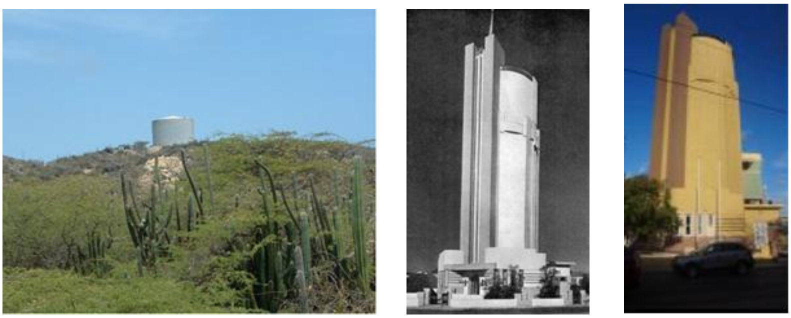


Figure 7.25: The water pumping station of the Desalination Department

According to procedure the common bacterial counts of the Aruba Header should be lower than 50 cfu/mL (colony forming units per milliliter) and especially regarding the *E-coli* and the *Legionella Pneumophila* bacteria counts should be 0 cfu/mL. The two industrial water tanks are connected to the suction header of three industrial water pumps that deliver industrial water to the Aruba Valero Oil Refinery and make up boiler feed water to the Power Production facility of W.E.B. Aruba N.V.
The Desalination Department makes daily a balance of the produced and distributed water.

The Aruban water distribution network
From the Aruba Header the drinking water is supplied by means of the four main transport lines to the drinking water tanks on the hills. In the distribution network the drinking water is mainly supplied to the customers by gravitational pressure of these water tanks and by pump pressure in low pressure zones. There are seven water tanks, seven pump houses and two booster pump station to assure a constant pressure in the distribution system. The total nominal capacity of the water tanks is 73,500 m^3 with a working capacity of 66,150 m^3. In the period of 1939 to 2002 two water towers with a capacity of 750 m^3 each, situated in Oranjestad and in San Nicolas was also part of the distribution network. In Figure 7.26, the picture of the Urataka water tank and the Water Tower in Oranjestad in 1939 and as renovated in 2012 is illustrated. These water towers have always been an attraction and

decoration for the landscape because of their peculiar architecture. Nowadays they are in restoration to national monuments.



1939 2012

Figure 7.26: The Urataka Water tank and the Water Tower of Oranjestad

The distribution pumps in the pump houses and the booster stations mitigate pressure losses during high consumption periods and maintain a constant distribution pressure. The distribution pumps also transport the drinking water to far away situated water tanks on the hills. Figure 7.27 illustrates the Paradera Pump house and distribution pumps.

Figure 7.27: The Paradera pump house and distribution pumps

Low pressure problems in the distribution network are often caused by partially plugged pipe lines, unreported leakages and high situated parcels. Booster pump stations are temporarily installed in those water delivery zones with pressure problem awaiting execution of upgrading projects. In Figure 7.28 the Mundi Fierno booster station is illustrated.

Figure 7.28: The Mundi Fierno booster station

As indicated in Figure 7.29, the distribution network is divided in the supply areas or pressure zones of the water tanks and the transport line to Valero Aruba Oil Refinery. An optimal distribution network is very essential because there are no natural water resources in Aruba and the rain fall is very limited throughout the years.
The water supply zones are Mundi Fierno, Urataka, Jaburibari, Savaneta, Sero Preto, Alto Vista and the Harbor tank C-239. The latter is the only tank that is not situated on a hill.

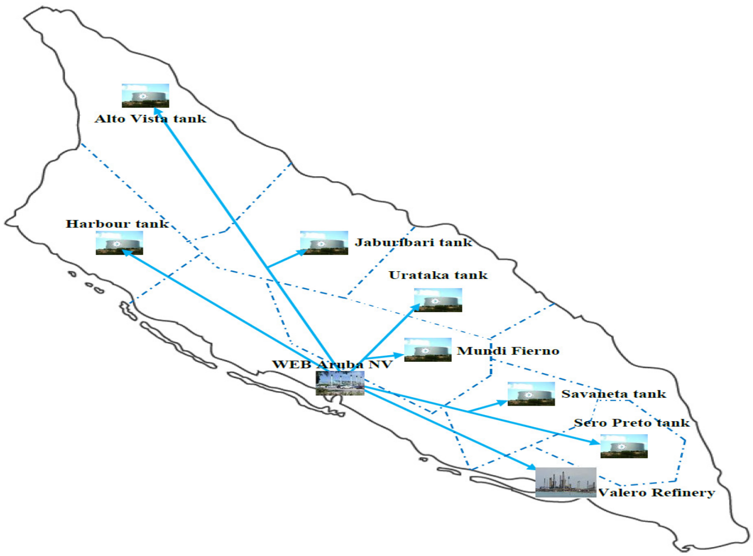


Figure 7.29: The main transport lines and the supply zones of the Aruba Distribution network

The distribution network consist of approximately 750 kilometers of cement-lined ductile iron pipe lines of 4 to16 inch diameters and copper pipe lines of 2 to 4 inch diameters. The materials used are of high quality with a life time span of 25 years. There are underground pipe lines and especially at the coast line the pipelines are up-ground because of the high level of the salty corrosive underground water.

The requirements of W.E.B Aruba N.V. for an optimal distribution network are among other:

- No or minimal leakages
- Pressure losses according to design
- No negative effect on the produced high quality water
- Sufficient water pressure at end users
- During failure or leakages a part of the network should be taken out of service without effecting the remaining part

Routine inspection is essential for optimal maintenance and operation of the distribution network. Leakages, plugged pipe lines, defect valves and occurrences of brown water can be directly detected and solved. The procedures for leakages mandated large leakages to be repaired within 8 hours and small to medium leakages to be repaired within 2 to 4 hours [7.30]. In the distribution network there are many so called dead ends, especially for future expansion. However, these dead ends are particularly prone to accumulation of dirt, suspended particles and corrosion products and promote micro-bacterial growth mainly due

to flow stagnation. These dead ends are according to procedure regularly flushed during water sampling for the laboratories. The optimal chemical drinking water conditioning applied since 1990 has significantly reduced flushing time of 60 minutes in 1992 to 15 minutes in 1995 [7.3]. Figure 7.30 shows a flushing point assembly in the distribution network.

Figure 7.30: An up-ground water transport-line with flushing facility at the South coast of Aruba

Household water connections

On the island of Aruba in principle all household are connected to the water distribution network. The household connections are submitted to the water delivery conditions of W.E.B. Aruba N.V. To be able to get a connection all requisite should be in compliance with the water delivery conditions. The household connections have increased since 1933 from approximately less than 100 to a total number of 39,742 per December 31, 2011 [7.32]. Figure 7.31 illustrates the number of connections from 1988 to the end of December 2011.

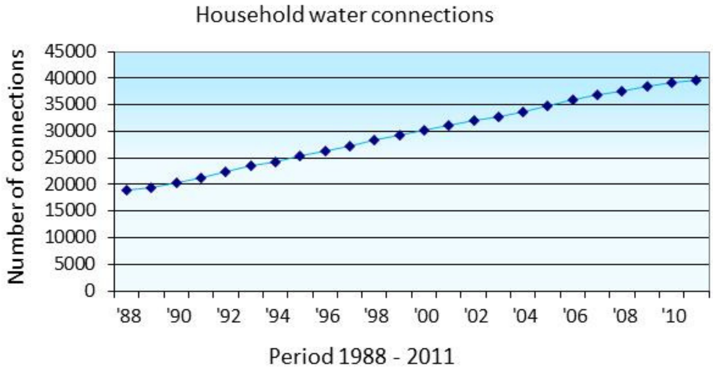


Figure 7.31: Household water connections in the period of 1988 to end of December 2011

At the moment there are as indicated above, 39,742 household connections for a total population of about 110,000 inhabitants resulting in an average of 3 inhabitants per household. On the island of Aruba therefore the average daily water consumption is about 30,183 m^3 and the average consumption per inhabitant is 253 liter/day.

The Non Revenue Water and the Infrastructure Leakage Index:

The Non Revenue Water (NRW)

According to the International Water Association (IWA) standard the Non Revenue Water (NRW) is defined as the difference of the distributed water and the water sales or the total yearly distribution and the billed water sales [7.33]. In Table 7.4 the components are given that according to the IWA contribute to the NRW.

Table 7.4 Components that contribute to the NRW [7.33]

System Input Volume	Authorized Consumption	Billed Authorized Consumption	Billed metered Consumption (including water exported in bulk)	Revenue Water
			Billed Unmetered Consumption	
		Unbilled Authorized Consumption	Unbilled Metered Consumption	Non Revenue Water (NRW)
			Unbilled Unmetered Consumption	
	Water Losses	Apparent Losses	Unauthorized Consumption	
			Metering Inaccuracies	
		Real Losses	Leakage on transmissions and/or Distribution Mains	
			Leakage and Overflows at Utility's Storage tanks	
			Leakage on Service Connections up to Point of Customer Metering	

The NRW accounts for water meters errors, administrative losses such as fire water, rinse and unauthorized water consumption such as theft and leakages. Important for lowering the NRW is a water balance of the whole water distribution system making possible the detection of all components contributing to the NRW. Optimal inspection of the water distribution system, timely detection and repair of leakages contribute to lowering the water losses. The Desalination Department and the Sector Water Distribution of W.E.B. Aruba N.V. make monthly a water balance in their monthly reports and it is controlled yearly by the department of the Internal Control and by external consultancies. Because of an optimal chemical conditioning of the drinking water and a good maintenance the water losses in the distribution system are very low. Also, the investments in the distribution system to renew old distribution pipes since the privatization of W.E.B. Aruba N.V. have contributed to lowering the water losses. The NRW of W.E.B. Aruba N.V. is about 4.11% in 2011 and is the lowest in comparison with the neighboring islands in the Caribbean region. In summary the low NRW is attained primarily because of:

- the independent status of the company
- a good investment plan
- a good operation and maintenance of the distribution system
- a high quality drinking water with optimal corrosion inhibition leading to very few breakage and leakages and less flushing
- a strict billing system
- a good water balance
- adequate tariffs.

Figure 7.32 illustrates the percentages Non Revenue Water in the period 1988 to 2011.

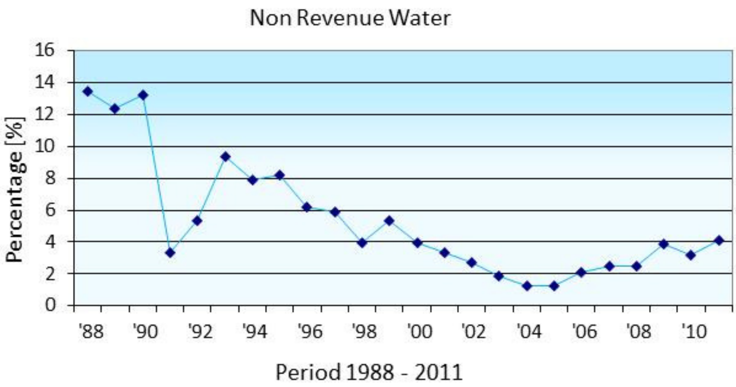


Figure 7.32: The NRW in the period of 1988 to 2011

For comparison the NRW of the other island in the Caribbean region are illustrated in Figure 7.33. In general a NRW of 15-20% is considered acceptable for a good maintained water distribution system [7.34].

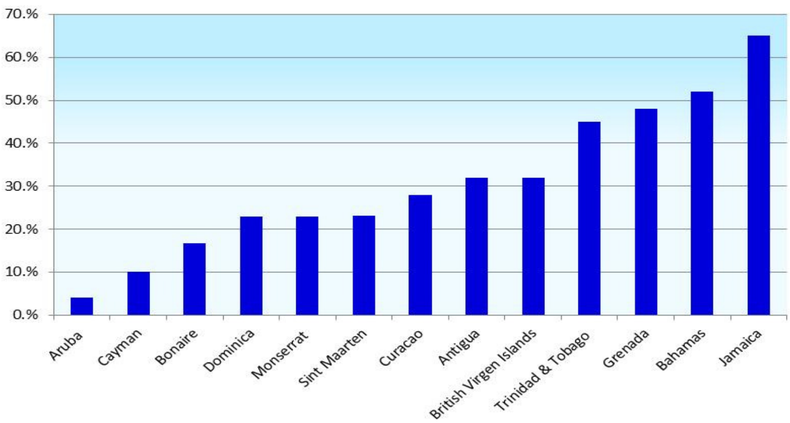


Figure 7.33: The NRW of some islands in the Caribbean region, [adapted from 7.26]

In Figure 7.33, it can be seen that the NRW for most of the Caribbean islands are between 20-70% so, outside the range for a well maintained water distribution system.

The Infrastructure Leakage Index (ILI)

The NRW was introduced by the *International Water Association* (IWA) to improve performance indicators such as the Non-accounted for water for water distribution system. Although recognized as a better indicator it does not give any indication about the maintenance and management status of the water distribution system. In cooperation with

the AWWA the *Infrastructure Leakage Index* (ILI) is introduced at the end of 1999 as a new performance indicator specifying the maintenance condition of a water distribution system [7.35]. The ILI is the ratio of the *Calculated Annual Real Losses* (CARL) and the *Unavoidable Annual Real Losses* (UARL) and is based on the best practice water balance of IWA as shown in Table 7.4.
The CARL is defined as the annual water losses minus the annual apparent losses. According to Table 7.4 the apparent losses is the sum of the unauthorized consumption and the metering inaccuracies. The CARL is obtained through the results of standardized water balance using the terminology determined according best practice by IWA [7.35]. The UARL is defined as the unavoidable physical real losses in a well maintained water distribution system due to leakages and bursts. Normally three types of bursts are considered, namely reported burst, unreported bursts and background losses. The value of the UARL is calculated using equation 7.16 with the parameters for the types of bursts calculated by IWA based on statistical analyses for a well maintained distribution system for different water transportation lines as shown in Table 7.5.

Table 7.5: Standard Unit Values Used for the Calculation of UARL [7.35]

Infrastructure Component	Background Leakage	Reported Bursts	Unreported Bursts	UARL total	Units
Mains	9.6	5.8	2.6	18	Liters/km of main/day/ meter of pressure
Service connections main curb stop	0.6	0.04	0.016	0.80	Liters/service connections/day/ meter of pressure
Service connections curb stop to meter	16	1.9	7.1	25	Liters/km of service connections/day/ meter of pressure

Source: Adapted from IWA/Aqua 48

The parameters are based on statistical analysis of international data, including 27 different water supply systems in good conditions in 20 countries [7.36; 7.37].

For the UARL the follow equation can be written:

$$UARL = (18*Lm + 0.8*Nc + 25*Lp)*P \quad (7.16)$$

With;

- Lm is Length of mains (km); Total length of transportation and distribution lines
- Nc is Number of service connection (main to customer meter at property line); this number might differ from number of customer meters
- Lp is service line between property line and customer meters (km)
- P is the average operating pressure when system is pressurized (m)

With the above equation the ILI can be defined as:

$$ILI = CARL/UARL = CARL/\{(18*Lm + 0,8*Nc + 25*Lp)*P\} \quad (7.17)$$

Using the ILI equation the ILI value is calculated for the water distribution systems of Aruba and the other Dutch Caribbean Islands, Curacao, Bonaire and Saint Martin as shown in Table 7.6 [7.38].
In Aruba and the Dutch Antilles, the factor Lp is zero due to the fact that the customer meters are located at or close to the property line.

Table 7.6: The calculated ILI value for Aruba, Curacao, Bonaire and Saint Martin [7.38]

	Aruba	Curacao	Bonaire	St. Maarten
Volume System input (m^3/Yr)	13,372,149	12,850,777	1,122,221	4,835,958
Pipe length (km)	642.1	2199.6	115.5	290
Number of service connections	28,638	49,300	9,008	4,342
Average pressure (m)	55	45	50	80
UARL (m^3/Yr)	693,390	1,298,100	169,460	235,850
CARL (m^3/Yr)	356,450	3,061,010	171,500	1,209,310
NWR (%)	3	27.5	15.4	26.6
ILI	0.51	2.36	1.01	4.76

As can be seen in Table 7.6 Aruba has a very low ILI value corresponding with the guidelines for ILI target set forth by AWWA for systems with very costly water production and practically no natural water resources. These AWWA guidelines for ILI targets [7.35] are shown in Table 7.7.

Table 7.7: AWWA Guidelines for setting an ILI target [7.35]

Target ILI Range	Water Resources Considerations	Operational Considerations	Financial Considerations
1.0 – 3.0	Available resources are greatly limited and are very difficult and/or environmentally unsound to develop.	Operating with system leakage above this level would require expansion of existing infrastructure and/or additional water resources to meet the demand.	Water resources are costly to develop or purchase; ability to increase revenues via water rates is greatly limited because of regulation or low ratepayer affordability.
3.0 – 5.0	Water resources are believed to be sufficient to meet long-term needs, but demand management interventions (leakage management, water conservation) are included in the long-term planning.	Existing water supply infrastructure capability is sufficient to meet long-demand as long as reasonable leakage management controls are in place.	Water resources can be developed or purchased at reasonable expense; periodic water rate increases can be feasibly imposed and are tolerated by the customer population.
5.0 – 8.0	Water resources are plentiful, reliable and easily extracted.	Superior reliability, capacity and integrity of the water supply infrastructure make it relatively immune to supply shortages	Cost to purchase or obtain/treat water is low, as are rates charged to customers.
Greater than 8.0	Although operational and financial considerations may allow a long-term ILI greater than 8.0, such a level of leakage is not an effective utilization of water as a resource. Setting a target level greater than 8.0- other than as an incremental goal to a smaller long-term target- is discouraged.		

Source: Adapted from AWWA Water Loss Control Committee

Client services, the water tariff and its relation to fuel oil cost

The department of the Client Service has since the privatization of the company invested on financial as well as on area of client satisfaction to fulfill the wishes of the client as much as possible. Recently an automated Client Information System (CIS) has been introduced to optimize the client services. Because of sufficient information to clients and a strict billing system the clients have developed a disciplined way of payment during the years.

The water consumption of all clients is monthly billed and cashed. If payment is due within two months a client received a reminder letter and the water meter is disconnected. There are only 0.5 % bad payers. The “payment-attitude “of the clients can be specified as follows:

- 87% of the clients pay on time
- 12% of the clients pay within 1 to 3 months
- 0,5% bad payers

There are no zones in Aruba where the inhabitants do not pay for water and where water theft is high (usually called red zones in the Caribbean region). Actually water theft is very rare. An important contribution to the good payment conduct is next to the strict billing system also an adequate tariff system. The average cost price for drinking water is UD$ 7.39

and for industrial water the cost price is US$ 7.13. The tariff system is based on the so called socializing system.
Since 1992 no tariff increase has been introduced on components not related to the heavy fuel oil. In Figure 7.34 the trend of the tariff and the Gulf Coast Platt price for heavy fuel oil for the period of January 2000 to September 2012 is illustrated [7.39]. It is clear from Figure 7.34 that the water tariff has practically the same trend as the heavy fuel oil price until 2010. In 2011 due to external forces (political) the company was forced not to adapt the water tariff according to the Heavy Fuel Oil increment with all the financial consequences. However, the water cost price is about 50% lower than the neighboring islands with comparable combined power- and water production processes. In the tariff all financial cost, depreciation cost, operation and maintenance cost are incorporated.

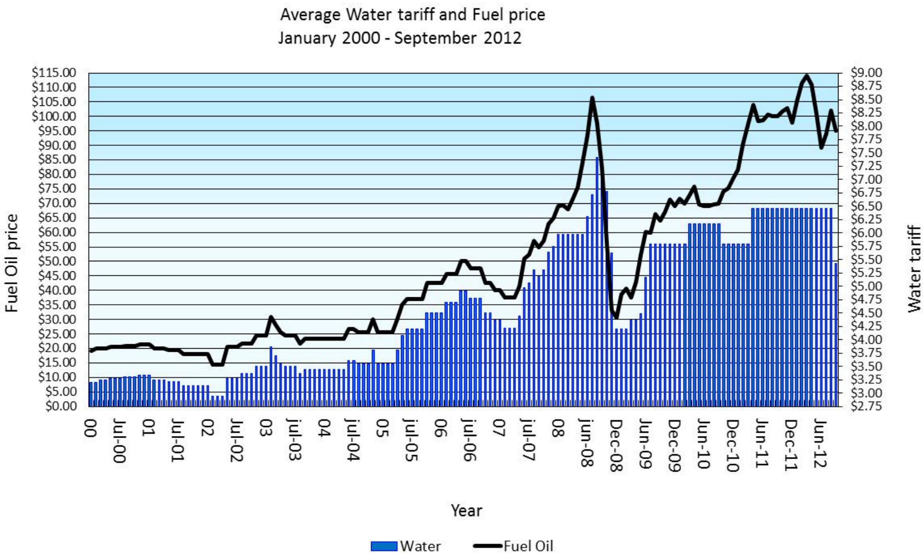


Figure 7.34: The trends of the water tariff and the heavy fuel oil prices [7.39]

The tariff system of W.E.B. Aruba N.V. for house hold is a so called layer system consisting of five layers dependent on the amount of water consumed. The first three layers are based on a fixed price and the other two are based on a variable price dependent on the price of the heavy fuel oil. The first layer is a fixed price for the consumption of the first three cubic meters of water and the second layer a fixed price per consumed cubic meter for the consumption within three to six cubic meters. The third layer is the same as the second layer with a different fixed price per consumed cubic meter for the consumption between six and twelve cubic meters.
The last two layers based on variable prices are for the consumption between twelve and twenty cubic meters and for consumption higher than twenty cubic meters. In Table 7.8 the

new water tariff for the water billing per August 2012 in comparison with the previous water tariff is shown [7.40]. As will be explained in Chapter 10 the reduction in water tariff was possible due to the partially commissioning of the second new more efficient SWRO with a capacity of 24,000 cubic meters per day.

Table 7.8: Water tariff system of W.E.B. Aruba N.V. [7.40]

Water tariff of W.E.B. Aruba N.V. as per August 2012					
Costumer	Monthly Consumption (m^3)	Previous tariff (AWG/m^3)	New tariff (AWG./m^3)	Tariff reduction (AWG)	Tariff reduction (%)
Residential	< 3	4.55	4.55		
	4 – 6	5.40	4.55	0.85	16
	7 - 12	7.55	6.25	1.30	17
	13 - 20	20.10	11.25	8.85	44
	> 20	24.50	15.25	8.95	37
Non residential	Fixed amount per m^3	12.80	9.50	3.30	26

AWG = Arubaanse Wettelijke Guldens, the Aruban Legal Currency

As a way of illustration the water billing for a fictive household client with a water consumption of 22 cubic meters is calculated below. The amount that the client should pay according to Table 7.8 for the same consumption in July and August 2012 is as follows;

July 2012		August 2012	
3 m3 * AWG. 4.55 =	AWG. 13.65	3 m3 * AWG. 4.55 =	AWG. 13.65
3 m3 * AWG. 5.40 =	AWG. 16.20	3 m3 * AWG. 4.55 =	AWG. 13.65
6 m3 * AWG. 7.55 =	AWG. 45.30	6 m3 * AWG. 6.25 =	AWG. 37.50
8 m3 * AWG. 20.10 =	AWG.160.80	8 m3 * AWG.11.25 =	AWG. 90.00
2 m3 * AWG. 24.20 =	AWG. 48.40	2 m3 * AWG.15.25 =	AWG. 30.00
22 m3	AWG.284.35	22 m3	AWG.185.30

Taking into account, the amount of AWG.1.00 for hiring of a water meter, the total amount of water consumption due for July and August 2012 is respectively AWG.285.35 and AWG.186.30, representing a total reduction of 34.71 %.

For commercial and trade, construction, hotels and Government there is a fixed tariff of AWG. 9.50 per cubic meter.

To close this section it is noteworthy that even though the water tariff is high and increasing because of the Heavy Fuel Oil cost the yearly domestic water consumption is practically unchanged as Figure 7.35 illustrates [7.41].

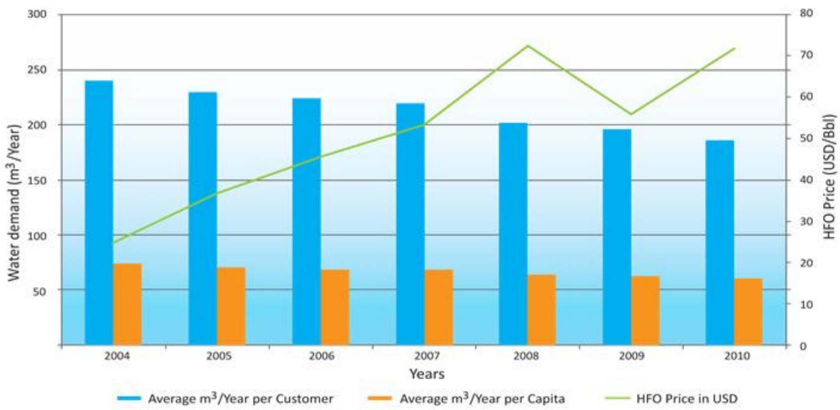


Figure 7.35: The domestic water demand of Aruba [adapted from 7.41]

The quality control and assurance in the water distribution:

The chemical water quality management

W.E.B Aruba N.V. maintains minimal the chemical guidelines specified by the World Health Organization. The laboratory of W.E.B Aruba N.V. has 21 strategically regional sample points in the water distribution network for monthly measurements of the pH, turbidity, iron and copper concentrations. The analysis results are monthly reported to Senior Management, the Government Health department and to the Production and Water Distribution departments. Figure 7.36 shows a schematic illustration of the strategically sample points in the distribution system.

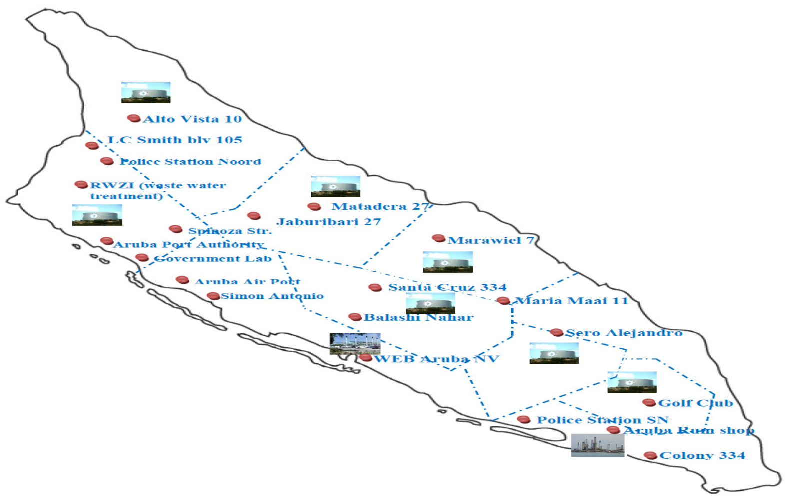


Figure 7.36: A schematic illustration of the water distribution sample points

A good quality control program enables proactive action to possibly needed chemical adaptation of the chemical conditioning in case of eventual occurring corrosion in certain section of the drinking water distribution network and to set up an effective flushing program.

Figure 7.37: Measurements at the Laboratory of W.E.B. Aruba N.V.

Once a year, a chemical and bacteriological quality audit is performed through a thorough water analysis by an external renowned laboratory. Figure 7.37 shows analysts performing measurements at the laboratory of W.E.B Aruba N.V.
PAHO is regularly invited to perform an intensive quality audit of the drinking water. According to their report the drinking water of Aruba is qualified as one of highest quality in the world as already mentioned in Chapter 2 [7.42].

The bacteriological water quality management
The Desalination and the Water Distribution Departments are in cooperation with the laboratory Department responsible for the bacteriological quality control of the distributed water. The bacteriological analyses are performed independently by the laboratory of the Aruban Government Health Department. At the strategic sample points the Health Department takes monthly samples in cooperation with the Distribution Department. It is mandatory that all process components before taken in operation either at the Production or the Distribution Department should be disinfected and bacteriological approved. The guide line is a value lower than fifty colony forming units per milliliters. Since 2000 a close work relationship is set up with Kiwa Water Research BV for advice on Legionella research and monitoring program for proactive preventive measures. Legionella is a water-borne microorganism that is not harmful for normal water consumption only as inhaled in water mist containing a high concentration of the microorganism. The genotype *Legionella Pneumophila* can cause legionellosis better known as Pontiac fever [7.43]. Biological aspect of drinking water is very complex in nature, therefore in this thesis a very brief description is given on the biological aspects. Moreover it is out of the scope of this dissertation.
In every drinking water system worldwide water borne microorganisms form biofilm on the distribution pipe surfaces. Of importance for bacteriological control is the production and delivery of well-conditioned biostable water not to promote further growth [7.44]. Recent

study showed that for Legionella to grow in the biofilms, protozoan hosts such as *Hartmannella vermiformis* should be present. These protozoans feed on the Legionella bacteria and once in the protozoa they parasitically reproduce themselves killing their hosts. Biofilm investigation in the Dutch Caribbean Islands has shown the existence of protozoans in biofilm in the distribution systems [7.45]. It is also known that variation in pH and temperature especially trace elements have a growth enhancement effect on microorganism in the biofilm, [7.46]. In this context effective conditioning of the drinking water is an aspect of major importance to guarantee the biological and chemical quality of the drinking water.

The Aruba drinking water produced by thermal and membrane desalination has a high biostability that no residual chlorine is necessary to guarantee biological quality. Research in the Netherlands showed that even though chlorine disinfection increases drinking water safety it poses more problems than benefits and the Dutch have gradually adopted a total drinking water system approach allowing production and distribution of biological safe drinking water without chlorine dosage [7.44, 7.47].

To conclude this section it is worth mentioning that for legionella research a biofilm monitor developed by Kiwa Water Research BV [7.48] is installed in the pipe-line of the water supply station of the Desalination Department to monitor the biofilm forming potential of the produced drinking water. Figure 7.38 shows the biofilm monitor installed on the premises of the Desalination Department.

Figure 7.38: The biofilm monitor on the premises of the Desalination Department

7.6 Conclusions

1. Although corrosion and scale formation in distribution lines carrying natural water have been studied in depth for many years, potable water produced by thermal desalination systems has very different properties. Thermal desalination water differs with respect to its aggressiveness to common materials of construction, the effectiveness of corrosion inhibitors, the ease of which its pH is affected, and in its interaction with air and the surfaces it contacts. Although in principle it is possible to re-mineralize the distilled water so that it mimics common natural water sources, such a practice is costly, unnecessary, and negates many of the unique benefits of pure desalination water.
2. Thermal desalination water is non-scaling, yet it is corrosive. Measures must be taken to reduce its aggressiveness, or more resistant materials of construction must be selected.
3. The corrosivity of desalination water follows the same principles of electrochemical corrosion as natural waters, however, corrosion inhibitor effectiveness and optimum product selection will often differ.
4. Pyrophosphate is very effective in reducing red/brown water complaints associated with thermal desalination water due to its ability to sequester and decolorize red rust accumulations, as well as its ability to form a protective film on steel surfaces. Pyrophosphate is better suited to desalination water than hexametaphosphate, even though both are polyphosphates and many texts do not distinguish between the two.
5. The combination of very low levels of pyrophosphate, zinc, and orthophosphate is a very effective carbon steel corrosion inhibitor package for thermal desalination water.
6. Polysilicates are effective copper corrosion inhibitors at low levels in thermal desalination waters, either alone or in combination with other inhibitors. Inhibitors that depend on adsorption, such as polysilicates, are much more effective in water that is substantially free of corrosive chloride and sulfate anions, such as thermal desalination water.
7. W.E.B. Aruba N.V. has succeeded due to the optimal corrosion inhibition program of the drinking water, good operation and maintenance of the water distribution system to obtain low NRW values in the range of 2.6-4.14%, the lowest value in the Caribbean Region.
8. The corrosion inhibition program of the drinking water has contributed to the well maintained condition of the distribution network as indicated by the calculated ILI value of 0.51 which is in the range 0.1 to 3.0 of AWWA guidelines for a water distribution system where there are practically no natural water resources and consequently a costly water production.

7.7 References

7.1. Current Drinking Water Standards USEPA Office of Water. http://www.epa.gov/safewater/ml.html.

7.2. Fontana, M. G., Corrosion Engineering, 3rd Edition, ISBN 0-07-021463-8, McGraw-Hill, Inc., USA, 1986.

7.3 Post, R. E., Marchena, F. A., et al., Water Treatment Technology for Desalination Systems-A decade of experience inhibiting corrosion and red water" in drinking water systems, Caribbean Conference, June 9-21, 2002, Aruba.

7.4. Hollander, O., Technical Seminar Electric Utility Plant Water Treatment, Houston, Texas USA, November, 1990.

7.5. Benson, A. S., Dietrich, A. M., et al., Evaluation of Iron Release Models for Water Distribution Systems, Critical Reviews in Environmental Science and Technology, 42:44-97, 2012.

7.6. Weed, R. H., Tvedt, T. J., Cotton, I. J., Erosion-Corrosion in Utility Systems, Technical Paper, BetzDearborn Water Management Group

7.7. http://koinsnet.org/tt/site/db/board/tech/upload/1 10000/224/Fundamentals of Corrosion.pdf

7.8. Tillmans, J., Die Chemische Untersuchung von Wasser und Abwasser," 2nd E., Wilhelm Knapp Halle, 1932.

7.9. Baylis, J. R., J.AWWA, Vol. 27, 1935, 220-234.

7.10. Langelier, W. F., "The Analytical Control of Anti-Corrosion Water Treatment," J. AWWA, Vol.28, No. 10, 1936, 1500-1521.

7.11. Post, R. M., Derived from the Langelier Saturation Index Chart. Personnel Communication.

7.12. Ryzner, J. W., "A new Index for Determining Amount of Calcium Carbonate Scale Formed by a Water," J.AWWA, Vol.36, No.4, 1944, 472-486.

7.13. Water and Waste Treatment Data Book, Permutit (Zurn) Company, Inc. 1986

7.14. Handbook of Industrial Water Conditioning, 8th Edition, Betz Laboratories, Inc., USA 1980, 174-176.

7.15. Water Treatment Handbook, Seventh edition, Volume 1, Degrément Suez, ISBN 978-1-84585-005-0, 1995

7.16. Van den Hoven, J. J., Van Meekeren, M. W. M., Optimale Samenstelling van Drinkwater, KIWA Mededeling 100, October 1988.

7.17. Emmer, F, N., McCallion, J., The Nalco Water Handbook, 567890 KPKP 865432, McGraw Hill, Inc., USA, 1979.

7.18. Guidelines for drinking-water quality, 2nd ed., Vole 1, Recommendations, World Health Organization, Geneva, 1993, 53-54.

7.19. Peabody, A. W., Bianchetti, R. L., Peabody's Control of Pipeline Corrosion, second edition, NACE International The Corrosion Society, ISBN 1-57590-092-0, 2001.

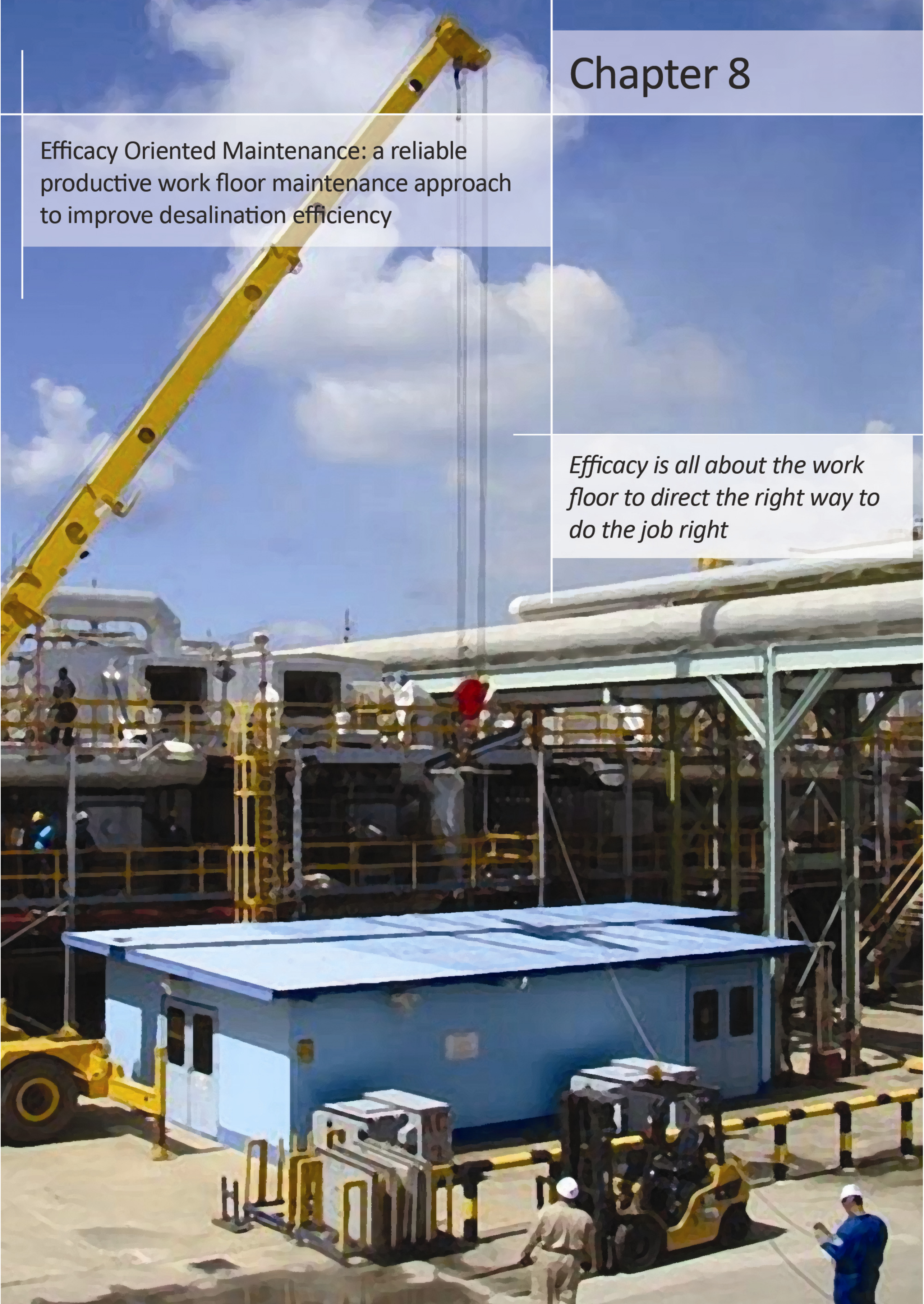
7.20. http://electrochem.cwru.edu/encycl/art-c02-corrosion.htm
7.21. Speller, F. N. J., Franlin Institute, Vol 193, pp 519-520, 1922.
7.22. Texter, C. R., Prevention of Corrosion in Hot water Supply Systems and Boiler Economizer Tubes. J.AWWA, Vol. 10, 764-772, 1923
7.23. Willard, J. N., SEM/EDXA Analysis of four Coral Stones From WEB in Balashi, Aruba, BETZ Analysis Report, June 1990.
7.24. Van der Kooij, D., Veenendaal, H. R., et al., Biofilm formation and multiplication of Legionella in a model warm water systems with pipes of copper, stainless steel and cross-linked polyethylene, Water Research 39 (2005) 2789-2798.
7.25. American National Standard for Cement-Mortar Lining for Ductile- Iron Pipe and Fittings for Water, American water Works association, ANSI/AWWA C104/A21.4-90, September 1, 1990
7.26. Khan, A. H., Desalination Processes and Multistage Flash Distillation Practice, Elsevier Science Publishers B.V., Amsterdam, 1986, 4.
7.27. Croes, L., The Aruba Experience to Achieve a Negligible Percentage of Non Revenue Water, The International Desalination Conference, Oranjestad, Aruba, 2007.
7.28. Van der Kooij, D., et al., Het legionella-probleem op de Nederlandse Antillen, CWTRI-BTO Legionella-Symposium, Aruba, April 2006.
7.29. Central Bureau of Statistics, Personal Communication.
7.30. Marchena, F. A., Water Distribution Experiences in Aruba, Guest Lectures at the University of the Netherlands Antilles, 2007.
7.31. Marchena, F. A., Alberts, V. A., et al., “Strategic Quality Program: Basic Efficiency Control for Brine Recirculating MSF Desalination Units”, Caribbean Conference, June 19-21, 2002, Aruba.
7.32. Croes, D. R., Annual Production Report 2011 W.E.B. Aruba N.V.
7.33. Lambert, A. O., International Report on Water Losses Management and Techniques, Report to IWA Berlin Congress, October 2001.
7.34. Bender, S.F., Shannon & Wilson Inc., Geotechnical and Environmental Consultants, CWWA, Cayman Islands, Personnel Communication, 2002.
7,35. Preston, S. J., Sturm, R., Understanding the Components of your Infrastructure Leakage Index (ILI) is necessary strategy to reduce the overall ILI value-especially in systems with a low ILI, http://www.waterloss2007.com/pdf_vortraege/Mittwoch/B8-1.pdf.
7.36. Lambert, A. O., Hirner, W., Losses from Water Supply Systems: Standard Terminology and Recommended Performance Measures, the blue pages-the IWA information source on drinking water issues, October 2000, 1-13.
7.37. Lambert A. O., et al., A review of Performance Indicators for Real Losses from water Supply Systems., Aqua, Vol 48 (1999), 227-237.

7.38. Eggebrecht, M. F., Calculating the Infrastructure Leakage Index (ILI) for W.E.B. Aruba N.V., Aqualectra N.V., W.E.B. Bonaire N.V., N.V. G.E.B.E., and Testing and Comparing their different Customer Water Meters, Internship Report W.E.B. Aruba N.V.-TU Delft - TU Dresden, July, 2009.
7.39. Marchena, F. A., Efficacy Oriented Operation and Maintenance; An important Step Toward Sustainable Conventional and Green Desalination Technology., Our Future With Green Energy Conference, Oranjestad, Aruba, September 2010.
7.40. Winterdaal, E. O. L., Department of Financial and Economic Affairs, W.E.B. Aruba N.V., 2009.
7.41. Oduber, L. H., Department of Technical Affaires, W.E.B. Aruba N.V., 2011.
7.42. Muñoz Elguera, A., Assessment of Water Quality Monitoring and Control in Aruba and Recommendations for Health Risk Reduction, PAHO/OMS Report, June, 2008.
7.43. Van der Kooij, D., Wullings, B. A., Occurrence and Genetic Diversity of Uncultured Legionella spp. in Drinking Water treated at Temperatures below 15 ^{o}C, Applied and Environmental Microbiology, Jan. 2006, 157-166.
7.44. Van der Kooij, D., Van Lieverloo, J. H. M., et al., Maintaining Quality without a Disinfectant Residual, Journal of AWWA, Volume 91, issue 1, January 1999.
7.45. Valster, R. M., Free-living protozoa in drinking water supplies, Community composition and role as hosts for legionella pneumophila, ISBN 978-90-8585-884-3, PhD Thesis University of Wageningen, 2011.
7.46. Yee, R. B., Wadowsky, R. M., et al., Effect of Temperature, pH, and Oxygen Level on the Multiplication of Naturally Occurring Legionella pneumophila in Potable Water, Applied and Environmental Microbiology, May, 1985, 1197-1205.
7.47. Van Dijk, J. C., Medema, G. J., The Dutch Secret: how to provide safe drinking water without chlorine in the Netherlands, Drink Water Eng. Sci., 2, 1-14, 2009.
7.48. Vrouwenvelder, J. S., et al., Manual Biofilm Monitor, Kiwa Water Research, Nieuwegein, The Netherlands, 2006.

Chapter 8

Efficacy Oriented Maintenance: a reliable productive work floor maintenance approach to improve desalination efficiency

Efficacy is all about the work floor to direct the right way to do the job right



Chapter 8

Efficacy Oriented Maintenance: a reliable productive work floor maintenance approach to improve desalination efficiency

Table of Contents:

Abstract

The corrosive seawater environment has always played an important role influencing efficiency, availability and reliability of both the thermal and membrane desalination units due to corrosion and fouling. As a result maintenance is also one of the important aspects influencing efficiency. Years of desalination experience has ultimately shown the human aspect as the eminent key performance factor increasing efficiency in the costly desalination process. A well maintained operation unit is of utmost importance contributing to efficiency improvement. In this context a novel maintenance approach with the human aspect as the key pivot has been introduced in the Desalination Department of W.E.B. Aruba N.V. in 1998 which significantly decreased pump and process failures and consequently increasing efficiency. The annual accumulative performance ratio of the Multi Stage Flashing evaporators, a measure for efficiency, is increased from 8.7 to 9.3 decreasing operation and maintenance costs. The main objective is to keep the annual performance ratio as closed as possible to the design value of 10. The Efficacy Oriented Maintenance approach is developed in analogy with the Efficacious Motivational Leadership approach introducing the concept of Maintenance Conscious Operations and Operation Conscious Maintenance through effectively involvement and empowering of the work floor personnel promoting an effective work floor quality team between operations and maintenance. After a brief introduction of the world wide historical development of maintenance concepts, the aspects of this new Efficacy Oriented Maintenance approach are described and compared with well-established Total Productive Maintenance and the Reliability Centered Maintenance according to predefined Critical Success Factors. The results achieved at the Desalination Department practicing this new Efficacy Oriented Maintenance approach are illustrated.

8.1 Introduction

Despite the enormous growth in manufacturing knowhow of the last decades, still all man-made equipment are prone to mechanical failures due to fatigue, wear and tear, breakdowns and sometimes incorrect design. To guarantee a continued production, regular maintenance is of essential importance. It is required to effectively reduce waste and run an efficient, continuous manufacturing operation. The cost of regular maintenance is also very small when it is compared to the cost of a major breakdown at which time there is no production. Until recently, maintenance was considered in many industries as a necessary evil, a cost center. However, more and more maintenance management is now viewed as a viable and valuable aspect to improve production assets [8.1].

The aggressive seawater environment with its high salt content and a high biofouling potential has always been a major concern and an essential aspect in the process of maintenance. External and internal corrosion, scaling, inorganic and biological fouling always had a detrimental effect on sustainability and reliability of the production units. It is also a well-known fact that after commissioning of a new constructed desalination plant, within a short period of time efficiency decrement is experienced due to particularly scaling and fouling of the heat transfer surfaces of the thermal evaporators and the membrane surfaces of the SWRO production units. As already mentioned in the previous chapters, special chemicals are due necessary to mitigate high temperature scaling and biofouling to increase process wise operation stability. Congruent with the growth in the technology development, desalination units are nowadays automated computer controlled complex systems with many control instrumentations, rotating equipments and electrical instruments.

Throughout the desalination activities at W.E.B. Aruba N.V., maintenance of the thermal evaporators has relied since its establishment in 1932, on the effectiveness of the conventional corrective maintenance approach and the scheduled preventive maintenance program as stipulated by the manufacturers. Practically, the main philosophy dominating process in operations was: “They design, We operate and You shall fix it”. Taken into account the inherited condition of the production assets at that time, it was obvious that this approach misses out on insights that others in the organization can contribute by making a tremendous difference in how the production assets are perceived and could be operated and maintained. Obviously, the first necessary starting point for maintenance improvement was the upgrading of this conventional scheduled maintenance approach. Consequently, in line with the initiation of the efficiency improvement process (as described before in chapter 3), I took the initiative to also develop a new maintenance approach. The introduction of this *Efficacy Oriented Maintenance* (EOM) concept, has significantly decreased pump and process failures and has increased the accumulative performance ratio of the Multi Stage Flashing (MSF) evaporators from 8.7 to 9.3 decreasing operation and maintenance costs. The target efficiency is the design performance ratio of 10.

In this chapter the development, and achievements realized with the application of the EOM concept in practice, will be in-depth described and compared with well-known and accepted maintenance concepts.
The remainder of this chapter is organized as follows. In the next section an historic overview is provided about the application of several maintenance concepts. This section is followed by a brief description in section 8.3 of the specially adapted conventional maintenance of the MSF evaporators and the preventive maintenance of SWRO at W.E.B. Aruba N.V. Section 8.4 gives a description of the developed work floor predictive preventive maintenance approach and the initial achieved results. In section 8.5 the development and application of the developed EOM concept will be described and explained. Further, in section 8.5 the added value of the EOM concept is discussed and a comparison is made about the similarities and differences between the EOM concept and existing maintenance concepts. Finally, section 8.6 provides figures about the achievements so far with the application of the developed EOM concept at W.E.B. Aruba N.V.

8.2 Maintenance concepts: an historic overview

The evolution of maintenance went through many phases from: (1) Simply replacement of the damaged tools to; (2) realizing that the effort and time to repair is much less than replacement to; (3) the acknowledgement of the fact that breakdown or damage through aging and usage could be prevented or reduced by simply caring and paying attention to; (4) the state of the tool during performance of the intended functions [8.2].
Increased technological knowledge and experience of failure root cause analyses and statistical interpretation and failure occurrence prediction methodology, have further optimized the maintenance management and control.
In this section, following Geraerds [8.3] an overview of the historical maintenance development in the periods before, during and after the Second World War is shortly described. From the prewar period up to now most importantly the *Mechanical* approach, the *Operations Research* approach, the *American* approach, the *British* approach, the *Japanese* approach, the *Failure Analyses* based approach and finally the *Capacitance* based approach can be distinguished.

The Mechanical Approach: Preventive Maintenance
Since the beginning of the Industrial Revolution till the end of the Second World War, machinery and installations behavior were primarily determined by mechanical processes. Electrical components were very simple and complex electronic control systems did not exist and shall follow much later. “Wear and Tear” were the two most dominant forms of

experienced failures. *Tear* was considered a design issue and the application of proper materials and dimensions could prevent failure from occurring so introducing the important aspect of "*Design out Maintenance*" (DOM).

The *wearing* process, a frequent occurring phenomenon because of two moving metallic surfaces in direct contact with each other, was the main cause of failure. This failure could be prevented from occurring by regular lubrication, making maintenance just another operations activity. The wearing process normally developed over a period of time before the particular component fails. This resulted in the maintenance approach promoting the replacement or reconditioning of the particular component in question in a fixed period before occurrence of failure, independently of the technical condition, introducing the well-known *Preventive Maintenance* (PM) or *Scheduled Maintenance* (SM) concept.

Despite being very costly Preventive Maintenance is still practiced nowadays. However, research has shown that this form of maintenance is only under certain circumstances effective. This *Used Based Maintenance* (UBM) is practically only effective in case of an increasing failure rate. However, in the case of a decreasing failure rate it would ultimately result in increasing the rate, as schematically illustrated in Figure 8.1 [8.4]. The fundamentals for a well-managed Preventative Maintenance program are the following seven basic steps [8.5]:

- Establish scheduling
- Break down the facilities into logical parts
- Develop an equipment list and assign equipment numbers
- Develop and issue preventive maintenance instructions
- Locate and/or develop equipment manuals
- Develop a managed inventory
- Monitor the program's effectiveness and make improvements

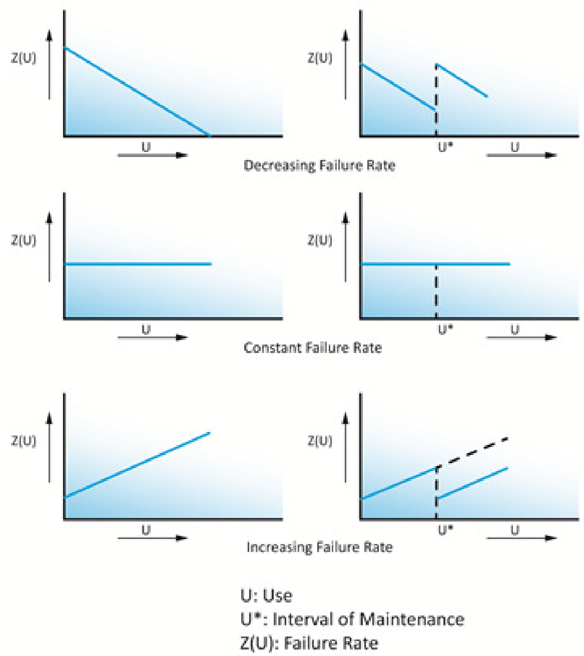


Figure 8.1: The failure rate dependency of Used Based Maintenance [8.4]

The Operations Research approach: The bath-tub curve

Operations Research (OR) was introduced by the British Army in the Second World War. At that time, support from scientists from different disciplines were requested to solve practical operations problems with which experts from the British Army were confronted with and were unable to solve. The contribution from scientists resulted in the introduction of fundamental mathematical tools to analyze the significant processes in operations and to compare theoretically alternative solutions. After the war practically all OR groups, also in the United States of America, were disbanded. The most important contribution of OR to maintenance was the statistical research on failure behavior to determine the appropriate maintenance in relation to a certain failure introducing the concept of probability and measureable variables as failure density, reliability and availability.

In the process of finding optimal solutions, a theoretical statistical model is presented with the intention to determine the optimal part of preventive maintenance to be carried out by comparing the preventive maintenance effort with the reduction in corrective maintenance activities or higher obtained availability. A second model introduced by OR is the well-known *Bath tub curve* as illustrated in Figure 8.2. This Bath tub curve suggests that all technical assets have an initial phase with a decreasing failure rate followed by an operation period with a constant failure rate and a final phase with an increasing failure rate.

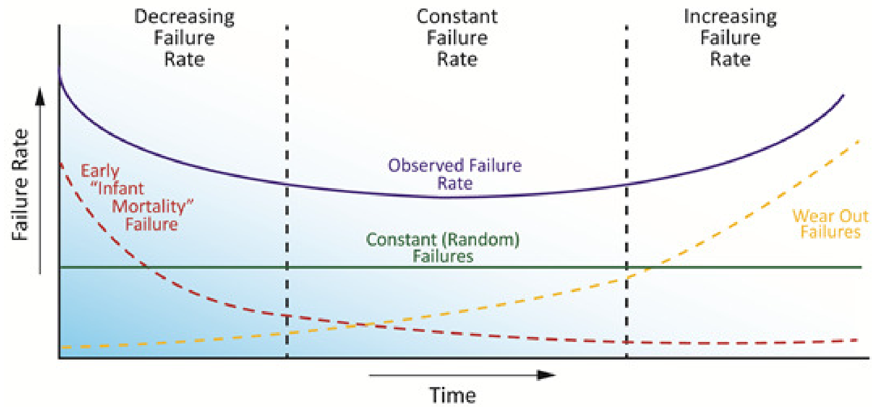


Figure 8.2: The Bath tub curve of the Operations Research [8.6]

Modern research has demonstrated that different technical systems can have different failure modes making this model actually just a presentation of the organizational efforts during commissioning, operations and decommissioning of a technical asset.

The American Approach: Life-cycle costing
After the Second World War it was experienced that the increasing usage cost of weaponry constrained and even jeopardized the budget available for new weaponry. Maintenance expenditure often appeared to account for many times the initial cost of the asset. Based on this experience a new approach was introduced that took care that in the procuring process of a new asset, not only the initial cost was evaluated but all following operational costs such as the usage costs and the decommissioning costs. This approach that became well known as *Life-Cycle Costing* (LCC) or *Whole-life Costing* (WLC) has since become a key component in the economic appraisal associated with evaluating asset acquisition proposals [8.7]. During the life of the asset, decisions about how to maintain and operate the asset need to be taken in context with the effect these activities might have on the residual life of the asset. If e.g. by investing 5% more per annum in maintenance costs the asset life can be doubled, this might be a worthwhile investment. Figure 8.3 illustrates life cycle cost of production assets [8.8].

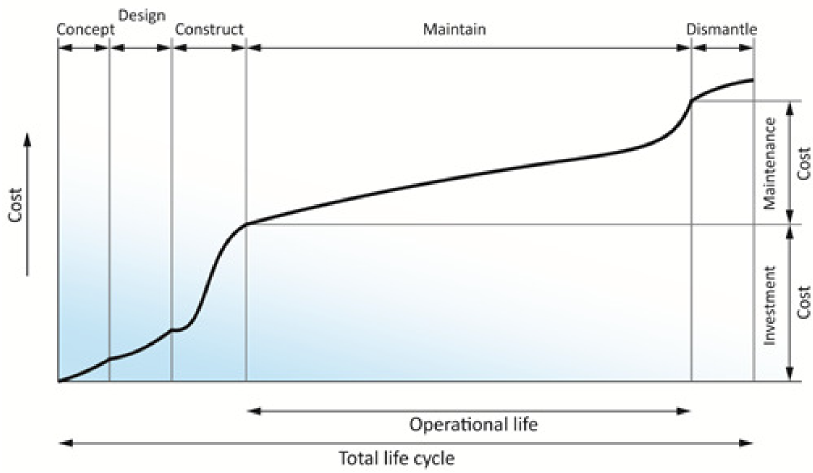


Figure 8.3: The total life cycle cost of a production asset [8.8]

The British approach: Terotechnology

Terotechnology was introduced in the United Kingdom of England in 1970 by a working group established in 1968 by the Ministry of Technology. Purpose of the working group at that time was to propose measures to improve maintenance in the UK. Terotechnology is defined as a combination of management, finance and technology, applied to the physical assets with the objective to attain economical life span cost. Terotechnology further covers the whole spectrum of aspects of the life cycle of assets from design, construction to decommissioning, with the important aspect of feedback of information about design, performance and costs. It also incorporates decisions about investment and replacement. Terotechnology has initially put a lot of attention on the importance of maintenance. However a major drawback of Terotechnology approach has been that it did not specify any techniques to meet the objectives.

The Japanese approach: Total Productive Maintenance

Total Productive Maintenance (TPM) was developed as a maintenance process for improving productivity by making processes more reliable and less wasteful. The objective of TPM is to maintain the plant or equipment in good condition without interfering with the daily process. To achieve this objective, preventive and predictive maintenance is required. TPM has been developed in Japan and successfully applied especially in the car industry. It was considered a major improvement on the adopted Preventive Maintenance approach especially by the redefinition of roles and responsibilities of operators and mechanics in routine preventive activities. Equipment availability was essentially improved by removal of the organizational lines between maintenance and production through a team approach improving equipment availability. Traditional organization lines between production and maintenance induced barriers that often prevent operators and mechanics from acting immediately to correct simple problems causing production upset. TPM main strategies suggest operators to assume responsibility and ownership of their equipments by performing basic first line preventative maintenance activities such as cleaning, routine inspections, and other tasks traditionally delegated to maintenance. It employs a team approach to continuous improvements whereby operations and maintenance systematically maintain and improve equipment effectiveness. Seiichi Nakajima, one of the most important Japanese pioneers of the TPM approach describes the five pillars toward productive efficiency as follows [8.9]:

- Maximize the effectiveness of all equipment
- Involve operators in daily maintenance
- Improve maintenance efficiency
- Training to improve skills
- Focus on maintenance prevention

The main objective of TPM is optimizing equipment effectiveness through eliminating the six big losses as is illustrated in Figure 8.4. The Total Equipment Effectiveness in percentage [%TEE] is defined as the product of the percentage of Availability [% A], percentage of Performance [% P] and percentage of Quality [% Q] as indicated by the following equation (8.1):

$$TEE = \%A \times \%P \times \% Q \quad (8.1)$$

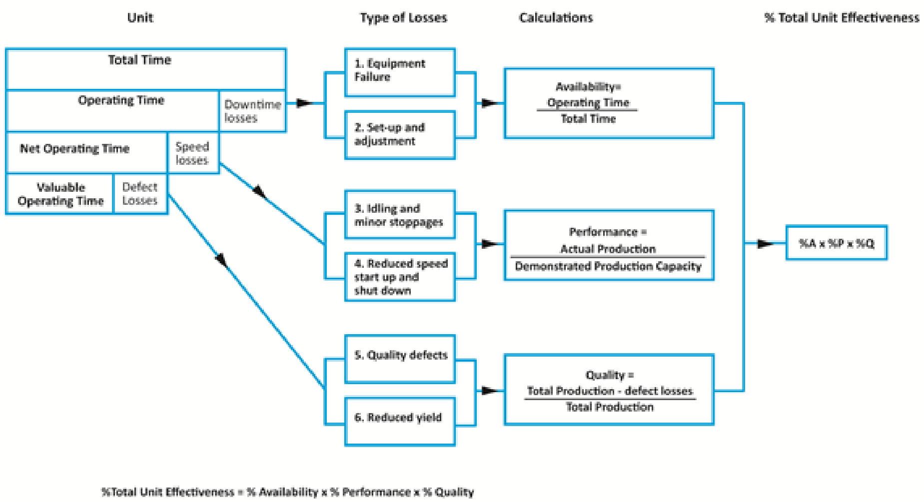


Figure 8.4: The Total Equipment Effectiveness [8.8]

Availability is defined as the ratio of operating time and total time, Performance as the ratio of actual production and demonstrated production capacity and Quality as the ratio of the total production minus defect losses and the total production.
One of the biggest advantages of TPM is the improvement of production capacity by restructuring workforce and improving employee skills. On the other hand the heavy reliance on time based preventive activities i.e. tasks executed periodically, according to a fixed schedule and failing to capitalize on predictive technologies despite improvement of machinery availability are considered major disadvantages.

The Dutch approach: Condition Based Maintenance
In the 1970s the costly preventive maintenance approach was significantly improved by the introduction of the *Condition Based Maintenance* (CBM) approach. In this concept, introduced in Holland at the University of Technology of Eindhoven, maintenance activities are planned and scheduled according to the results of periodic analyses and evaluation of technical variables indicating the condition of assets' components [8.10]. This concept has played an important role in the optimization of the maintenance costs by eliminating the unnecessary or the late replacement of components according to a fixed scheduled period in the usage based preventive maintenance concept. Comprehension and knowledge of the physical processes leading to failures was the basis for the innovative concept that there is no single failure mode as the well-known Bath tub failure mode but several failure modes according to the *Reliability Centered Maintenance* (RCM) [8.11]. Figure 8.5 illustrates six possible failure modes of technical components.

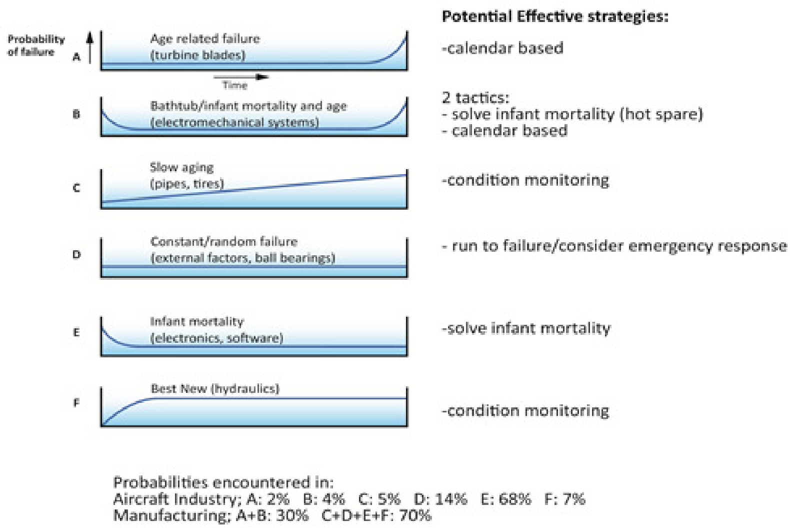


Figure 8.5: The six possible failure modes of technical components [8.8]

High capacity and fast computers that became available in the last decades, have significantly improved statistical failure analyses and maintenance control. The advance in Information Technology resulted a/o in *Computer Maintenance Management Systems* (CMMS) that dominate modern maintenance approaches, especially for the effective network planning of the different maintenance activities of complex production assets.

United States: the Reliability Centered Maintenance approach
The *Reliability Centered Maintenance* (RCM) approach has actually been developed in the late 1960s especially in the aviation industry in the United States of America as response on the growing awareness of the disadvantages of the costly, but widely applied Preventive Maintenance approach. RCM is defined as a process to determine what must be done to assure that any physical asset continues to do what it is intended to do according to its present operation context. The RCM is a method with the main objective to determine the maintenance activities for operation wise critical components of production assets based on seven questions. The seven questions are as follows [8.12]:

- What are the functions and associated performance standards of the asset in its present operating context?
- In what way does it fail to fulfill its functions?
- What causes each functional failure?
- What happens when each failure occurs?
- What can be done to predict or prevent each failure?
- What should be done if a suitable proactive task cannot be found?

The RCM process based on these seven questions is schematically illustrated in Figure 8.6.

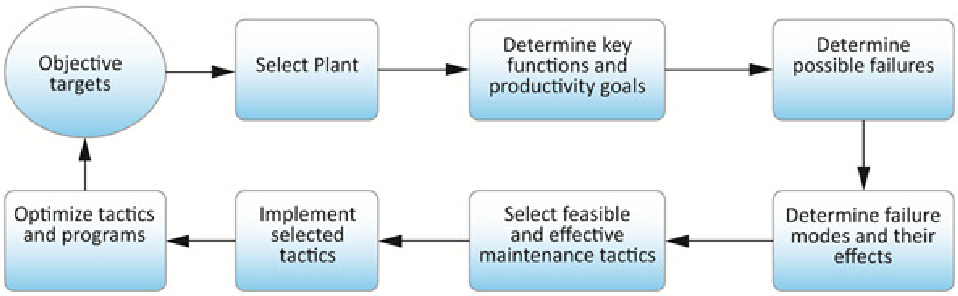


Figure 8.6: The maintenance activity assessment process of RCM [8.8]

The main strategy of Reliability Centered Maintenance (RCM) is to accurately assess the equipment conditions to achieve maximum plant reliability. This is done by means of the application of statistical analysis of machine-failure histories and strengthening of the maintenance-engineering partnership through a team approach, to optimize equipment investments through optimizing design, purchasing, delivery and installation. In the Reliability Centered Maintenance (RCM) approach, the time-directed tasks performed according to a rigid time schedule, are directed by regularly monitored equipment conditions. The Failure Mode and Effect Analysis (FMEA) and the historical failure and breakdown data of production assets' components, are the guiding principles for the statistical determination of failure probability rates [8.12]. To determine the maintenance-investment risks, probability rates of components are combined with the criticality level of a particular process. This will help to prioritize the more likely to fail components for maintenance. However, planned maintenance cannot improve the reliability designed into process equipment. This points out the main disadvantage of the Reliability Centered Maintenance in the sense that it addresses reliability from a process-importance level, but disregards equipment's ability to function [8.13].

The Capacitance approach:
Maintenance is nowadays experienced as a huge opportunity for cost savings in industry improving availability, reliability and efficiency. Most companies are considering maintenance as the single largest controllable cost opportunity by measurably raising plant profitability. Traditionally even with the new improved maintenance approaches as *Total Productive Maintenance* (TPM) and *Reliability Centered Maintenance* (RCM) the main point is to maintain equipment to continue production as designed for. In a production plant this means that the physical plant assets (machinery) is designed, manufactured and installed to continue to fulfill its intended function to productions and that changes in productions either do not occur or do not affect machinery requirements. A new approach came up in the 1990s, by increasing its effectiveness by maximizing capability and capacity instead of simply maintain equipment. Traditional maintenance encourages plant processes practically to stay the same and is actually more reactive than proactive by continually reacting to changes in production requirements. However, Maintenance departments should never neither simply maintain machinery nor only ensure machinery to meet its originally intended purposes. Maintenance should be called *Capacitance* indicating the main objective to provide capacity and to actually meet and even exceed demand [8.13]. The definition of capacitance is as follows:
"Capacitance provides manufacturing capacity in an efficient, profitable manner, unconstrained by original plant design or the design capacity of any piece of machinery, proactively searches for more capacity staying ahead for future production requirements" [8.13].

The Capacitance approach is based on the combination of valuable components of the Total Productive Maintenance (TPM), Reliability Centered Maintenance (RCM) and the *Reliability Based Maintenance* (RBM) that have received widespread attention in modern industries, forming a new maintenance structure as illustrated in Figure 8.7 [8.13]. In a nutshell, the strategy of the RBM approach has as guiding principle the usage of predictive data to optimize planning of the preventive maintenance activities to improve the reliability of production asset's components by means of the integration of base lining, benchmarking and continuous improvement practice through the promotion of the application of predictive technologies and proactive philosophies [8.13]. The main importance of the predictive and proactive strategy of the RBM divulges from the combination with the TPM and the RCM practically eliminating the disadvantages and improving the advantages of these concepts. It is also noteworthy that these new maintenance approaches have also introduced in the early 1980s the Reliability Engineering as a new discipline in the applied technological sciences.

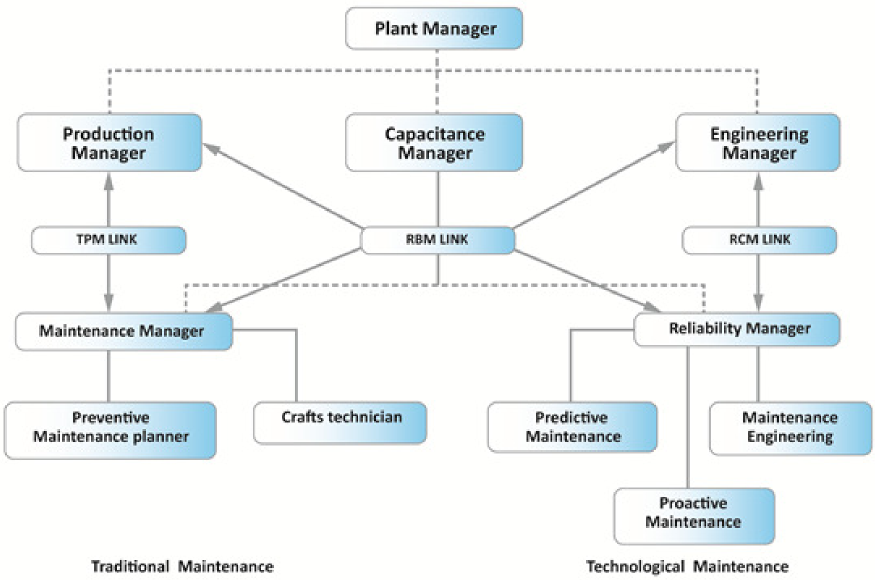


Figure 8.7: The structure of the Capacitance approach [8.13]

Concluding remarks about the overview of maintenance concepts

As can be seen from Figure 8.8, the historical development of maintenance can be divided in three periods. The first generation from 1930 to 1950 characterized by the reactive maintenance, LCC and the OR. The main maintenance philosophy is "Fix it when it is broke".

The second generation from 1960 till 1980 is dominated by the preventive or scheduled maintenance approach according to the main philosophy "Fix it before it breaks". This period is also characteristic for the comprehension of maintenance as a potential cost saving function for a company. At the end of this period effective maintenance concepts have been developed such as *Total Productive Maintenance* (TPM) and *Condition Based Maintenance*

(CBM), introducing the importance of the failure process. Initial effective control of the maintenance activities by effective scheduling and planning is evident in this period with the availability of rather big slow computers. The third generation is characterized by the upgrading of the condition monitoring process. In the *Predictive Maintenance Approach* (RCM and RBM), a sophisticated monitoring system is used for this purpose. Maintenance activities are executed according to the *Failure Modes and Effect Analysis* (FMEA). Reliability and maintainability are now considered key design factors. Leadership, multi skilling and team work are essentials toward excellence in maintenance to increase profitability of the business.

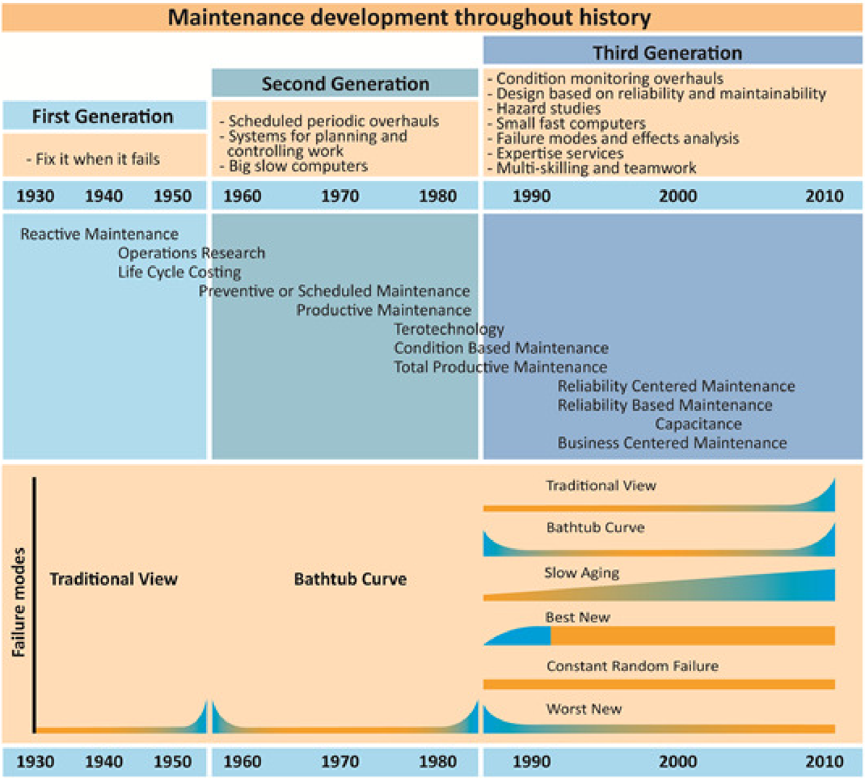


Figure 8.8: An historical overview of maintenance approaches, [composed from 8.12 and 8.14]

Figure 8.8 also illustrates that till the 1980s the one-failure-mode concept dominated the maintenance philosophy. Thorough analysis of the failure process in the late 1980s resulted in the recognition that there are practically six failure modes that can be distinguished. The maintenance philosophy in the late 1980s can be characterized as "Fix it according to its predicted break". More recently, improved maintenance methods like *Total Productive*

Maintenance (TPM), *Reliability Centered Maintenance* (RCM), *Business Centered Maintenance* (BCM) and *Reliability Based Maintenance* (RBM) have received widespread attention in industries. The conception that maintenance should not only keep or retain the production capability of production assets but should also increase capacity resulted finally in a new approach, *Capacitance.*

8.3 The conventional maintenance program of the desalination units

This section describes the specially adapted conventional maintenance program of the MSF evaporators, the SWRO unit and the procurement system of W.E.B. Aruba N.V.

The scheduled maintenance program of the MSF evaporators:
In the process toward optimized desalination efficiency the first priority of operations is maximum uptime and minimum downtime by means of a vital structured operation and maintenance program, leading to high productivity, efficiency and low operating cost. The specially adapted maintenance program of the MSF evaporators at W.E.B. Aruba N.V. is conventionally based on the manufacturer proposed structured maintenance in accordance to the reactive preventive American approach of a scheduled maintenance program. This program consists primarily of an annual scheduled general inspection and maintenance program of four weeks and quarterly condenser cleaning to mitigate biofouling. Corrective maintenance is applied especially in an emergency situation. The yearly scheduled General Inspection (GI) as it is called at W.E.B. Aruba N.V. allows for thorough external and internal inspection and repair of the evaporators and offers an excellent training time for maintenance personnel in a controlled work environment. Figure 8.9 illustrates some of the maintenance activities during a GI of an MSF evaporator at the Desalination Department of W.E.B. Aruba N.V., including the introduced pre GI meeting and the post GI performance test.

1. Pre GI- meeting

2. External Inspection

3.Vessel cover removal

4. Intake screen removal

5. Internal inspection

6. Brine pump removal

7. Hydrolase long tubes

8. Brine heater cleaning

9. Repair vacuum pipe

10. Closing vessels

11. Performance post GI

12. Plant in Operation

Figure 8.9: Maintenance activities during a GI of an MSF evaporator at W.E.B. Aruba N.V.

Minor repairs during the scheduled outage prevent unscheduled costly reactive repairs. Planning is very important, starting with a pre shutdown maintenance checklist according to manufacturer’s recommendations incorporating contribution of operations, maintenance and inspection by key personnel. In this stage it is important to review all maintenance requests that have been delayed for whatever reasons and should be included. Actually the shutdown period is an excellent time to catch up on all maintenance facets. The important phases in the conventional maintenance program in the MSF evaporator adopted for the MSF evaporators at W.E.B Aruba N.V. are shortly described in this section [8.15].

Pre shutdown inspection activities:

In general these involve inspections of the structure and the key components to determine whether further maintenance is needed. It is a good moment for ordering parts and to perform the necessary pipe prefabrication to reduce down time. Dedicated maintenance and operations personnel first walk around the evaporator for a pre inspection to:

- look for air and water leaks
- add part that needed further inspection during shutdown

- inspect structural concrete columns for stress cracks
- inspect walkways and other structure noting where repairs and painting is needed
- check for deteriorated or damaged insulation
- measure piping that have to be replaced and fabricated before shutdown
- determine whether mechanical or chemical tube cleaning is necessary

The most important components of the MSF evaporator in the pre shut down inspections that should be checked are the instruments, pumps, motors, vacuum system and electrical devices before shutdown. The pre shut down team usually prepares a list of malfunctioning instruments. Those showing signs of corrosion and replacement parts are ordered. Pumps are checked against manufacturer's performance curve for proper discharge pressure, capacity and head.

The Mechanical Department in conjunction with the Purchasing Department make sure that replacement parts are available or ordered for pumps component more prone to wear such as bearings, mechanical seals, packing and gaskets. The electrical motors are checked for power consumptions, operating temperatures, vibrations and noise. The entire vacuum system is inspected for air leaks and the operating hours of the nozzles are checked. All faulty or questionable electrical components, especially breakers, relays and motor starters, are listed by the Electrical Department and spare parts are ordered before shutdown. It is worth mentioning that in an island situation on time ordering of necessary parts and components are of duly importance.

Inspections and repair activities during shutdown:

After shut down, the evaporator is drained and rinsed with fresh water to remove all the salt water and the covers of the vessels are removed and the manholes are opened allowing the evaporator to dry as soon as possible to begin with the internal inspection. If extensive repairs, not foreseen in the pre shut down inspection, are detected at this stage implying major corrective maintenance activities, another shutdown should be planned. After all, scheduled maintenance and repairs are much less disruptive, as well as less costly than are emergency reactive maintenance actions. In a nutshell, in the pre shutdown inspection one needs to concentrate on the following evaporator shell side inspection and repairs:

- *Flash chambers*

Inspection should concentrate on possible holes, thin shell plates or loose parts on the stage divider partitions, end walls floor plates, brine gates and brine hoods exhibiting corrosion or erosion essentially caused by poor pH control in acid plant, poor flow velocity and physical erosion by sands and grid. Damaged carbon steel part should preferably be repaired by replacing corroded sections with new carbon steel plates instead of welding patches.

- *Liners*

The brine recirculation flow section of the flashing chambers are plated with stainless steel liners. These liner materials can work loose from stage walls and floor plates because of stress, poor installation and improper welds. Leaving vessels wet during shutdowns can also induce stagnant condition corrosion. Major liner repairs are usually performed on manufacturer's recommendation and supervised by manufacturer's service engineers.

- *Distillate troughs*

Due to poor accessibility, the distillate troughs are inspected for leaks by hydrostatic test with potable water. Leaks are serious resulting in poor distillate quality and are particularly prevalent in the down comer area due to aggravated corrosion caused by poor venting, incomplete deaeration as indicated by low pH of the distillate and failure to flush troughs with potable water at shutdowns. Repairs should also preferably be performed by replacing carbon or stainless steel sheets instead of patching.

- *Demisters*

During inspection loose, misaligned or plugged demisters due to scale or salt deposits and corrosion may be observed. Excessive feed water chlorination and poor venting of non-condensable gasses are mostly the primarily causes of mesh wire corrosion. Scale or salt deposits are the result of improper pH control of the brine recirculation causing calcium carbonate scale on the mesh. If the mesh wire is powdering the demister should be replaced. Calcium carbonate scales or deposits can be removed by a mild acid cleaning and further rinsing with fresh water and dried by blowing air. Corroded section of the demister holder should be replaced with more corrosion resistant stainless steel material.

Internal tube side inspection during shutdown:

After removing the tube-inlet-inserts, the brine heater tubes and the long tubes of the heat recovery section and the condenser are mechanically cleaned by hydro-lasing or bullet shooting to remove deposits on the heat transfer surfaces. Deposits are formed by scaling and fouling limiting heat transfer and increasing heating steam requirements lowering overall efficiency and economy. As in depth explained in Chapter 4 and 5, fouling is the result of biological growth due to lack or ineffective disinfection of the seawater feed and scaling is caused by excessive operating temperature, out of range brine concentration and improper control of the high temperature anti-scaling chemical treatment. After the tube cleaning activities the evaporator is hydro tested for internal tube-side inspection examining tubes, tube sheets and water boxes as shortly described below;

- *Long tubes*

During this inspection often ruptured tubes and weepers (leaks between tube sheet hole and the tube) can be found. Leaking tubes are usually the result of corrosion, poor venting and improper flows. At the other hand weepers are caused by improper tube rolling, thermal shock by dramatic temperature changes and water hammers. Important in this inspection stage is to look for corroded tube ends, thin tube walls and leaking tube plugs. Corroded tube end can be associated with biological growth, improper plant operation and erosion by high flow velocity together with sand and grit. Ruptured tubes should be plugged by hard wooden or phenolic plugs and bronze and brass plugs should be avoided. Tube inserts, commonly made of polypropylene can help eliminate corroded tube inlet failures.

- *Tube sheets*

Surface damages as result of corrosion and erosion may be evident during inspection. Corrosion in this case is particularly due to biological growth especially in the low temperature vessels, low pH and excessive chlorination. Erosion-corrosion due to abrasive action of sand in recirculation brine and incorrect flow velocity may be observed.
Severe damage requires replacement especially if faulty tube holes prevent tube expansion to prevent weepers. A general rule of thumb is necessary replacement when 20% of tube holes are larger than 0.2-0.3’’ greater than the outside diameter of the tubes. Tube sheet replacement and re-tubing is a major time-consuming repair activity that cannot be performed during a routine scheduled maintenance and should be performed under supervision of the manufacturer’s engineer.

- *Water boxes*

The inspection of the water boxes concerns leaks at the attachment to the stage end plates, the condition of the flange of water box covers or for liner failure caused by stresses, cracking and corrosion.
No matter how carefully designed and constructed a desalting plant may be, it can only meet its potential if properly maintained. Some degrees of corrosion, scaling and general wear are simply facts of plant life. Careful repair schedules enable smooth and efficient operation.

The scheduled maintenance program of the SWRO unit:
The new SWRO technology for seawater desalination, as already explained in Chapter 2, is since 2008 commercially applied at W.E.B. Aruba N.V. This was done for energy economic reasons, to increase desalination efficiency. It is, compared to the MSF evaporators, technologically a simple filtration process without any energy intensive evaporation-condensation phase transformation. The main components are the micro- or ultra-filtration system for the pretreatment of the raw seawater feed, the reverse osmosis hyper filtration

process for the production of fresh water and the necessary process utilities such as the pumping system, control instruments, electrical and mechanical equipment and the Human Machine Interface (HMI) components.
The SWRO is considered a low maintenance desalination process where in the design phase optimal use is made of the Design Out Maintenance (DOM) concept especially in the high pressure section to minimize corrosion by proper material selection and process automation. The maintenance program of the SWRO is practically a planned time or running hour based preventative replacement or repair activity with the emphasis on regular inspection and routine servicing according to manufacturer's recommendations for all assets components.
In addition to this scheduled maintenance program, condition or corrective maintenance will be also needed to prevent performance losses or running to failure. As many components warn that they are on the verge of failing, operations predictive on line condition monitoring activities and routine visual inspection are an essential part of the preventative maintenance program of the SWRO desalination unit. Trending of normalized process parameters, membrane differential pressure, permeate flow or salt passage, are crucial in the SWRO operations [8.16; 8.17]. As explained in depth in Chapter 4 and Chapter 5, scaling and marine biofouling are two important factors affecting sustainability and reliability in seawater desalination. In the SWRO technology this is so pronounced that without efficient chemical treatment sustainable desalination is impossible. This makes the *Chemical Based Preventative Maintenance* (CMPB) program as named at the Desalination Department at W.E.B. Aruba N.V., a predominantly part of the preventative maintenance activities. In this section the CBPM introduced and practiced at W.E.B. Aruba N.V of the intake system, the pretreatment system and the membrane sections and the pre membrane section piping system to increase SWRO efficiency are more in depth described. As will be explained in Chapter 9, a novel environmentally friendly chemical free osmotic membrane cleaning process has been developed to improve the CBPM.

The Chemical Based Preventative Maintenance program:

- *The open seawater intake system*

The open seawater intake system consists of two centrifugal pumps in a concrete basin with stationary screens. The priming system is adapted according to recommendations of the Desalination Department in the design stage to create the possibility of hot standby of the redundant intake pump to mitigate marine biofouling and marine microbiological induced corrosion. To mitigate corrosion and biofouling the intake pumps are rotated according to the daily intermittent chlorine disinfection frequency. The intake screens are periodically, every three months, removed and mechanically cleaned by hydro blasting. Divers removed accumulated dirt and silt from the intake basin and scraped macro-bio growth from the surfaces of the intake structure. The chlorine disinfection mitigates biological growth in the piping system of the intake pumps and the raw seawater pretreatment system.

- *The raw seawater pretreatment system*

The main components of the raw seawater feed pretreatment asset are a set of 12 multimedia filters (MMF) consisting of 3 banks of 4 MMF, a filtered seawater buffer tank and a bank of 5 cartridge filter housings, containing 75 cartridges each. The multi-media filters have a filtering capacity of 20 microns and the cartridge filters are rated with a 5 micron filtering capacity. The pretreatment infra-structure is maintained according to conventional preventive maintenance activities recommended by manufacturers or according to W.E.B. Aruba N.V.'s standards. The main experienced operational problem is persuasive marine biofouling as explained in Chapter 5 and daily intermittent chlorine disinfection and MMF back washing with chlorinated filtered seawater flow is introduced as a measure for effective bio growth control. Silt Density Index (SDI) and turbidity measurements of the filtered seawater are taken every shift as an operational predictive maintenance measure to control the functioning of the MMF filters and cartridge filters. The cartridge filters are replaced when a differential pressure of approximately 0.6-0.8 bar is reached. A sodium bisulfite solution is injected before the cartridge filters system to de-chlorinate the filtered seawater feed to avoid chlorine damage of the polyamide membranes. The SWRO membranes are very susceptible for marine biofouling and scaling making the Chemical Based Preventive Maintenance an essential part of the preventative maintenance program of the SWRO technology. The Clean In Place unit is therefore a crucial part of the SWRO unit to guarantee sustainability by increasing reliability and availability.

- *The chemical cleaning of the membranes*

The SWRO fresh water production unit consists of trains of pressure vessels housing each 7 membrane-elements. Micro-organism coming in with the seawater feed once attached on the membranes surfaces, may proliferate and form a persuasive biofilm matrix hampering the water permeation of the membranes. Due to concentration polarization, supersaturated dissolved inorganic salts may precipitate on the membrane surfaces reducing production efficiency and salt retention. Inorganic scaling is prevented by dosing of an effective antiscalant. To control biofouling and inorganic scaling on the membrane surfaces, chemical cleaning of the membranes is due necessary as soon as the membrane spacer side normalized differential pressure reach a 15% increment of the normal operational differential pressure to avoid permanent damage of membranes. It is also recommendable if a decrease of 10-15% of the permeate flow and a 10-15% increase of salt passage is experienced [8.18]. This Clean In Place process includes rinsing of the membranes with product water and the application of alternatively a low pH and a high pH solution and a surface active solution according to the recommendation and specification of membrane manufacturers or chemical suppliers. The CIP procedure normally applied at the Desalination Department is as follows [8.19]:

1. Flushing of the high pressure vessels with fresh product water to remove residual seawater in the spacer side of the membranes.
2. Cleaning with a 1000 ppm solution BetzDearborn DCL32 ™: Sodium Bisulfite (SBS), low pH.
    a. Fill the CIP tank with the SBS solution and circulate for 10 minutes
    b. Stop circulation and soak for one hour and circulate for 5 minutes
    c. Repeat step (a) 5 times; the SBS should be in contact with the membranes for a minimum of 5 hours.
3. Cleaning with Kleen MCT-404 ™: Anionic surfactant
    a. Dump the SBS solution and flush the CIP tank
    b. Fill the CIP tank with MCT 404 and circulate for 45 minutes
    c. Keep the MCT 404 solution in the CIP tank while adding the additional chemicals
4. Cleaning Kleen MCT-411™ ; high pH
    a. While circulating CIP solution add 10 pails of MCT-411
    b. While circulating CIP solution add an Optisperse ADJ561™ (Caustic soda) to increase pH to 12.2.
    c. Circulate this CIP solution for a minimum of 90 minutes or until the solution reaches a temperature of 35 ^{o}C. This temperature limit should not be exceeded.
    d. Circulate for 10 minutes, soak for 1 hour
    e. Repeat step (d) for 6 hours to a maximum 12 hours.
5. Change the cartridge filters of the CIP system once every 3 CIPs.

The Desalination Department of W.E.B. Aruba N.V. has also successfully introduced the chemical cleaning of the pressure exchanger of the energy recovery system to eliminate bio growth and the chance of recontamination after a CIP procedure. The persuasive biofouling experienced at the SWRO at W.E.B. Aruba N.V. lead to the introduction of the sanitation procedure for the whole piping system from the intake system till the membrane pressure vessels as will be explained below.

The sanitation procedure:

As a measure to totally control biofouling, a sanitation procedure has been introduced to especially mitigate the possibility for recontamination after CIP procedures.
The sanitation procedure developed by the Desalination Department at W.E.B. Aruba N.V. consists of the usage of different biochemical and distillate water to alter the osmoregulation of the cells of the micro-organisms in combination with a novel osmotic environmental friendly membrane cleaning procedure. The SWRO desalination process is

adapted to use the filtered seawater buffer tank and the product water buffer tank for the sanitation procedure. A patent is registered for this novel membrane cleaning process as will be discussed in detail in chapter 9. The sanitation procedure in short is as follows;

1. Shut down the SWRO desalination unit and after removing all the cartridge filters drain the unit thoroughly including the pretreatment system.
2. Flush the system with pure distillate water thoroughly and soak for 1 day.
3. Blind off the SWRO trains and fill the filtered seawater buffer tank with 250 ppm chlorinated distillate water and fill the whole system including the pretreatment and energy recovery system with chlorinated distillate and soak till the next day.
4. Flush the whole system with distillate and repeat the filling and soaking process as in step 3 with biodispersants such as biomate MBC-2881™ .
5. After flushing remove the blind plates from the SWRO trains and clean the SWRO and BWRO membrane according to the new developed osmotic membrane cleaning process with distillate acidified with carbon dioxide.
6. CIP the SWRO trains according to the normal CIP procedure including a step with the biodispersant MBC-2881™.

It is worth mentioning that after application of this new sanitation procedure in 2010 the SWRO desalination unit is put back in operation with an efficiency ratio of 3.72 kWh/m^3, actually 7 percent lower than the design value of 4.00 kWh/m^3. Since the first startup the average efficiency was 4.45 kWh/m^3. Extensive chemical cleaning of membranes and damaged membrane interconnectors can cause permanent damage of membranes increasing salt passage causing low quality product water due to high conductivity and possibly micro biological contamination. In this situation on line detection of the damaged membrane and a well thought-out membrane change program is an important operation and maintenance activity guaranteeing sustainable SWRO-operation.

Online membrane probing and membrane change program:
The two pass SWRO-BWRO desalination unit is designed to produce fresh water with a quality of 15 ppm Total Dissolved Salts (TDS) to maintain the high quality of the Aruba drinking water to control corrosion in the distribution system as explained in Chapter 7. Permanent membrane damage due to intensive chemical cleaning process or long term operation at higher than the normalized differential pressure usually alter the permeation capability of membranes causing higher salt passage. When a membrane train produces poor quality fresh water the high pressure vessels is isolated and a membrane probe test is performed to identify the defected membrane. The membrane probe is a simple device consisting of a stainless steel tubing with a connecting valve to connect to the end cap on the vessel and a sample flexible plastic hose or a stainless steel tubing. The tubing is inserted

at different distances in permeate tubes of the membranes in the vessel. A sample is taken of the permeate of all the membranes in the subsequent vessel to identify the defected membrane. Figure 8.10 shows operators of the Desalination Department performing the membrane probe test.

a: probing of the membranes

b: permeate analysis during probing

Figure 8.10: Desalination operators performing the membrane probe testing

In normal SWRO operation commonly the first lead membrane elements are usually prone to biofouling and the last membrane element to inorganic scaling due to concentration polarization and higher concentration of the seawater feed. Membrane manufacturers normally guarantee a design life time of 5 years for new membranes. In practice membranes have reached operational life time of ten years and longer [8.19]. To guarantee optimal efficient desalination a membrane change program is essential. The membrane change program applied at W.E.B. Aruba N.V. is based on replacing the two lead membranes of all pressure vessels after the third operation year. In this change process the two new membranes are installed as last elements and the remaining elements are pushed up front in the pressure vessel. Subsequently every year hereafter a new membrane element is installed the same way. Figure 8.11, illustrates the membrane changing process by operation and maintenance personnel.

Figure 8.11: The membrane changing activity at the Desalination Department

It is noteworthy to emphasize the achieved strict leak free operation of the SWRO desalination unit as an essential part of our desalination operation and maintenance strategy. In our endeavor to achieve excellence in desalination we have acknowledged the importance of optimal scheduling and planning of maintenance activities toward sustainable desalination efficiency improvement. In this preventative maintenance process, procurement and inventory management in general and particularly of the necessary spare parts play a usually underestimated crucial role. In the next section this procurement and inventory process of W.E.B Aruba N.V. will be shortly described.

The procurement system of W.E.B. Aruba N.V.:

The most import value of maintenance is characterized as customer satisfaction through the best quality and service, quickly at the lowest cost and at minimal risk. In this context of optimizing internal and external service, increasing quality of maintenance, reducing risk and costs of maintenance activities, management of spare parts, logistics and on time availability of crucial assets spare components, the Purchasing and Inventory Department of W.E.B. Aruba N.V. also plays a major role in efficient operations and maintenance toward desalination excellence.

Considering an island situational based operations and maintenance process, optimal inventory management guaranteeing the maintenance value gives an extra dimension to the importance of the Purchasing and Ware house Department. Honoring this usually forgotten importance of this department in the operational continuous efficiency improvement process, this section is dedicated to the inventory management describing very briefly the Purchasing and Warehouse of W.E.B. Aruba N.V. [8.20].

Purchasing and Warehouse of W.E.B. Aruba N.V.

The Purchasing and Warehouse is a department resorting within the Maintenance Division. The department is divided in two sub-departments, the Purchasing section and the Inventory section. Each section has a supervisor that reports directly to the Procurement and Materials Superintendent. There is one administrative-assistance for the department. The purchasing process for services, none-store materials and the store material inventory process are schematically illustrated in Figure 8.12.

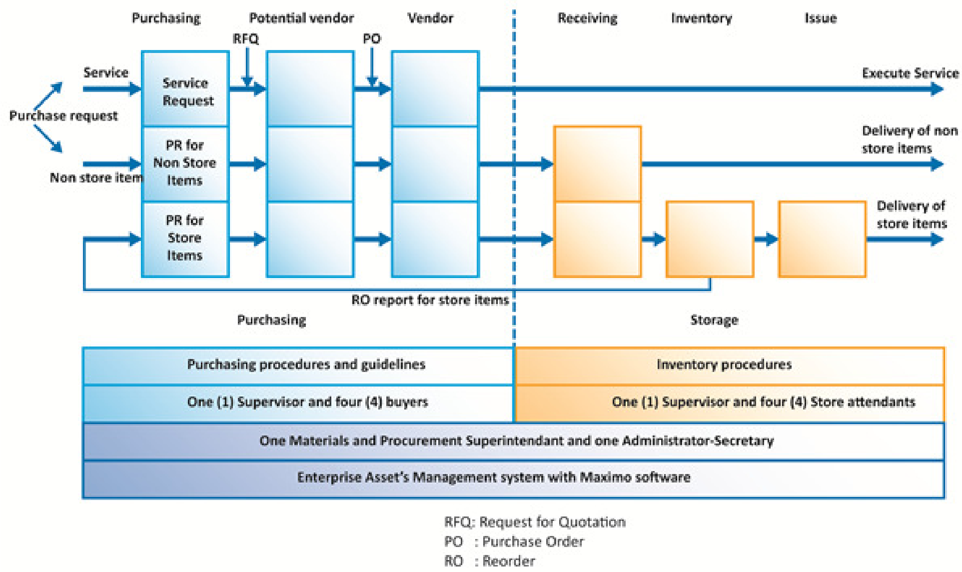


Figure 8.12: The schematic of the purchasing and inventory system of W.E.B. Aruba N.V.

The Purchasing section is responsible for all the purchasing activities for W.E.B. Aruba N.V. This includes store materials, non-store materials and services. Purchasing guidelines and procedures are in place purposely guaranteeing a transparency purchasing policies. The policies include: Vendor Qualification, Private Tender (Bid Process), Single Sourcing, Generating and Approvals of Purchase Request (PR), Request for Quotation (RFQ) and Purchase Order (PO). The purchasing process as schematically illustrated in the left corner of Figure 8.12 starts with a purchasing request of the departments of concern. The Purchasing department prepares according to the specification of the PR an RFQ for potential vendors. After receipt, evaluation and acceptance of the RFQ in accordance with the purchase requesting departments a PO is placed for the selected vendor.

Most items carried in Inventory are replacement parts for the operating equipments and the water distribution network. The usage of the replacement parts are very erratic and are essential for the Production Department. Furthermore there are the basic supplies in storage such as office and safety supplies.

Of importance is the minimum inventory quantity specified in accordance with the Operations and Maintenance Departments. In order to have a control on the value of the Inventory, a decision tree is applied for all new store items, which consists of five criteria's:

- Risk Criteria: Failure of the part has a direct effect on the functioning of the mayor equipment or emergency units
- Cost Criteria: How expensive is the part

- Specific Criteria: How specific is this part; can it be used only on one or very few equipment
- Delivery Time: How long can the item be on the island?
- Shelf life: What is the shelf life of the item?

These criteria's will decide if an item will be stored and in which quantity. In Figure 8.13, the *Inventory Decision Tree* (IDT) is illustrated for the Risk Criteria.

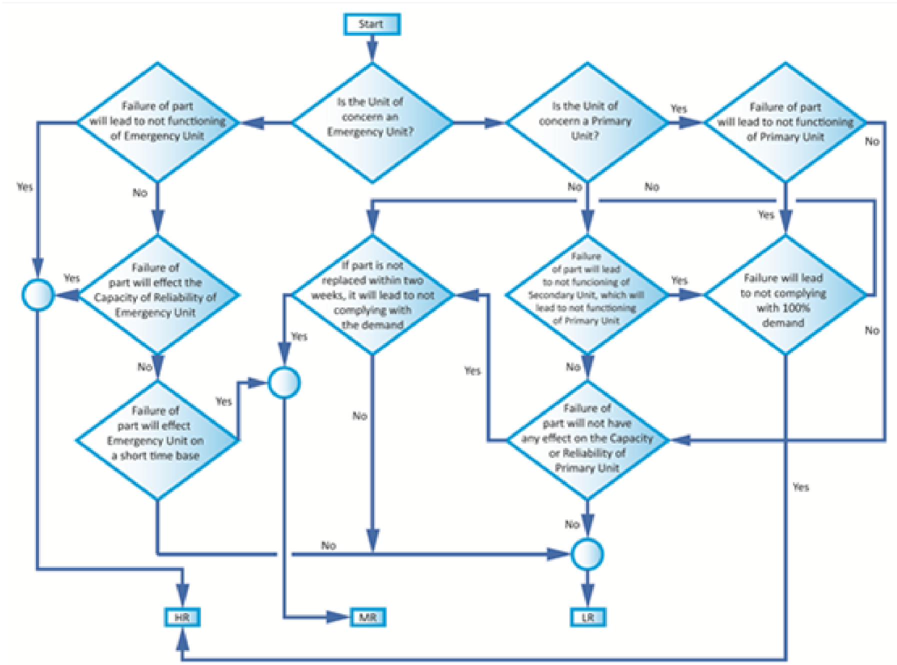


Figure 8.13: The Inventory decision tree of W.E.B. Aruba N.V.

A cycle count procedure is also in place, where everyday items are count, based on an ABC-classification, where the fast moving and expensive items may be counted more than once in a year. This procedure is illustrated in Figure 8.14.

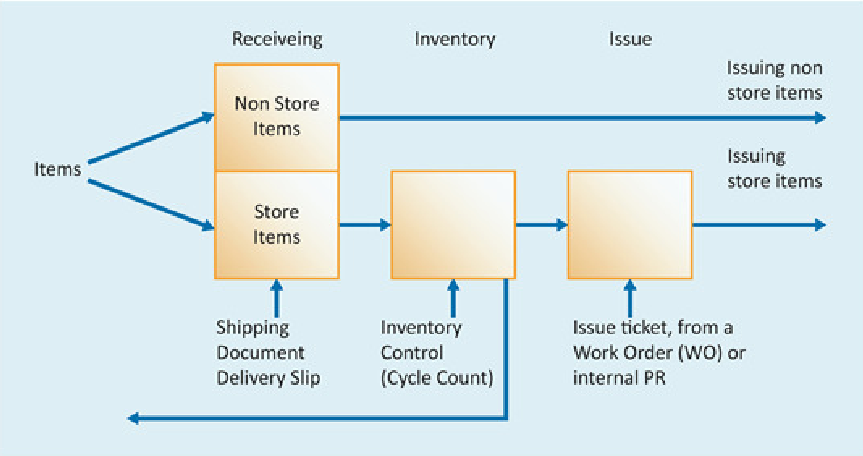


Figure 8.14: The inventory work flow of W.E.B. Aruba N.V.

The spare parts are classified in the following categories; Capital Spares Parts, "Initial" spare parts and Normal spare parts.
The Capital Spares Parts are further divided in Machinery Spares and Water Distribution pipe lines. For a spare part to be defined as a Machinery Capital spare, it has to comply with all the following criteria:

- Machinery spares which are specific to a particular item of fixed asset or a group of identical fixed assets i.e., they can be used only in connection with a particular fixed asset or a group of identical fixed assets
- Their use is expected to be irregular
- The acquisition value is greater than AWG 10,000 (US$ 6,000) ; (AWG is the legal currency of Aruba)
- Long Delivery Time (> 12 weeks)
- Machinery spares that are required for proper functioning of a particular item of a fixed asset, that has a significant impact on production capacity
- When the related fixed or all identical fixed assets are disposed of, these spares are to be discarded, since they are an integral part of the fixed asset.

The machinery spares of the nature of a capital spare will be capitalized separately at the time of their purchase whether procured at the time of purchase of the fixed asset concerned (Project), where the charges are allocated to the concerned Project, or subsequently during Operations. Machinery spares of the nature of a capital spare should be considered as assets and the total depreciation cost of such capital spares should be

allocated on a systematic basis over a period not exceeding the remaining useful life of the principal fixed asset to which they relate. For the procurement of these capital spares, a "Project Dossier" (AFE-approval for expenditure) is required.
The machinery spares of the nature of a capital spare will be stored physically in the storehouse at zero value. The storehouse will keep a separate administration in the Inventory system of these items. At the storehouse, the *Enterprise Assets Management* (EAM) system Maximo is used. After issuing of one of these spares, a "Project Dossier" (AFE-approval for expenditure) is required for procurement of a new spare or for re-conditioning of the used spare.
The other Capital Spare is the Water Distribution Pipe lines. Here are all pipes of the size bigger than 2 inches, including fittings, which are required for the Water Distribution Capital Project. These items are considered Work-In-Progress items and depreciation will initiate after completion of Project. These Water Distribution Pipe lines will also be stored physically in the Warehouse and a separate administration is kept in the Inventory system. The purchasing of these items is on demand.

The delivery or acquirement of Non-Capital spare parts during a Capital Project is specified as follow:

Existing Inventory Items, which are existing spare parts already in Inventory. These new spares are received in Inventory at "zero" value and the received quantity will be added to the actual balance on hand of these spares in Inventory, without increasing the total value, i.e. the average value per item will decrease temporarily.
The new Inventory Items will become spare in Inventory after complying with the Decision tree and received at "zero" value. After the issue of these spares, they will be procured and stored at the procured value. The acquisition or capitalization of the initial non-capital spares should be purchased and capitalized during the time of purchase of the fixed asset concerned (Project) and are incorporated in the Normal Spare Parts Inventory according to the definitions above. All other spares are considered Normal Spares that are kept in Inventory that does not fall in the category mentioned above. To conclude this section it is worth mentioning that regularly meeting with operations and maintenance and planning departments are organized to improve communication and to optimize the inventory and purchasing process to facilitate on schedule execution of the general inspection and maintenance of the production assets improving efficiency in operations in general and efficiency in desalination in particular.

8.4 Toward a work floor predictive preventative maintenance approach

This section describes the as found degrading maintenance condition of the desalination asset, the specially adapted continuous desalination improvement's road map to involve the supporting departments toward an improved structured maintenance program and the development of a new work floor predictive preventative maintenance approach. The promising improvement results obtained with this new maintenance approach are described. These results had encouraged the development of the Efficacy Oriented Maintenance approach as will be outlined in the next section.

The as found maintenance condition of the MSF evaporators

Despite the application of manufacturer's proposed scheduled maintenance program by the Maintenance Department, the as found degrading maintenance condition of the inherited MSF evaporators in 1997 pointed out the necessity to revisit this conventional scheduled maintenance program and its possible transformation into a new maintenance approach with effective involvement of the operational and maintenance work force.

The Multi Stage Flash (MSF) evaporators, including the newer MSF evaporators constructed in the beginning of the 1990s, were advancing a degrading maintenance condition mainly due to overdue maintenance and the consequently long-term exposure to the detrimental effect of the aggressive seawater environment causing internal and external corrosion.

Due to the commonly experienced production decay at that time and a lack of operation and maintenance planning and effectiveness and omission of an effective investment plan to cope with increasing water demand, the consequently threatening water scarcity forced the "run to kill" desalination operational and maintenance approach. On different parts of the desalination units, snowy salts deposits were the visible results of many leakages promoting external corrosion. This was further worsened, because removed isolation materials after repairing perforation in vessels and piping were usually not reinstalled. Also the necessary painting of the desalination units was not performed as a preventive maintenance measure in a long period of time.

The poor relationship between the Desalination and Maintenance departments also contributed to the deficient operation and maintenance situation. This rivalry relationship could in general be characterized as "the unit failed because it was not fixed well" and the counter reaction "the unit failed because it was not well operated". Furthermore, the desalination units and corresponding process equipment were taken out of production and handed over to maintenance without trouble shooting, without any form of work permit and without any proposal for the expected maintenance work to be performed. Effective communication, relationship or teamwork practically did not exist between the two departments. There were also no General Inspection or maintenance meetings held between the two departments. The relationship of the Equipment Inspection group of the Engineering Department with the Maintenance Department could also be characterized as

very resistive. Maintenance of the desalination assets was in essence regarded as a sole function and responsibility of the Maintenance Departments.
Regarding housekeeping, it was remarkable that on the water production premises and under the MSF evaporators, regularly used material and maintenance equipment and tools could be found. It was not unusual to find maintenance equipment stored under an MSF evaporator for months awaiting the next shut down for the scheduled maintenance activity. With respect to safety, maintenance activities were usually performed without the necessary adequate personnel protective gear. Working with sulfuric acid and other chemicals without the prescribed safety measures was a common practice. There were no housekeeping and safety controls performed and no safety talks and meetings commonly held either by the Desalination Department or the Maintenance Departments and the work force of both departments was also not trained to do so.
Further a main deficiency of the conventional scheduled maintenance program as practiced at W.E.B. Aruba N.V, is that it consider maintenance only as a function of the Maintenance Departments and that scheduling and planning are function of maintenance line management practically without involvement of the work force. This misses out on insights that others in the organization, especially the work force responsible for the execution of operation and maintenance activities can contribute by making a tremendous difference in how the Desalination assets are perceived to improve operation and maintenance. This omission was the driving force for me to promote the development of a new maintenance approach based on the concept of efficacy, effective involvement and empowering of the operational and maintenance work force in a close work floor partnership to improve the maintenance condition of the Desalination asset. In this context the initial developed roadmap toward Desalination Excellence is specially adapted to incorporate Maintenance and Engineering support and sustain to facilitate the development of this new maintenance approach to support the desalination journey toward continuous desalination efficiency improvement.

The roadmap toward a maintenance efficacy approach

Considering the perceived as found degrading maintenance condition it was obvious that attaining a higher level of desalination efficiency improvement, an effective work relationship with supporting Maintenance Departments and the Engineering Department is of imminent importance to diminish the rivalry culture creating the opportunity to revisit and possibly restructuring and improvement of the scheduled maintenance program of the desalination units. The progressively obtained successes at the Desalination Department with the Efficacious Motivational Leadership and the Mahatma Gandhi leadership strategy directed the way in establishing a firm interdepartmental work relationship on line executive and work floor level promoting Operations and Maintenance and Engineering interdepartmental team work and partnership. After establishing a firm internal

Desalination Department team the road map toward desalination performance improvement is specially adapted to effectively incorporate the supporting Maintenance and Engineering department in the journey toward Desalination Excellence as a joint endeavor of all involved guaranteeing efficient water production. In this effort practically all the performance improvement steps as initially applied at the Desalination Department are evaluated and repeated, but now iteratively within an interdepartmental jointly shared vivid vision and mission toward the envisioned Desalination Excellence.
The acknowledged Personnel performance and Desalination Assets' performance improvement aspects (as detailed in Chapter 3) in the phases of the desalination socio-technical improvement program are discussed with the supporting Maintenance and Engineering Departments and specially adapted into the following interdepartmental desalination performance improvement critical areas:

Personnel performance improvement aspect

1. Application of leadership efficacy to establish a firm operation and maintenance work force relationship to promote effective interdepartmental communication and teambuilding.
2. Operation and Maintenance Work floor motivation through effective involvement and empowering to establish a motivated clean and safe desalination work environment promoting creativity and innovation.
3. Stimulation of Departments' internal team building as a condition for a sound interdepartmental team building.
4. Sustain and sharing the Desalination's vision and mission to direct the path forward toward the envisioned Desalination Excellence to jointly guarantee the production of high quality water with a well operated, maintained and engineered desalination asset.

The Passion and Fear motivational and Human Attitude metaphoric models and the Mahatma Gandhi leadership strategy and the Efficacious Motivational Leadership approach formed the foundation to support and consolidate the interdepartmental human performance improvement process toward improving the desalination asset.

The Desalination Assets' performance improvement aspects

5. Support of Maintenance and Engineering to further upgrade the documented work flow processes, the conventional scheduled maintenance and to improve the monitoring system. Collaborative support to increase safety and housekeeping is also necessary.

6. Maintenance and Engineering support for the upgrading of the desalination process and monitoring system, the developed key performance indicators and the proposed desalination improvement projects. The Operation, Maintenance and Engineering work

climate should be transformed to consider innovation and the application of new technologies.

7. Sustain interdepartmental team building and relation building to improve maintenance of the desalination assets and the introduction of Service letter Agreements to support the Quality Management System of the Desalination Department to promote ownership and accountability and continuous improvement.
8. Maintenance and Engineering's support and sustain to work out the Quality Management system toward a Continuous Desalination Efficiency Improvement Process.

The specially adapted road map including the plan of action to remediate the distinguished interdepartmental critical performance improvement areas is illustrated in Figure 8.15.

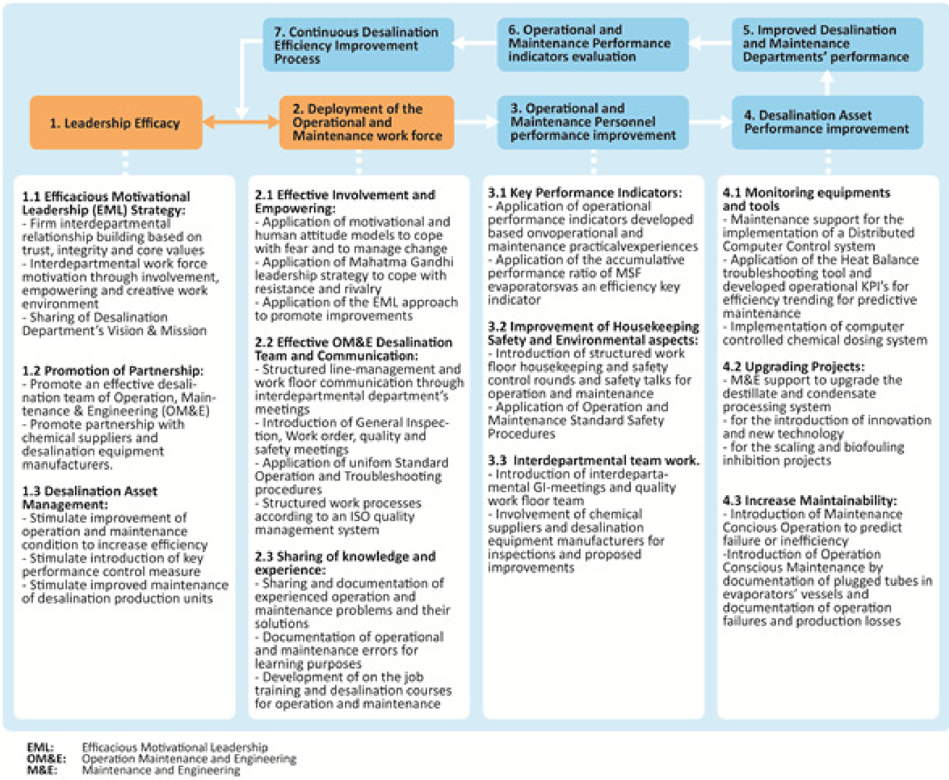


Figure 8.15: The specially adapted road map toward the Continuous Desalination Efficiency Improvement Process

This road map indicated the necessary successive determined relationship and partnership building steps leading to a new structured efficacy maintenance approach enforcing the jointly journey toward Desalination Excellence. The basis (as indicated in Chapter 3) is leadership efficacy to enable effective involvement and empowering of the desalination operational and maintenance work force to efficiently take care of the desalination asset in a sound partnership with Engineering, Laboratory, Chemical Supplier and Equipment Manufacturers. The ultimate results are efficient seawater desalination processes regulated with targeted key performance indicators to guarantee the production of high quality water satisfying all stakeholders in a continuous improving desalination process adding value to the company. The proposed plan of actions in the first four improvement steps of the road map to reach the envisioned improved Desalination Operational and Maintenance performance in the Continuous Desalination Efficiency Improvement Process with effective interdepartmental collaboration is further specified:

1. Leadership efficacy

In the Desalination Excellence's endeavor, leadership efficacy is consider the motivational pillar and enabler to continuously drive the operational and maintenance work force, in the context of efficacy, toward motivated effective participation in interdepartmental teams and partnership to increase human performance improving operational and maintenance processes and the desalination asset's performance. The end result is an excellent seawater desalination producing high quality drinking and industrial water to the satisfaction of all stakeholders and so adding value to the Company. In this context the main points of attention are Efficacious Motivational Leadership strategy promoting partnership to sustain effectively the management of the Desalination asset.

1.1 Efficacious Motivational Leadership (EML) strategy

In this improvement step the leadership strategy is directed to establish a firm relation with the operational and maintenance work force based on integrity, mutual trust and respect and according to company's core values to primarily eliminate the existing rivalry. A firm desalination management-work force relationship is considered determinative to further promote the efficacious motivational concept of effective participative involvement and empowering of the work force to reach out toward an improved performance. In this context socio-technological motivational and human attitude models were applied as metaphors to promote and manage change and to stimulate work floor motivation and collaboration. A creative and motivated desalination interdepartmental work environment is pursuit and endorsed to improve work floor performance ensuring participation to vividly sustain the shared vision and mission toward the envisioned Desalination Excellence. To cope with the experienced work force's resistance to company's rules and policy and to eliminate rivalry, the Mahatma Gandhi Leadership strategy is applied based on the opportunity to challenge rules and processes but in the context to collaboratively show the right way to do the job right.

1.2 Promotion of Partnership

The Efficacious Motivational Leadership approach is further applied to consolidate the desalination interdepartmental team to lay the foundation for a firm partnership of Operations with supporting Maintenance and Engineering Departments to assure a well maintained and engineered desalination asset. The partnership with chemical suppliers and desalination equipment manufacturers is promoted to improve inspections and to facilitate evaluation and introduction of proposed new cost effective chemicals and technical applications for desalination operational and maintenance performance and efficiency improvement.

1.3 Desalination Asset Management

Leadership efficacy acts as enabler stimulating evaluation of operation and maintenance condition to increase desalination efficiency. The developed trendable operational parameters are evaluated and upgraded with maintenance experiences and jointly used as control measures for desalination operational performance and efficiency improvement. Furthermore, documentation of process failures and production losses are promoted in cooperation with maintenance and engineering to assess the maintenance condition of the desalination units and to determine the most critical operation areas needing maintenance attention. The use of the developed key performance indicators are promoted to predict the need of preventative maintenance, and so setting the basis for a predictive preventative maintenance approach.

2. Deployment of the Operational and Maintenance work force

The operational and maintenance work force being closest to the desalination units is considered the most important human key performance improvement factor. The main objective of the continuous desalination improvement process is attaining the result of efficient desalination operation through the effective deployment of the operational and maintenance work force to grow toward a firm Desalination Team improving human and desalination asset performance. In this context the main areas of attention are effective involvement and empowering, effective team building and communication and internal sharing of desalination operational and maintenance knowledge and experience to enable effective deployment. To reach this goal the following actions are pursuit.

2.1 Effective involvement and empowering

To enable effective participation, the Passion and Fear motivational model and the Human Attitude models are applied with the intension to explain the different experienced habits, behavior and attitudes at the work floor such as fear for mistakes, negativism, resistance for change, demotivation and the “rivalry comfort zone’ culture inducing comprehension and a motivated interdepartmental work climate. Especially the Mahatma Gandhi leadership strategy is introduced to cope with resistance for the company rules and the existing departments' rivalry. With the application of the motivational and human attitude models the diminishing operational and maintenance work force's rivalry is further enforced and the importance of effective communication and teambuilding endorsed as a condition for performance improvement.

2.2 Effective Operation, Maintenance and Engineering desalination team and communication

To stimulate effective operational and maintenance's line management-work floor communication structured interdepartmental GI meetings, safety and quality meetings and daily work order meetings were introduced to discuss operational and maintenance performance, safety and housekeeping and to promote and facilitate jointly maintenance scheduling and planning. To further promote team work the interdepartmental work flow procedures were standardized to enable uniform performance. The supporting departments are involved to upgrade the initiated quality management system to control and assure performance improvement and to increase work satisfaction. Service Letters Agreements according to ISO standards were proposed and approved.

2.3 Sharing of knowledge and experience

Sharing of desalination operational and maintenance knowledge and experience is considered as a useful action and promoted as such to enable participation and to enhance deployment of the desalination work force to document experienced operational and maintenance problems and their solutions. Operational and maintenance errors are reported and documented for learning purposes to diminish the fear for mistakes and to promote growth on technical operational and maintenance areas. The set-up of a desalination operation and maintenance course and on the job training and self-education is stimulated.

3. Operational and Maintenance Personnel performance improvement

To improve personnel performance the attention is concentrated to increase awareness for the efficiency control of the desalination production units and to maintain a clean and safe working environment. The importance of interdepartmental team work to achieve performance improvement is emphasized and promoted. The endorsed points of attention for performance improvements in this aspect are key performance indicators, improvement of housekeeping, safety and environmental aspects and interdepartmental team work.

3.1 Key performance indicators

The developed key performance indicators based on operational experiences are applied and updated with maintenance experiences to monitor biofouling and scaling of the desalination production units and are used for jointly scheduling and planning of the necessary condenser and tube cleaning to increase efficiency. To trend and control the efficiency of the Multi Stage Flash (MSF)-evaporators the accumulative performance ratio is introduced. The main goal is to increase efficiency awareness by the use of key performance indicators to regulate and improve operational and maintenance personnel performance. To further promote improved work floor operational and maintenance human performance and self-development a zero target is introduced for complaints and problems to be solved on line-management level.

3.2 Improvement of housekeeping, safety and environmental aspects

To further improve human performance the awareness and importance for maintaining a clean and safe desalination work environment is emphasized and constantly identified with the importance and value of the product Water. Regularly cleaning actions of the desalination premises are organized including the supporting department's line-management to stimulate the support of the housekeeping and safety control round of the operational personnel. Safety talks are introduced during the pre-shift meetings and weekly maintenance safety meetings were introduced. To promote environmental protection, all chemicals used are approved for use in drinking water and are environment friendly according to the National Sanitation Foundation (NSF) standards. All operational and maintenance work is performed with the necessary prescribed personnel protective gear. Furthermore, the application of Standard Safety Operation Procedure is introduced as mandatory.

3.3 Interdepartmental team work

To further increase desalination operational and maintenance personnel performance, interdepartmental teamwork is promoted and consolidated through biweekly quality meetings with the supporting Maintenance and Engineering departments. Also an interdepartmental work floor quality team headed by the Lead Operator is introduced to assure the maintenance of a clean and safe desalination work environment and the self-control and assurance of the quality of executed maintenance activities. Effective teambuilding training is organized to facilitate team work between Operation and Supporting Departments. The support of the chemical supplier and the desalination equipment manufacturer is introduced for jointly inspection and evaluation of the desalination process if necessary.

4. Desalination asset performance improvement

To enable improvement of the desalination asset the upgrading of the monitoring and control system and the distillate and condensate processing system is proposed. Further the development of an improved structured maintenance approach of the desalination asset is stimulated in an interdepartmental team work environment. So, in this aspect the monitoring equipment and tools, upgrading projects and an effective maintenance approach based on efficacy to effectively increase maintainability of the desalination production units are specified as main areas of attention.

4.1 Monitoring equipments and tools

The implementation of a distributed control system is proposed and evaluated in cooperation with the Maintenance Instrument Department to improve the monitoring system of the MSF evaporators and the distillate processing system and to improve trending of key performance indicators. The application of the heat balance troubleshooting tools developed in cooperation with Engineering Department is promoted. The Pace Setter computer controlled chemical dosing system is introduced to improve the dosing system of the distillate post treatment.

4.2 Upgrading projects

The under capacity of distillate and condensate processing system was further evaluated in conjunction with Maintenance and Engineering Departments. Proposed upgrading projects are outsourced for detailed engineering and implementation to cope with current and future capacity increase.

The aspects of foaming, biofouling and scaling hampering efficient and stable desalination operation are evaluated in cooperation with chemical suppliers and desalination equipment manufacturers. The application of new technology and innovation is promoted to further increase desalination efficiency.

4.3. Increase maintainability

All outstanding corrective maintenance activities are documented and proposals are made for the maintenance department for planning and execution to increase maintainability of the desalination units. Operation coordination of maintenance work is introduced to stimulate team work. The introduction of the Maintenance Conscious Operation concept (maintaining the production unit by optimal in target operation control) is introduced enabling the prediction of failures and inefficiency setting the basis of a predictive preventive maintenance. Visual inspection and vibration check of the rotating equipment is introduced during control rounds. Vibration measurements and Infrared thermo graphic analysis of electrical leads is introduced as a basis for the conditioned based maintenance. To promote the Operation Conscious Maintenance concept a preventive maintenance program for all controls and instruments is introduced and strictly applied by the Maintenance Instrument Department. Furthermore, documentation of plugged tubes is promoted as an indication of the maintenance condition of the MSF evaporators and failures and their effect on production losses are documented to determine the critical areas needing effective maintenance emphasizing the Operation Conscious Maintenance, setting the basis of reliability based maintenance approach. The conventional scheduled maintenance of the MSF evaporators is reevaluated and upgraded setting the basis for a new structured maintenance approach as will be outlined in more details in the following sections.

5. Improved Desalination and Maintenance Departments' performance
The envisioned results of the improved Desalination Department performance is a motivated work force efficaciously controlling the upgraded desalination processes and well maintained desalination asset in a creative environment of interdepartmental team work under the direction of efficacious motivational leadership to produce efficiently the high quality drinking water and industrial water. An Efficacy Oriented Maintenance approach is in place to safeguard the maintenance condition of the Desalination assets.

6. Operational Performance Indicators evaluation
Predefined operational performance indicators such as targets for frequent absenteeism and efficiency increase were developed and applied for the evaluation and control of the improved Desalination Department performance. A quarterly efficiency, maintenance and safety report for the work floor is issued as motivation for improving performance. Zero targets for work floor unsolved complaints, discord and friction and safety incidents are set.

7. Continuous improvement process
The initiated work floor and desalination asset's operational and maintenance performance improvement is subjected to continuous evaluation according to targeted key performance indicators (KPI's). If necessary the KPI's are adjusted challenging a next higher performance level.

The time frame of the implementation of the desalination performance improvement process in cooperation with the supporting departments is schematically illustrated in Figure 8.16.

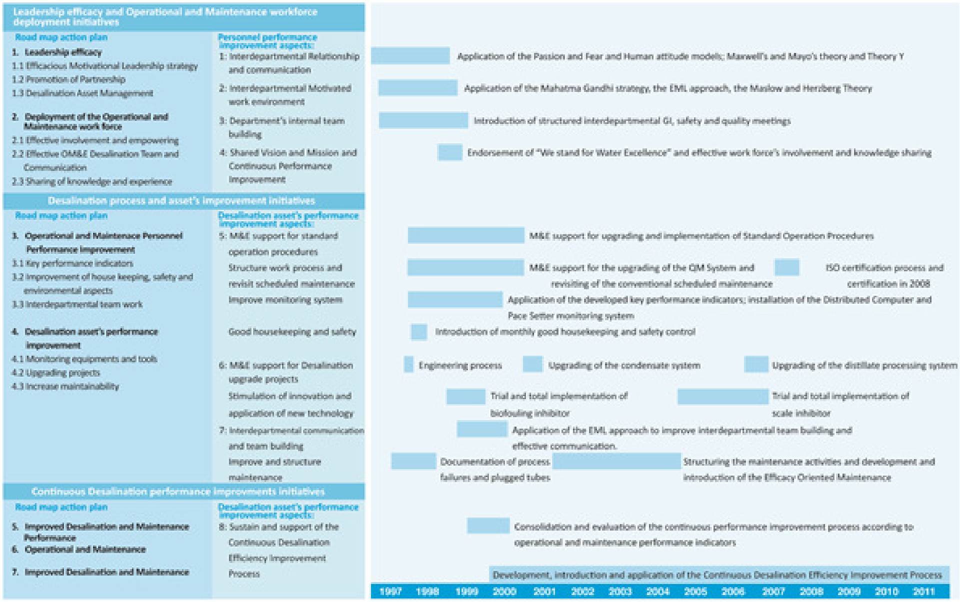


Figure 8.16: Maintenance and Engineering support of the Continuous Desalination Efficiency Improvement Process 1997 to 2011

The first steps toward a predictive preventive maintenance approach

Despite a thoughtful road map, the implementation of an intuitively developed process toward a straightforward outlined goal sometimes differed from the actual plans due to the unconscious application of the iteratively Deming's plan-do-check-act principle and unforeseen circumstances and obstacles. The applied maintenance improvement process at the Desalination Department on the whole is as follows:

To initiate the envisioned improvement process of the desalination asset's maintenance, the starting point was the interdepartmental joint effort to evaluate, concretize and upgrade the conventional scheduled maintenance forming the basis of a structured scheduled preventive maintenance program assuring an interdepartmental operation and maintenance partnership. In this context, structured pre GI and post GI meetings, quality and safety meetings and daily work order meetings on supervisory level were introduced. All outstanding corrective maintenance activities were documented in cooperation with Equipment Inspection group and scheduled together with Maintenance Departments for execution during the planned yearly GI's.

After performing practically all the outstanding corrective maintenance, including paint work, increasing the maintainability of desalination assets, a preventive maintenance

program is introduced for all major critical rotating components of the MSF evaporators and especially for all controls and instruments.
Vibration monitoring system for rotating equipment and infrared thermo graphic analysis for electrical lead elements and conduits were introduced to promote condition based maintenance to further upgrade the scheduled preventive maintenance. Visual inspection and vibration check in the operation shift control rounds were introduced. Necessary condenser and long tube cleaning are jointly planned according to the trends of the key fouling parameters.

Acknowledging the omission of involvement of the maintenance work force in planning and scheduling of maintenance activities as a major disadvantage of the upgraded conventional scheduled preventive maintenance approach, the maintenance improvement process continued in the direction to develop a work floor productive maintenance approach. Based on the initiated documentation of failures and developed key operational performance indicators as a joint operational and maintenance work force effort, the first step is set toward a predictive preventive maintenance approach. The leading principle was empowerment and involvement of maintenance work force to sustain the operational work force, using their knowledge and experience to document all operational and maintenance experienced practical problems and the applied solutions. The maintenance and operations condition of the desalination assets are further categorized with support of the Engineering Department. The main obstacle to overcome is gaining the trust and confidence of the maintenance work force to diminish the rivalry culture and distrust in superiors. As usually the entwinement of basic human knowledge with serendipity and real caring gives the direction and solution.

Initially a lot of effort is done by both sides to improve relationship to create an operational and maintenance desalination team work in a motivated desalination environment but fortuitously a great opportunity came up in December 1997 and at the end of January 1998 to introduce and fortify the imminent concept of efficacy. In a nutshell, coping with water production shortage the GI of the MSF evaporator Aqua Chem#2 was due necessary in a short period of time of less than 12 days because of the annual construction industry holiday normally starting the 15th of December. Due to the absence of both the Head and Lead Supervisor of the Mechanical Maintenance Department, Maintenance Management proposed to me to direct this very short period-GI. This opportunity was grasped to passionately motivate and challenge the maintenance work force to jointly prove their always raised argument that they know better than line management how to plan, schedule and do their maintenance job. This short period-GI was successfully prepared and executed with intense involvement of the maintenance and operational work force without the ever

experienced work floor complaints about inspections and incorrect planning. Furthermore, the GI was executed without overtime.
At the end of January 1998 with all the six MSF evaporators in operation, the internal water storage was decreasing. In cooperation with operation and maintenance work force the production capacity was increased by modifying brine gates and performing condenser cleaning, which was usually planned as a four days' work, within one working day. Shut down of the MSF evaporators for condenser cleaning in one working day while water storage was decreasing solved the problem within a month. After two months a total production of 37,112 cubic meters per day, e.g., 3 percent higher than the nominal capacity of 36,000 cubic meters per day was obtained.
The basis for an intensive collaboration was set to improve the conventional scheduled evaporator's maintenance with an additional work floor Predictive Preventive Maintenance approach forming the precursor of the Efficacy Oriented Maintenance approach.
To further fortify mutual respect, involvement and knowledge sharing in solving technical problems basic desalination operation and maintenance and team building training programs were organized with participation of key work floor personnel, Engineering Department and line management. The main purpose of the training sessions was to learn from the work floor and to exchange practical experience and knowledge and theoretical explanation for in practice experienced desalination issues. The main basis for the work force's Maintenance Conscious Operation and the Operation Conscious Maintenance concepts was set.

The applied methods and obtained results in the initial maintenance improvement process to define the status of the desalination assets, the application of the developed key performance indicators and the troubleshooting tools will be further explained.
Since 1998 the amount of plugged long tubes in MSF evaporators and the loss of production due to failure occurrences and the availability of the production units due to planned and unplanned outages are documented to set the basis for the novel Operation Conscious Maintenance concept. As indicated in the preceding chapters the developed key operational parameters based on work floor operational and maintenance experiences and knowledge were the first significant successes inducing the novel Maintenance Conscious Operation concept. In cooperation with the supporting Engineering Department the heat balance trouble shooting tool has been developed as an operational predictive efficiency decay technique. The maintenance work force was involved in the application of this predictive tool establishing the basis for the work floor predictive preventive maintenance approach.
To further improve communication and motivation for continuous desalination improvement, quarterly a one-page operation and maintenance work floor report is edited.
It is worth mentioning that these first successful steps have transformed the existing

operation and maintenance rivalry into the Operation Conscious Maintenance and the Maintenance Conscious Operation attitude. These first successful achievements are highlighted below.

Operation Conscious Maintenance

The usual manufacturer directed corrective scheduled maintenance program of the MSF Desalination units up to 1999 consists of a yearly General Inspection (GI) and Maintenance with duration of four weeks. Condenser cleaning and cleaning of the bowl assembly's screening basket of the intake pumps takes place on average every three months with duration of three to four days. As already mentioned in Chapter 4 with the biochemical treatment of the seawater the quarterly cleaning of the heat rejection section is practically reduced. After several years of operation, with the improved intensified control of the corrosive 98% concentrated sulfuric acid dosing as scale inhibitor, a good indication of the maintenance condition of the MSF evaporators is the amounts of plugged tubes in the brine heater, heat recovery section and heat rejection section. A general rule of thumb for the good condition of a heat exchanger is an amount of plug tubes less than 10%. In Table 8.1 the total amount of plugged tubes of the MSF evaporator from 1997 till 2007 are illustrated.

Table 8.1: Number of plugged tubes of the MSF evaporators until 2007

	No. of tubes	AC-1		AC-2		AC-3		AC-4		AC-5		AC-6		AC-7	
		No	%	No	%	No	%	No	%	No	%	No	%	No	%
V-101	2202	46	2.09	14	0.64			1	0.05			68	3.09		
V-102	2202	137	6.22	1	0.54			25	1.14	1	0.05	28	1.27		
V-103	2202	19	0.86					1	0.05						
V-104	2202	5	0.23												
V-105	2202			1	0.05	1	0.05								
V-106	2202							4	0.18	1	0.05				
V-107	1730			1	0.06									7	0.40
Total		207	1.39	17	0.11	1	0.01	31	0.21	2	0.01	96	0.64	7	0.05
Brine heater	1418	4	0.28	10	0.71	10	0.71	4	0.28	8	0.56	1	0.07	88	6.21

Note:

1. *V101-V 103 are high temperature heat recovery and V104-V106 are low temperature heat recovery vessels.*
2. *V107 is the heat rejection section and the brine heater is the heat input section*
3. *AC-6; V101 and V102: Most tubes plugged because of leakages due to under rolling of tubes*
4. *AC-7; Brine heater tube leakages due to ammonia corrosion caused by oxygen intrusion in LP Steam*

Number of plugged tubes is lower than 10%.

As shown in Table 8.1 even the oldest desalination units Aqua Chem#1 (AC-1) and Aqua Chem#2 (AC-2) do not have plugged tubes either in the brine heater, heat recovery section nor the heat rejection section surpassing the 10% limit, and the amount of plugged tubes in the first three high temperature vessels are far less than 10%, indicating the satisfactorily operation and maintenance condition of the desalination units. Especially, the improved control of the concentrated sulfuric acid's dosing had decreased tube leaks caused by acid corrosion and under deposit corrosion.

For further improvement of maintenance of the MSF desalination units a first step was done to document experienced problems and failures during operation starting from 1997. This is important to determine the critical areas of the MSF desalination units. As illustrated in Table 8.2 the failures are correlated to the loss of production to have an impression of the impact on operation of those failures creating awareness of the importance of reliability of the desalination components.

Table 8.2: Lost of production due to planned and unplanned Outages from 1997 to 2011

Failures	Hours	Production loss (mT)	% of total production	% of unplanned outage
Pumps	2919.0	579,203	0.31	4.52
Condenser and V106	18,681.0	4,671,442	2.48	36.48
Acid leak	669.5	98,113	0.05	0.77
High conductivity	4,573.5	1,127,030	0.60	8.80
High tank level	19584.5	3,995,976	2.12	31.20
Power house failure	3,735.0	832,519	0.44	6.50
Electrical	1,113.0	273,887	0.15	2.14
Instrumentation	1,441.5	351,850	0.19	2.75
Antifoam	303.0	58,775	0.03	0.46
Process failures	3,475.9	818,270	0.43	6.39
General Inspection	37,701.6	9,410,437	5.00	
Others	8,158.5	1,983,530	1.05	
Total	102,376.0	24,201,032	12.86	
Total distillate production (mT)	188,246,770			

In the advancing operations and maintenance activities motivationally supported by the work floor to further improve the control of the MSF evaporator's operation condition, the initiative was taken to regulate the capacity utilization of the MSF evaporators by documenting the planned and unplanned outages. Figure 8.17 and Figure 8.18 illustrate the availability of the MSF evaporators in 2009 respectively with regard to planned maintenance and with regard to total down time including unplanned maintenance as documented by the Lead Operator.

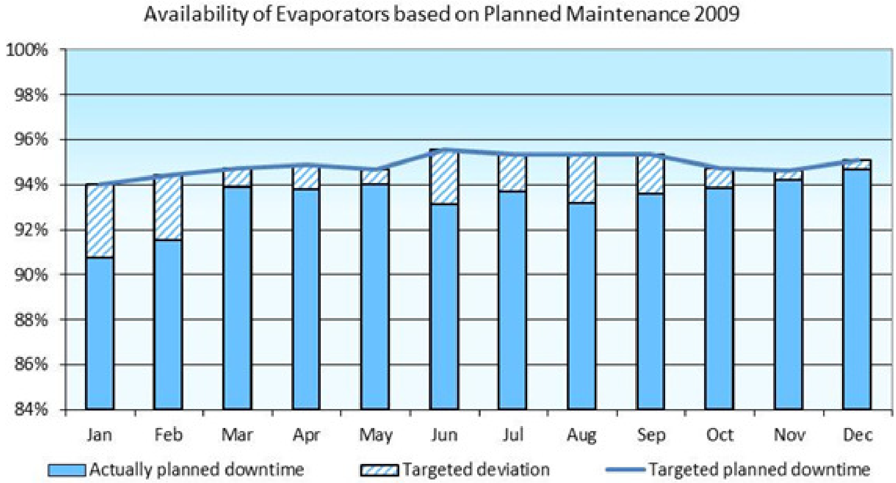


Figure 8.17: The availability of the MSF evaporators in 2009 regarding planned Maintenance

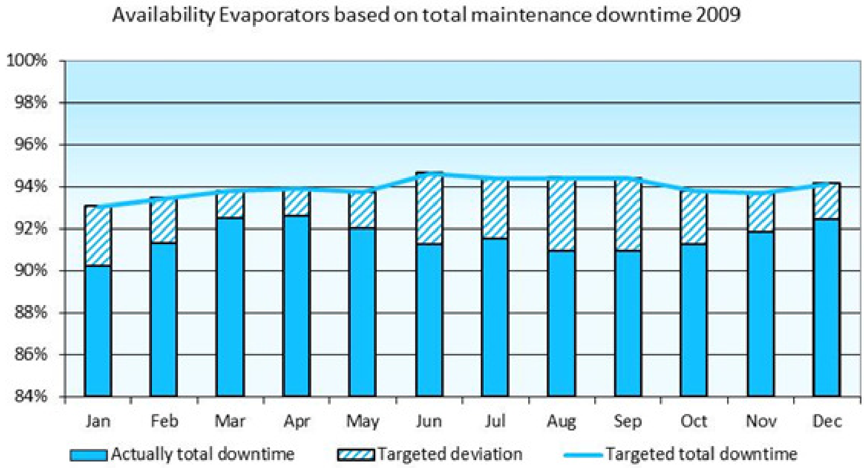


Figure 8.18: The availability of the MSF evaporators in 2009 regarding total maintenance down time

The next step in the continuous maintenance improvement process was the application of the developed key performance indicators using practical work floor operational and maintenance experience suitable for trending to promote a maintenance conscious operational approach setting the first steps in the direction of a work floor predictive preventive maintenance concept as explained below.

Maintenance conscious operation

The MSF desalination process at W.E.B. Aruba N.V. is controlled with an up to date Distributed Control System with Citect software for Windows NT and an ABB Instrumentation MODCELL monitoring and control system. This DCS system has been implemented in 1998 to increase efficiency control replacing the existing outdated semi-automatic manual Genesys control system. The MSF desalination units are in general characterized by a stable reliable operation, although a gradually decrease in production and performance ratio is always experienced in the first three months of operation. The production decreases from approximately 6,300 cubic meters a day to about 5,800 cubic meters a day and the unit then has to be shut down for condenser cleaning. Respectively, the performance ratio usually declines from about 10.3 to the targeted minimum value of 8.5. After condenser cleaning the production and efficiency are always increased. As mentioned above to improve efficiency of the desalination units, great effort is done to define key performance parameters to optimize operation. The starting point is transforming operation experience in key parameters that are useful to trend. Using the trial and error method the condenser's fouling ratio, the ratio of the distillate flow to the seawater flow, was defined to trend the biological induced fouling of a MSF desalination unit [8.21]. As shown in Figure 8.19, this fouling ratio increases as biofouling of the condenser increases.

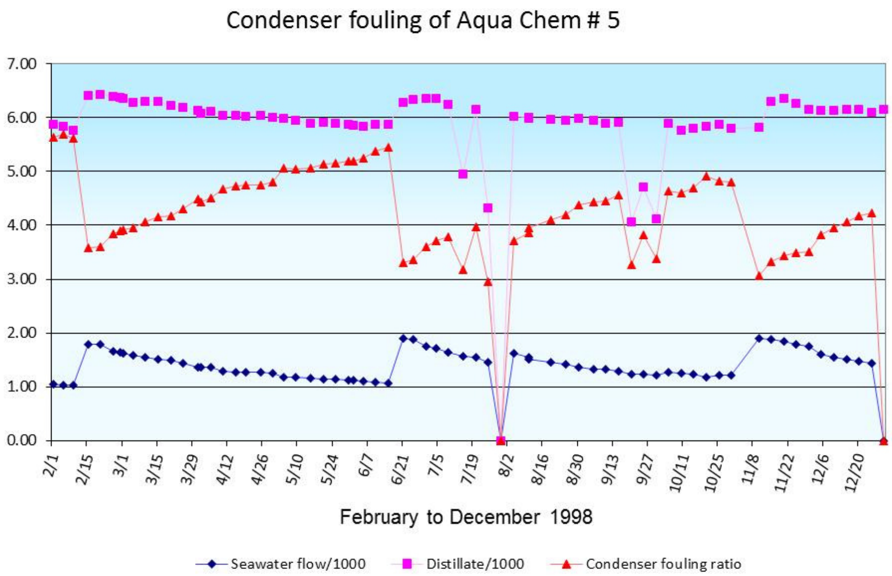


Figure 8.19: The condenser's fouling ratio

As already explained in Chapter 4 this condenser's fouling ratio resulted to be very useful evaluating the biochemical effectiveness of the innovative Clam Trol CT-2^{TM} dosing during

the trial at Aqua Chem#5, to control marine biofouling in the condenser. This trial started in July 1999 and as explained in Chapter 4, from this period on the condenser's fouling ratio kept practically unchanged, indicating practically no biofouling in the condenser.
As mentioned above based on operation experiences key parameters were defined to improve efficiency control of the MSF desalination units indicating an operational predictive maintenance approach. Parameters to trend the fouling of the brine heater and that of the heat recovery section due to scaling is further optimized with support of the Maintenance and Engineering Department, especially to evaluate the biocide and the high temperature antiscalant trials at the desalination unit Aqua Chem#5. The concept of the moving performance ratio is introduced and calculated three different ways based on flows and by thermodynamic balances. This method resulted also to be very useful for trouble shooting and to double check accuracy of the crucial flow instruments during operation and especially during a trial. All critical operation data (flows, temperature and pressure of all stages) is filled in a heat balance performance monitoring sheet to calculate the necessary parameters. The heat balance performance monitoring sheet designed for use by the operational personnel to promote operation conscious predictive maintenance at the Desalination Department is illustrated in Table 8.3.

Table 8.3: The heat balance operation performance evaluation sheet

Heat Balance AC # 5			Design Data	10-Mar-04	Formula	Instrumentation
Parameter	Instrument	SI-unit				
Distillate/Seawaterflow	FR-104/F-100		0.141	0.139	m_d/m_{sw}	F-100, FR-104, TI-1, TI-118
Performance Ratio or GOR,	**FR-104/FR-105**		10.5	**10.34**	$PR = m_d/m_{lps}$	FR-105, FR-104, TI-36, TI-118
Performance Ratio 2 (PR2)	*Overall heat bal.*		*10.5*	*10.21*	$PR2 = m_d*(h_{lps}-h_c)/((Q_d+Q_{cw}+Q_{bd})-Q_{sw})*10^6*(PR/PR2)_{design}$	F-100, FR-102, FR-104, FR-109, TI: 1,2,3,36,118, TR-120
Performance Ratio 3 (PR3)	*Brine heater bal.*		*10.5*	*10.45*	$PR3 = m_d*(h_{lps}-h_c)/(m_{rb}*c_{p,rb}*dT\ BH)$	FR-101, FR-104, TR-120, TI: 3,36,106,117,118
Energy Ratio (ER) or EPC		*kg/1000kJ*	*4.75*	*4.70*	$ER = m_d/(Q_{bh}*1000)$	F-101, FR-104, TI: 3,106,117,118
Steam Power Consumption (SPC) design chart		*kJ/kg*	*227*	*244*	$SPC_d = f(m_d)$, design chart	FR-104, TI-118
Steam Power Consumption (SPC) actual		*kJ/kg*	*221*	*225*	$SPC_a = f(Q_{bh2}, m_d)$	FR-104, FR-105, TR-120, TI: 36, 118
Heat Streams					**Heat Streams**	**Heat Streams**
Heat In = Q_{lps} - Q_c		MJ/hr	52.8	57.8	$Q_{in} = Q_{lps}-Q_c$	FR-105, TR-120, TI-36
Heat Abs = Q_{sw}-Q_{cw}-Q_{bd}-Q_d		MJ/hr	-50.4	-56.0	$Q_{abs} = Q_{sw}-(Q_{cw}+Q_{bd}+Q_d)$	F-100, F-102, FR-104,FR-109, TI: 1,2,3,118
Heat avaliable brine heater		MJ/hr	52.8	57.8	$Q_{in} = Q_{lps}-Q_c$	FR-105, TR-120, TI-36
Heat gained brine heater		MJ/hr	52.5	57.2	$Q_{bh} = m_{rb}*c_{p,rb}*dT\ BH/1000000$	F-101, TI: 3, 106, 117
Heat rejected condenser		MJ/hr	51.1	52.4	$Q_{sw} = m_{sw}*c_p*(T_{cw\_out}-T_{cw\_in}))/1000000$	F-100, TI-1, TI-2
Heat Balances					**Heat Balances**	**Heat Balances**
Heat Out/Heat In		%	99.1%	99.3%	Q_o/Q_i	F-100,FR-102,FR-109,FR-104,FR-105, TI: -1,-2,-3,-118, TI-36, TR-120
Heat Absorbed/Heat Avail.		%	95.5%	96.9%	Q_{abs}/Q_{in}	FR-105, TR-120, TI-36, F-100, F-102, FR-104,FR-109 TI: 1,2,3,118
Heat brine/Heat avail in brine heater		%	99.5%	99.0%	Q_{bh}/Q_{in}	FR-105, TR-120, TI-36, F-101, TI: 3, 106, 117
Heat reject./Heat avail brine heater		%	96.8%	90.6%	Q_{sw}/Q_{in}	FR-105, TR-120, TI-36, F-100, TI-1, TI-2
Heat Rej./Heat Gained		%	97.3%	91.5%	Q_{sw}/Q_{bh}	F-101, TI: 3, 106, 117, F-100, TI-1, TI-2
Brine Heater Performance					**Brine Heater Performance**	**Brine Heater Performance**
Duty based on Brine flow		MJ/hr	52.5	57.2	$Q_{bh1} = m_{rb}*c_{p,rb}*dT\ BH/1000000$	F-101, TI: 3, 106, 117
BH Heat load based on condensate flow		MJ/hr	52.5	57.8	$Q_{bh2} = Q_{in} = m_c*(h_{lps}-h_c)/1000000$	TR-120, FR-105, TI-36
LMTD		^oC	7.75	7.47	$LMTD_{bh} = [(T_c-T_{bh\_in})-(T_{lps}-TBT)] / Ln[(T_c-T_{bh\_in})/(T_{lps}-TBT)]$	TR-120, TI-36, TI-117, TI-106
HTC		KJ/m^2hr^oC	11,914	13,447	$HTC_{bh1} = Q_{bh1}/(A_{bh}*LMTD_{bh})*1000000*0.2388$	F-101, TI: 3, 106, 117, TR-120, TI-36
Fouling Status		% design	100	**113%**	$FS_{bh} = HTC_{bh1}/ HTC_{design}*100\%$	F-101, TI: 3, 106, 117, TR-120, TI-36
Heat Rec. Section Performance (V101 - V106)					**Heat Rec. Section Performance (V101 - V106)**	**Heat Rec. Section Performance (V101 - V106)**
Heat transfered recovery section		MJ/hr	567.3	579.3	$Q_{rs} = m_{br}*(h_{br,o}-h_{br,i})/1000000$	F-101, TI-117, TI-3
LMTD		^oC	6.27	6.15	$LMTD_{rs} = [(TI106-TI117)-(TI121\_36-TI3)] / Ln[(TI106-TI117)/(TI121\_36-TI3)]$	TI-3, TI-117, TI-121_36, TI-106
HTC		KJ/m^2hr^oC	6,898	7,185	$HTC_{rs} = Q_{rs}/(A_{rs}*LMTD_{rs})*1000000*0.2388$	F-101, TI-117, TI-3, TI-121_36, TI-106
Fouling Status		% design	100	**104%**	$FS_{rs} = HTC_{rs}/ HTC_{design}*100\%$	F-101, TI-117, TI-3, TI-121_36, TI-106
Condenser Performance					**Condenser Performance**	**Condenser Performance**
Heat rejected condenser		MJ/hr	51.1	52.4	$Q_{rsc} = m_{sw}*c_{p,sw}*(T_{cw,o}-T_{sw,i})/1000000$	F-100, TI-1, TI-2
LMTD		^oC	6.35	6.34	$LMTD_{rsc} = [(TI118-TI1)-(TI121\_36-TI2)] / Ln[(TI118-TI1)/(TI121\_36-TI2)]$	TI-118, TI-1, TI-2, TI-121_36
HTC		KJ/m^2hr^oC	6,093	6,254	$HTC_{rsc} = Q_{rsc}/(A_{rsc}*LMTD_{rsc})*1000000*0.2388$	F-100, TI-1, TI-2, TI-118, TI-121_36
Fouling Status		% design	100	**103%**	$FS_{rsc} = HTC_{rsc}/ HTC_{design}*100\%$	F-100, TI-1, TI-2, TI-118, TI-121_36

The heat balance performance stimulated the concept of Operation Conscious Maintenance pointing out the importance of accurate calibrated instruments and cleaned long tubes increasing heat transfer and consequently thermal efficiency.

To further improve communication and enhance motivation a one page report regarding efficiency, availability of the production units and safety are compiled for the operation and maintenance work floor on a quarterly basis. In Figure 8.20, this quarterly information report for the work floor is illustrated.

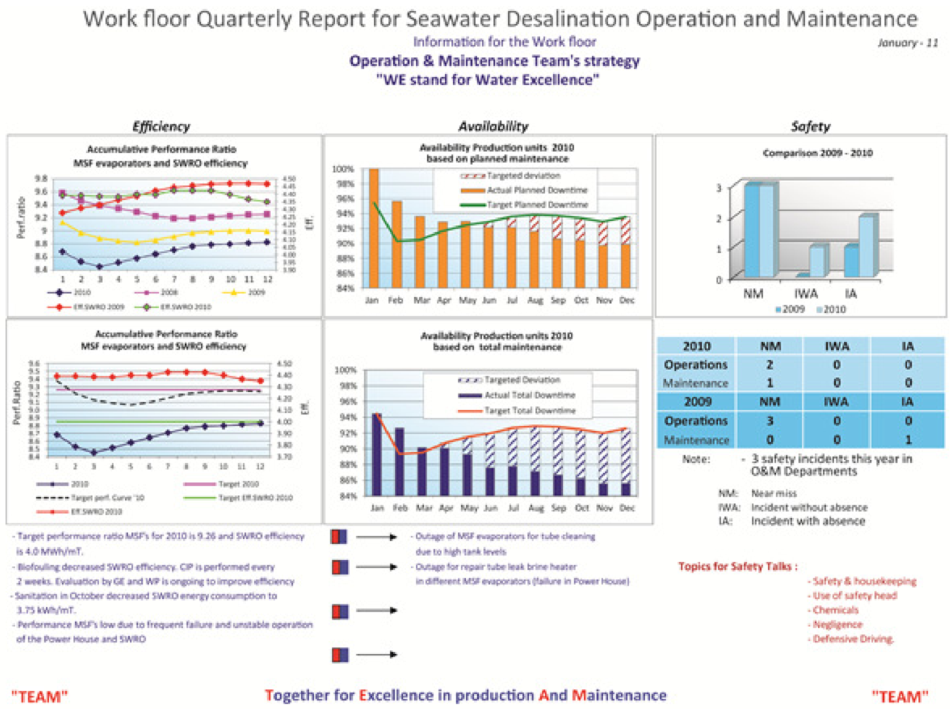


Figure 8.20: Quarterly information for the work floor

In summary the Maintenance Conscious Operation and the Operation Conscious Maintenance approach as developed at the Desalination Department is an endeavored work floor simple predictive preventative maintenance concept promoting proactively combined operation and maintenance prevention of failure occurrences assuring sustainably efficient desalination. This program has been further developed, as will be described more in depth in the next section from a primitive predictive preventative maintenance program to an

Efficacy Oriented Maintenance approach decreasing the GI period from four weeks to less than 12 working days and increasing the GI interval from 12 months to 18-20 months. Failures in process and pump failures and waste in produced water are drastically reduced with the application of this work floor Efficacy Oriented Maintenance approach.

8.5 The development of the Efficacy Oriented Maintenance (EOM) approach

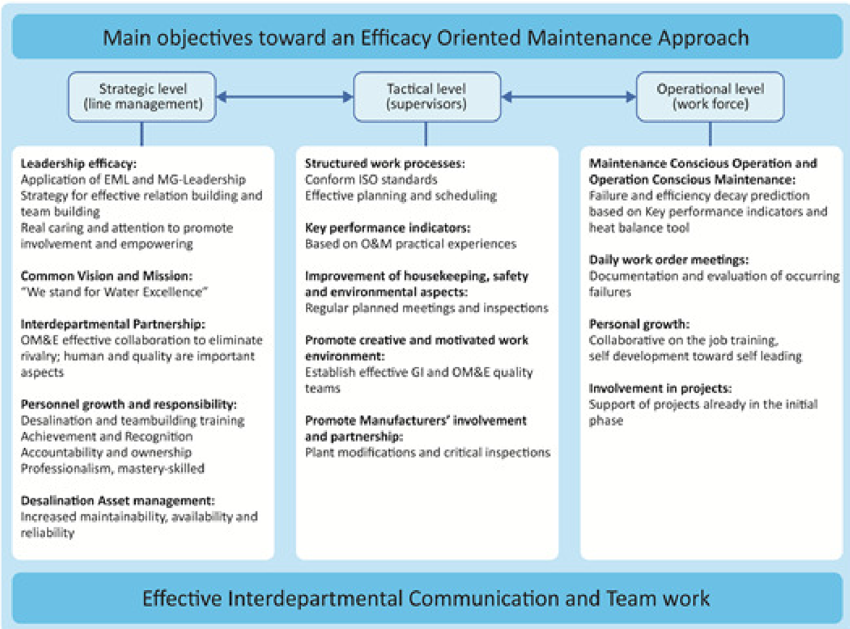
This section describes the development and application of the Efficacy Oriented Maintenance (EOM) approach and gives an introductory comparison of the similarities and differences with the in the industry well adopted Total Productive Maintenance (TPM) and the Reliability Centered Maintenance (RCM).

Toward the Efficacy Oriented Maintenance approach

Already from the initial start of the journey of the Desalination Department toward excellence in desalination supported by the Efficacious Motivational Leadership the awareness grew that to reach this goal a firm work relationship with the Maintenance Departments should be established. The initial small successes with the simple process-wise initiatives toward a predictive preventative maintenance approach, as explained in the previous section, set forth inertia for the development of a new operations and maintenance strategy and philosophy for efficiency improvement in desalination. Striving to obtain a well maintained desalination unit with optimized reliability and availability in cooperation with the supporting Maintenance Departments is crucial for a sustained efficient operation. The successful approach of valuing the knowledge and experience of operational and maintenance work floor personnel was the guiding principle for the development of the Efficacy Oriented Maintenance Strategy. The main goal of the Efficacy Oriented Maintenance approach is continuous efficiency improvement in seawater desalination for the production of the highest quality drinking water and industrial water through effective involvement and empowerment of the work floor personnel, the most invaluable human asset of the company as indicated in Figure 8.21. The ultimate goal is to reach out for Excellence in desalination, which in this context is defined, in analogy with the physical property of a liquid, the critical point in the continuous improvement process, where proposed changes occur without a transitional state potential energy as explained in Chapter 3.

Figure 8.21: The basic aspects of the Efficacy Oriented Maintenance Strategy

The first basic starting point of the Efficacy Oriented Maintenance strategy is the maintenance conscious operations with reference to the assumption that the operators being close to the desalination units can perform visual inspections of rotating and monitoring equipment and by trending key performance parameters they can promote operation-wise preventive and predictive maintenance. On the other hand the maintenance work floor personnel highly aware of their importance in the continuous desalination efficiency improvement process will duly perform their activities operation-consciously to assure optimal availability, reliability and sustainability.
The main objectives on the different Line-management (Strategic), Supervisory (Tactical) and work floor (Operational) levels of the conceptual draft of the efficacy oriented maintenance approach broadly in line with the road map's action plan are further schematically illustrated in Figure 8.22. The foundation is effective interdepartmental communication and team work.



EML: Efficacious Motivational Leadership
GI: General Inspections
MG: Mahatma Gandhi
OM&E: Operation Maintenance and Engineering

Figure 8.22: The key objectives of the conceptual draft of Efficacy Oriented Maintenance approach

The objectives of the Efficacy Oriented Maintenance approach are specified as follows:

On Strategic (line management) level
In accordance with the abovementioned Leadership Efficacy process step, specified in the action plan of the road map for effective work force participation, the Efficacious Motivational Leadership approach and the Mahatma Gandhi strategy (as also detailed in Chapter 3) is applied to pursuit the establishment of a firm relationship on work floor level and on line management level of the Desalination Department with all Maintenance Departments and the Engineering Support Department. Of importance on this strategy level is the development of a shared vision and mission in the context of "We stand for Water Excellence" toward a common goal of efficient reliable production of one of the world's highest quality drinking water. The human aspect and the quality aspect are central and of utmost importance to transpose the traditional operations and maintenance culture oriented rivalry mind set to a team based approach of ownership, goal-directed to excel in desalination. The basic guideline is to effectively care for the people (the human asset) so they will surely efficiently take care for the equipment (the Physical assets) so we all can definitely solidify the ergonomically care for the desalination business (the Commercial and Financial assets).
The main strategic efforts to achieve this goal are essentially based on the established practicability of the theories of Douglas M. McGregor, Elton G. Mayo, Frederick I. Herzberg and Abraham H. Maslow and the developed Desalination's Hierarchy of Needs, which (as explained in Chapter 3) resulted to be effective at the Desalination Department:

- Work relationship, work environment can be improved by simply honestly giving attention and care for the personnel as the Hawthorne effect of Elton Mayo.
- The work force has the ability for problem solving and given the proper conditions, they will accept responsibility and exercise self-control and self-direction in accomplishing objectives to which they are committed according to the Douglas M. McGregor's Theory Y.
- Promoting recognition for achievement, improving work environment and also increased responsibility and accountability to execute a job well done increased motivation according to Frederick I. Herzberg's Two Factor Theory.
- The Mahatma Gandhi leadership strategy giving the work floor personnel the opportunity to challenge policies and work processes however linked with input for improvement has reduced the job dissatisfaction effect of policy and administration according to the Frederick I. Herzberg's Two Factor Theory.
- Participation in the development of a shared desalination vision and mission promoted the partnership mind set instead of the rivalry culture.
- Structured job and work description, desalination courses and training on the job has foreseen in the basic need to maintain the job (Survival need) and to feel secure and save

to perform the job well done as required (Safety need) according to the Abraham H. Maslow's Hierarchy of Needs and the Desalination's Hierarchy of Needs as explained in Chapter 3.

Effective desalination operation and maintenance courses and cooperatively on the job training are promoted to master the operation and maintenance function increasing desalination professionalism to increase maintainability, availability and reliability assuring effective management of the Desalination asset.

On tactical (Supervisory) level

The objective is to develop and sustain an effective team of operation and maintenance on line-management and supervisory level promoting optimal collaborative planning and scheduling of General Inspections and outages and cultivating awareness for housekeeping, safety, health and environmental aspects in desalination. The effective team should safeguard the performance of the operation and maintenance function according to the ISO quality management system and encourage a creative and motivated work environment to increase efficiency and capacity and regulate performance according to key performance indicators. The effective team should also promote operation and maintenance knowhow and experience exchange with manufacturers to improve design, trouble shooting and efficiency improvement.

Interdepartmental partnership is one of the most important aspects achieving these tactical goals. A very simple method applied at the Desalination Department was the introduction of basic desalination operation and maintenance and team building training programs with participation of key work floor personnel, Engineering Department and line executives with the main purpose to learn from the work floor. Exchanging practical experience and knowledge and theoretical explanation for in practice experienced desalination issues increased mutual respect and involvement and knowledge sharing in solving technical problems. This also facilitated the formation of teams with members from the departments of concern to further loosing up barriers between the departments:

- GI team to promote joined efforts to planning and scheduling, coordination and control during GI activities introducing desalination unit handing over, performance test and acceptance procedures.
- OM&E Quality and Inspection team for joint trouble shooting and problem solving for major failures and to improve safety, housekeeping and promote environmental friendly desalination.
- Manufacturers and chemical supplier are invited to participate in the evaluation of critical inspections and eventual modification of the desalination units and desalination processes.

On operational (Work force) level

The efficacious motivational leadership should promote the establishment of an effective team of operations and maintenance at work floor level to improve communication, to stimulate a creative motivated work environment and a Quality Work Floor Team for visual inspection, trouble shooting, process failures and efficiency decay prediction based on the key performance indicators, good housekeeping and safety. To further improve the efforts set forth on tactical level the following is introduced:

- Daily work order meeting of supervisors and once a week on superintendent level to assure execution or for higher up approval if necessary.
- Collaborative quality control to eliminate all possibility of finger pointing.
- Promote self-leadership and self-development.
- Reporting mistake is appreciated to mitigate the fear. Mistakes are considered opportunity for improvement and lessons learned.
- Collaborative work floor knowledge exchange to foster personal growth.
- Introduction for the first time at W.E.B. Aruba N.V. of the involvement of operational and maintenance personnel also from the work floor in the early stages of new projects and project teams for sustain and quality control during erection and commissioning of new desalination plants and distillate processing systems.

Based on the specified main objectives on strategic, tactical and operational level the proposed Efficacy Oriented Maintenance approach is characterized by reaching out to the state of Desalination Excellence through a generalized step wise improvement process consisting of five transitional phases or states. This maintenance approach is further supported by the efficacious motivational leadership inducing self-leadership and self-development toward a firm foundation of the Maintenance Conscious Operation and Operation Conscious Maintenance. The EOM's process steps or transitional states toward excellence in operations and maintenance are specified as follows:

1. The work floor involvement transitional state

The first transitional state is characterized by the job entrancing leadership role of the EML approach focusing on a firm relationship building. The strategy and policy is mainly directed on involvement and empowering of the work floor personnel to create a motivated work environment promoting an effective operation and maintenance team and proud for their job.

The objective, required activities and deliverables for this phase are as follows:

Objective:

- The objective of this work floor involvement transitional state is to increase the maintainability of the desalination units by eliminating all outstanding corrective maintenance activities with a motivated Operation and Maintenance work floor team working in a creative work environment.

Required and performed activities to reach this objective:

- In this state the whole production asset is inspected by the OM&E quality team to determine and document the maintenance condition of the desalination asset. All reported outstanding corrective maintenance and proposed modifications should be executed in the yearly GI's conform planning.
- The OM&E safety team performs a thorough inspection of the desalination asset regarding safety, housekeeping and environmental aspect of the desalination asset according to planning.
- The OM&E GI team planned and scheduled the maintenance activities according to the documentations of the OM&E safety and quality teams. The proposed necessary plant changes and modification are discussed with manufacturers or chemical supplier for approval and scheduled for implementation to improve production and to promote the Design Out Maintenance for new desalination units.

Deliverables according to required activities:

- A complete OM&E documentation of the maintenance condition of the desalination asset.
- A complete OM&E documentation regarding safety, housekeeping and environmental issues.
- At the end of this transitional phase all the asset is in a well maintained condition.

This state is characterized by increased job satisfaction inducing the motivation toward the next level of Proactive Corrective Preventive Maintenance approach.

2. The Work floor Proactive Corrective Preventive Maintenance transitional state
This second transitional state is characterized by the concretization of the line executive OM&E team. In this phase the dominating leadership role is empowering according to the EML approach. For this phase the objective, required activities and deliverables are:

Objective:

- The objective of the proactive corrective preventive maintenance transitional state is the concretization of the GI team's planning and scheduling capacity and the implementation of all the basic elements of the work floor productive preventive approach inducing proactive corrective action to ensure maintainability of the desalination asset.

Required and performed activities to reach this objective:

- To improve scheduling the OM&E GI team makes a break-down of the facilities in logical parts and develops an equipment list and procedures for preventive instructions.
- The OM&E GI team together with inventory department set up a managed inventory of spare parts and on time purchasing of materials and parts needed for GI's or planned shutdown.
- Operation and Maintenance Departments structure and document all operation and maintenance manuals.

Deliverables according to the required activities:

- A structured GI document with scheduling and planning procedures and preventive maintenance instructions.
- A document listing all equipment and allocated equipment numbers.
- A well-managed inventory and purchasing procedures for on time delivery for planned preventive activities.

This stage is the foundation to envision the next step toward structured operation and maintenance work processes characterizing the work floor condition based maintenance approach.

3. The Work floor Condition Based Maintenance Approach transitional state

In this third work floor condition based maintenance transitional phase the main efficacious motivational leadership role is still empowering focusing to induce accountability as the main mind set of the coherent line executive and work floor team.
The objective, required activities and deliverables for this phase are as follows:

Objective:

- The objective of the work floor condition based maintenance approach is the establishment of the operation maintenance conscious operation approach with visual inspection by operators and the operation conscious maintenance by equipment's condition monitoring by maintenance work floor. The Operation and Maintenance work processes are structured and described according to the required ISO standardizations. Maintenance work is performed according to the agreed upon Service Letter Agreements.

Required and performed activities to reach this objective:

- During shift control rounds the operator on duty performs visual inspection of rotating equipment and check lubrication oil levels. All pressure and temperature gauges are controlled. Any inconsistencies are reported and work orders are made for replacement or repair.

- Maintenance work floor personnel perform vibrational monitoring on a regular schedule and due necessary maintenance activities are executed based on the condition of the equipment. In this state the conditioned based maintenance concept based on replacement of assets' components according to periodic measurement of predefined key parameters indicating the component failing process is practiced eliminating the costly replacement according to a fixed schedule period independent of the condition of a component.

Deliverables according to the required activities:

- In this transitional stage the basis is set forth for the important concept of Maintenance Conscious Operation and Operation Conscious Maintenance to increase availability of the desalination assets.
- Documentation of periodic measured key equipment parameters.
- An according to ISO standardized operation and maintenance work processes and procedures.

The well-defined structured work processes forming the basis of doing the right job effectively and efficiently in the right way as mainly directed by the work floor induces the personnel work satisfaction necessary to envision the next transitional state of Mastery satisfaction and reliability characteristics of the reliable productive work floor maintenance approach.

4. The Reliable Productive Work floor Maintenance Approach transitional state

In this transitional state of reliable productive work floor maintenance a very important phase is reached in the growth process changing the traditional culture oriented rivalry mind set toward a coherent ownership of and accountability for the production assets inducing operations reliability and maintenance reliability. Leading the departments is according to the delegating leadership role according to the EML strategy. The objective, required activities and deliverables for this phase are as follows:

Objective:

- The establishment of an effective operations and maintenance work floor quality team to effectively perform quality control and assessment to guarantee reliability of the desalination units to ensure operational safety and health aspects, good housekeeping and environmental protection.

Required and performed activities to reach the objective:

- Quality audit training and reliability courses are organized for operational and maintenance work floor and line executive.
- Every two weeks internal quality audit are scheduled and performed on supervisory level and work floor level.
- Every month a scheduled safety and good housekeeping audit is performed by Operation during shift.
- Work orders are issued for reported necessary maintenance and housekeeping activities.

Deliverables according to the required activities:

- Quality and safety audit reports prepared by the shift supervisor.

5. The Work floor Predictive Maintenance Approach transitional state

The fifth transitional state of the Work floor Predictive Maintenance Approach is governed by the enhanced situational leadership role of self-leading of the Efficacious Motivational Leadership strategy. The objective, required activities and deliverables for this phase are as follows:

Objective:

- In this transitional stage the objective is to reach mastery level in operations and maintenance with optimal skilled knowledgeable and experienced work floor personnel and line executives performing predictive maintenance inducing desalination professionalism.

Required and performed activities to reach this objective:

- The Operation shift personnel performs evaluation of key performance indicators such as the condenser's fouling ratio and trending key operation parameters to predict the probability of failures and production and efficiency decay.
- The Maintenance work floor personnel performed scheduled predictive vibration measurements of rotating equipment and infra-red thermo graphic analysis of electrical equipment.

Deliverables according to the required activities:

- Operations deliver trends of the key performance indicators for evaluation with Maintenance Department. Together with the heat balance maintenance activities can be predicted and planned.
- Vibration analyses and Infra-red analyses report of the Maintenance work floor for scheduling predicted maintenance activities.

This state assures the optimized care for equipments already initiated in the third transitional state and established the personnel mastery satisfaction. This mastery transitional state with initiated passionate continuous improvement mind set is the precursor of the ultimately desired level of excellence in desalination forming the basis envisioning the final state of the Efficacy Operations and Maintenance approach.

6. The Efficacy Operations and Maintenance approach state
This is the envisioned final stage of the Efficacy Oriented Maintenance strategy to reach Desalination Excellence with an efficient self-sustaining Desalination Operation and Maintenance team promoting the continuous improvement process where desalination knowledge and experience is transformed in wisdom. According to the EML strategy this phase is supported by the top enhanced situational leadership role of excelling toward excellence satisfaction. In this phase the objective, required activities and deliverables are as follows:

Objective:

- The objective in this final phase of Efficacy Operation and Maintenance approach is to establish a high state of caring for the desalination business contributing to the commercial and financial wellness of the company with an efficient self-sustained desalination team transforming desalination knowledge and experience into wisdom.

Required and performed activities to reach this objective:

- The establishment of a continuous learning process and on the job training program supported by the Desalination Management to keep track and focus on the continuous desalination efficiency improvement initiatives.

Deliverables according to the required activity:

- Mastery skilled operation and maintenance work floor personnel
- Well maintained and operated desalination asset

The Efficacy Oriented Maintenance frame work and decision tree policy
The Efficacy Oriented Maintenance approach focuses in particular on practical operations, maintenance and modification facet of the complete asset life cycle management from asset strategy through the whole planning, evaluation toward procurement and commissioning and asset disposal process. All the transitional states toward excellence in operations and maintenance are subjected to the continuous improvement process on strategic, tactical and operational level to fortify all the necessary actions of the transitional state of concern envisioning the next step to the succeeding transitional state emphasizing the dynamic character of this desalination efficiency improvement process. Both the Asset

life Cycle maintenance management and the Continuous Desalination Efficiency Improvement Processes form together with the Efficacious Motivational Leadership strategy the foundation of the Desalination Operation and Maintenance Pyramid of Excellence. Figure 8.23 illustrates the frame work of the EOM approach which is founded on the different objectives for maintenance improvement on strategic, tactical and operational levels as depicted in Figure 8.22. The frame work is primarily set up in accordance to EFQM model of leadership efficacy as the enabler to effectively deploy the operational and maintenance work force to best operate and maintain the desalination asset and processes to obtain the desired performance results of efficient high quality water production to fully satisfy all stake holders. The main objective is to safeguard and guarantee a continuous desalination improvement process toward Desalination Excellence.

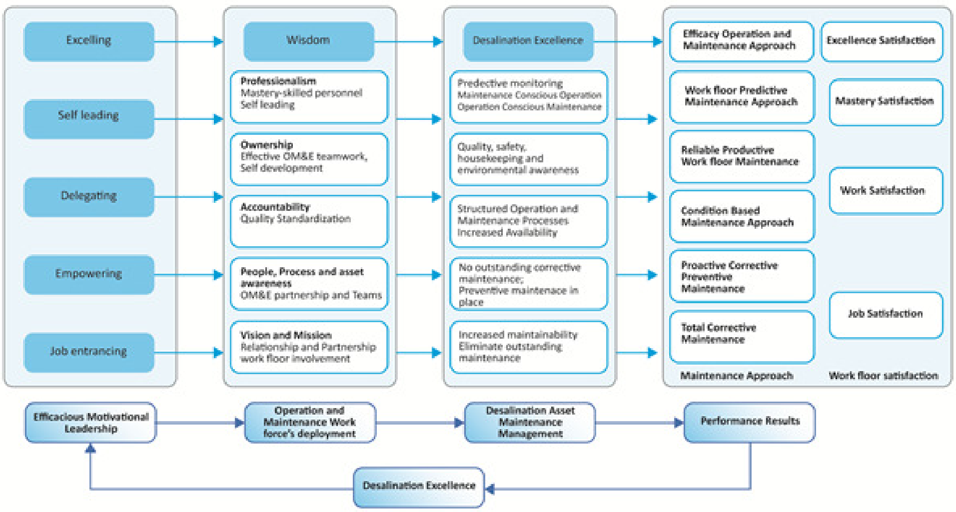


Figure 8.23: The frame work of the Efficacy Oriented Maintenance Approach

The Operation and Maintenance Pyramid of Excellence based on the EOM frame work as promoted at the Desalination Department is illustrated in Figure 8.24.

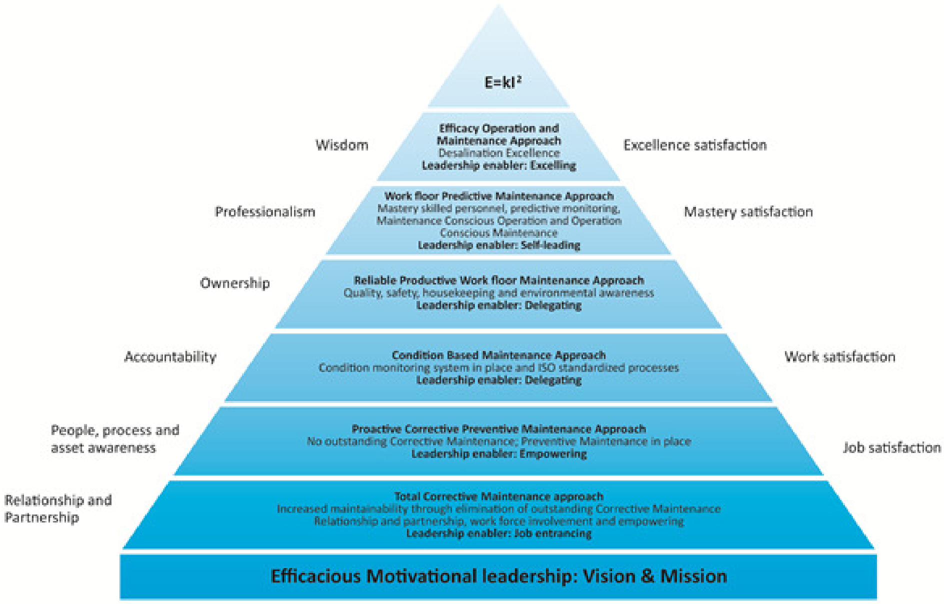


Figure 8.24: The Operation and Maintenance Pyramid of Excellence

In theory maintenance concepts are a general structure describing all the corrective, preventive and condition based maintenance interventions and forms the frame work from which the assets specific maintenance policies are developed and in particular the embodiment of the role of maintenance as an operation function in a company [8.23]. In the Efficacy Oriented Maintenance policy, in particular regarding the importance of human health and safety aspect of drinking water, quality is next to technical and economic aspect a feasibility criterion in the decision process toward selecting a maintenance activity. As mentioned before the first important step in the EOM approach is the corrective maintenance to upgrade the desalination asset. The most important and critical components are then identified. Normally in practice the run to failure policy is always considered first, no matter the criticality of subsequent component, e.g. the application of the Failure Based Maintenance. Regarding a critical component subsequently the technical feasibility, the economic feasibility and the quality feasibility is considered in the maintenance activity decision process as indicated in Figure 8.25. In the proposed EOM decision tree the selected maintenance activity is successively Failure Based Maintenance (FBM), Design Out Maintenance (DOM), Operation Conscious Maintenance (OCM), Condition Based Maintenance (CBM) and Used Based Maintenance (UBM).

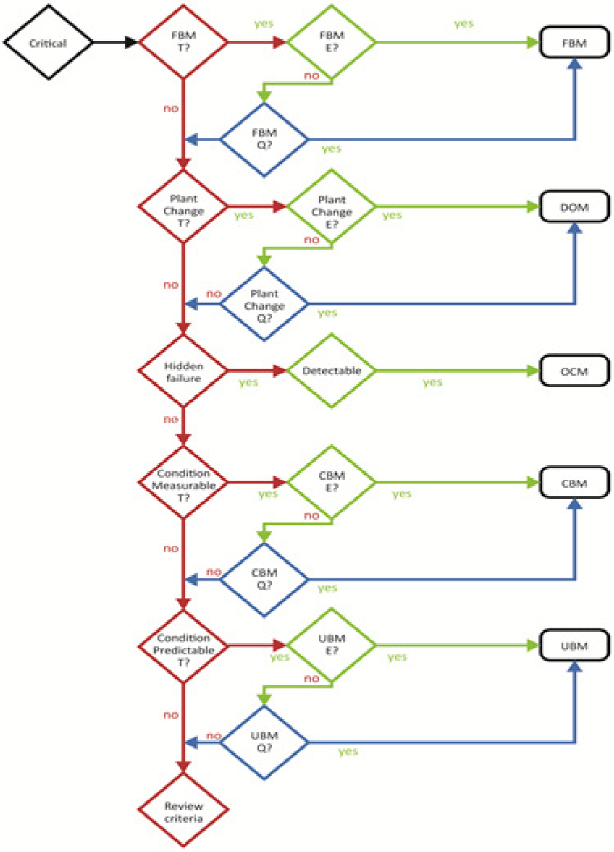


Figure 8.25: The Efficacy Oriented Maintenance activity decision tree

The Efficacy Oriented Maintenance approach, however is on the job developed in analogy with the Efficacious Motivational Leadership strategy without practically any sound know how of existing improved preventive maintenance concepts applied in industry and without any consultancy support, effectively eliminating the rivalry culture between the two essential departments for the desalination efficiency improvement process. An introductory comparison is performed with two well-known maintenance concepts, the Total Productive Maintenance approach and the Reliability Centered Maintenance to evince the effectiveness of this new maintenance approach as will be further elaborated on in the next section.

A comparison of the EOM approach with accepted maintenance models

In this section an introductory comparison is performed of the EOM with the TPM and the RCM. For the sake of simplicity the similarities and differences of the two approaches are first determined and compared with the EOM [8.22].

An effective strategy for comparison of maintenance concepts is based on key Critical Success Factors (CSF) that are derived from the modern time necessary prerequisites of the maintenance function to comply with the production of high quality products in accordance with the requisites of all stakeholders [8.24].

The Critical Success Factors (CFS)

The effectiveness of a new developed maintenance concept to meet the necessary prerequisites of the maintenance function fulfilling the objectives of optimal maintainability, availability and reliability in a cost-effective manner and in accordance with safety and environmental regulations can be evaluated regarding the following Critical Success Factors [8.24]:

- Focus on asset functionality:
  The maintenance strategy should have asset performance improvement as the main focal point incorporating measurable performance indicators as a regulator for managing asset's performance improvement.
- Control and assurance:
  The maintenance strategy should assure fulfillment of the prerequisites of stakeholders and verifiable measures as a performance control and management tool.
- Cost control:
  The maintenance strategy should assure cost control as a necessary measure in the optimization of the improvement process.
- Improvement assurance:
  Performance results should be documented and analyzed for continuous improvement optimization.
- Team support:
  The maintenance strategy should promote and support an effective team of operations and maintenance key players improving communication, motivation and work coordination.
- Engineering involvement:
  The maintenance strategy should include maintenance and operations key personnel in the early design stages of new assets.

Comparison of EOM with TPM and RCM

Despite the successful practical application at the Desalination Department of W.E.B. Aruba N.V. a preliminary study is performed to compare the effectiveness of the Efficacy Oriented Maintenance with the in most industries well adopted Total Productive Maintenance and the Reliability Centered Maintenance based on the abovementioned Critical Success Factors [8.22]. For an effective comparison the similarities and differences of the three concepts are first considered.

The most important similarities between EOM, TPM and RCM are:

- Operation and performance of production units are the main focus point for all three maintenance concepts.
- Performances are documented and monitored.
- Failures are assessed according to their impact on performance and production.
- Partnership of operation, maintenance and engineering is promoted.
- Performance and failure analysis are performed in teams.
- Results are safeguarded by well documented operation and maintenance manuals.
- Introduction and application require active role of management and line executives and a change in culture and mindset.
- Audits are performed as a control measure for progress monitoring.

Although the abovementioned similarities between EOM and the other two concepts also some important differences can be distinguished [8.22]:

- EOM concentrates more on efficiency improvement, TPM on assets effectiveness and RCM on functionality.
- EOM concentrates on occurred failures and failure prediction, TPM considers more occurred failure and RCM on assessment of all possible failures.
- In the EOM concept the maintenance activities are determined according to a decision tree but less systematic then RCM. In the TPM concept the maintenance activities are determined by the small groups.
- In the EOM and TPM operations are involved in maintenance and in the RCM concept at a lesser extent.
- In the EOM the emphasis is actually on the whole life cycle while in the RCM the new asset and in the TPM the asset already in use are emphasized
- In the EOM the human aspect in particular the work floor personnel is very important although in both the TPM and RCM the technical aspect is the main focal point
- The EOM is a simple concept and easy to implement, however the RCM and TPM are well known for their complexity for introduction and application
- The EOM is implemented without the need for external consultancy while for both TPM and RCM this is a necessity.
- The focal point of the EOM is the maintenance conscious operation and the operation conscious maintenance and the self-leading and self-development aspect, both TPM and RCM elaborate to a lesser extent on these subjects.

According to this introductory study the EOM has a lot of similarities with both the RCM and the TPM concepts but apparently the EOM leans more towards TPM. To conclude this section the comparison of the three concepts according to the Critical Success Factors as performed in the preliminary study is illustrated in Table 8.4.

Table 8.4: The CSF-comparison of the EOM, TPM and RCM concepts

Critical Success Factor	RCM	TPM	EOM
Focus on functionality	Focus on all possible failures	Focus on occurred failures	Focus on possible and occurred failures
Control and assurance	Regular audits and risks assessment	Regular audits and motivation	Motivation, work floor quality team; ISO audits of work process
Cost control	LCC is the bases	LCC is the basis	ROI based on performance increase
Improvement assurance	Focus to improve asset performance through failure risk management; do not specify continuous improvement	Its main focus is on continues improvement through eliminating the 6 big losses	Focus on continuous improvement through operation conscious maintenance. Eliminating all production losses
Team support	Focus on team work for function-failure analyses	Focus on small group team work	Focus on line and work floor team work; human aspect is important
Engineering involvement	Focus is on the design phase	Focus is on involvement for modification	Focus is on involvement in the early stages of design, during commissioning and construction

As mentioned above all three concepts focus on the whole asset life cycle, however the value of RCM is more evident in the engineering design phase, while in TPM and EOM evidently the focal point is in the optimization of production units in the operation-use phase. It is worth mentioning that the EOM in practice was also very effective in the end phase of the life cycle extending the techno-economic life of the MSF evaporators and still performing as design. This life cycle value aspect of the maintenance concepts are schematically illustrated in Figure 8.26.

For a relatively short term implementation of a company specific maintenance approach the EOM is because of its simplicity preferable above the more intensive RCM and TPM having a long term implementation time frame. Further, according to the modern view point in maintenance science, company specific approaches are recommended and are considered the newest generation of maintenance approaches [8.23].

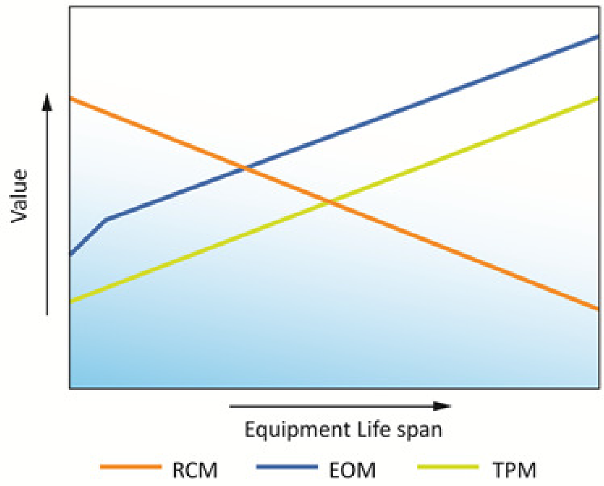


Figure 8.26: The asset's life cycle value of the EOM, TPM and RCM concept

The Efficacy Oriented Maintenance concepts has since 1998 successfully been applied at the Desalination department resulting in a significant decrease of failures and significant efficiency increase of the desalination production units as will be explained more in depth in the next section.

8.6 Major achieved results with the Efficacy Oriented Maintenance

With the introduction of the Efficacy Oriented Maintenance approach following the first step to a preventive maintenance back in 1997 at the Desalination Department of W.E.B. Aruba N.V., progressively small successful steps were achieved improving internal and external communication with supporting departments on work floor and line executive level. A first breakthrough was the realization of an improved housekeeping and increased safety awareness due to improved collaboration with the Maintenance Departments increasing motivation to proceed with the journey set forth reaching out to excellence in operations and maintenance. Visitors of the Desalination Department were often impressed with the operation and maintenance condition of the desalination units, as quoted (a former vice-president of Ionics Inc.):

"Dear Sirs, It was a pleasure to have an opportunity to meet and break bread with you in Aruba a few days past. I would like to commend WEB as your facility is one of the best looking and best run MSFE plants I have ever visited" [8.25].

The Efficacious Motivational Leadership strategy was the corner stone in the development of a firm relationship between two competing and opposing departments moving away from an old-established rivalry and mind set of "it broke because you did not fix it right" and oppositely " it broke because you did not operate it well". On strategic level the lofty goal of the Efficacy Oriented Maintenance to continuously improve desalination efficiency through effective involvement and empowerment of the operations and maintenance work floor personnel was successfully reached through the well-established motivated work floor quality team. The increased safety awareness on the work floor level is considered a major achievement. As indicated in Figure 8.27 the safety incidents have decreased since 2000 and in coherence herewith the reported safety issues and unsafe situation and work execution have increased.

Figure 8.27: The safety incidents and the coherent reported safety issues of The Desalination Department

Supporting the strategy, further the following major technical achievements have been obtained [8.26].

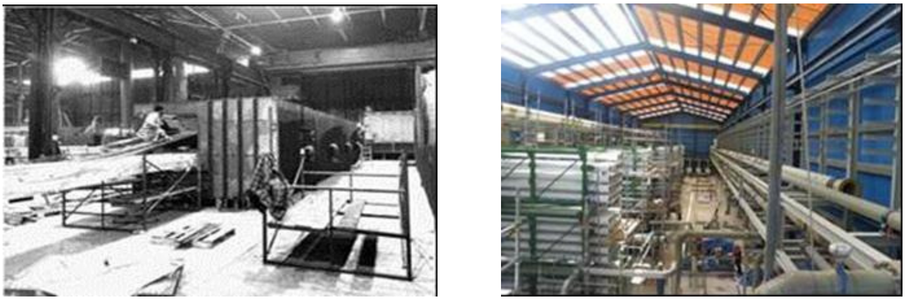
On tactical level

An effective team of the Desalination Department with all supporting departments has been established on line executive level creating the foundations for a firm relationship, mutual understanding to promote good communication, good housekeeping and safety awareness and environment protection encouraging creative work environment to increase desalination efficacy toward optimal maintained and operated desalination assets. The complaints on the work floor level between the Operation and Maintenance Department needed management attention are practically none occurring since the end of 1999.

The General Inspections are effectively planned and scheduled together introducing a new cleaning procedure of the long tubes of the MSF evaporator in four days increasing effectiveness of maintenance and operation efficiency. This became possible due to the created opportunity to hydrolase the long tubes of all six vessels of the MSF evaporator at the same time. Since 2000 scheduled maintenance according to the yearly operation and maintenance plan are executed according to planning. Only in particular circumstances of instability of the Power Facility and higher water demand of the oil refinery, usually exceeding more than 200% the maximal contracted water delivery of 4500 m^3 per day, General Inspection and maintenance are postponed as mandated by Senior Management for commercial reasons.

The period of the General Inspection and maintenance of the MSF evaporators were reduced from four weeks to two weeks and the interval increased from 12 months to 18-20 months. Feed back to manufacturers was optimized to improve design and team work is promoted effectively addressing and solving operational problems with the MSF evaporators and the SWRO desalination unit. In Chapter 1 it was already mentioned that due to information of knowledgeable operation and maintenance personnel of W.E.B. Aruba N.V. the design performance ratio of the MSF evaporators has been increased from 9 to 11.5 in 1998. Aqua Chem #7 went in operation with a performance ratio of 11.7 in the commissioning period in 1998. The SWRO energy consumption design value of 4 kWh/m^3 is decreased to 3.72 kWh/m^3 with the applied sanitation and the new osmotic membrane cleaning procedure in 2010.

According to the Efficacy Oriented Operations and Maintenance approach, key work floor personnel from both departments are now involved already from the initial phase in the project process for the acquisition of a new desalination unit. This was not a common practice at W.E.B Aruba N.V. Figure 8.28 illustrates the construction of an MSF evaporating vessel at Aqua Chem Inc. and the involvement of the Operation and Maintenance Department in the SWRO#2 project.



a: Copper tubes installation in MSF vessel   b: O&M involvement in SWRO#2 project

Figure 8.28: The construction of an MSF evaporating vessel and the SWRO#2

On operational level

The Efficacious Motivational Leadership and the Mahatma Gandhi effect have firmly established a sound work floor relationship forming the cornerstone of the Maintenance Conscious Operation and Operation Conscious Maintenance concept leading to the self-leading Operational and Maintenance work floor quality team. The operators being close to the production units perform visual inspections of rotating and monitoring equipment and by trending key performance parameters using the heat balance trouble shooting and monitoring procedures they promote operational preventive and predictive maintenance. The mechanical and electrical maintenance work floor performs predictive vibration monitoring of the rotating equipment and preventive Infra-Red thermography measurements of electrical leads and conduits mitigating practically all unpredicted mechanical and electrical failures. As illustrated in Figure 8.29, since the introduction of the EOM approach in 1998 the pump failures of the MSF evaporators have decreased practically linearly from 450 hours to less than 50 hours annually in 2011.

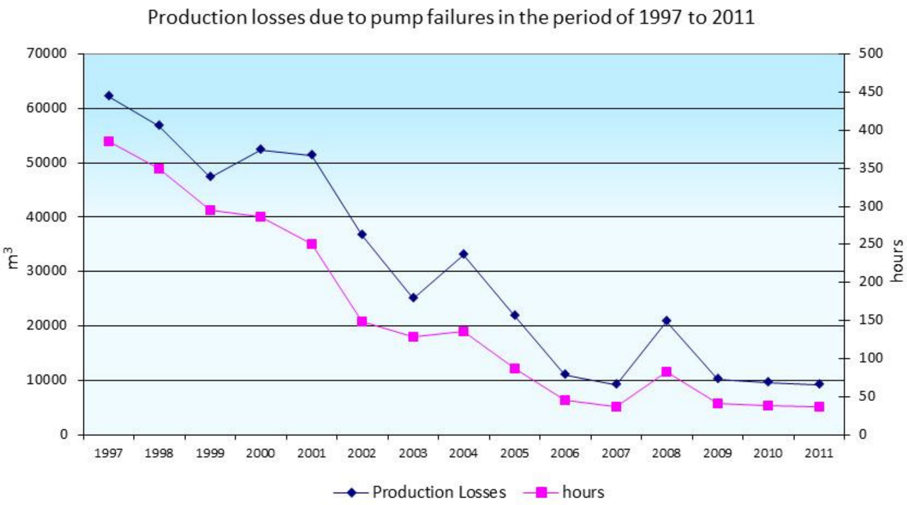


Figure 8.29: Production losses due to pump failures in the period of 1997 to 2011

Likewise failures in operational process due to tube leak, distillate high conductivity, monitoring instrument failure, vacuum problems corrosion, scaling and fouling have dropped significantly practically exponential since 1998 as is indicted in Figure 8.30.

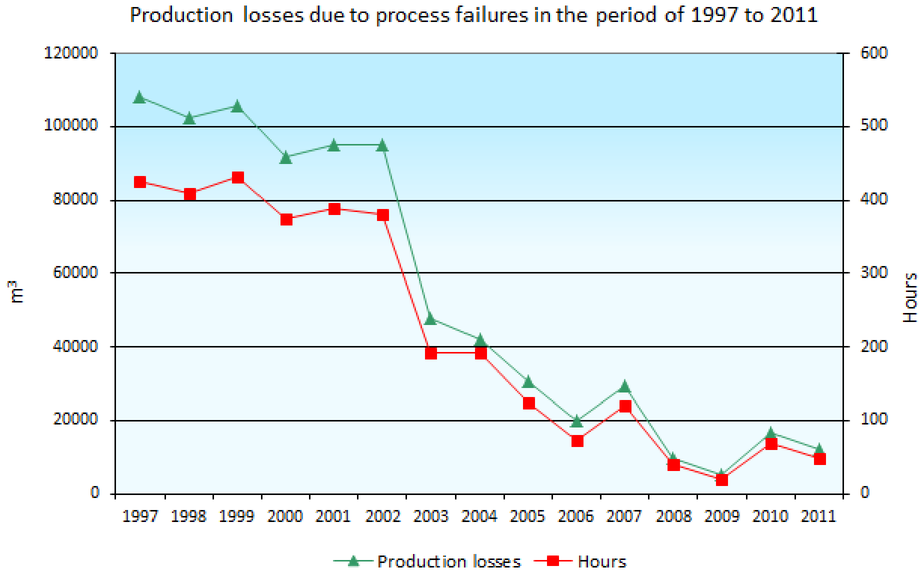


Figure 8.30: Production losses due to process failures in the period 1997 to 2011

As shown in Figure 8.30, the process failure hours decreased from approximately 550 hours to 20 hours annually. One major achievement of the work floor quality team complying with the strategic objective of the efficiency oriented operation and maintenance is the realization of the desired efficiency improvement in desalination. Since 1997 the accumulative performance ratio of the MSF evaporators increased from a value of 8.7 to 9.3 in 2008 as is shown in Figure 8.31. At the Desalination Department the lowest acceptable performance ratio is set at 8.5 regarding efficiency optimization, determining the required efficiency operational range from 8.5 to 10, or if possible above this design value.

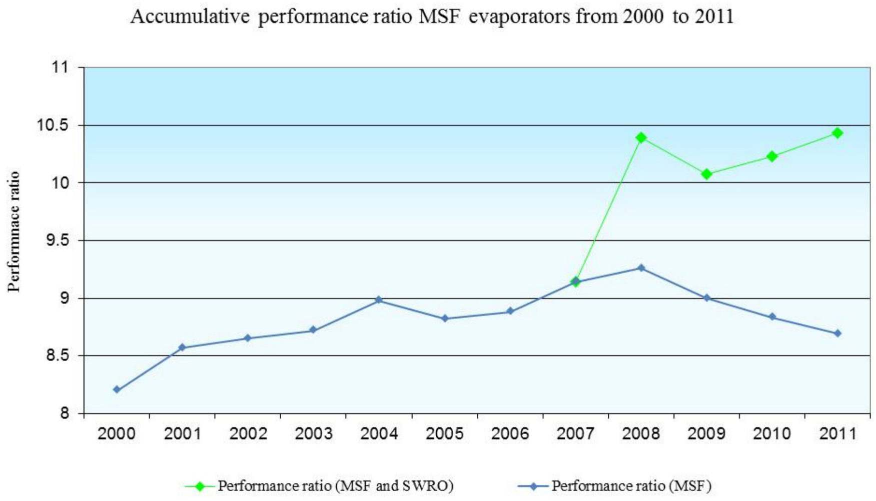


Figure 8.31: Accumulative Performance Ratio of the MSF evaporators from 2000 to 2011

To get an impression of the importance of the performance ratio an increment from 9.0 to 9.3 means an energy savings of US$1,730,000.00 based on a heavy fuel oil price of US $75.00 per barrel [8.27].

The decay of the performance ratio of the MSF evaporators since 2009 is practically due to the very inefficient operation of the new installed SWRO in 2008 struggling with heavy persuasive biofouling. All attention is concentrated to improve SWRO efficient operation as mandated by Senior Management. At the end of 2009, Senior Management made the decision to drastically reduce maintenance cost because of the intended decommissioning of 4 MSF evaporators in the first half of 2011. This had an impact on efficiency demonstrating the importance of efficient maintenance for the continuous improvement process. In 2011 continuous water delivery to the oil refinery higher than the contracted volume further impacted the GI planning.

On the other hand including the equivalent performance ratio of the SWRO calculated based on the low pressure steam equivalent of the energy consumption of the SWRO shows since 2008 an MSF-SWRO performance ratio above 10, indicating the importance of the introduction of new technology to increase efficiency.

Major objectives of the Efficacy Oriented Maintenance strategy are also next to improve availability and reliability to increase design capacity and exchange operational and maintenance experience with manufactures to improve design. As already mentioned in Chapter 3 the oldest MSF evaporators Aqua Chem#1 and Aqua Chem#2 was put back in operation after their yearly general inspection and maintenance in 2001 with a performance and operation capacity better than their first performance test nineteen and eighteen years

before. The Aqua Chem #1 is put out of production in 2008 after more than 25 years still producing at design condition. The 27 years old Aqua Chem #2 was in 2012 still in operation with a production and performance according to design.
Another objective of importance in the EOM approach is water production waste due to high conductivity (high salt content of the distillate) which can be minimized through effective operational control. As Figure 8.32 illustrates, Operations succeeded in 2011 to achieve an annual water production waste reduction of about 90% compared with the high annual waste in 2001.

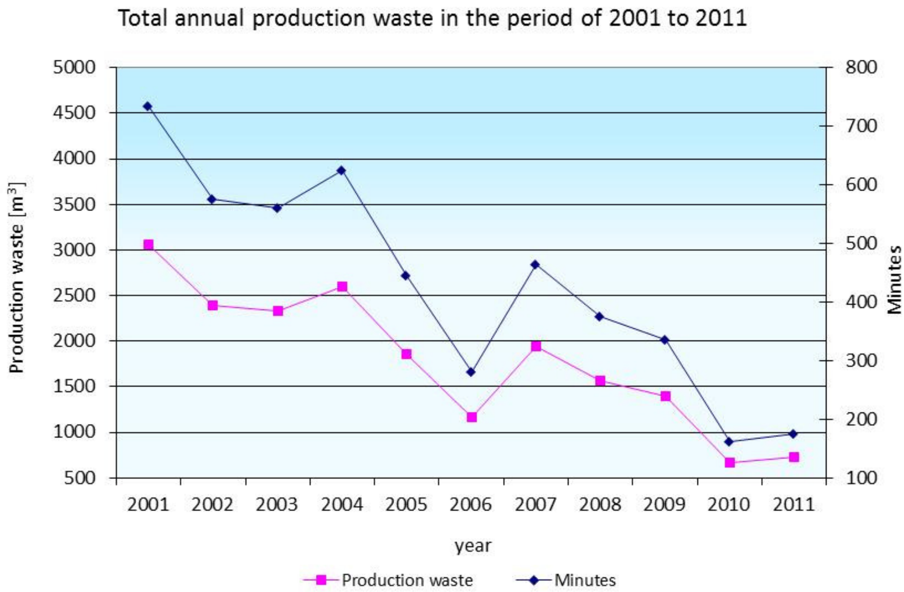


Figure 8.32: The annual water production waste due to high distillate conductivity from 2000 to 2011

The production of high quality drinking water and the successes with desalination operation and maintenance has contributed to a well maintained and operated water distribution system. As already described in Chapter 7 in conjunction with an improved client service W.E.B. Aruba N.V. has managed to realize a percentage of Non Revenue Water of about 2.6% to 4.11%, actually the lowest in the Caribbean region and an Infrastructure Leakage Index (ILI) of 0.51 indicating a well maintained water distribution system according to the specified target by the American Water Works Association (AWWA) for drinking water supply systems with practically no natural water resources and a costly water production as the case in Aruba. To conclude this section it is worth mentioning that the qualitative indicative preliminary internship study [8.22] evaluating the effectiveness and acceptance of the EOM concept based on the Participant Observation of the Qualitative Research Methods

[8.28] interviewing 9 key OM&E persons shows that this innovative maintenance concept was well-accepted by the majority of all involved with operations and maintenance of the desalination units. The results are shown in Table 8.5.

Table 8.5: Effectiveness and acceptance of the EOM concept

Changes due to EOM	Agree
Leadership towards relational style	89.9%
Increase in ownership	100 %
Positive attitude of interdepartmental colleagues	100 %
Increased asset performance due to EOM	100 %
Decease in failure due to EOM	100 %
Improvement of interdepartmental team	78 %
Increased motivation	100 %

8.7 Conclusions

1. Maintenance has evolved throughout the evolution of mankind inherently to the technological evolution since the Industrial Revolution from a necessary evil toward a profit contributing operation function.
2. Maintenance is next to the human aspect, the chemical aspect and the aspect of innovation and the application of new technology an important key aspect of the Continuous Desalination Efficiency Improvement Process.
3. The Efficacy Oriented Maintenance concept developed at the Desalination Department of W.E.B. Aruba N.V. has proven very useful decreasing pump and pump failures up to 85% during a decade and increasing efficiency from 8.3 to 9.3.
4. The Efficacy Oriented Maintenance is, according to modern maintenance philosophy, a company customized maintenance concept representing the recently fourth generation of the maintenance evolution.
5. The involvement and empowering of the work floor personnel, sharing and applying their practical knowledge is the guiding key success factor of the Efficacy Oriented Maintenance.
6. The Efficacy Oriented Maintenance undoubtedly has contributed to the cost effective seawater desalination at W.E.B Aruba N.V. and with its simplicity complying with the fundamental concept of science, the comprehension of nature in the total beauty of simplicity.
7. The introductory evaluation of the effectiveness of the Efficacy Oriented Maintenance applying the Participant Observation according to the Qualitative Research Method, interviewing key persons in the Desalination and Maintenance Departments on line executive and work floor level has undoubtedly shown the acknowledgement of the value of the Efficacy Oriented Maintenance.

8. The introductory comparison study indicated that the Efficacy Oriented Maintenance concept although independently developed has some resemblance to the well-known Total Productive Maintenance and the Reliability Centered Maintenance.
9. The Efficacy Oriented Maintenance has proven the principle of Business Common Sense in developing a maintenance concept according to van Kessel [8.28].

8.8 References

8.1. Campbell, J.D., Reyes-Picknell, J. V., Uptime-Strategies for Excellence in Maintenance Management, 2nd edition, Productivity Press New York, 2006.

8.2. Geraerds, W. M. J., Toward a theory of maintenance, R. Bureau e., The Organization of Logistic Support Systems, The English University Press Ltd., London, 1972, 297-329.

8.3. Geraerds, W. M. J., Onderhoud in vogelvlucht, Onderhoudsmanagement: B1020, May 1987

8.4. Gits, C. W., Design of maintenance concepts, International Journal of Production Economics, 24 (1992) 217-226.

8.5. Gross, J. M., Fundamentals of Preventive Maintenance, Amacom, 2002, New York, USA.

8.6. http://www.weibull.com/hotwire/issue22/hottopics22.htm

8.7. http://en.wikipedia.org/wiki/Economic_appraisal

8.8. Reliability & Maintenance Management System, Training Manual, Proprietary Information of W.E.B. Aruba N.V., January 2003.

8.9. Nakajima, S., Introduction to Total Productive Maintenance, Productivity Press, Cambridge MA, 1989.

8.10. Geraerds, W. M. J., The EUT maintenance model, International Journal of Production Economics, 24 (1992) 209-216.

8.11. Levitt, L., The Handbook of Maintenance Management, Industrial Press Inc. New York, USA, 1997.

8.12. Moubray, J., Reliability-centered Maintenance, 2nd Edition, Industrial Press Inc., New York, New York, 2009

8.13. Peterson, G., Jendzurski, T., Bernard, A., Capacitance: Redefining Maintenance, Chemical Engineering, August 1994.

8.14. Geraerds, W. M. J., Ontwikkelingsfasen in het onderhoud, Onderhoudsmanagement: B2010, May 1987.

8.15. Thomas, G. O., Maintaining Multi-Stage Flash Desalting Plants, Aqua Facts, Volume III, June 1984, Aqua Chem Inc.

8.16. Wes, B., Reverse Osmosis, A Practical Guide for Industrial Users, ISBN 0-927188-03-1, Tall Oaks Publishing, Inc., Littleton, CO, USA, 1995.

8.17. Wilff, M., The guidebook to Membrane Desalination technology, ISBN 0- 86689-065-3, Balaban Desalination Publications, L'Aquila, Italy, 2007.

8.18. Technical Operations and Maintenance Manual, GE Ionics, 2008.
8.19. Watson, I. C., Morin, O. J., Henthorne L., Desalting Handbook for Planners, 3rd Edition, US Department of the Interior, Bureau of Reclamation, Research and Development Program Report No.72, July 2003.
8.20. Croes, G. B., Personnel Communication, W.E.B. Aruba N.V., 2010.
8.21. Marchena, F. A., Alberts, V. A., et al., A Strategic Quality Program: Basic Efficiency control for Brine Recirculating MSF Desalination Units., Caribbean Conference 2002, From Seawater to Drinking Water, Oranjestad Aruba, June 19-21, 2002.
8.22. Tromp, J., Efficacy Oriented Maintenance model, a maintenance innovation, BSc thesis, University of the Netherlands Antilles, 2011.
8.23. Waeyenbergh, G., Pintelon, L., A framework for maintenance concept development, International Journal of Production Economics 77 (020) 299-313.
8.24. Kessel van, N. I., Critical Success Factors for a maintenance strategy: RCM, TPM or GBV, Onderhoudsmanagement, August 1995, (in Dutch).
8.25. Mayer Steele, S., Personal Communication, email August 14th, 1999.
8.26. Marchena, F. A., Efficacy Oriented Operation and Maintenance: An important Step Toward Sustainable Conventional and Green Desalination Technology, Our Future with Green Energy Conference and Trade Fair, September 29th - October 3rd, 2010, Oranjestad , Aruba.
8.27. Marchena, F.A., Justification of the 4 days MSF evaporator's tube cleaning, Internal Report W.E.B. Aruba N.V., 2009.
8.28. Qualitative Research Methods: A Data Collector's Field Guide"

Chapter 9

Innovative desalination concepts to improve desalination efficiency

Aruban drinking water supply innovation in bygone days

Innovation is brightening the twilight in the technological darkness

Chapter 9

Innovative desalination concepts to improve desalination efficiency

Table of Contents:

Abstract

Innovation is another important factor contributing to efficiency increase in desalination technology. In this chapter the innovative technologies such as the chlorine disposal process, the carbon dioxide fluidized bed desorption tower, the hybrid Osmosis Reverse Osmosis (ORO) membrane desalination process and an online environmentally friendly chemically-free SWRO-BWRO membrane cleaning process are described. A chlorine disposal process has been developed and applied for the save and environmental disposal of used damaged chlorine one ton-containers posing a safety, health and environmental hazard at W.E.B Aruba N.V. For the disposal of gaseous chlorine through the drain plugs of the one ton-containers with damaged valves, a special hood assembly was designed and successfully applied. In the process to eliminate the use of sulfuric acid as scale inhibitor in the MSF evaporators, a conceptual innovative fluidized bed-tray type carbon dioxide desorption tower has been developed and patented. To further improve the efficiency of the membrane technology a conceptual hybrid membrane technology consisting of a combination of an Osmosis process unit and a Reverse Osmosis process unit, the ORO desalination process, was designed and patented for the desalination of seawater. Biofouling of SWRO membranes and scaling of BWRO has a detrimental effect on the efficiency of the SWRO process. Intensive chemical cleaning of the membranes is often the only solution to mitigate membrane fouling ensuring stable desalination. In this context, an environmental friendly on line osmotic chemical-free membrane cleaning process was designed and successfully applied increasing efficiency and availability. A patent is also registered for this osmotic membrane cleaning process. An innovative conceptual design of a combined membrane Power and Water production facility, eliminating the use of conventional fuel, is briefly introduced for further conceptual development. The conceptual design of a hybrid MSF evaporator and Osmosis unit and the thermodynamic minimum energy green desalination are also presented for further development to promote green desalination by diminishing the use of chemical additives in the thermal flash desalination.

9.1 Introduction

The development and application of innovative technologies has historically worldwide improved efficiency in practically all industrial processes. The Desalination Department of W.E.B. Aruba N.V. has proactively played an important pioneering role in the global desalination activities by successful application and development of innovative technologies to improve seawater desalination efficiency. In the attempt to further optimize desalination technologies, recently important innovation has been applied. As described in the preceding chapters, in 1990 a more effective antifoam and the pyro and orthophosphate corrosion inhibition technology was successfully applied enabling stable evaporation and eliminating red and blue water occurrences in the distribution network [9.1]. The introduction of a new non-oxidizing biocide in 1995 and the development and application of a new high temperature antiscalant for the elimination of sulfuric acid as scale inhibitor in 2004 have significantly increased thermal desalination efficiency [9.2, 9.3]. The impulse to excel to optimal operation and maintenance efficiency has also stimulated the development of new desalination innovation at the Desalination Department of W.E.B. Aruba N.V. During the period of the Aquanova Controlled Flash evaporators, liquid chlorine was used and for many years, the one-ton chlorine containers were stored after usage on the premises of W.E.B. Aruba N.V. forming a potential safety, health and environmental hazard. Chlorine gas is a very toxic and hazardous chemical component. In this context, an innovative safe and environmental friendly chlorine discharge process is designed consisting of withdrawal of chlorine gas out of the one-ton container with a seawater jet-ejector and dosed in the seawater flow to the condenser of the decommissioned Aquanova evaporator. The quantity of the dosed chlorine gas is controlled and regulated with a chlorine dosing apparatus according to environmental regulations. A by-pass system is installed in the chlorine dosing apparatus for further removal of the residual chlorine gas from the container. A special discharge hood assembly is designed for the discharge of the full container with damaged inoperable valves containing a quantity of one thousand kilogram of liquid chlorine. In section 9.2 the developed chlorine disposal process to eliminate the one-ton containers and the special innovative designed hood assembly to discharge the one-ton containers with damaged valves are described in detail.

Since the 1960s, concentrated sulfuric acid is successfully applied as scale inhibitor in thermal desalination. Although very efficient, sulfuric acid is a potentially high-risk health, safety and environmental hazardous chemical. A tray type carbon dioxide desorption tower is designed for the possibly elimination of sulfuric acid as scale inhibitor in the MSF evaporators. This conceptual design, as described in detail in section 9.3, is based on the principle of thermal decomposition of bicarbonates in seawater and removal of the produced carbon dioxide in transfer units by means of fresh stripping steam or vapor.

The stripping steam is removed from the combination of transfer units by means of an ejector system. A combination of a fluidized bed tray column is designed to increase efficiency of the carbon dioxide stripping process. The incoming seawater feed is pumped through the tube bundle containing fluidized particles and is preheated by the warm seawater flowing shell side of the tube bundle in a special down comer. In the top unit, the seawater feed is heated with condensing steam. This seawater flows downward over trays where carbon dioxide is stripped by steam or vapor. A conceptual design of a special cavitation-eduction sieve tray and alternative transfer units are also described. A patent is registered in 2003 for this conceptual carbon dioxide desorption tower.
Nowadays SWRO is well known as the most energy efficient seawater desalination technology. To further increase efficiency of this membrane technology, a conceptual design of the hybrid ORO desalination process is introduced and patented in 2009. This conceptual design, as described in section 9.4 is based on a hybrid combination of the Osmosis and Reverse Osmosis process. In the Osmosis process unit fresh water is withdrawn from the seawater with the concentrated pure sodium chloride effluent of the Reverse Osmosis process unit. The diluted sodium chloride solution effluent of the Osmosis process unit is the feed for the Reverse Osmosis process where it is separated in the concentrate and a permeate flow of fresh water. Alternatives for this hybrid process such as the use of a recoverable suitable chemical to increase the osmotic pressure of the sodium chloride solution, the use of a saltpan for the production of the pure sodium chloride solution in combination with a solar pond are also proposed to enhanced efficiency increment of the hybrid ORO process. In these new hybrid ORO desalination processes eventually present boron can be easily removed with sodium hydroxide without the risk of precipitation of divalent and trivalent salts on the surfaces of the RO membranes whereas chemical and marine biological fouling is also practically eliminated in this new hybrid ORO desalination process. Because of the lower working pressure the new hybrid ORO desalination process is energetic favorable than the conventional SWRO and has a lower energy consumption per cubic meter produced drinking water.
Despite intensive pretreatment of the seawater feed, chemical- and biofouling of membranes is a frequent problem lowering availability and efficiency in conventional SWRO desalination technology. Conventional chemical off-line clean in place with alternative low pH and high pH solution is time consuming, costly and environmental unfriendly. In section 9.5, a conceptual design of an innovative environmentally friendly chemical-free cleaning process for SWRO-BWRO membranes is described. This conceptual design is based on the on-line osmotic membrane cleaning process with product water acidified with carbon dioxide of the re-mineralization unit of the drinking water system. The osmotic process is initiated by means of lowering the recovery rate of the SWRO and BWRO membranes and increasing the osmotic pressure of the seawater feed by increasing its concentration and

temperature. This conceptual design and alternatives enhancing effectiveness are further in depth described. This osmotic membrane-cleaning concept has been successfully applied at the first SWRO production unit of W.E.B Aruba N.V. troubled with heavy and persuasive biofouling. Energy consumptions, lower than the design target have been achieved after practically two years of operation with twice a month severe chemical cleaning. The SWRO manufacturer has considered this achievement a worldwide success and the Desalination Department was granted the GE WPT's Proof not Promise award. A patent is registered for this innovative osmotic membrane-cleaning process. Section 9.6 gives a brief introduction of an innovative membrane combined Power and Water plant based on the hybrid combination of the Electro-dialysis Reversal and the SWRO-BWRO technology together with innovative conceptual designs for a MSF evaporator-Forward Osmosis hybrid and for the thermodynamic minimum energy green desalination process. These concepts need further research and development.

It is noteworthy that a similar Osmosis Reverse Osmosis hybrid is designed for seawater desalination by the UK company Modern Water with different draw solution. A full scale commercial plant with a production capacity of 100 m^3 per day is installed in the Al Wusta region of the Sultanate of Oman [9.4]. This plant is in operation with the efficiency and biofouling mitigating capacity and practically without any chemical cleaning of membranes as predicted for the ORO process in section 9.4 of this chapter.

9.2 An innovative disposal system to empty one-ton chlorine containers

The development of the chlorine discharge process

In the operation period of the Aquanova controlled flash evaporation technology from 1974 to 1995 for the desalination of seawater, liquid chlorine was dosed in the seawater feed as already mentioned in Chapter 4 to control marine biofouling in the condensers. As can be seen in Figure 9.1, the one-ton chlorine containers were stored after usage on the premises and during the years becoming a serious potential safety, health and environmental hazard because of the corrosive sea environment, especially the one-ton containers having damaged dosing valves. In the past, some attempts were made by former employees to empty these containers by opening the valves in the open atmosphere causing serious environmental and safety hazard due to the escape of chlorine gas. These actions were immediately stopped by the responsible governmental departments [9.5].

Chlorine is at room temperature and atmospheric pressure a green yellow gas with a characteristic sharp odor. Chlorine gas has a specific gravity of 2.5 times greater than air. So when leakages occur chlorine tends to accumulate in lower spaces [9.6].

The volume ratio of liquid chlorine and gaseous chlorine is so that when one volume unit of liquid chlorine evaporates at 20 ^{o}C and atmospheric pressure, 475 volume units of chlorine gas is formed [9.6]. A leakage of liquid chlorine is therefore far more hazardous that a chlorine gas leak.

Chlorine does not react with oxygen in the air and it is in the liquid form nor in the gaseous form explosive and combustible, however chlorine gas can take over the role of oxygen and enhance combustion of other components [9.7]. In the temperature range of 170 ^{o}C to 200 ^{o}C and the pressure range of 1 to 10 atmospheres, the combustion of iron can take place spontaneously in the presence of chlorine gas. A high content of carbon in iron seems to promote this self-combustion. Cast iron with high carbon content seems to combust under certain circumstances already at room temperature. At temperature exceeding 80 ^{o}C one has to take into account that dry chlorine gas can corrode steel due to the combustion of iron. This chemical reaction releases a lot of heat and the chemical reaction can be accelerated by increasing temperature and humidity [9.7].
Chlorine has both in liquid and in the gaseous phases a strong tingling and burning effect on human tissues causing serious damage of skin and the mucous membranes of eyes and bronchi. Depending on the condition of the individual, the contact time and the chlorine concentration the effect can range from light itching to death due to pulmonary edema. Pulmonary edema occurs when the alveolus has become permeable for blood due to the damaging effect of the inhaled chlorine. Most people can detect chlorine because of its characteristic odor already in the concentration ranging from 1 to 5 ppm. The *Maximal Acceptable Concentration* (MAC) for chlorine is 1 ppm during a maximal contact time of 8 hours. This concentration is equivalent to 3 milligrams per cubic meters of air [9.8].

Figure 9.1: One-ton chlorine containers stored on the premises of W.E.B. Aruba N.V.

In 1992 becoming aware of the existence of these one-ton chlorine containers and their safety, environmental and toxicological hazardous potential, a safe and environmentally friendly process is designed and developed using the chlorine dosing system of the decommissioned Aquanova #3 evaporator to remove the residual chlorine gas of the one-ton chlorine containers. A special innovative dosing hood was also designed to empty the chlorine containers with damaged dosing valves through the drain plug. One of these containers was still full filled containing one thousand kilogram of liquid chlorine. The objectives of the proposed chlorine gas discharge process and the innovative design are as follows:

- The disposal of the one ton chlorine containers should be performed in a safe and environmental friendly way
- The designed process should be approved by a certified company
- The chlorine discharge concentration in the lagoon should be according to international regulations and guidelines
- The chlorine discharge activities should be perform according to approved operation procedures
- The chlorine discharge of the containers with damaged valves should be done considering all safety measures
- The chlorine discharge process should be performed in cooperation with all responsible Governmental Departments
- The disposal process should be cost effective compare to other external proposals.

The used chlorine one-ton containers on the premises of W.E.B. Aruba N.V. were discharged by means of the modified chlorine dosing system of the decommissioned Aquanova #3 evaporator as indicated in Figure 9.2. In this developed chlorine disposal process the residual chlorine gas are withdrawn from the one-ton containers (1) by means of a seawater jet-ejector. The dosage of the chlorine gas is controlled and regulated with a chlorine dosing apparatus of Wallace and Tiernan (2) with a dosing capacity of 7.5 kg of chlorine gas per hour [9.9]. The chlorinated seawater effluent (a) of the seawater jet-ejector system (4) is directed to the suction of the seawater intake pump (6) of the decommissioned Aquanova #3 evaporator (7). The seawater feed (b) is pumped through the condenser section and the brine blowdown trench of this evaporator into the outlet of the cooling water channel of the Power House for further neutralization and dilution of the chlorine before discharge into the lagoon [9.10]. This chlorine discharge process is schematically illustrated in Figure 9.2.

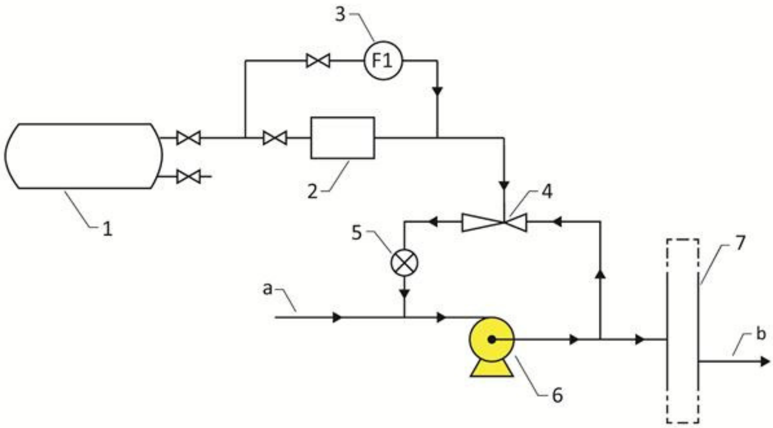


Figure 9.2: The schematic of the developed chlorine disposal process

The specification of the components in the simplified process schematic is as follows:

1. The one ton chlorine container
2. The chlorine gas dosing equipment
3. The bypass with flow meter
4. The seawater jet ejector
5. The sample point in the ejector effluent
6. The intake pump
7. The condenser section of the Aquanova #3 evaporator
   a. The seawater feed
   b. The chlorinated seawater to the cooling water channel

The removal of chlorine gas continues until there is no over-pressure in the chlorine one-ton container (1). However, there is always a residual quantity of chlorine gas left over in the container. For the removal of this residual chlorine gas the chlorine dosing apparatus (2) is upgraded with a bypass system (3) connecting the container directly with the seawater jet-ejector system (4). With this bypass system (3), under-pressure can be created in the one-ton container (1) removing any contained residual chlorine gas. The removal of the residual chlorine gas can be controlled with the flow meter installed in the bypass system (3). As an extra control measure, a sample point (5) is installed in the effluent of the seawater jet-ejector system (4). If the flow meter of the bypass system (3) indicates that there is no more residual chlorine gas present, the second dosing valve is carefully opened for air ventilation of the one-ton container (1). The vented chlorine container is then disconnected from the chlorine discharge system, rinsed with water and scrapped in pieces with a torch, as shown in Figure 9.3.

Figure 9.3: The rinsing and scrapping of the one-ton containers

The discharge of the chlorine containers is performed in two phases. In the first phase, the chlorine containers with dosing valves in good conditions and containers with broken and or removed dosing valves are disposed of the residual chlorine gas and scrapped. In the second phase, the chlorine one-ton containers with damaged dosing valves, presenting a high safety and environmental hazardous risk potential, are discharged. For the discharge of the chlorine containers with damaged dosing valves an innovative dosing cap is designed and the hood with vent valve of the emergency kit B for one ton container were adapted according to the new design to remove the chlorine gas through the drain plug [9.11]. This new dosing cap is schematically illustrated in the Figures 9.4.

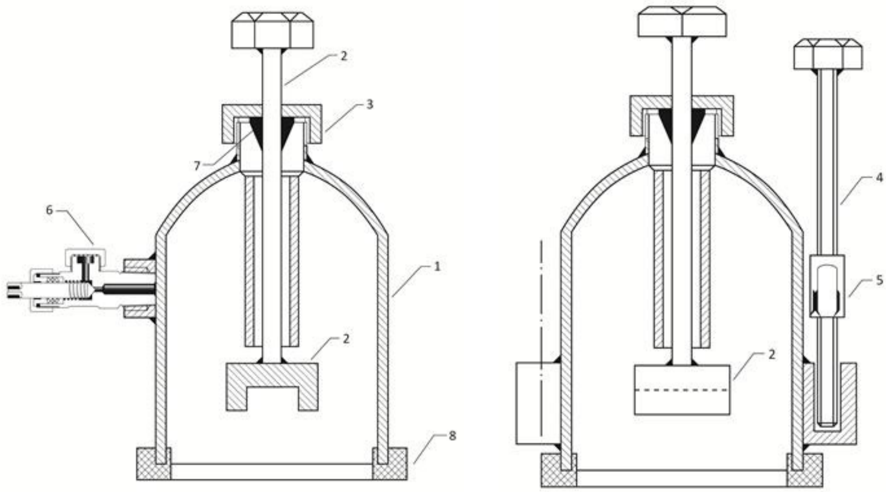


Figure 9.4: The schematic of the special dosing hood assembly

The specifications of the main components of the dosing hood assembly are as follows:

1. The hood assembly with vent valve
2. The wrench socket to rotate the plug
3. The nut with a conical seal to tighten the wrench socket
4. The cab screw
5. The yoke to fasten the hood to the container
6. The dosing valve
7. The conical Teflon gasket
8. The sealing gasket

For the disposal process, the personnel wearing total encapsulated gas suit cracked loosen the drain plug with a wrench, fit the wrench socket to the drain plug and connect the hood assembly to the container by means of a chain connected to the yoke of the cap screw (4). With the cap screw, the hood assembly (1) is further firmly tightened to the container. The nut (3) is then firmly hand tightened to seal the wrench socket (2) to eliminate chlorine gas leakage. After installation, the hood assembly (1) is connected to the chlorine disposal system to start the disposal process of the chlorine in the cooling water channel.

Figure 9.5: The installation of the special designed hood assembly

In Figure 9.5, the installation of the disposal hood assembly and the container connected to the chlorine disposal system are illustrated. As indicated in Figure 9.5, one of the most important aspects of the chlorine discharge process is complying with all the necessary safety precautions as mandatory for a safe execution as will be described in the following sections.

Health, safety and environmental aspects of the chlorine discharge process

Notwithstanding omission of the necessary regulation of the Island of Aruba one of the stringent objectives with respect to the development and execution of the disposal process are the safety, health and environmental aspects. With respect to the safety and health aspects, a Plan of Action is concretized in cooperation with KEMA N.V. and in cooperation with the Governmental Departments of concern such as the departments of Technical Inspection, the Fire Fighting and the Industrial Health Care. This plan of action includes the procedures for the save handling, transportation and disposal process especially for the disposal of chlorine gas from the containers with damaged valves. KEMA and AKZO-Arnhem/Amsterdam, as a requisite approved these procedures [9.10]. As further safety and health measures total encapsulating gas suit and self-contained breathing apparatus were available and used by the personnel during disposal of high risk one-ton containers to prevent exposure to possible escape of chlorine gas as shown in Figure 9.5.

With respect to the environmental aspect, a simple estimation of the residual chlorine concentration in the outlet of the cooling seawater channel of the Power House shows that the above designed process is environmental friendly. During the chlorine discharge activity, the normal flow of the cooling seawater for the turbine condensers of the Power House of W.E.B. Aruba N.V. is about 14.400 m^3 per hour. The seawater intake pump of the decommissioned Aquanova #3 evaporator has a capacity of 1.800 m^3 per hour. The dilution factor in the outlet channel is thus nine. At a maximal dosing rate of 7.5 kg chlorine per hour the chlorine concentration in the seawater feed is 4.07 ppm resulting in a chlorine concentration of 0.45 ppm in the outlet of the cooling water channel going to the nearby lagoon. In this calculation, actually the consumption of chlorine is not taken into account. During the disposal process, the maximal dosage rate is maintained at 6 kilogram per hour resulting in an estimated discharge concentration of 0.36 ppm of residual free chlorine in the seawater effluent of the cooling seawater channel. In general, a concentration of free chlorine lower than 0.5 ppm is considered not harmful for living organism in seawater [9.12].

It is worth mentioning that the cooling water is further diluted in the lagoon and actually free chlorine was not detectable in samples taken at a distance of one and a halve meter from the discharge point in the lagoon.

During the chlorine disposal process of the one-ton containers with high-risk valves, a seawater spray system is used in cooperation with the Fire Fighting Department of Aruba as an emergency system for eventual leakages creating a water curtain to pull down and neutralize any cloud of escaped chlorine gas. This seawater spray system is illustrated in Figure 9.6.

Figure 9.6: The chlorine disposal system with the seawater curtain

Even though chlorine is known as a very aggressive, toxic, health threatening and environmentally hazardous chemical component, safe handling is guaranteed taking into account the characteristic properties of chlorine and the safety measures to be taken. Therefore, the backgrounds of all the developed and implemented disposal procedures were the toxicity, physical and chemical properties of chlorine.

The financial aspect of the chlorine disposal project

The chlorine disposal cost according to the proposal of the ERC Company specialized in chlorine disposal is estimated at AWG. 390,000.00. The total cost of the disposal project as executed by W.E.B. Aruba N.V. is AWG 58,586.00, resulting in a saving of {(AWG.390,000.00 – AWG 58,586.00)/AWG390,000.000} * 100% = 85%. Following, a short financial statement of the chlorine disposal project is given in Table 9.2.

Table 9.2: A short financial statement of the chlorine disposal project [9.10]

Activity	Cost AWG.	Subtotal AWG.	% of total
A: Repair and upgrading chorine disposal system			
A_1: The work shop department	1,583.00		
A_1:The Electrical department	310.00		
A_1: The Water Production Department	450.00		
A_1: The Instrument Department	1.524.00	3,867.00	7
B: Process costs			
B_1: Electrical energy consumption	8,775.00		
B_2: Fire fighting	5,300.00		
B_3: Operation costs	21,855.00	35,660.00	60
C: Cost of safety materials			
C_1: Personnel protective gear	19,059.00	19,059.00	33
	Total cost	58,586.00	

Cost for material and personnel are included

As can be seen form Table 9.2 the cost for upgrading the chlorine discharge system, operational and safety are respectively 7%, 61% and 33% of the total project cost.
It is worth mentioning that the disposal of the chlorine one-ton containers is successfully executed in the period of July 1992 to October 1992 without any safety and environmental incident.

9.3 An innovative CO_2 desorption to eliminate sulfuric acid in MSF technology

Toward a step wise CO_2 desorption method for scale inhibition

In the process of eliminating the use of sulfuric acid as scale inhibitor in the MSF evaporators at W.E.B. Aruba N.V. a conceptual design is made of a step wise carbon dioxide (CO_2) desorption tower to remove CO_2 out of the seawater with steam and or vapor as a stripping phase to inhibit scale formation. The conceptual design is based on the principal of transfer units where after some transfer units fresh steam and or vapor is used as a stripping phase to promote the removal of CO_2 from the seawater [9.13, 9.14]. The objectives of the new design are:

- The environmental friendly scale inhibition in the MSF evaporation technology
- The elimination of concentrated sulfuric acid as scale inhibitor in MSF evaporators
- The increase of safety, health and environmental aspects
- The increase of efficiency of MSF evaporators
- The decrease of corrosion in MSF evaporators

Scale formation in MSF evaporators with recirculation brine

Seawater has a total alkalinity of bicarbonates and carbonates of approximately 120 ppm as calcium carbonate. As already explained in Chapter 5 calcium carbonates precipitate out of the bulk of seawater and deposit on the heat transfer surfaces with the following results:

- Decrease of heat transfer
- Decrease of efficiency
- Blockage of the long tubes
- Decrease of production

To inhibit scale formation in MSF evaporators with recirculation brine the following technologies are commonly used:

- The dosing of concentrated acid in the makeup seawater and removal of the liberated CO_2 in the deaerator.
- The dosing of an organic polymer or polyphosphates that mitigates the formation and deposition of scale by crystal deformation and dispersing. These are known as High Temperature Antiscalants (HTA).

The new method for scale inhibition

In seawater, the bicarbonates and carbonates are in chemical equilibrium with the carbon dioxide dissolved in seawater according to the following chemical reaction:

$$2HCO_3^- \Leftrightarrow CO_2 + CO_3^{2-} + H_2O \quad (9.1)$$

This chemical reaction can be forced more in the direction of the carbon dioxide production by:

- Chemically: by pH reduction true acid dosing
- Physically : true pressure reduction and temperature increase

The new technology is based on the physicochemical shifting of the chemical equilibrium in the direction of carbon dioxide in a step-wise carbon dioxide desorption tower as illustrated in Figure 9.13.

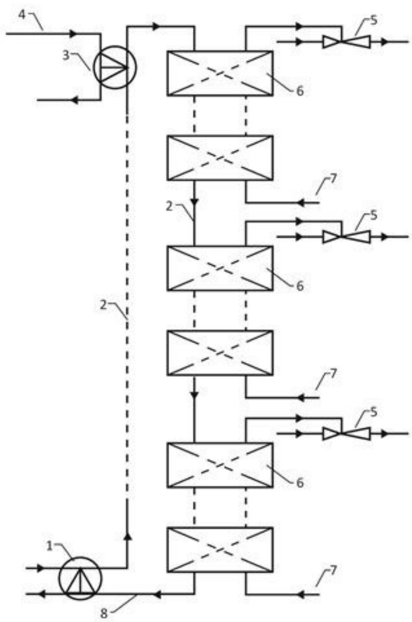


Figure 9.13: The schematic of the Carbon dioxide desorption tower

The specification of the process flows and process components in Figure 9.13 are as follows:

1. The seawater feed pre-heater
2. The seawater feed of the desorption tower
3. The steam seawater heater
4. Low pressure steam flow
5. The ejector system
6. Transfer unit
7. The stripping steam /vapor.
8. The degassed seawater stream

The conceptual design is as stated above a step wise CO_2 desorption tower based on the principle of transfer units (6) where fresh steam or vapor (7) is used after several transfer units to enhance the desorption of CO_2 out of the seawater stream (2). The seawater stream (2) is preheated in the heater (1) with degassed seawater stream (8) coming from the transfer units and with condensing steam in the heater (3). The stripping steam (7) is removed from the transfer unit combination (6) through an ejector system (5). The carbon dioxide gas acidified the vapor or steam (7) which will enhance the decomposition of bicarbonates in the gas-liquid interface [9.15]. To enhance carbon dioxide desorption efficiency, a fluidized bed desorption column is conceptually designed as described in the following section.

The development of the carbon dioxide fluidized bed desorption tower

For an efficient desorption of CO_2 out of the seawater a conceptual design is made of a fluidized heater-tray desorption tower, as shown in Figure 9.14.

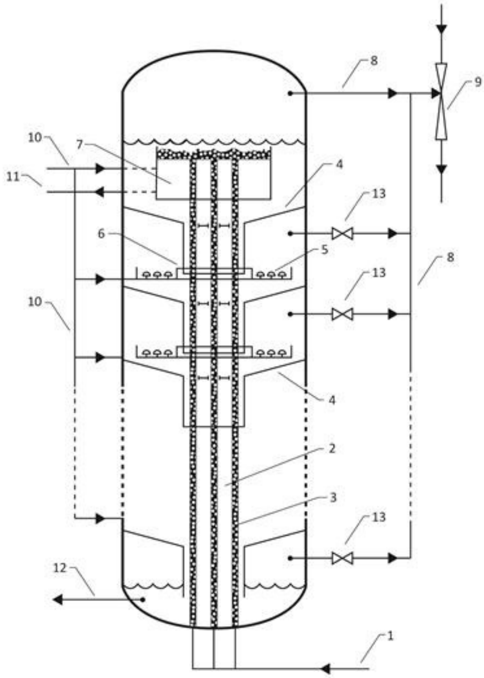


Figure 9.14: The conceptual design of the fluidized bed-tray desorption column

The specification of the process flows and process components in Figure 9.14 are as follows:

1. The seawater feed to the carbon dioxide desorption tower
2. The fluidized bed tube heat exchanger
3. Tube with fluidizing particles
4. Down comer
5. Bubble cap tray
6. Tray weir
7. The steam heat exchanger
8. Venting line
9. Ejector system
10. Low pressure steam flow
11. Heat exchanger condensate
12. De-carbonated seawater
13. Control vent valves

In this conceptual design the seawater stream (1) is pumped upwards in a tube bundle (2) with fluidizing particles (3) and is preheated after each transfer unit with hot seawater (12) flowing along the outside of the tube bundle in a special down comer (4). In the last transfer unit (7) the seawater feed is heated with condensing steam (10). The downwards flowing seawater (12) flows in a down comer (4) through an overflow weir across a tray plate (5) and is degassed with steam or vapor. The vent gasses (8) are withdrawn out of the desorption column with steam or vapor (10) through an ejector system (9). With the valves (13) the pressure is controlled after the transfer units. In addition, a conceptual design is made of a special sieve plate based on a special plate to create the effect of pressure reduction and suction by means of turbulence where the gas phase does not have to break through the liquid phase but is withdrawn by the liquid phase by means of eduction, improving the efficiency of the sieve. This sieve plate is given the name of Cavitation-Eduction plate (CE-plate). This CE-plate is illustrated in Figure 9.15 and in Figure 9.17.

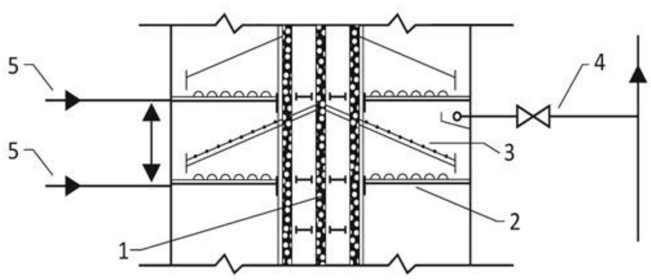


Figure 9.15: The Cavitation-Eduction tray plate

The specification of the process flows and process components in Figure 9.15 are as follows:

1. Tube bundle with fluidizing particles
2. The tray plate
3. The CE-sieve plate
4. Venting system
5. Low pressure steam flow

The tray plate-fluidization transfer unit is illustrated in Figure 9.16. In this transfer unit, the preheated seawater flows in the down comer (4) shell side along the tube bundle with the fluidizing particles (1) across the tray plate to the next transfer unit. CO_2 is removed with the vent flow (6) through the venting system (5).

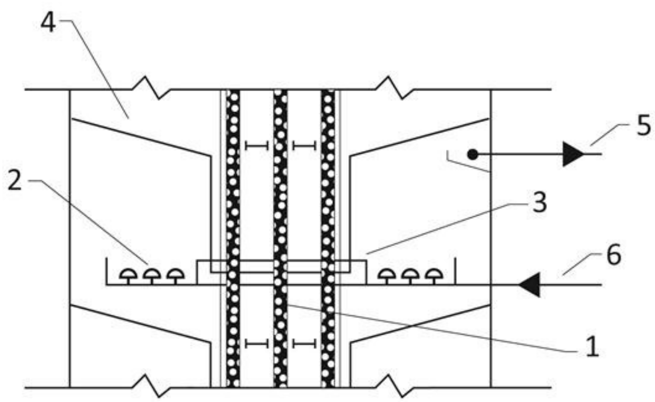


Figure 9.16: The tray plate fluidization transfer unit

The specification of the process flows and process components in Figure 9.16 are as follows:

1. Tube bundle with fluidizing particles
2. The tray plate
3. The tray weir
4. Down comer
5. Venting system
6. Vent flow

The transfer unit consisting of the combination CE sieve plate, the tray plate and the tube bundle with fluidizing pipe bundle is illustrated in Figure 9.15. In this transfer unit, the warm seawater flows over the CE- sieve plate (3) to the tray plate (2) and from here to the next transfer unit. The stripping steam flowing through the tray plate flows through the perforations of the CE plate (3) and is removed through the venting system. An alternative of this tray plate fluidization transfer unit is illustrated in Figure 9.17.

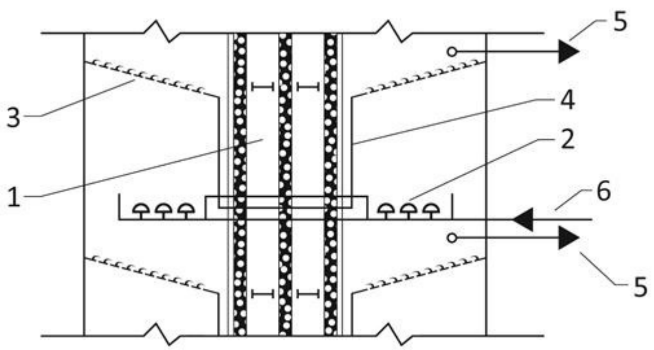


Figure 9.17: The Combined Cavitation Eduction and tray plate

The specification of the process flows and process components in Figure 9.17 are as follows:

1. Tube bundle with fluidizing particles
2. The tray plate
3. The CE-sieve plate
4. Down comer
5. Venting system
6. Vent flow

This transfer unit consisting of a combination of the tray plate, CE-sieve plate and the tube bundle with fluidizing particles is practically the same as the transfer unit shown in Figure 9.16 with the difference that the upper side of the down comer is foreseen of a CE-sieve plate (3). In addition to the fluidized bed concept, a conceptual design of a packed bed desorption tower is also made as illustrated in Figure 9.18.

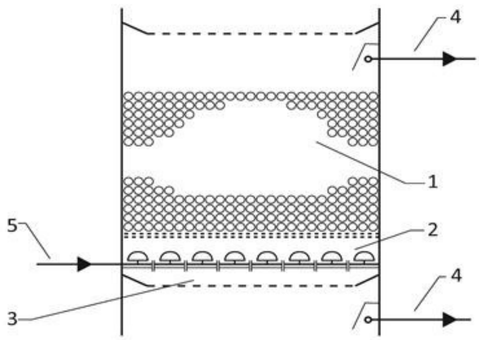


Figure 9.18: The packed bed transfer unit

The specification of the process flows and process components in Figure 9.18 are as follows:

1. Packed bed with particles
2. The steam distributor
3. The liquid distributor
4. Venting system
5. Low pressure steam flow

If efficient CO_2 desorption is possible with only pressure reduction the transfer units can consist simply of a packed bed with a packing material with a high specific transfer surfaces. The stripping steam is delivered through the steam distributor (2) and flows through the bed and is removed from the packed bed by means of the venting system (4) connected to an ejector-system.

The preheated seawater flows downwards across the packing material and through the liquid distributor (3) to the next transfer unit.

Advantages of the new scale inhibition method

This conceptual design of the carbon dioxide desorption for the elimination of concentrated sulfuric acid as scale inhibition in MSF evaporators has the following advantages:

- An environmental friendly elimination of the use of concentrated sulfuric acid as a scale inhibitor in MSF evaporators
- With an efficient design the cost are comparable with use of sulfuric acid
- An efficient heat transfer due to the fluidization in the pipe bundle
- An efficient mass transfer due to the combination of the Cavitation-Eduction tray plate transfer unit
- The fluidizing system mitigates biofouling and scale formation in the pipe bundle
- Efficient MSF operation, because of the possibility to warm up the seawater make up, can be maintained with even fouled heat recovery section together with a clean condenser and a higher seawater flow through the condenser.

9.4 A new hybrid Osmosis Reverse Osmosis (ORO) desalination process

Toward developing the Osmosis Reverse Osmosis desalination process

As already mentioned in the preceding chapters, desalination of seawater is becoming worldwide an important process for the production of drinking water to prevent the shortage of drinking water in arid areas. Traditionally the thermal desalination technology is applied, from which the MSF and the MED evaporators are the most important. The reverse osmosis membrane technology introduced in the mid-1950s has taken since the 1990s a market conquering position, especially due to new development in the area of the membrane technology and the energy recovery systems [9.16]. This desalination technology better known as the Seawater Reverse Osmosis (SWRO) is now together with the MSF technology the largest seawater desalination processes for the production of drinking water. The desalination of seawater is still a costly process and everywhere in the world, attempts are still being made to develop more efficient and economic desalination processes. The last years the osmosis process introduced in the beginning of the 1950s, nowadays better known as the Forward Osmosis is getting more attention. In this section, an innovative hybrid process is described consisting of an Osmosis process unit and a Reverse Osmosis process unit for the desalination of seawater.

The Osmosis process

Osmosis is a natural phenomenon in which water is transported by diffusion from a diluted solution to a more concentrated solution until equilibrium is reached.

The diffusion transport takes place through a semi permeable membrane that separates the two solutions. Actually, the concentrated solution is diluted in this process. The driving force in this physical transport phenomenon is the higher chemical thermodynamic potential of the diluted solution with respect to concentrated solution. The equilibrium is reached at a certain pressure difference between the diluted and the concentrated solution. This pressure difference is called the osmotic pressure. With this process, fresh water can be drawn from seawater by means of a more concentrated solution having a higher osmotic pressure than seawater. With the use of a suitable solution, where the chemical components can be reversibly recovered from the diluted solution for reuse, fresh water can be economically produced from seawater. The use of a solution of ammonia bicarbonate (NH_4HCO_3-solution) as the concentrated draw solution for fresh water is a well-known example [9.17]. The concentrated solution in the osmosis process is further denoted as the permeation solution in this description. The dissolved chemical components NH_4^+ and HCO_3^- are recovered as ammonia gas NH_3 and carbon dioxide gas CO_2 for reuse in the permeation solution by heating of the diluted permeation solution.
The necessary energy for this osmosis process is the osmotic pressure of the permeation solution and the thermal energy for the recovery of the necessary chemical components. This osmosis process has lower energy consumption and a higher recovery rate and does not need intensive seawater pretreatment as the reverse osmosis process described below [9.18].

The Reverse Osmosis process
In the natural osmosis process as described above, fresh water is transported by diffusion through a semi permeable membrane from the diluted solution to the concentrated solution. Because of this natural phenomenon, a pressure difference is established between these two solutions separated by a semi permeable membrane with the higher pressure at the side of the concentrated solution. By applying a pressure on the concentrated solution higher than this osmotic pressure, fresh water can be transported in the opposite direction to the side of the diluted solution. In accordance to this process, fresh water can be produced by means of a semi permeable membrane from seawater by applying a pressure to the seawater higher than its osmotic pressure. This is the principle of the reverse osmosis membrane technology, Sea Water Reverse Osmosis (SWRO), for the desalination of seawater. For the desalination of seawater with the reverse osmosis technology pressures in the range from 60 to 75 bar are necessary [9.16].

The pretreatment of the seawater is of utmost importance for the Seawater Reverse Osmosis process to prevent scale formation of inorganic chemical components and marine biofouling on the membrane surfaces. The physical pretreatment consist of conventional filtration by means of sand filters and micro filters and the application of the new membrane filtration technology such as nano-filtration and ultra-filtration. The chemical pretreatment consist of the application of chemicals for the prevention of scale formation and disinfectants to prevent marine biofouling and chemicals for the boron reduction. An innovative conceptual hybrid desalination process has been developed based on the osmosis process with a pure concentrated sodium chloride solution as the draw solution and the reverse osmosis process to desalinate the diluted sodium chloride solution of the osmosis process. A detailed description of this hybrid osmosis-reverse osmosis process is given in the next section.

The hybrid Osmosis and Reverse Osmosis (ORO) desalination process

The desalination of seawater by means of the Reverse Osmosis membrane technology at high pressure has to cope with many scaling and fouling problems of the membranes. This fouling process is caused by precipitation of salts of soluble divalent and trivalent anions and cations naturally present in seawater. The salts of monovalent ions are practically all soluble and do not precipitate. The microbiological fouling of the membranes is a frequent occurring problem. In addition, the boron normally present in the seawater is according to the World Health Organization (WHO) guidelines at a concentration higher than 0.3 ppm in drinking water a threat for the environment and human health. In the desalination process of a pure sodium chloride solution with the Reverse Osmosis technology the fouling of the membranes by scaling, microbiological fouling and the boron problem is minimized and or eliminated. The ORO process, a hybrid combination consisting of an Osmosis process unit and a Reverse Osmosis unit makes this process possible using a concentrated sodium chloride solution as the permeation solution for the Osmosis process unit. The Reverse Osmosis unit is applied to recover the concentrated permeation solution for the Osmosis process unit and for the production of drinking water. In general, the Reverse Osmosis process is not considered an adequate option for the recovery of the concentrated sodium chloride solution needed for the Osmosis process unit due to the required high working pressure, being even higher than with seawater desalination [9.17]. In this description an explanation is given of the ORO process that is quite more energetic favorable. The conceptual design of the hybrid ORO desalination process is based on the recirculation of a portion of the permeate of the Reverse Osmosis process unit [9.19, 9.20]. The recirculation of the permeate serves to further dilute the effluent of the Osmosis process unit to a concentration that is practically almost equal to the concentration of the seawater. A simplified schematic process diagram of the hybrid ORO process is illustrated in Figure 9.19.

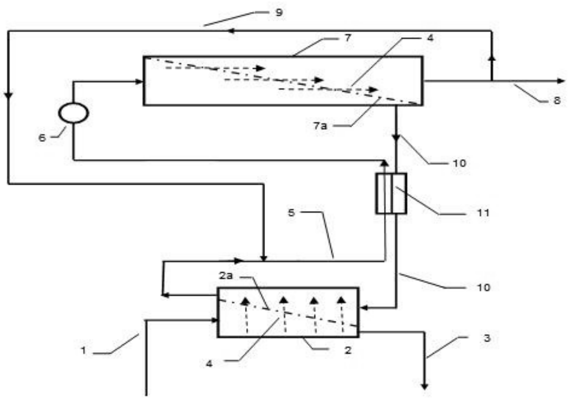


Figure 9.19: A schematic process diagram of the hybrid ORO process

The specification of the process flows and process components are as follows:

1. The seawater feed to the Osmosis process unit
2. The Osmosis process unit; 2a osmosis semi-permeable membrane
3. The seawater effluent of the Osmosis process unit
4. The fresh water flow
5. The feed flow of the Reverse Osmosis process unit
6. The booster pump
7. The Reverse Osmosis process unit; 7a reverse osmosis permeable membrane
8. The permeate of the Reverse Osmosis process unit
9. The recirculation permeate flow
10. The concentrate flow of the Reverse Osmosis process unit
11. The energy recovery system

As shown in Figure 9.19 fresh water (4) is extracted from the seawater flow (1) through a semi-permeable membrane (2a) in the Osmosis process unit (2) by means of the concentrate flow (10) coming from the Reverse Osmosis process unit (7).
This sodium chloride solution concentrated in the Reverse Osmosis process unit is used as the permeation (draw) solution. The concentrated seawater flow (3) is pumped back to the sea. The transport of fresh water continues until the sodium chloride solution has reached a maximum dilution degree. This diluted permeation solution from the Osmosis process unit (2) is the feed flow (5) for the Reverse Osmosis process unit (7). For an efficient operation of the Reverse Osmosis process unit, the feed flow (5) should have practically almost the same concentration as seawater (1). The working pressure of the Reverse Osmosis unit (7) is then practically the same as a normal SWRO unit. By recirculation of a part of the permeate (9) the Reverse Osmosis feed flow (5) can further be diluted.

The amount of the recirculation flow (9) depends on the permeation capacity or the dilution degree of the Osmosis process unit (2). Depending on the retention capacity of the osmosis membrane the diluted permeation solution of the Osmosis process unit contains few boron, divalent and trivalent anions and cations. The feed flow (5) of the Reverse Osmosis process unit (7) is pressurized to the desired working pressure by the energy recovery system (11), for example a pressure exchanger, and by the booster pump (6). In the energy recovery section (11) the high pressure of the concentrate flow (10) is utilized. After exchanging energy in the energy recovery system the concentrate flow (10) is used as feed flow for the Osmosis process unit (2). With a suitable Variable Frequency Device (VFD) the pressure variations of the combination booster pump and pressure exchanger can be optimized in such a way making the application of high pressure pump superfluous especially for the startup of the Reverse osmosis unit. In the Reverse osmosis process unit (7) the feed flow (5) is separated through the semi-permeable membrane (7a) into a concentrate flow (10) and a permeate flow of fresh water (8). For the production of high quality water with a concentration of Total Dissolved Solids (TDS) in the range of 10 to 15 parts per million (ppm) a two pass SWRO consisting of a high pressure SWRO and a low pressure BWRO is normally utilized. The first pass, the high pressure SWRO unit produces permeate with a concentration in the range of 350 to 600 ppm TDS. This permeate of the first pass is then further desalted to a concentration in the range of 10 to 15 ppm TDS in the second pass normally called the Brackish Water Reverse Osmosis (BWRO).

The ORO hybrid alternative with a two-pass Reverse Osmosis process unit

Figure 9.20 illustrates a simplified schematic of the hybrid ORO process with a two-pass Reverse Osmosis consisting of a high-pressure process unit and a low-pressure BWRO process unit.

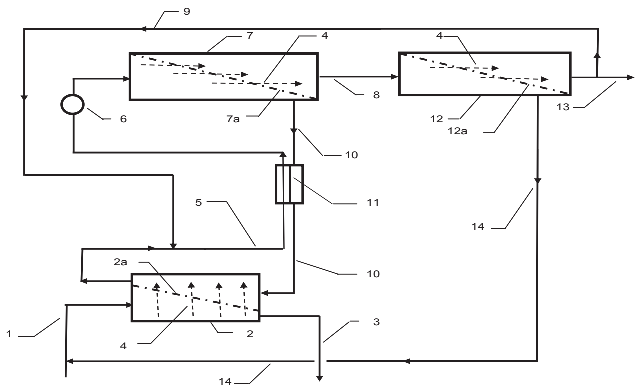


Figure 9.20: A schematic of the hybrid ORO process diagram with a two-pass Reverse Osmosis process unit

The specification of the process flows and process components are as follows:

1. The seawater feed to the Osmosis process unit
2. The Osmosis process unit; 2a osmosis semi-permeable membrane
3. The seawater effluent of the Osmosis process unit
4. The fresh water flow
5. The feed flow of the Reverse Osmosis process unit (diluted NaCl solution)
6. The booster pump
7. The Reverse Osmosis process unit; 7a reverse osmosis semi-permeable membrane
8. The permeate of the Reverse Osmosis process unit
9. The recirculation permeate flow
10. The concentrate flow of the Reverse Osmosis process unit
11. The energy recovery system
12. The BWRO process unit; 12a reverse osmosis semi-permeable membrane
13. The permeate flow of the BWRO process unit
14. The concentrate flow of the BWRO process unit

This alternative is basically the same as the hybrid ORO process described above with the exception that the permeate flow (8) of the Reverse Osmosis process unit (7) is separated by means of the semi-permeable membrane (12a) in the low pressure BWRO process unit (12) in a permeate flow (13) of high quality fresh water and a concentrate flow (14). A portion of the permeate (9) of the BWRO process unit (12) is recirculated for dilution purposes of the feed flow (5) of the Reverse Osmosis process unit (7). An advantage of this alternative is that the concentrate (14) of the BWRO process unit (12) is used to dilute the seawater flow (1) entering the Osmosis process unit (2) increasing the water permeation capacity of this process unit. Consequently the recirculation flow (9) can be reduced due to the higher dilution of the feed flow (5) because of this higher permeation capacity and the lower salt concentration of the permeate flow (13) of the BWRO process unit (12) resulting in higher water production capacity. The concentrate flow (14) can also be used to dilute the feed flow (5), not indicated in Figure 9.20, but the dilution of the seawater is preferred to increase the concentration difference between the seawater feed and the permeation solution and so enhancing permeation of fresh water. An alternative for this hybrid ORO desalination processes with and without the two-pass Reverse Osmosis process unit are illustrated respectively in Figure 9.21 and Figure 9.22.

The ORO hybrid with dosage of a suitable chemical to increase osmotic pressure

The main purpose of this alternatives is to minimize and or eliminate the recirculation permeate flow (9). This alternative also gives the possibility to decrease the working pressure of the Reverse Osmosis process unit (7), further increasing the energy efficiency.

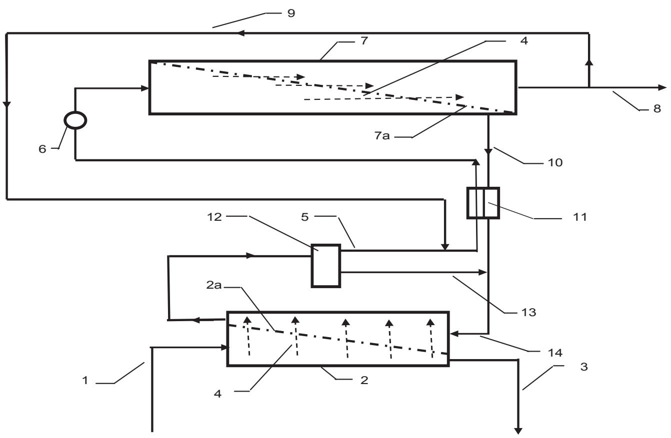


Figure 9.21: A schematic presentation of the hybrid ORO process with a separation process unit

The specification of the process flows and process components are as follows:

1. The seawater feed to the Osmosis process unit
2. The Osmosis process unit; 2a osmosis semi-permeable membrane
3. The seawater effluent of the Osmosis process unit
4. The fresh water flow
5. The feed flow of the Reverse Osmosis process unit
6. The booster pump
7. The Reverse Osmosis process unit; 7a reverse osmosis permeable membrane
8. The permeate of the Reverse Osmosis process unit
9. The recirculation permeate flow
10. The concentrate flow of the Reverse Osmosis process unit
11. The energy recovery system
12. The separation unit for removal of the chemical components
13. The flow of removed chemical components
14. The feed flow to the Osmosis process unit

In this ORO hybrid the permeation solution is a diluted pure sodium solution with a concentration maximally equal to the concentration of the seawater flow (1). The osmosis process is now possible by adding a suitable chemical component (13) to this permeation solution to increase the osmotic pressure of the feed flow (14) of the Osmotic Process unit (2). In the Osmosis process unit, just as described above, fresh water (4) is drawn from the seawater flow (1). After the Osmosis process step the chemical component is removed from the diluted effluent in a separation process unit (12). The flow of the chemical components

(13) is added again to the concentrate flow (10) for reuse to increase the osmotic pressure of the permeation solution (14) for the Osmotic process unit. A prerequisite for a suitable chemical component is that it should be reversibly recovered from the diluted effluent of the Osmosis process unit (2) without being consumed. A solution of ammonia bicarbonate (NH_4HCO_3-solution) is an example of suitable chemical component to be used to increase the osmotic pressure. The dissolved chemical components NH_4^+ and HCO_3^- in the permeation solution are recovered as ammonia gas NH_3 and carbon dioxide gas CO_2 for reuse in the permeation solution by heating of the diluted permeation solution in the separation unit. In this alternative, the feed flow (5) to the Reverse Osmosis process unit (7) is after the separation unit a dilute sodium chloride solution with a salt concentration lower than seawater. The working pressure of the Reverse Osmosis process unit (7) is now lower that the working pressure of a conventional SWRO, resulting in an energetic more favorable desalination process.
Figure 9.22 illustrates in analogy with Figure 9.20 a simplified schematic of the hybrid ORO process with a two-pass Reverse Osmosis process unit and a separation process unit.

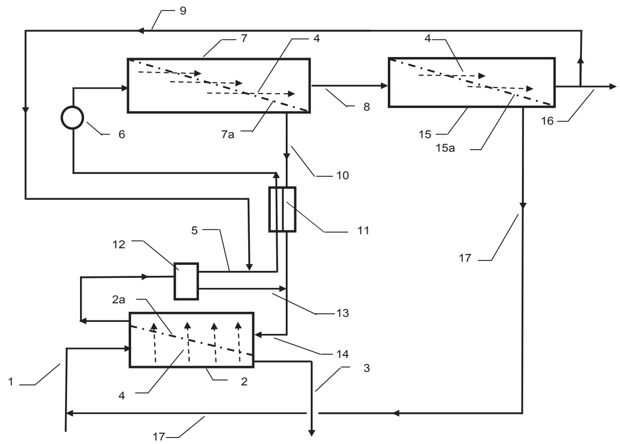


Figure 9.22: A schematic presentation of the hybrid ORO process with a two-pass Reverse Osmosis process unit and a separation process unit

The specification of the process flows and process components are as follows:
1. The seawater feed to the Osmosis process unit
2. The Osmosis process unit; 2a osmosis semi-permeable membrane
3. The seawater effluent of the Osmosis process unit
4. The fresh water flow
5. The feed flow of the Reverse Osmosis process unit
6. The booster pump
7. The Reverse Osmosis process unit; 7a reverse osmosis permeable membrane
8. The permeate of the Reverse Osmosis process unit

9. The recirculation permeate flow
10. The concentrate flow of the Reverse Osmosis process unit
11. The energy recovery system
12. The separation process unit for removal of the chemical components
13. The flow of removed chemical components
14. The permeation feed flow to the Osmosis process unit
15. The BWRO process unit; 15a reverse osmosis semi-permeable membrane
16. The permeate flow of the BWRO process unit
17. The concentrate flow of the BWRO process unit

This alternative has also the dilution advantage of the seawater flow (1) of the Osmosis process unit (2) with the concentrate (17) of the BWRO process unit (15) increasing the permeation capacity of the Osmosis process unit and decreasing the amount of chemicals to increase the osmotic pressure of the permeation solution. By minimizing or eliminating the recirculation permeate flow, the increased permeation capacity of the Osmosis process unit and decreasing the working pressure of the Reverse Osmosis process unit this alternative hybrid ORO process has a higher water production capacity and lower energy consumption per cubic meter of produced water than a conventional SWRO.

The ORO hybrid in combination with a saltpan and salinity gradient solar pond
The application of natural salt production for the preparation of the concentrated salt solution and the energy of a solar pond for the separation process for the chemical components makes this new hybrid ORO process more economical and energy efficient and environmental friendly. In combination with the natural salt production in saltpans, a salinity gradient solar pond of a pure sodium chloride solution can be constructed. Solar energy is transformed into heat and is stored in the lower concentrated bottom liquid layers of the salinity gradient solar pond. The concentration and the temperature of the salt solution are much higher in the bottom liquid layers. Temperatures in the range of 26 to 85 ^{o}C can be obtained in a salinity gradient solar pond [9.21]. The osmotic pressure of a solution is direct proportional to the concentration of the dissolved ions and with the temperature of the solution. The bottom liquid layers of a solar pond have therefore a high osmotic pressure making it suitable as a permeation solution for an osmosis process.
In Figure 9.23 a simplified schematic of the hybrid ORO process with a two pass Reverse Osmosis process unit in combination with a salinity gradient solar pond of pure sodium chloride solution and a saltpan for natural salt production is illustrated. In this alternative, the concentrated seawater effluent (3) from the Osmosis process unit (2) is directed to a saltpan (18) for the natural production of salt. A portion of the concentrate flow (10) of Reverse Osmosis process unit (7) is directed to the salinity gradient solar pond (17) of pure sodium chloride solution. A warm concentrated sodium chloride solution (15) from the

bottom liquid layer of the solar pond (17) is mixed with the concentrate flow (10) forming the warm concentrated permeation solution feed to the Osmosis process unit (2). This hybrid ORO process alternative is an environmental friendly desalination process with minimal waste flows. Optimizing this hybrid ORO process can lead to a high degree of a Zero Discharge process.

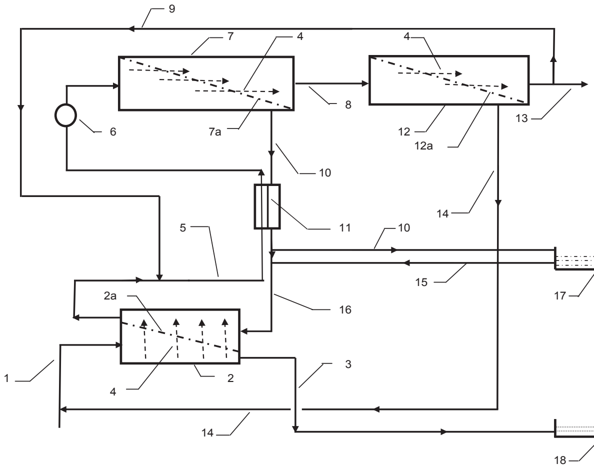


Figure 9.23: A schematic presentation of the hybrid ORO process with a two-pass Reverse Osmosis unit, a saltpan and a solar pond

The specification of the process flows and process components in Figure 9.23 are as follows:

1. The seawater feed to the Osmosis process unit
2. The Osmosis process unit; 2a osmosis semi-permeable membrane
3. The seawater effluent of the Osmosis process unit
4. The fresh water flow
5. The Feed flow of the Reverse Osmosis process unit
6. The booster pump
7. The Reverse Osmosis process unit; 7a reverse osmosis semi-permeable membrane
8. The permeate of the Reverse Osmosis process unit
9. The recirculation permeate flow
10. The concentrate flow of the Reverse Osmosis process unit
11. The energy recovery system
12. The BWRO process unit; 12a reverse osmosis semi-permeable membrane
13. The permeate flow of the BWRO process unit
14. The concentrate flow of the BWRO process unit
15. The warm concentrated flow from the salinity gradient solar pond
16. The permeation feed flow to the Osmosis process unit
17. The salinity gradient solar pond of pure sodium chloride solution
18. The saltpan for the natural production of salt

In the alternatives with a separation process unit, as illustrated in the Figures 9.21 and 9.22, the heat of the salinity gradient solar pond can be used in the separation process unit for the recovery of the chemical components. It is further worth mentioning that with the use of the high osmotic pressure of the warm concentrated solution of the salinity gradient solar pond, the use of a chemical component and the separation process will be superfluous. Due to the absence of divalent and trivalent ions in this new hybrid ORO desalination process, boron eventually present in the feed flow can be easily removed with sodium hydroxide without the risk for precipitation of divalent or trivalent ions salts on the surfaces of the Reverse Osmosis membranes. The use of an antiscalant to prevent scaling is minimal due to absence of before-mentioned chemical components. Because of practically low fouling tendency, the chemical Clean in Place (CIP) as with conventional SWRO is not necessary, drastically increasing both the lifetime and operational availability of the membranes making this process more economical.
Designing the hybrid ORO desalination process with an optimal flow rate across the membranes, the surfaces of the membranes will be maintain clean by the removal of possible deposits on the surfaces by the turbulent action of the liquid phase moving with a relatively high velocity across the membrane surfaces. The turbulent flow alongside the membrane surface causing this membrane cleaning effect is called the *Critical Cross Flux* (CCF). By applying a pure concentrated sodium chloride solution, possibly precipitated sodium chloride salts due to super saturation because of concentration polarization at the membrane surfaces are easily removed with a warm water rinse in either the Osmosis process unit as in the Reverse Osmosis process unit. This in contrast to the laborious Clean In Place process for the chemical cleaning of the membranes in a conventional SWRO with alternating low pH and high pH cleaning chemicals.

Advantages of the new hybrid ORO desalination process

- The working pressure of the Reverse Osmosis process unit is lower than the working pressure of a conventional SWRO because of the possibility of using a pure sodium chloride solution with a concentration lower than seawater. The new hybrid ORO desalination process has because of this fact more favorable energy consumption than the conventional SWRO.
- Because of the use of a pure sodium chloride permeation solution the chemical and marine biological fouling of the membrane surfaces is practically nil.
- Boron eventually present in the feed is easily removed with sodium hydroxide dosing with practically no risk for precipitation of salts of divalent and or trivalent ions on the membrane surfaces.
- The Clean in Place (CIP) as with the conventional SWRO with alternating low pH and high pH chemicals is practically not necessary because of the very low fouling tendency in the hybrid ORO desalination process.

- In the new hybrid ORO desalination process the chemical cleaning of the surfaces of the membranes fouled with sodium chloride salts precipitated due to concentration polarization can simply be removed by rinsing with warm water.
- The use of antiscalant chemicals is practically not necessary because of the low risk for scaling because of the use of a practically pure sodium chloride solution for the feed of the Reverse Osmosis process unit.
- The design of the hybrid ORO desalination process at the Critical Cross Flux promotes the cleanliness of the membrane surfaces due to the turbulence action of the liquid flowing across the surface in both membrane process units.
- The reversible recovery of the chemical components to enhance the permeation capacity of the feed flow to the Osmosis process unit practically eliminates the recirculation of permeate for dilution of the feed flow to the Reverse Osmosis process unit making the ORO desalination process more economical than the conventional SWRO.
- With the low working pressure of the Osmosis process unit in the new hybrid ORO desalination process the pretreatment of the seawater feed is much simpler as compared with the conventional SWRO process.
- The new hybrid ORO desalination process in combination with a salinity gradient solar pond of pure sodium chloride solution and a saltpan for the natural production of salt is an environmental friendly process that can be optimized to a Zero Discharge process.
- Conventional SWRO processes can be converted to the new hybrid ORO desalination process without many retrofits.

9.5 An innovative chemical-free osmotic on line membrane cleaning process

Toward development of the osmotic on-line membrane cleaning process

The commercial application of the SWRO technology for the seawater desalination for the production of drinking water has conquered the last decennia globally an important place as one of the largest seawater desalination processes. Innovations in the membrane and energy recovery technology made the SWRO the most energy efficient process. For production of high quality drinking water, permeate of the high pressure SWRO pass with a concentration of 400-600 ppm Total Dissolved Solids is further purified in the second pass to a concentration of 10-15 ppm. This second pass is usually called the Brackish Water Reverse Osmosis (BWRO). Chemical and bacteriological fouling of membranes is still a frequently occurring problem despite intensive pretreatment of the seawater feed. Regular chemical cleaning is necessary to maintain a stable operation. The conventional periodically chemical cleaning consisting of circulation with a low pH and a high pH solution cleaning and alternatively rinsing with a surface active solution and sometimes a bio-dispersant is time consuming, laborious, costly and environment unfriendly. Besides that the membrane-trains of concern must be taken out of production for the cleaning process affecting plant availability. An introductory short description of the pretreatment of the seawater feed and the chemical membrane cleaning is given below.

The pretreatment of the seawater feed

For an efficient and effective membrane separation process, the surfaces on the membranes must be free of contaminants. The precipitation of inorganic chemical components due to super-saturation caused by concentration polarization at the membrane interface and the marine biological growth can drastically foul membrane surfaces and consequently reducing stable operation. Intensive seawater pretreatment may significantly mitigate membrane fouling. In this most important part of the membrane desalination process the physical and the chemical pretreatment can be distinguished. The physical pretreatment consist of the conventional filtration by means of multimedia sand filters, micro cartridge filters and the modern membrane filtration technology applying nano-filtration and ultra-filtration. The chemical pretreatment process consist of the dosing of chemicals to inhibit scale formation, coagulants and flocculants to enhance conventional filtration, continue or intermittent disinfectants to mitigate biofouling and chemicals to reduce the boron concentration. Despite optimal pretreatment of the seawater feed, in practice membrane microbiological fouling and scaling occurrences cannot be effectively prevented which make the frequent chemical membrane cleaning also an important part of the SWRO process.

The chemical cleaning of membranes

The prevention of membrane surface contamination is as described above very important for the maintenance of availability and stable operation of the SWRO desalination process. The chemical cleaning process, in the practical technical jargon well known as the Clean In Place (CIP), is next to the pretreatment of the seawater feed the most important part ensuring membrane surface cleanliness enhancing the membrane water separation process. The membrane surfaces are practically a suitable place where marine microorganisms can adhere and in this way build a biofilm. In the literature, it is known that in seawater present dormant microorganisms adhere on the membrane surfaces and because of the rich nutrient environment especially induced by the degradation products of the disinfection process become active and they proliferate causing membrane biofouling [9.22]. In the English literature, these dormant microorganisms are known as "*viable but not cultivable*" (VBNC) bacteria.

Chemical contamination of membrane surfaces is in principle caused by super-saturation of salts due to concentration polarization induced by the diffusion process in the interfacial area at the membrane surface [9.23, 9.24]. Especially alkaline scaling of bicarbonate and carbonate salts of bivalent ions takes place. Because of the continuous concentrating process of the seawater feed, the last membranes in the SWRO pressure vessel are more prone to scaling. The BWRO membranes are not susceptible for biofouling as the SWRO membranes have a high microorganism's retention. They are largely prone to alkaline scaling because of the high recovery rate and the high pH necessary for the boron removal. The periodical chemical cleaning of the SWRO membranes, depending on the biofilm forming potential of the seawater feed has a frequency of twice a month or two or three times a year. The chemical cleaning is very time consuming and laborious process consisting of alternatively off-line rinsing of the SWRO with BWRO feed, recirculation and soaking with a low pH solution, rinsing with BWRO feed, circulation with an anionic surface-active solution, rinsing with BWRO feed, recirculation and soaking with a high pH solution, rinsing with BWRO feed and finally startup of the SWRO train. The chemical cleaning process of one SWRO train may have a duration of two days and has further an enormous impact on the marine environment due to the high chemical consumption and is very costly. In this context a new innovative chemical-free process is developed for the on-line cleaning of the SWRO-BWRO membranes based on the osmotic process to loosen accumulated contamination on the membrane surfaces that further can be removed by means of the sweeping-away effect of the turbulent seawater feed flow at the Critical Cross Flux alongside the membrane surfaces. The principle of this new membrane cleaning process is based on inducing the osmotic process across the membrane surface by lowering the recovery rate and by increasing the temperature and the salt concentration of the seawater feed. The usage of carbon dioxide acidified product water of the re-mineralization process further significantly enhances the membrane cleaning process. In consequence, the BWRO membranes are on-line cleaned by lowering the recovery rate and rinsing the membranes with carbon dioxide acidified product water to effectively remove alkaline scale. This innovative chemical-free membrane cleaning process is in depth described in the following section.

The conceptual design of the osmotic on-line membrane cleaning process

The SWRO desalination technology as elaborated on above, frequently has to cope with membrane fouling problems. To prevent permanent membrane damage, water production is allowed until practically a pressure drop of approximately 0.2 bar across the membrane concentrate section is reached. When reaching this maximum pressure drop outage of the relevant SWRO train is necessary to chemical clean the membranes. Frequent chemical cleaning can significantly reduce membrane lifetime. As also mentioned above, the conventional chemical cleaning is laborious, costly and stressful for the environment. In this context, an innovative simple on-line membrane cleaning process is designed making the intensive chemical usage superfluous [9.25]. This process is very economical and environment-friendly by eliminating the chemical consumption and increasing the availability of the SWRO-BWRO process.

The basics of the osmotic membrane cleaning process

The guiding principle of this innovative environment-friendly and chemical-free osmotic membrane cleaning process is reducing the recovery rate until practically no permeate is produced. By reducing the recovery rate, the seawater feed pressure is automatically reduced through the variable frequency control system of the constant pressure regulation process. Figure 9.24 illustrates a schematic process diagram explaining the basic principles of this osmotic membrane cleaning process.

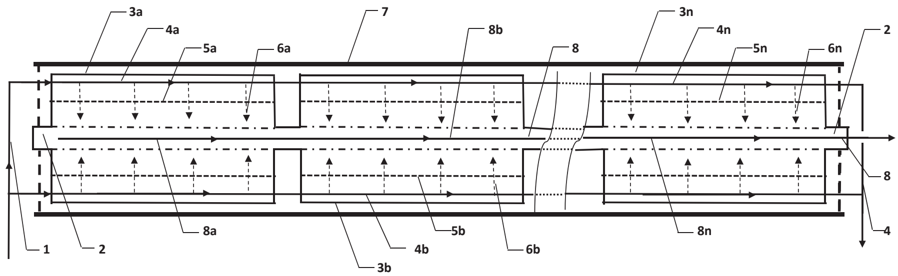


Figure 9.24 a

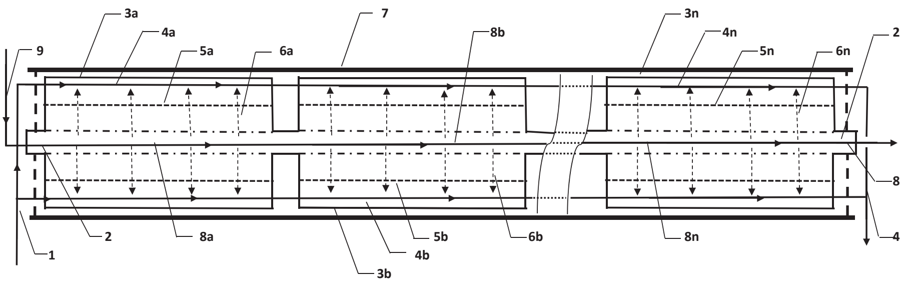


Figure 9.24 b

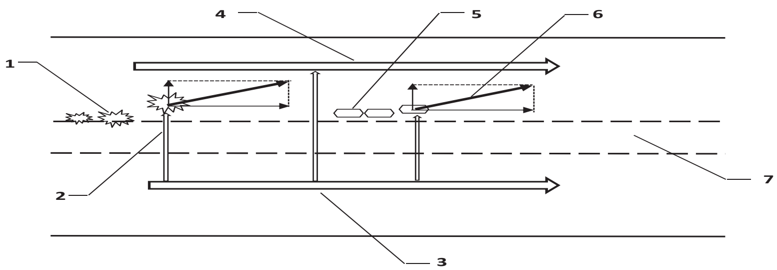


Figure 9.24 c

Figure 9.24: The basic principles of the osmotic membrane cleaning Process

The specification of the process flows and process components in Figure 9.24a and b are as follows:

1. The SWRO seawater feed flow.
2. The permeate collecting tube.
3. The membrane element (3a-3n).
4. The concentrate flow (4a-4n).
5. The semi-permeable membrane surface (5a-5n).
6. The osmotic fresh water flow (6a-6n)
7. The SWRO pressure vessel.
8. The permeate flow (8a-8n)
9. The product water acidified with carbon dioxide.

Figure 9.24c:
1. Microorganisms.
2. The osmotic fresh water flow.
3. The permeate flow.
4. The concentrate flow.
5. Chemical scales.
6. The resultant force.
7. The semi-permeable membrane.

As indicated in Figure 9.24a, during normal SWRO operation the seawater feed (1) is separated in the first membrane element (3a) through the semi permeable membrane (5a) in a fresh water permeate flow (6a) and a concentrated brine flow (4a).
This concentrate flow (4a) is further separated in the succeeding membrane elements (3b) to (3n) of the SWRO pressure vessel (7) through the semi permeable membranes (5) to (5n) in the permeate flows (6b) to (6n) and the concentrate flows (4b) to (4n). In a conventional SWRO pressure vessel, normally seven to eight membrane elements are installed. The fresh water flows (8a-8n) produced in the membrane elements are collected in the permeate-collecting tube (2) and transported to a buffer tank or a permeate header. These are not indicated in Figure 9.24a.
In a conventional SWRO, the concentrate flow (4) is directed to the energy recovery system for energy exchange with the seawater feed. Figure 9.24b illustrates schematically the basic principle of the innovative chemical-free osmotic membrane cleaning process. In this process, the recovery rate of the SWRO train is simply reduced until the working pressure equals the osmotic pressure of the seawater feed (1). In this situation, the dynamic osmotic equilibrium exists where there is no more a net transport of fresh water (6a) from the concentrate flow (4a) through the semi-permeable membrane (5a) of the membrane element (3a) to the permeate flow (8a) in the permeate collecting tube (2). Further reducing the recovery rate, consequently reducing the seawater feed pressure, the natural osmosis process will dominate and a net transport of fresh water (6a) will take place from the

permeate flow (8a) through the semi permeable membrane (5a) in the direction of the concentrate flow (4a).
This osmotic induced fresh water flow (6a) will diminish the concentration polarization and the contaminations on the membrane surfaces will be lifted up facilitating the removal by the turbulent concentrate flow (4a) alongside the membrane surfaces. By refreshing the permeate flow with a portion of the product water acidified with carbon dioxide, osmotic diffusion transport of acidic fresh water (6a) takes place through the semi-permeable membrane (3a) enhancing dissolution of alkaline chemical components due to the high solubility in low pH solution. The low pH fresh water alters the osmoregulation process of microorganisms enhancing the removal of biofouling. Figures 9.24c illustrates schematically this acidified fresh water's enhanced removal effect of contaminants.
The microorganisms and the chemical scales experienced a resultant force (6) in the direction away from the surface because of the lifting force of the fresh water osmotic flow ((2) and the shear stress of the concentrate flow (4) facilitating removal by the critical cross flux effect. The cleaning process of BWRO membranes is accordingly the same as the SWRO osmotic membrane cleaning process, however due to the high quality of the BWRO feed (SWRO permeate), BWRO membrane fouling consists mainly of alkaline scales, so rinsing with acidified product water will suffice for effective membrane cleaning.

The osmotic cleaning process with high temperature and concentrated seawater feed
The osmotic pressure of a salt solution is directly proportional to the salt concentration and the temperature. Increasing the salt concentration and the temperature of the solution will consequently increase its osmotic pressure. The application of this salt solution property can practically eliminate the technique of reducing the recovery rate promoting the practicality of on-line osmotic membrane cleaning process. Figure 9.25 illustrates schematically a process diagram of this osmotic membrane cleaning process.

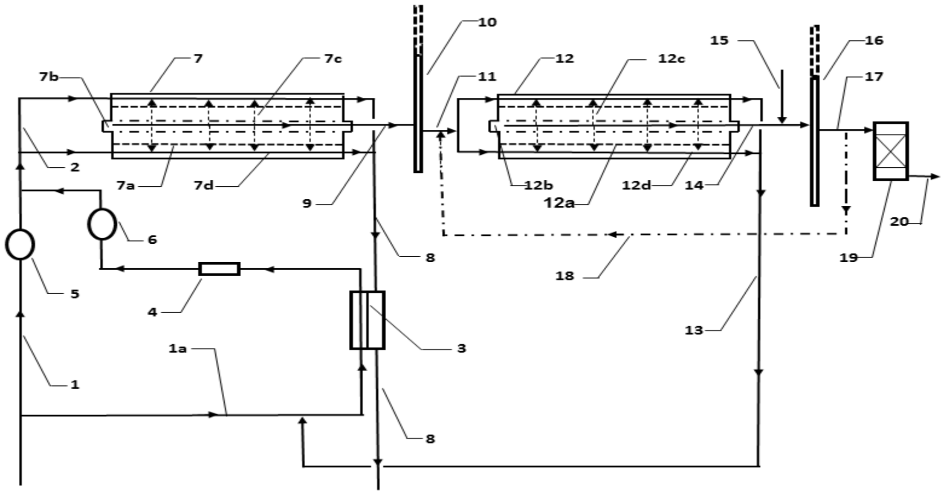


Figure 9.25: The high temperature and high concentration osmotic membrane cleaning process

The specification of the process flows and process components in Figure 9.25 are as follows:

1. The pretreated SWRO seawater feed. (1a seawater feed to ERI)
2. The pressurized SWRO seawater feed.
3. The energy recovery system (ERS)
4. The electrical heating element.
5. The high pressure seawater feed pump
6. The ERS booster pump.
7. The SWRO pressure vessel (7a semi-permeable membrane, 7b permeate collecting tube, 7c the osmotic fresh water flow, 7d the membrane concentrate flow)
8. The SWRO concentrate flow.
9. The SWRO permeate flow.
10. The SWRO permeate header.
11. The BWRO feed flow.
12. The BWRO pressure vessel (12a semi-permeable membrane, 12b permeate collecting tube, 12c the osmotic fresh water flow, 12d the membrane reject flow).
13. The BWRO reject flow.
14. The BWRO product water.
15. The carbon dioxide injection.
16. The acidified BWRO product water header.
17. The mineralization unit product water feed.
18. BWRO acidified rinse water feed
19. The drinking water mineralization unit.
20. The post-treated drinking water.

Figure 9.25 illustrates a two-pass reverse osmosis desalination process consisting of a high pressure SWRO (7) and a low pressure BWRO (12). In this two-pass SWRO-BWRO desalination unit, the high-pressure pump (5) pressurizes the pretreated seawater flow (1) to the required working pressure for the SWRO unit (7). The intake and the pretreatment section are for the sake of simplicity not illustrated in Figure 9.25. A portion of the seawater feed (1a) is directed to the low-pressure side of the energy recovery system where it is pressurized by the concentrate flow (8) of the SWRO unit (7) and the booster pump (6) to the required working pressure. In the high pressure SWRO unit (7) the pressurized seawater flow (2) is separated by the reverse osmotic water diffusion through the semi-permeable membrane (7a) in a concentrate flow (7d) and permeate (9) collected in the permeate collecting tube (7b).The permeate (9) is directed to a buffer tank or a header (10) of the BWRO feed water (11). In the BWRO unit (12) the feed water flow (11) is separated by the reverse osmotic diffusion of fresh water through the semi-permeable membrane (12a) in a reject flow (12d) and a high quality product water flow (14) collected in the permeate collecting tube (12b).

The reverse osmotic fresh water flow through the SWRO-BWRO membranes are also for the sake of simplicity not illustrated in Figure 9.25. For optimal energy efficiency, the BWRO reject flow (13) is directed to the low-pressure side of the energy recovery system (3). The product water (14) is acidified with carbon dioxide (15) for the re-mineralization process of the drinking water post treatment process and is pumped to the header or buffer tank (16) of the product water (17) from where it is pumped to the lime stone re-mineralization system (19). After the re-mineralization system, the drinking water (20) is pumped to the drinking water tanks. The above described water production process continuous until the maximum permissible high working pressure and pressure drop of the membrane concentrate side is reached due to chemical and microbiological fouling of the SWRO membranes surfaces (7a) and those of the BWRO membranes (12a). The SWRO-BWRO trains concerned are taking off-line for the periodic chemical cleaning of the membranes. In this innovative osmotic membrane cleaning process after reducing the recovery rate of the SWRO unit (7), the salt concentration of the seawater feed (2) is increased by altering the flow balance of energy recovering system (3) to the lag flow operation-mode of the pressure exchangers permitting more mixing with concentrate (8) increasing the conductivity of the seawater feed (1a). The electrical heater (4) increases the temperature of seawater feed (1a) with increased concentration. SWRO membrane usually can support temperatures up to 45 ^{o}C. The working pressure of the seawater feed (2) is not sufficient for the reverse osmotic water diffusion process through the semi-permeable membrane (7a) due to the increased osmotic pressure of the seawater feed (2). At the membrane surface that is in contact with this warm more concentrated seawater flow (7d), the natural osmotic process will take place inducing a permeate flow (7c) from the permeate collecting tube through the semi-permeable membrane (7a) in the direction of the concentrate flow (7d). This natural

osmotic membrane cleaning process minimizes further reduction of the recovery rate. The removal process of chemical and microbiological fouling is as explained above.
During normal operation precipitation of alkaline chemical components, especially carbonates and bicarbonates due to the high pH of the BWRO feed (11), contaminates the membrane surfaces. A sodium hydroxide solution is normally dosed to increase pH to approximately 10 enhancing the boron removal. The BWRO osmotic membrane cleaning consists of lowering the recovery rate inducing the natural osmotic water diffusion (12c) from the permeate collecting tube through the semi-permeable membrane to the concentrate flow (12d) to remove contamination on the membrane surfaces (12a). The dosing of the sodium hydroxide solution is stopped and the BWRO feed (11) is mixed with acidified product water (18) to reduce the pH enhancing alkaline scale dissolution. This innovative osmotic membrane cleaning process can also preventively be applied in a predetermined period keeping the SWRO-BWRO membranes free of contamination. The usage of normal SWRO process water for the osmotic cleaning process practically eliminates the intensive chemical consumption of the chemical clean in place significantly reducing environmental chemical impact and water production cost.
Another improvement is the simplification of the SWRO design omitting the Clean In Place system and the corresponding chemical flow neutralization equipment for discharge in the sea. The preventive chemical-free maintenance of clean membranes and the possibility of on-line membrane cleaning increase the lifetime of the membranes and the availability and reliability of the SWRO-BWRO process. Further the effectiveness and the efficiency of the SWRO desalination technology are improved. The only concomitant energy consumption is the electrical heater (4) for the temperature increase of the seawater feed (1a). An environment-friendly alternative is the application of solar energy of a salinity gradient solar pond for the elimination of the electrical heater (4) as described next.

The osmotic membrane cleaning process in combination with a salinity gradient solar pond and a saltpan
An alternative for the abovementioned osmotic cleaning process to eliminate the electrical heater (4) to increase the temperature of the seawater feed (1a) and further enhancing the osmotic cleaning process by rinsing the reversed permeate flows (7c) and (12c) with acidified product water is illustrated in Figure 9.26.
This SWRO-BWRO desalination process is in essence the same as the one illustrated in Figure 9.25, only differing in the fact that a partial flow (8b) of the concentrate flow (8) of the SWRO unit (7) is diverted after pressure exchange in the energy recovery system (3) to the salinity gradient solar pond (23). In the salinity gradient solar pond, temperature reaches up to 26-85 ^{o}C due to solar energy conversion and heat storage in bottom liquid layers.

The bottom layers also have a higher concentration and the eventually precipitated carbonates can settle down on the bottom. As indicated in Figure 9.26, in this osmotic membrane cleaning process of the SWRO membranes (7a) the seawater feed (1a) is mixed with the warm concentrated solution (24) of the salinity gradient solar pond (23) to increase the osmotic pressure of the seawater feed (2) to the SWRO unit (7).

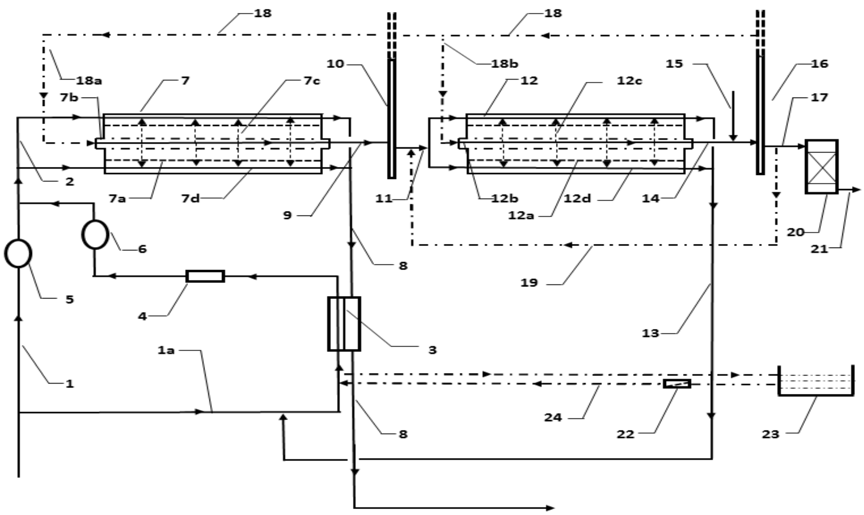


Figure 9.26: The osmotic membrane cleaning process in combination with a salinity gradient solar pond.

The specification of the process flows and process components in Figure 9.26 are as follows: (Process flows and components 1-17 are the same as in Figure 9.25):

18. Permeate acidified product rinse water; 18a to SWRO and 18b to BWRO.
19. BWRO feed acidified product rinse water.
20. The drinking water mineralization unit.
21. Post treated drinking water.
22. Salinity gradient solar pond cartridge filters.
23. Salinity gradient solar pond.
24. Warm concentrated mixing solution

The micro-cartridge filter system (24) removes entrained suspended precipitated salts out of this warm effluent of the salinity gradient solar pond. By reducing the recovery rate and the high osmotic pressure of the warm concentrated seawater feed (2) the normal working pressure is not sufficient anymore to maintain the reverse osmosis separation process through the semi-permeable membrane (7a). At the membrane surface that is in contact with this warm more concentrated seawater flow (7d), the natural osmotic process will take

place inducing a permeate flow (7c) from the permeate collecting tube (7b) through the semi-permeable membrane (7a) in the direction of the concentrate flow (7d). To enhance removal of contamination on the membranes surfaces (7a) acidified product water (18a) is introduced in the permeate-collecting tube (7b) to rinse the collected fresh permeate flow. Osmosis of this acidified permeate (7c) through the semi-permeable membrane (7a) also inhibit precipitation of carbonates in the concentrate flow (7d).
The osmotic cleaning process of the BWRO membranes is the same as the cleaning process illustrated in Figure 9.25 with the exception that the removal of scale is enhanced by replacing the permeate flow (12c) with the acidified product water (18b). In this particular situation, the alkaline scale is directly dissolved in the membrane surface-scale interface making the removal by the Critical Cross Flux effect more effective than in the previous process with recovery rate reduction. A saltpan for the production of pure sodium chloride solution can further improve the conceptual design of this osmotic membrane cleaning process as illustrated in Figure 9.27.

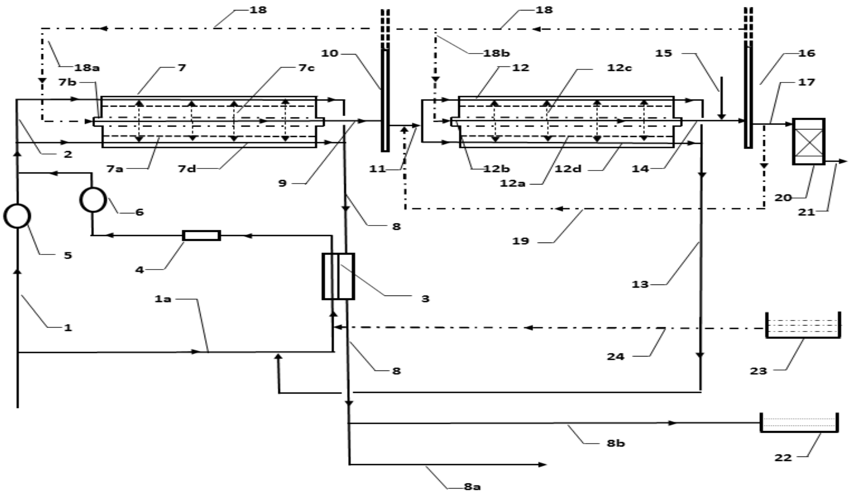


Figure 9.27: The osmotic membrane cleaning process with a saltpan and a salinity gradient solar pond combination

The specification of the process flows and process components in Figure 9.27 are as follows: (Process flows and components 1-21 are the same as in Figure 9.26).

22. Saltpan.
23. Salinity gradient solar pond (8b concentrate feed to the saltpan)
24. Warm concentrated pure sodium chloride solution.

The application of a saltpan makes the construction of a salinity gradient solar pond of pure sodium chloride solution possible, eliminating the eventual precipitation of super-saturated carbonates and other salts in the salinity gradient solar pond. As indicated in Figure 9.27 a portion of the concentrate flow (8b) is directed to the saltpan (22) for the natural production of pure sodium chloride. This sodium chloride is used to make the pure sodium chloride solution for the salinity gradient solar pond (23). As illustrated in Figure 9.27, in this osmotic membrane cleaning process of the SWRO membranes (7a) the seawater feed (1a) is mixed with the warm concentrated pure sodium chloride solution of the salinity gradient solar pond (23) to increase the osmotic pressure of the seawater feed (2) to the SWRO unit (7). This process eliminates the eventual precipitation of carbonates possibly occurring in the salinity gradient solar pond made with a portion of the concentrate flow (8). The BWRO osmotic cleaning process is analogical to the cleaning process illustrated in Figure 9.26. With this new innovative osmotic SWRO-BWRO membrane cleaning process, the SWRO desalination technology is an environment-friendly economical process with optimized energy consumption. It is a first step toward green desalination.

Advantages of this new chemical-free osmotic membrane cleaning process

The advantages of this new innovative environment-friendly and chemical-free osmotic membrane cleaning process can be summarized as follows:

- Based on the possibility of reducing the recovery rate in combination with increase of salt concentration and temperature of the seawater feed a simple effective membrane cleaning process is developed eliminating the intensive chemical usage of the conventional chemical membrane cleaning process, the Clean In Place (CIP).
- Elimination of the intensive chemical usage of the conventional CIP process makes this osmotic membrane cleaning process very environmental friendly.
- Elimination of the intensive chemical usage of the conventional CIP process increases the membrane lifetime and usage time drastically reducing the membrane replacement costs.
- The possibility to perform this osmotic membrane cleaning process on-line increases the availability of the SWRO-BWRO reducing maintenance and operation costs.
- The possibility to perform this osmotic membrane cleaning process preventively mitigates the persuasive membranes surfaces biofouling optimizing the yearly energy consumption per cubic meter produced product water.
- The natural osmotic water diffusion transport gives the opportunity for efficient removal of contaminations pressed on the membrane surfaces due to the high pressure of the reverse osmosis process enhancing removal due to the critical cross flux mechanism.
- The possibility to use the warm concentrated salt solution of a salinity gradient solar pond eliminates the application of an electrical heater reducing the energy consumption of the osmotic membrane cleaning process.
- The application of a saltpan for the production of a pure sodium chloride solution for the salinity gradient solar pond eliminates the possibility of precipitation of super-saturated

salts in the warm bottom liquid layers of the salinity gradient solar pond of concentrate solution.

- The new innovative on-line osmotic BWRO membrane-cleaning process with acidified product water is a simple and economical process compared with the conventional membrane cleaning with expensive special inorganic and organic surface-active chemicals.
- This new innovative osmotic membrane cleaning process utilizing common process flows of the SWRO production unit eliminates the additional CIP system with corresponding CIP process flows.
- Conventional SWRO-BWRO desalination processes are simply retrofitted for the application of this new osmotic membrane cleaning process.

To conclude this section it is worth mentioning that the application of the new innovative osmotic membrane cleaning process as described in Figure 9.25 has successfully eliminated persuasive membrane biofouling at the existing SWRO#1 at W.E.B Aruba N.V. reducing the average energy consumption of 4.45 kWh per cubic meter of produced permeate to value of 3.72 kWh per cubic meter produced permeate. This attained value is lower than the average energy consumption of 4 kWh per cubic meter produced product water during the first performance test.

9.6 Innovative desalination concepts toward Green Desalination

Globally, research activities are directed toward Green Innovation for the development of alternative sustainable energy technologies, recently more catalyzed by the increasing cost of fossil fuel, to reduce production cost. In the seawater desalination technology as frequently stated in this thesis it is practically impossible for stable desalination operation without chemicals. The discharge of the brine containing the necessary chemical additives for stable operation may have a detrimental effect on the marine ecosystem [9.26]. In the context of Green Desalination, next to this important aspect of energy cost reduction especially in the costly desalination technology the elimination of the chemical usage is very important to mitigate the impact on the marine environment. The Osmotic chemical free membrane cleaning process and a biofilter in the seawater feed to mitigate biofouling of membranes [9.27] are first important promising steps in this direction. In this section three conceptual innovative proposals are shortly described to promote Green Desalination innovation research with respect to: (1) chemical additives elimination; (2) green energy production without the use of fossil fuel; and (3) the ambitioned *Thermodynamic Minimum Energy Green Desalination (TMEGD)*. These concepts are subject for further conceptual design.

An innovative Osmosis-MSF evaporation hybrid process
As thoroughly explained in Chapter 5 costly special chemicals, the high temperature antiscalants, are needed to mitigate scale formation hampering evaporation efficiency in MSF evaporators. Seawater is actually a sodium chloride solution contaminated with bivalent and trivalent salts and natural surface active components. Evaporation of pure sodium chloride solution will eliminate the possibility of scale formation and biofouling in MSF evaporators and possibly reduce excess foaming. In analogy of the ORO process as described in section 9.5, an innovative Osmosis-MSF evaporation hybrid process may create the possibility for seawater desalination without costly chemical additives. Figure 9.28 illustrates this Osmosis-MSF hybrid presented at the International Desalination Conference 2007 in Aruba.

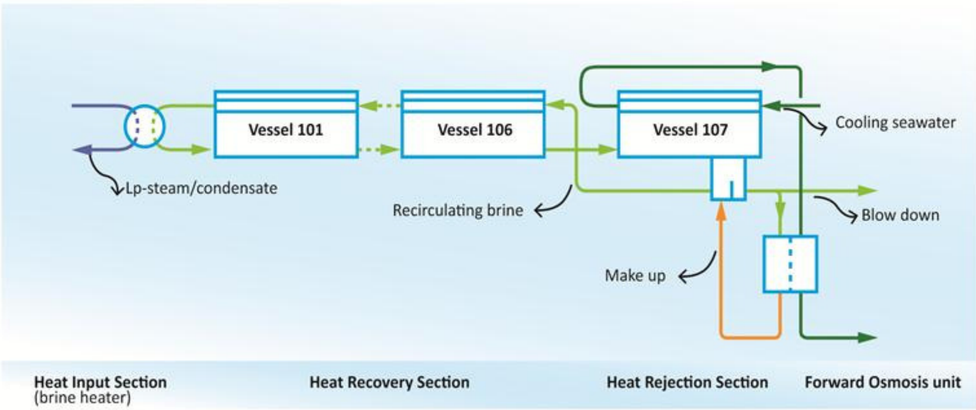


Figure 9.28: The innovative Osmosis -MSF evaporation hybrid [9.17]

In the Osmosis process unit the recirculating brine of the MSF evaporation unit now consisting of a concentrated sodium chloride solution is used as the permeation solution to draw fresh water from cooling seawater in the osmosis process unit. The diluted sodium chloride effluent of the Osmosis process unit will be evaporated instead of seawater in the MSF evaporator [9.17]. The common blowdown flow in conventional MSF evaporators containing chemical additives is eliminated. The only effluent to the sea is the concentrated seawater effluent of the osmosis process unit.

A Green membrane combined Water and Power production concept
Globally the scientific attention is concentrated nowadays on Green Energy to eliminate and replace the use of conventional fossil fuel to protect the environment. In this context of sustainable green technology, another basic concept is proposed for further research and development. This concept is the sustainable green membrane combined Power and Water Production plant as illustrated in Figure 9.29 [9.28].

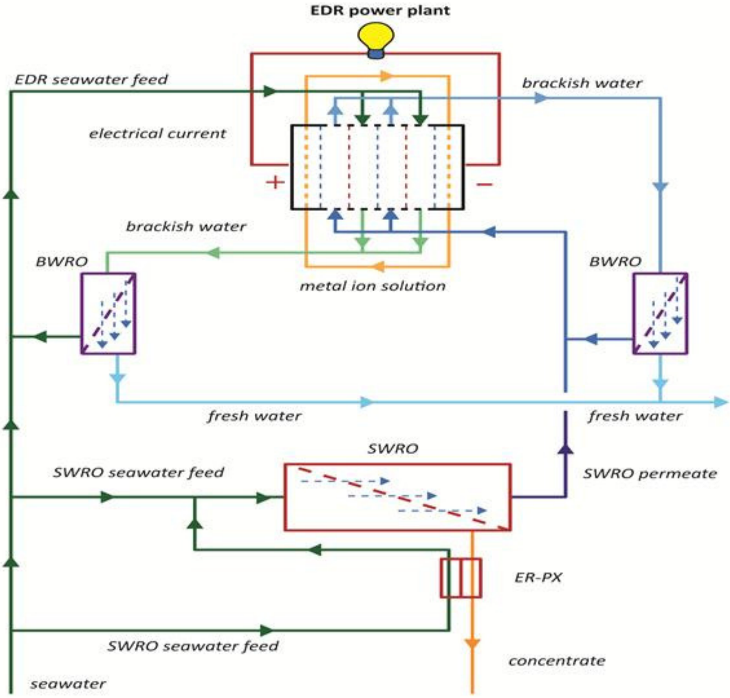


Figure 9.29: A green membrane Water and Power production concept [9.28]

The concept of the Green Membrane Water and Power Production (GMWPP) is based on the Blue Energy process for the energy production with the *Electro-Dialysis Reversal* (EDR) membrane technology as developed by Wetsus [9.29].

In this green membrane combined water and power production concept, electrical energy is produced in EDR process unit where seawater and fresh desalinated water exchange ions. The effluents of the EDR process unit are brackish water. The brackish water effluents of the seawater feed side and the fresh water feed side of the EDR process unit are desalinated in BWRO process units producing drinking water. The reject flows of the BWRO units are circulated back to respectively the seawater feed and the SWRO permeate feed of the EDR Power production unit.

The SWRO process unit produces the fresh desalinated water feed for the EDR Power Production unit. In the energy recovery system with pressure exchangers (ER-PX) energy are exchanged between the concentrate flow and the SWRO feed flow. In this conceptual proposal energy and drinking water are produced only with seawater as basic raw material without the necessity of fossil fuel. It is noteworthy that in this concept the energy can also be produced based on the *Pressure Retarded Osmosis* (PRO) membrane process. Pressure Retarded Osmosis (PRO) can be considered as an intermediate process between osmosis and reverse osmosis where a hydraulic pressure is applied opposing the osmotic pressure difference but still having a net water flux toward the permeation (draw) solution [9.30].

The proposed Thermodynamic Minimum Energy Green Desalination (TMEGD-) process
The envisioned Green Desalination perspective is the chemical free seawater desalination with the thermodynamic minimum energy consumption of 0.70 kWh/m^3 fresh water produced [9.31] with the EDR or PRO based membrane green fossil fuel free energy production. In this paragraph the *Closed Circuit Desalination* (CCD-) process of Desalitech Ltd. and the proposed Osmosis Reverse Osmosis alternative is briefly described.
With the development of the SWRO technology the usual desalination energy consumption is reduced from 24-12 kWh/m^3 of the thermal evaporators to about 6-2.5 kWh/m^3. New current development in the SWRO technology especially the *Closed Circuit Desalination*^{TM} (CCD-) process with an energy consumption of 1.35 kWh/m^3 [9.32] is already pointing towards future desalination with the ambitioned theoretical thermodynamic minimum energy consumption of 0.7 kWh/m^3. This CCD reverse osmosis process is based on recirculating the concentrate until the desired recovery level is reached. The concentrate is then replaced with fresh seawater to flush the membranes without disrupting permeate production. Toward reaching the theoretical minimum energy desalination energy consumption I propose the *Thermodynamic Minimum Energy Green Desalination* (TMEGD-) process consisting of the developed *Osmosis Reverse Osmosis* (ORO) process desalinating a pure sodium chloride solution as described in section 9.5 to be adapted to improve this CCD concept by eliminating the intermittent concentrate refreshing cycle and to use an ERI pressure exchanger operating in the lag flow condition (pumping more concentrate to the SWRO feed) instead of a common circulating pump as in the CCD process. This *Osmosis Reverse Osmosis Closed Circuit Desalination* (ORO-CCD-) process (as illustrated in Figure 9.30) is in the conceptual design phase.

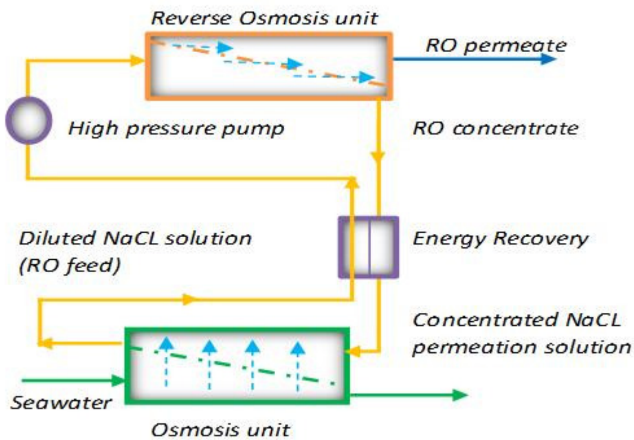


Figure 9.30: The Close Circuit ORO process

To close this section it is noteworthy to mention that globally technological innovations in many industries are considered the most important driver to company competitive success and that the increasing importance of innovations is due partly to the globalization of markets [9.33]. Without arguing this statement, the importance of innovation has to be seen more in the context of motivation and broadening the scientific knowledge promoting environmentally sound technological development to satisfy the global green sustainable need.

9.7 Conclusions

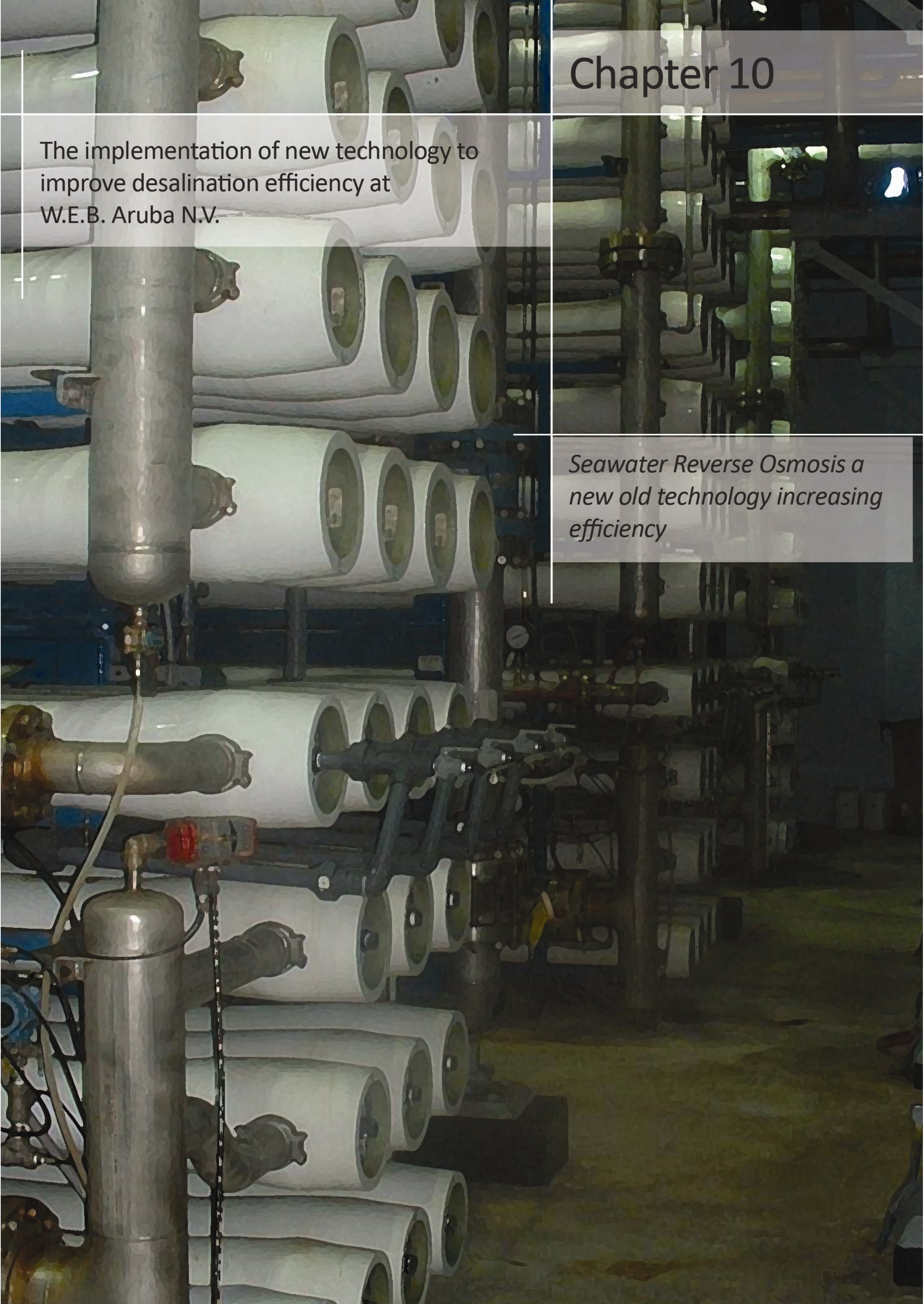
1. The chlorine disposal project has proven that dedication, teamwork motivation, self-confidence and perseverance are the key factors for the successful implementation of an economical solution for practical problems with high safety, health and environmental risk potential.
2. The conceptual design of the combined fluidized bed-tray heat exchanger is an innovative physical-chemical technology for the elimination of the use of concentrated sulfuric acid as scale inhibitor in MSF evaporators.
3. The conceptual design of the hybrid ORO process for the desalination of seawater is an efficient and economical improvement of the conventional SWRO eliminating the scaling and biological fouling on the membranes and reducing the working pressure.
4. The conceptual design of the on-line osmotic membrane cleaning process is an effective environment-friendly chemical-free membrane cleaning process increasing efficiency and decreasing production and maintenance cost.
5. The conceptual design of the Osmosis-MSF hybrid for the evaporation of a pure solution of sodium chloride will eliminate scaling in MSF evaporation without the use of special chemical and also mitigate the foaming tendency of the recirculating brine.
6. The conceptual proposal of the Green Membrane Water and Power production plant is an innovative concept eliminating the necessity of fossil fuel.
7. The Closed Circuit Desalination technology is a prospective process toward the Thermodynamic Minimum Green Energy Desalination concept.
8. Further scientific and pilot research is needed to develop the above-mentioned innovated conceptual designs especially the Green Membrane Water and Power Production concept.

9.8 References

9.1. Marchena, F. A., Post, R. E., et al., Water Treatment Technology for Desalination Systems- A decade of experience inhibiting corrosion and red water" in drinking water systems, Caribbean Conference, June 9-21, 2002, Aruba.

9.2. Marchena F. A., Post, R. M., et al., A New Method for Controlling Marine Growth in Desalination Plant Intake Systems, Caribbean Desalination Conference 2002, June 21-23, Aruba.
9.3. Marchena, F. A., Uytiepo, B. A., Plant Experience on New Antiscalant Technology for MSF plants, IDA World Congress- Maspalomas, Gran Canaria, Spain, October, 2007.
9.4. Thompson, N. A., Nicoll, P. G., Forward Osmosis Desalination: A Commercial Reality, International Desalination Association World Congress, September 4-9, 2011, Perth, Australia.
9.5. Engelbrecht, G. A., Chlorine Leakage Incident Barcadera, Internal Report, Department of Environmental Affairs Aruba, May, 1987.
9.6. Chlorine, Manual for Safe Work., Technical Services., Akzo Zout Chemie Nederland BV., 6th edition, Amsterdam, The Netherlands, 1981.
9.7. Chloor, veilige behandeling in de haven, Arbeidsinspectie P no 92, 3de druk., 1982.
9.8. Kimbert, C. J., Coble, R. J., A Comprehensive Study of the Use of Chlorine Gas for residential Swimming pools, University of Florida, Gainesville, Florida, USA, December 1995.
9.9. Wallace and Tiernan, Operation Manual Chlorine Dosing Equipment,
9.10. Marchena, F. A., The Safe Disposal of 37 Damaged One-ton Chlorine Containers at W.E.B. Aruba N.V., W. E. B Aruba N.V. Internal Report., February 1993.
9.11. The Chlorine Manual, The Chlorine Institute Inc., 5th edition 1986
9.12. Koops, F. B. J., Mulder, A. R., Cooling water Chlorination, Report No. 74.011, Akzo Zout Chemie Nederland B.V., The Netherlands, February, 1974.
9.13. Marchena, F. A., Franken, N. N., Stepwise CO_2 desorption from seawater with stripping steam or vapor for the mitigation of scale in MSF evaporation, patent number 010910.22, Buro of Intellectual Properties of Aruba, March 2003.
9.14. Marchena, F. A., Franken, N. N., Stepwise CO_2 desorption from seawater with stripping steam or vapor for the mitigation of scale in MSF evaporation, patent number 1025361, Octrooicentrum Nederland, April 2005.
9.15. Minnich, K., Aqua Tech Inc., Milwaukee, USA, Personal Communication, 2002
9.16. Khan, A. H., Desalination Processes and Multistage Flash Distillation Practice, Elsevier Science Publishers B.V., Amsterdam, 1986.
9.17. Wessels, L. P., Marchena, F. A., et al., Improved Cleaning of Spiral Wound Membranes and Forward Osmosis Reduces Cost of Seawater Desalination, International Desalination Conference, Oranjestad, Aruba, June 2007.
9.18. Cath, T. Y., Childress, A. E., Elimelech, M., Forward osmosis: Principles, applications, and recent developments, Journal of Membranes Science 281 (2006) 70-87.
9.19. Marchena, F. A., Vrolijk, V. R. J., Een Innovatief hybride Osmose en Reverse Osmosis (ORO) ontzoutingsproces voor de productie van drinkwater. Octrooi 1035431, Octrooibureau Nederland, 03 november 2009.

9.20. Marchena, F. A., Vrolijk, V. R. J., Een Innovatief hybride Osmose en Reverse Osmosis (ORO) ontzoutingsproces voor de productie van drinkwater. Octrooi OCT, Bureau of Intellectual Property Aruba, June 29, 2007.
9.21. Lu, H., Watson, J. C., et al., Thermal Desalination using MEMS and Salinity-Gradient Solar Pond Technology, University of Texas, U.S. Department of Interior, El Paso, Texas, USA, August 2002.
9.22. Winters, H., Fairleigh Dickinson University, USA, Personnel Communication, 2005.
9.23. Verberk, J. Q. J. C., Application of Air in Membrane Filtration., PhD Thesis Technological University of Delft, The Netherlands, 2005.
9.24. Meer van der, W. G. J., Mathematical Modeling of NF and RO Membrane Filtration Plants and Modules., PhD Thesis Technological University of Delft, The Netherlands, 2003.
9.25. Marchena, F. A., Wever, R. P. M., et al., Een innovatieve milieuvriendelijke chemicaliën vrije osmotische reinigingsproces voor het in bedrijf reinigen van SWRO- en BWRO membranen. Octrooi 1038485, NL Octrooicentrum, 18 februari 2013.
9.26. Lattemann, S., Höpner, T., Seawater Desalination: Impact of Brine and Chemical Discharge on the Marine Environment, ISBN 0-86689-062-9, Balaban Desalination Publications, L'Aquila, Italy, 2003.
9.27. Liderman, B., Biofiltration to Control Biofouling, http://www.waterworld.com/articles/wwi/print/volume-28/issue-2/regulars
9.28. Marchena, F. A., Efficacy Oriented Operation and Maintenance: An Important step Toward Sustainable Conventional and Green Desalination Technology, Our Future with Green Energy, Oranjestad Aruba, October 2010.
9.29. http://www.wetsus.nl/research/research-themes/blue-energy
9.30. Cath, T. Y., Childress, A. E., Elimelech, M., Forward osmosis: Principles, applications, and recent developments, Journal of Membranes Science 281 (2006) 70-87.
9.31. Spiegler, K. S., El-Sayed, Y. M., A Desalination Primer, Balaban Desalination Publications, ISBN 086689-034-3, Santa Maria Imbaro (Ch), Italy, 1994.
9.32. Stover, R. L., A New Process for Low Energy Desalination, Desalitech Ltd presentation, CaribDA Conference & Exhibition, June 2012, Aruba.
9.33. Schilling, M. A., Strategic Management of Technological Innovation 3th edition, ISBN 978-007-128957-3, McGraw-Hill International Edition, Singapore 2010.



Chapter 10

The implementation of new technology to improve desalination efficiency at W.E.B. Aruba N.V.

Seawater Reverse Osmosis a new old technology increasing efficiency

Chapter 10

The implementation of new technology to improve desalination efficiency at W.E.B. Aruba N.V.

Table of Contents:

Abstract

During the history of seawater desalination for the production of drinking water on the island of Aruba, the impulse to increase operation and maintenance efficiency has stimulated the implementation of new seawater desalination technologies. Experienced and knowledgeable operation and maintenance personnel have also contributed to improve design in many areas of seawater desalination. The thermal evaporation desalination activities experienced a performance ratio increase from 1-1.5 to 10-11.5 during the years. Especially in the application of new scale inhibition technologies Aruba was a trendsetter. However, the negative operational experiences with the revolutionary Aquanova MSF evaporation technology and the SWRO plate and frame membrane technology respectively in the 1980s had slowed down the impulse for innovation for a quite long period.
Forced by the significant increase in fuel oil cost, W.E.B. Aruba N.V introduced the new membrane technology in 2008 to improve desalination efficiency and consequently reducing water production cost. Preceding the introduction of the SWRO technology extensive feasibility and environmental studies were performed in cooperation with external consultants such as KEMA N.V., Royal Haskoning B.V. and DHV Holland B.V.
The evaluation process for the implementation of the SWRO is described in detail in this chapter. Already during the first year of operation, this new membrane technology suffered severe membrane biofouling. In cooperation with GE Ionics, the Desalination Department team performed an extensive study and applied different alternative membrane chemical cleaning procedures to mitigate membrane biofouling. The application of beach well is proposed to guarantee higher quality seawater feed to increase the availability and reliability of the SWRO production unit. The biofouling mitigation investigation and the feasibility studies for the application of beach well are discussed in detail in this chapter.

10.1 Introduction

Since 1932, Aruba has played a major role in the application of thermal desalination for the production of drinking water and has always endeavor the application of new technology to increase efficiency and sustainability. Obtained and shared practical operation and maintenance experiences with manufacturers have significantly contributed to improvement of thermal evaporation design, research and development. The desalination activity has followed and contributed to desalination market since the application of the single effect evaporator with a performance ratio of 1-1.5, the Multi Effect Distillation (MED) with performance ratio of 6 and the introduction of the more robust and efficient Multi Stage Flashing (MSF) evaporators with a performance ratio of 9-11.5.
Most of the problems encountered in the practical desalination operation such as scaling and corrosion have been solved in Aruba introducing the first successful chemical application for scale inhibition increasing worldwide the sustainability and stability of thermal seawater desalination. A brief historical overview of the implementation of new technology is elaborated on in section 10.2.
During the period 1990 to 1998, W.E.B. Aruba N.V. was forced, due to rapid economic growth, to increase production capacity with five new desalination units. For all these production units the MSF technology was chosen despite the high-energy consumption because of reliability, good operation experience and lack of time to evaluate new technologies. A change was forced around 2004 toward the SWRO desalination technology, because of the significantly increment in the water production cost due to rapid increases in heavy fuel oil cost. Other contributing factors are the facts that a number of the mayor hotels were considering the installation of their own SWRO units to reduce water cost and the increment in complaints from domestic consumers due to the increased cost of drinking water. W.E.B. Aruba N.V. performed extensive feasibility and environmental studies regarding the consideration for implementation of this new technology as a viable option to reduce water cost. These studies directed Management decision to the construction of a SWRO with a capacity of 8000 cubic meters per day in 2007 and to the decision to replace all existing MSF evaporators with the SWRO technology when they reach their economic life span. In 2010, further increase in heavy fuel oil cost and consequently increase in production cost has accelerated the decision to procure and construct a new SWRO with a capacity of 24,000 cubic meters per day with commissioning planned in the second quarter of 2012 replacing four MSF evaporators before reaching their economic life span. The evaluation process for the implementation of the membrane desalination technology is described in section 10.3.
Already in the period following commissioning of the new SWRO severe biofouling was experienced despite the intensive pretreatment of the seawater feed from the open intake causing production and efficiency decay. Many attempts in cooperation with GE Ionics' experts applying different chemical cleaning procedures to mitigate biofouling failed to

meet targeted design production and efficiency value. After all these attempts, the application of natural filtered seawater of beach wells is proposed as seawater feed for the existing SWRO and the new SWRO to be constructed. After approval of Management, Schlumberger Water Services Inc. drilled six monitoring wells and one production well to test the lithology, the lime stone aquifer hydrology and the production capacity of the proposed beach well zone.
The physicochemical and bacteriological characteristics were analyzed to determine the quality and suitability of the natural filtered beach well raw water as seawater feed for the membrane desalination technology. A novel pilot installation consisting of an Early Warning System with a Membrane Fouling Simulator and a Biofilm Monitor is applied to quantify the physicochemical and biofouling potential of the natural filtered beach well raw seawater and is compared with the open seawater intake system.
This intensive evaluation of the Beach well intake alternative for the SWRO desalination unit is described in section 10.4.

10.2 A brief historical overview of the implementation of new technologies

W.E.B Aruba N.V. has played throughout the years of intensive commercial desalination activities a major role supporting the implementation of new desalination technologies to improve sustainability, availability and reliability in operations and maintenance as described in detail in the preceding chapters. These desalination activities have followed the desalination market trend introducing new technologies increasing desalination efficiency. The first applied single effect thermal evaporator technology in 1932 had a performance ratio of 1 to 1.5. This desalination plant used 14 bar low-pressure steam boilers to produce the heating steam for these MED plants. In 1958, the construction of a combined Power Plant and Water plant of 15 MW and 10.000 cubic meter of fresh water per day significantly increased thermal efficiency. This plant consisted of two 60 bar high-pressure steam boilers and 2 backpressure steam turbines of 7.5 MW for the electricity production. Waste steam from the back-pressure steam turbines were used as low pressure heating steam for the five more efficient MED evaporators with a performance ratio of 5 to 6 and a production capacity of 2000 m^3/day each indicating an increase in efficiency of about 300% without taking into account the contribution of the combined cycle thermal efficiency. In the 1960s, the introduction of the MSF technology with a performance ratio of 9 to10 further increased desalination efficiency with another 50%. The expansion of the power plant with the more efficient condensing and extraction turbines of 33 MW in 1963-1964 further increased thermal efficiency. The backpressure turbines had an efficiency of 0.1 MW per metric ton consumed high-pressure steam compare to the efficiency of 0.22 MW per metric ton of high-pressure steam of the condensing turbines. In 1985, the MSF desalination had replaced all the existing MED plants. The MSF technology with a total equivalent energy consumption of 24 kWh/m^3 was until 2008 efficiently applied at W.E.B. Aruba N.V. making Aruba worldwide the showcase for the MSF desalination technology. Due to the rapid increase in the heavy fuel oil cost in 2004 water production cost significantly increased, forcibly inducing evaluation of more economical desalination technologies leading to the introduction of the more energy-economical membrane technology. After an intensive study in cooperation with different consultants as explained in the next section, Management made the decision to take the challenging step toward the new membrane technology after more than seventy-five years of excellent thermal desalination. In 2008, the new commercial GE Ionics SWRO desalination unit with a capacity of 8.000 cubic meters per day and an efficiency of 4kWh/m^3 went in operation replacing the Aqua Chem #1 MSF evaporator commissioned in 1983 inducing the end of the MSF desalination supremacy in Aruba. It is noteworthy that Aqua Chem#1 ended the supremacy of over half a century of the MED technology. This SWRO plant is approximately 70% more energy-efficient than the MSF technology. In 2010, the decision was made to construct a new SWRO plant with a total capacity of 24.000 cubic meters per day with an efficiency of 3.75 kWh/m^3 replacing four existing MSF evaporators. Figure 10.1 illustrates the applied desalination technologies to increase desalination efficiency since 1932.

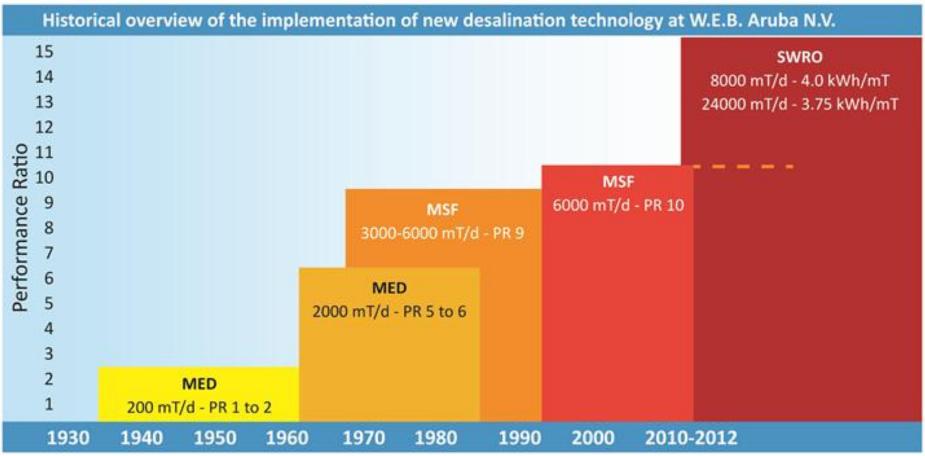


Figure 10.1: The applied desalination technologies at W.E.B. Aruba N.V.

As mentioned before W.E.B. Aruba N.V. has managed through the years to maintain efficient operation with the costly MSF evaporators mainly due to excellent operation and maintenance knowledge and the use of efficient special chemicals. The globally experienced significant increment of the heavy fuel oil cost merely forced the change to the new membrane technology.

As indicated in Chapter 8, the SWRO water production cost is lower than the MSF water production cost at a heavy fuel oil cost above US $25.00 a barrel. It is also worth mentioning

that to further increase energy efficiency, W.E.B. Aruba N.V. had introduced the efficient reciprocating engines burning heavy fuel oil in 2004 for the electricity production.
The intension is to use the flue gasses of these reciprocating engines to produce low pressure and medium pressure steam in waste heat boilers for the remaining MSF evaporators for the energy-competitive production of high quality industrial water.
A 30 MW wind turbine park consisting of ten 3MW wind turbines introduced in 2009 the alternative energy technology in Aruba representing 18% of the total energy production capacity, actually a global trendsetting for implementation of green energy.
The construction of a second wind park of 30 MW promoted by the current Government of Aruba toward a fossil fuel free green Aruba is currently in evaluation. Figure 10.2 illustrates the challenging steps taken by W.E.B. Aruba N.V. implementing new technologies to improve efficiency in both the water and energy production processes toward mitigation of environmental pollution reducing the carbon dioxide emission in the atmosphere.
Figure 10.2 illustrates the relation between the overall efficiency increment and the reduction in the Heavy Fuel Oil consumption. Furthermore, it also clearly illustrates a significant reduction in Heavy Fuel Oil consumption with the application of new technology compared with the no change situation in water and energy production technology.

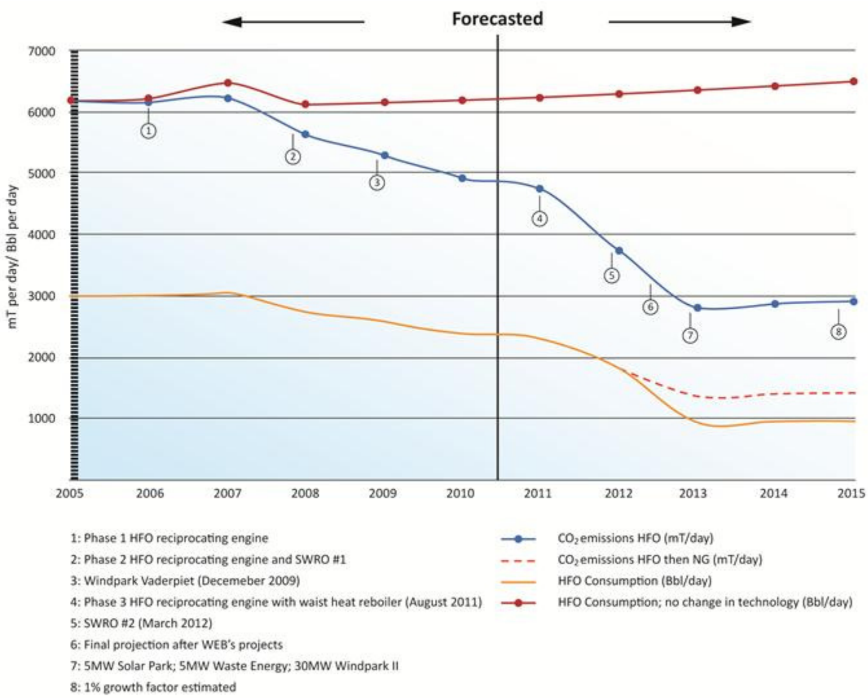


Figure 10.2: Reduction of HFO consumption and CO_2 emission with new Technology [10.1]

Figure 10.3 shows the new reciprocating engines and the Vestas BOO wind park at Vaderpiet, at the east coast of Aruba.

Figure 10.3: The reciprocating engines and the Wind Park.

The major problems encountered in seawater desalination hampering sustainability, reliability and efficiency are high temperature scale formations, corrosion and biofouling. As described in detail in Chapter 4 and Chapter 5 the most effective antiscaling agents such as the ferric chloride, the concentrated sulfuric acid and the phosphonate polymeric high temperature scale inhibitors were first developed and successfully applied in Aruba, even so the first successful application of an environment-friendly non-oxidizing biocide.
To close this section the schematic diagram of the combined Power and Water production process at W.E.B. Aruba N.V. is illustrated in Figure 10.4.

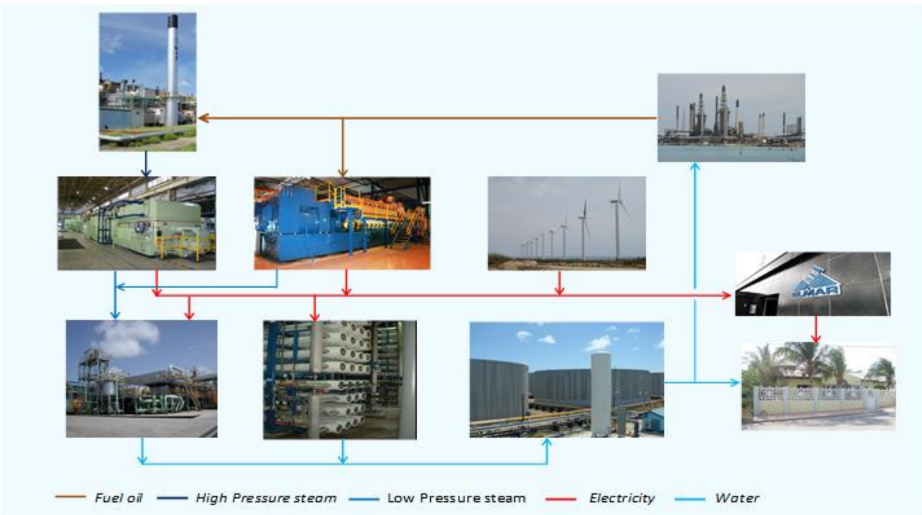


Figure 10.4: The schematic diagram of the Power and Water production process of W.E.B Aruba N.V.

10.3 The evaluation process toward the implementation of the SWRO technology

Developments in the local market and the pre-feasibility studies

During the period of 1990 to 1998, W.E.B. Aruba N.V. was forced due to rapid economic growth to increase production capacity with new evaporators in each of three successive years: Aqua Chem#3 in 1990, Aqua Chem#4 in 1991 and Aqua Chem#5 in 1992.
Two additional evaporators were built in two three-year period namely Aqua Chem#6 in 1995 and Aqua Chem#7 in 1998. For all these desalination units MSF technology was chosen because of reliability, good operation experience and lack of time to evaluate new technology [10.2]. In addition, the negative operational experiences with the new desalination technologies in the 1980s, the Aquanova Controlled Flash evaporator and the plate and frame SWRO have surely influenced the decision. It is worth mentioning that although MSF evaporators according to common desalination experience are very costly in operation due to the high energy-consumption, W.E.B Aruba N. V. has managed to realize the lowest water tariff in the region due to;

- Maintenance of a high performance ratio during operation
- Good control of water quality which significantly reduced corrosion in the water distribution system
- Low maintenance cost since all plants are similar
- Well maintained and operated distribution system. Actually, the non-revenue water according to the IWA standard is 2.6-4.11% of the total distributed water [10.3].

The globally gradual increase in Heavy Fuel Oil cost since 2002 and developments in the local market forced W.E.B. Aruba N.V. to evaluate more economical seawater desalination alternatives for the low cost production of drinking water.

Developments in the desalination market conditions in Aruba

There have been some new developments in the local water market over the past 10 years due the high water cost. W.E.B. Aruba N.V. has managed to maintain its water tariff constant for almost ten years since 1992. With the rapid increase in Heavy Fuel Oil price worldwide, the water tariffs had to be adapted for the higher energy cost. However, the water tariffs in Aruba are still one of the lowest in the region especially compared to the other Dutch Caribbean Islands. Even with this relatively low water price, some major hotels were considering the installation of their own SWRO to lower their water cost. With the increasing water cost, the population also began to complain. In spite of the monopoly position of W.E.B. Aruba N.V., Management made the decision to evaluate these developments and needs in the local market. DHV Water B.V. from Holland was contracted in 2003 to evaluate the feasibility for the mayor hotels installing their own SWRO units and the feasibility for W.E.B. Aruba N.V. to reduce the water cost by means of the SWRO technology [10.4].

Feasibility study of DHV Water B.V.

In their first study, DHV Water B.V. documented the needs of the major hotels and their water consumption [10.5]. It was feasible for the hotels to install their own SWRO unit but further investigation indicated that they were not interested in the production of their own water because it is not their core business. DHV Water B.V. further investigated the feasibility for W.E.B. Aruba N.V. to reduce water cost by installing a SWRO [10.6]. For this study, the following alternatives were considered:

- Expansion with SWRO at W.E.B. Aruba N.V.'s premises
- Expansion with SWRO near the hotels
- Expansion with MSF at W.E.B. Aruba N.V.'s premises
- Use of treated waste water
- Decrease of water demand of the hotels

The use of treated water and the decrease of water demand resulted to have a negligible impact. Table 10.1 illustrates the calculated investment cost and exploitation cost of SWRO with a capacity of 2,500-8,000 cubic meters per day producing low to high quality water. As can be seen from Table 10.1, the SWRO with a capacity of 8,000 cubic meters per day had the lowest exploitation cost of 1.5 US$ per cubic meters or 0.6 US$ cents per gallon.

Table 10.1: Cost Calculation of DHV Water B.V. [10.6]

Option/Water Quality	Production Capacity (m^3/day)	Investment Costs M AWG. (M US $)	Exploitation Costs AWG/m^3 (US$/ m^3)
SWRO at WEB high quality	2,500	30.5 (16.9)	4.2 (2.3)
SWRO hotels site low quality	2,400	22.9 (12.7)	3.7 (2.1)
SWRO hotels site medium quality	5,000	32.6 (18.3)	2.8 (1.6)
SWRO hotels site high quality	8,000	46.2 (25.7)	2.7 (1.5)
SWRO hotels site high quality	2,500	26.8 (14.9)	4.0 (2.2)
MSF at WEB	6,000	28.6 (15.9)	4.9 (2.7)

Water Quality:

Low: *Gardening water; 30% of total hotel consumption*

Medium: *Laundry, toilets, cooling towers; 35% of total hotel consumption*

High: *Potable water; 35% of total hotel consumption*

As further indicated in Table 10.1, low quality water suitable for gardening represents 30%, medium quality water suitable for laundry represents 35% and high quality water suitable for potable water for showers represents 35% of the total consumption of the hotels. The summary of the findings of DHV Water B.V. are as follows:

- SWRO for the hotels is a feasible option
- However, the hotels are satisfied with W.E.B. Aruba N.V.'s high quality water and are really not interested in producing the water themselves
- The most economical option is the construction of a SWRO plant with a capacity of 8000 cubic meters per day in the vicinity of the hotels
- The SWRO should produce medium quality water as well as high quality drinking water

The studies leading to the implementation of the SWRO technology

In 2005, KEMA N.V. and Royal Haskoning B.V. were contracted to conduct a more in depth study for the more economical production of energy and water through 2025. One of their major proposals concerning efficient desalination is the application of the SWRO technology replacing the MSF evaporators. In the SWRO evaluation process, W.E.B. Aruba N.V. further had to address concerns about the economic impact, the impact of the SWRO water quality on the population, the impact on the desalination operational and maintenance personnel and the impact on the environment. In this respect, Kiwa N.V. and Ecovision B.V. were contracted in 2005 to perform an extensive study of respectively the impact on the water quality and the impact on the seawater environment, in particular the marine eco system. The Engineering Support Department of W.E.B. Aruba N.V. in cooperation with the Desalination Department performed an intensive economical comparative study of the MSF evaporation and the SWRO desalination technology. These evaluation studies are briefly summarized below.

The Green field study of KEMA N.V.

The KEMA N.V. findings, based on the Green Field-method, as documented in their final report Energy Aruba 2025, revealed the following most economical options for efficient power and water production up to 2025 [10.7]:

For Power production, they advised:

- Steam production with Pet Coke Boilers
- Reciprocating Engines burning Heavy Fuel Oil

For Seawater desalination the most economical option is:

- Reverse Osmosis (RO) technology

Further, in their study they advised as an Implementation Strategy to replace all the existing MSF evaporators with SWRO desalination units at the end of their economic life. In their study, KEMA N.V. made a Multi Criteria Analysis (MCA) to compare SWRO, MED and MSF desalination units in the capacity range of 6,000 to 10,000 cubic meters per day considering criteria such as cost price, operational management, flexibility and energy consumption. As can be seen in Table 10.2, the findings clearly favored SWRO over MED and MSF.

Table 10.2: Multi-criteria analysis of KEMA N.V. for 6,000-10,000 cubic meters per day SWRO, MSF and MED [10.7]

Criterion	Value (weight)	RO	MED	MSF	RO Total	MED Total	MSF Total
Cost Price	30%	0	0	-1	0.00	0.00	-0.30
Operational Management	20%	0	-1	1	0.00	-0.20	0.20
Cost Price Development	20%	1	0	-1	0.20	0.00	-0.20
Flexibility	15%	1	-1	-1	0.15	-0.15	-0.15
Energy Consumption	5%	-1	0	-1	-0.05	0.00	-0.05
Quality	5%	-1	1	1	-0.05	0.05	0.05
Environment/ surroundings	5%	1	-1	-1	0.05	-0.05	-0.05
Total	100%				0.30	-0.35	-0.50

Environmental study of Eco Vision N.V.

To address the concern about the impact on environment Eco Vision B.V. was contracted to evaluate the effect of the brine discharge on the marine eco system. For their study, Eco Vision used the Aqua SEA Stream Model of Vatnaskil Consulting Engineers and the bathymetric studies of Landmark B.V. [10.8, 10.9].

The findings of the study indicated that there is:

- Negligible adverse effect of the SWRO discharge on the marine eco system due to the dilution effect of the seawater in the lagoon
- Negligible marine live of importance in the vicinity of the brine discharge
- SWRO discharge will reduce the thermal pollution of the MSF discharge on the marine eco system.

In Figure 10.5, the simulation of the salt concentration dilution profile of the SWRO brine discharge is shown [10.9].

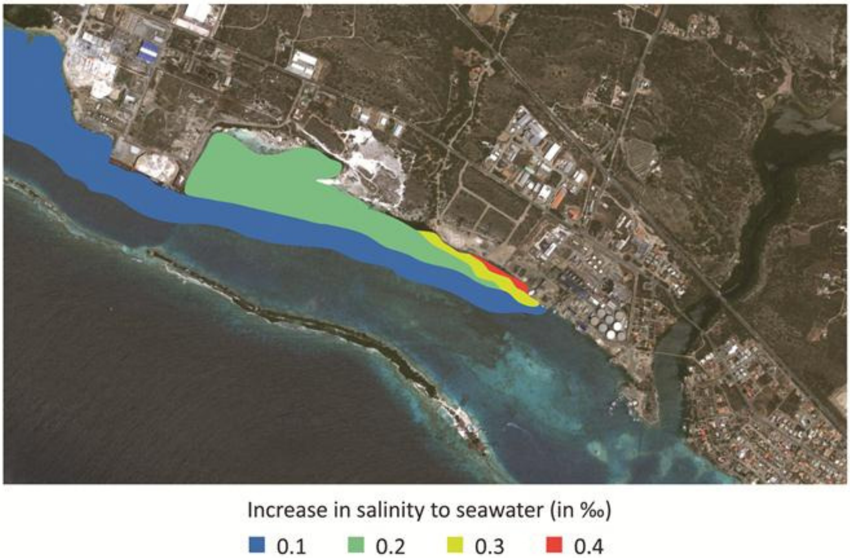


Figure 10.5: The salt concentration profile of the SWRO brine discharge [10.9]

The effect of SWRO-permeate on the finished drinking water quality
In 2005, KIWA N.V. was contracted to evaluate the effect of SWRO product water on the quality of the drinking water. KIWA based his calculation on the *Corrosion Index* (CI) defined as the sum of the chloride concentration and twice the sulfate concentration divided by the *Total Inorganic Carbon* (TIC) as indicated in equation 10.1.:

$$CI = [Cl^{-}] + 2[SO_4^{2-}]/TIC \qquad (10.1)$$

The TIC is defined as;

$$TIC = [CO_3^{2-}] + [HCO_3\text{-}] + [CO_2] \qquad (10.2)$$

The calculated CI should be lower than one according to Dutch standards [10.10]. The CI was calculated for one pass SWRO and two pass SWRO with natural re-mineralization and with improved re-mineralization with CO_2 injection to increase hardness. The alternative operation conditions considered are:

- First alternative is the situation with one SWRO and 6 MSF and outage of one or two MSF
- Second alternative is the situation of two SWRO with 5 MSF and outage of one or two MSF

Table 10.3: Corrosion index calculation of KIWA N.V. [10.10]

	Single Pass RO	Single Pass RO + CO_2 dosing	Double Pass RO	Double Pass RO + CO_2 dosing
RO-permeate	108	19.5	26.4	2.4
1 RO + 5 MSF	9.5	4.4	1.1	0.5
1 RO + 4 MSF	11.5	5.2	1.3	0.6
1 RO + 3 MSF	14.8	6.3	1.7	0.7
2 RO + 4 MSF	20.8	8.1	2.4	0.8
2 RO + 3 MSF	26.0	9.5	3.1	1.0
2 RO + 2 MSF	34.8	11.5	4.3	1.2

The findings as documented in Table 10.3 clearly indicate that a two pass RO with improved re-mineralization will have no impact on the drinking water quality. The Corrosion Index for the considered alternatives is less than one. In the production situation with only one SWRO the Corrosion Index is about 2.4 indicating that even with improved re-mineralization the drinking water is still corrosive. For the sake of clarification, a one pass SWRO produces product water with total dissolved solids of about 400 ppm, the two pass SWRO consist of a SWRO and a BWRO and produces product water with a total dissolved solids of 10 to 15 ppm.

Return on Investment (ROI) calculation of the Engineering Department of W.E.B. Aruba N.V.
To address the concern about the economic impact the Engineering Department of W.E.B. Aruba N.V. calculated, using the *Thermo Economic Model* (TEM) from Fichtner, the Return on Investment (ROI) for an 8,000 cubic meters per day SWRO plant and MSF plant [10.11]. Based on an Investment Horizon of 18 years, Loan duration of 8 years, loan interest of 8% per year, inflation rate of 3% per year and an applied discount rate of 10% per year the calculation showed that investment in an SWRO is more attractive. The ROI is 19.12% for SWRO compared to a ROI of 7.28% for MSF as indicated in Table 10.4.

Table 10.4: ROI calculation by the Engineering Department using the Cash Flow Model [10.11]

Summary ROI evaluation SWRO and MSF				
Description	Unit	Recip	SWRO	MSF
Capacity	MW mT/day	24	8,000	8,000
Investment Horizon	Annum (a)	18	18	18
Loan Duration	Annum (a)	8	8	8
Loan Interest Rate	%/a	6.68	8.00	8.00
Inflation Rate	%/a	3	3	3
Applied Discount Rate	%	10.00	10.00	10.00
Net Present Value @ 10% Discount Rate: AWG. 2005			*31,180.557*	*(7,966.628)*
Internal Rate of Return %			*19.22*	*7.28*

Comments: *1: O&M of Recip, SWRO & MSF indexed with inflation rate*
2: O&M of Recip, SWRO & MSF corrected for start-up year
3: Depreciation correction for start-up year
4: Evaluation using marginal savings as per base 2005 (No Recip, no new MSF)
5: HFO Price per barrel constant 2005 USD 35.000

The impact on W.E.B. Aruba N.V.'s personnel

According to the EML model in the context of efficacy, efficient involvement and empowering of in particular the work floor personnel in the efficiency improvement process is of imminent importance, as already elaborated on in Chapter 3. For the successful introduction of the new SWRO technology, this is vital. The two main concerns of the personnel were the different water quality and the unfamiliarity with the new technology. To cope with these concerns W.E.B. Aruba N.V. has included in his introduction strategy for this new technology:

- Plants visits for key personnel and board members of the personnel Union of W.E.B. Aruba N.V.
- A plan for regular communication with personnel and public
- A plan for extensive orientation and training

An extensive communication and evaluation program with personnel and the Union was put in place to develop a department philosophy and strategy for the introduction and operation of the new desalination technology [10.12].

The decision of W.E.B Aruba N.V. to choose for SWRO

Based on all the studies made, W.E.B. Aruba N.V. decided to move toward the SWRO technology and to construct their first 8000 cubic meters per day SWRO desalination unit on its premises for the following reasons:

- Excellent economics,

- 2000 cubic meters per day additional capacity required in 2007,
- Aqua Chem#1 has reached the end of its economic life,
- Gaining operational and maintenance experience with the SWRO technology.

According to a subsequent more extensive study by KEMA NV (Energy Aruba 2025), the decision was also made to gradually replace all other existing MSF evaporators with SWRO desalination units when they complete their economic life [10.13]. The foreseen incentives are:

- Stabilization of the water production cost,
- Gradually reducing the water cost in the future,
- To keep the water tariff one of the lowest in the region (Dutch Caribbean).

Due to the continuing rapid increase of the Heavy Fuel Oil cost in a short period reaching a price of approximately $ 100.00 per barrels in 2008-2009, W.E.B. Aruba N.V. was again forced to revise its investment plan. A new decision was made after an intensive study to install a 24.000 cubic per day SWRO desalination unit on a fast track basis replacing four MSF evaporators at the end of the last quarter of 2011. The tendering process started in the second half of 2009 with the planning to start construction in the second half of 2010.
The intensive studies and experiences of the construction of the first SWRO has promoted the fast track project planning for the second SWRO production unit. Considering the high biofouling potential of the seawater as indicted in Chapter 4, the Desalination Department proposed to evaluate the use of natural filtered seawater from beach well for the SWRO seawater feed. Intensive chemical and biochemical evaluation of the test production wells drilled on site demonstrated the high quality of the well water as explained in the following section.

10.4 The evaluation of beach wells to mitigate biofouling in the SWRO process

The beach well testing program of Schlumberger Water Service Inc.

In the first years of operation with the new SWRO desalination unit with the conventional open seawater intake, severe and persuasive membrane biofouling was experienced despite intensive pretreatment of the seawater feed. After intensive efforts in cooperation with GE Ionics, some positive results were obtained mitigating biofouling and increasing efficiency and availability [10.14]. However, the frequency of the membrane cleaning and micro cartridge filters replacement have been lowered but it is still much higher than the design target of twice a year. After all these efforts the Desalination Department team proposed to Management to evaluate the application of beach wells or offshore sea wells to obtain natural filtered seawater feed for the SWRO desalination unit to control membrane biofouling [10.15]. It is a well-known fact that natural filtered seawater or brackish water feed is usually of very high quality and due to limited seasonal environmental influences of very constant composition [10.16]. Beach well intake systems for SWRO desalination units have the advantage of the filtration provided by the seafloor materials and the aquifer sedimentation rocks to reduce suspended solids and microorganism and to stabilize the water chemistry. Men have produced fresh water with the riverbed filtration system already for thousands of years [10.17]. After approval of the beach well proposal, Management of W.E.B. Aruba N.V. contracted Schlumberger Water Services USA Inc., to perform a feasibility study for the application of beach well as alternative seawater feed intake system for the SWRO desalination process. In this section, a short description of this beach well testing program is illustrated.

The main objective of the beach well feasibility study was to determine the usability of an alternative intake system for the existing 8,000 m^3/day SWRO including the additional planned SWRO with a capacity of 24,000 m^3/day and the projected near future capacity increase with another 8,000m^3/day. The total production capacity of the membrane technology for the near future is projected to be 40,000 m^3/day. Based on a fresh water recovery factor of 50% the actual seawater feed demand will be 80,000m^3/day. Taking also into consideration a safety redundancy factor of 25% the target seawater feed supply capacity of the alternative beach well intake is set to 100,000 m^3/day. For this feasibility study, Schlumberger Water Services Inc. drilled five monitoring wells and one production well for a short term and long term pumping test. The test well results indicated a production zone with favorable conditions for this alternative SWRO intake system having both a high transmissivity and filtration capacity indicated by the low obtained Silt Density Index (SDI) values below 3. However, the main technical operational concern associated with this alternative intake system at W.E.B. Aruba N.V. is the large pumping capacity in a relative small filtered raw seawater production area. The main technical concerns are the ability to produce economically the required target volume of raw seawater feed retaining the high quality natural filtration. Optimal alternative intake systems design is based on the balance of these two factors. There is a variety of different design options for alternative intake systems, however the best design concept proposed for W.E.B. Aruba N.V. is a series of vertical beach wells, as indicated in Figure 10.6, located roughly parallel to the shore.

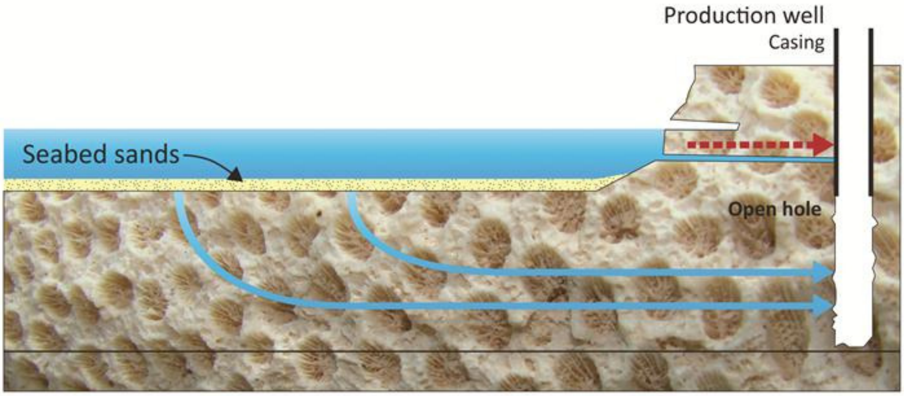


Figure 10.6: The proposed beach well's design concept for W.E.B. Aruba N.V., [10.18]

Further preliminary modeling done by Schlumberger Water Services Inc. using aquifer hydraulic data obtained from an *Aquifer Performance Test* (APT) of the 6 hours short term pumped production well indicated that the target seawater feed is obtainable with acceptable well water level drawn-downs from onshore production well making offshore production well testing unnecessary. Schlumberger Water Services Inc. drilled five monitoring wells and one production test well with a track mounted air-hammer drilling rig using air circulation to carry the cuttings and produced water upwards to land surface through the annulus between the drilling string and borehole [10.18]. Air-hammer drilling has the advantage to penetrate rapidly even through very hard rock and does not involve usage of drilling fluids such as bentonite muds. These drilling fluids need to be removed from the formation prior to production to prevent serious membrane fouling. Figure 10.7 illustrates the well drilling activity on the premises of the Desalination Department.

Figure 10.7: Drilling of beach wells at W.E.B. Aruba N.V.

The monitoring wells were constructed by first drilling a borehole with a nominal diameter of 25 cm to the top of the production zone and by cementing in place to land surface a 20 cm schedule 40 PVC casing with Portland cement. After grouting, the wells were completed by drilling a 14 cm diameter open hole through the lime stone rock. The open-hole construction is hydraulically more efficient than screened completion [10.19]. Figure 10.8 illustrates the construction diagram of a monitoring well.

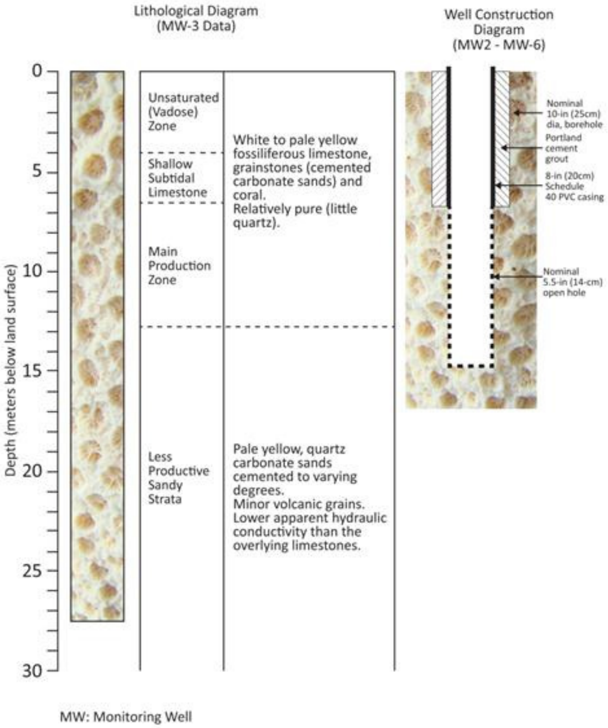


Figure 10.8: A Schlumberger Water Services Inc. monitoring construction well Diagram [10.18]

The details of the construction wells and the wells testing results are summarized in Table 10.5.

Table 10.5: The well construction details and test results [10.18]

Well Construction and Testing Summery							
Well No.	MW-1	MW-1	MW-1	MW-1	MW-1	MW-1	PW-1
Cased depth (m)	18.6	6.8	6.8	19.0	9.2	6.6	6.2
Total depth (m)	18.6	15.6	27.6	27.6	15.6	15.6	15.2
Casing diameter (in/cm)	4/10	8/20	8/20	8/20	8/20	8/20	12/31
Screened interval (m)	4 to 18.6	NA	NA	NA	NA	NA	NA
Pumping Test Results							
Pumping rate (m^3/min)	0.15	1.0	1.1	0.85	1.1	-	2.72
Drawdown (m)	0	0.6	0.2	0.18	1.46	-	0.87
Specific capacity (m^3/min/m)	-	1.86	5.39	4.60	0.75	-	
Silt Density Index (SDI)*	-	-	2.05	-	-	-	
Salinity (ppt)	34.2	32.4	31.5	17.9	-		33.0

ppt = parts per tons; NA = non applicable

Depths are below land surface

At low pumping rates, the results were positive, with the exception of monitoring well number six, indicating SDI values lower than 3 and very low drawdown. The open-hole interval of the number six well consisted of unconsolidated sands and the borehole consequently filled due to collapsing back at 9.1 meter below land surface.

For an alternative intake system, the local geology is very important. The lithology of the production area is reviewed by evaluation of the cuttings brought up to surface by the air-hammer drilling device. As indicated in Figure 10.8, the strata encountered down to 10 m below land surface for the monitoring beach well number 3 consists of relatively pure limestone. This limestone is classified as carbonate grainstone, which is cemented carbonate sand. The upper limestone consist of varying amounts of coral stone presumably of the Pleistocene age which has been diagenetically altered by the re-crystallization of the original coralline aragonite into polymorph calcium carbonate [10.18]. The strata between 9.6 and 12.6 meters have a mixed lithology consisting of pure limestone and a darker colored sandy grainstone mixed with common quartz and volumetrically minor dark volcanic sand grains indicating the coral-volcanic origin of the island. Below 12.6 meters, the strata consisted mainly of disaggregated quartz and carbonate sands with minor volcanic sand grains. The strata between 6 to 15 meters below surface were indicated as the main production zone.

The Aquifer Performance Test (APT) was performed to obtain site-specific data of the aquifer transmissivity, the particular hydraulic property of importance indicating the drawdowns during pumping and thus yields of this production zone. The APT was done by pumping test the Production Well #1 and monitoring the level in the monitoring wells number one and two, situated respectively on a distance of 50 and 90 meters from the production well. The test shows average maximum drawdowns of 0.9 meter for the Production Well #1 and 0.088 meter for the Monitoring Well #2. The APT test revealed very high transmissivity of 28,000 m^2/d indicating minimal well interference, which is very favorable for the proposed beach well alternative intake system if the limestone aquifer of the production zone is present across the production site. Figure 10.9 illustrates a common open-hole beach well intake configuration.

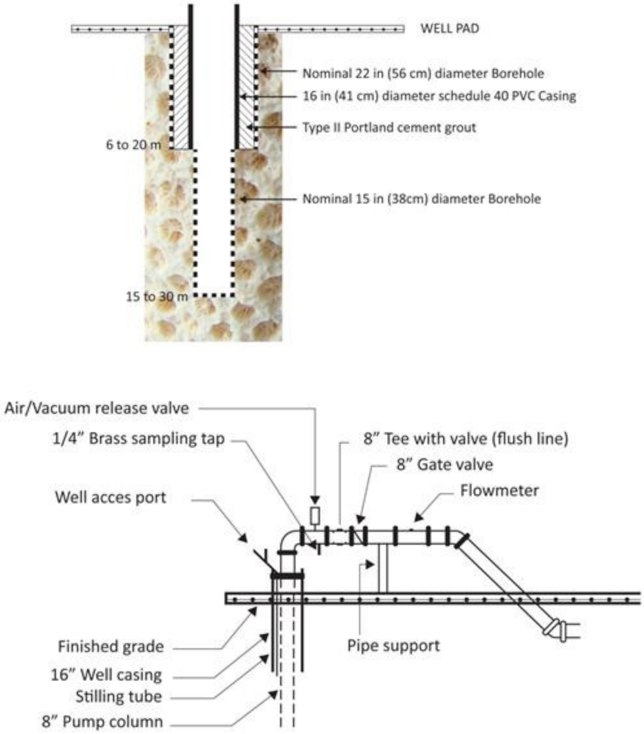


Figure 10.9: A common open-hole beach well intake configuration [10.18]

The short term pumping test results indicate that the alternative beach well intake system with high transmissivity of the lime stone aquifer production zone producing seawater feed with low SDI's values in the range of 2-3 is suitable for the production of 32,000 m3/day of drinking water with the membrane technology. Further a long-term pumping test and chemical and bacteriological analyses were performed to confirm the production capacity and the quality of the raw seawater feed as will be explained in the next section.

The physicochemical and bacteriologic analyses during well pumping test

The results of the geological survey performed by Schlumberger Water Services USA Inc. to determine the hydrological feasibility of the alternative beach well intake system as described above were very promising indicating high transmissivity of the subsurface lime stone aquifer and clear produced raw seawater feed with very low SDI values. However, these preliminary results were based on a short-term pumping test with duration of six hours. The Desalination Department of W.E.B. Aruba N.V. in cooperation with the Engineering Department performed a long-term uninterrupted pumping test of 7 days using a diesel powered centrifugal pump to evaluate the Production Well #1's yield and the quality of the natural filtered raw seawater at the recommended pumping capacity of 1000 GPM (5,472 m3/day). During the 7 days test the average pumping capacity of 2200 GPM (11,992m3/day) was achieved and maintained, which is about 220% of the recommended pumping capacity. To measure the drawdown in the monitoring wells, an electronic pressure transducer is installed in the wells at 10 feet below static water level. As illustrated in Table 10.6, the drawdown in the monitoring wells #1 and #2 were practically constant during the pumping test at a pumping rate higher than recommended [10.19].

Table 10.6: Static water levels in the monitoring wells one and two during pump Test [10.19]

Date	Time	MW-1 BLS (ft.)	MW-2 BLS (ft.)	EPT (PW-1) Diver D6432 BLS (ft.)	EPT (MW-1) Diver 78422 BLS (ft.)	EPT (MW-2) Diver 78421 BLS (ft.)
Nov 24	07:55		14.2			24.2
	07:58	12.1			22.1	
	08:37			17.7		
Nov 25	07:20	12.1	14.5			
Nov 26	07:20	12.2	14.2			
Nov 27	08:00	12.1	14.4			
Nov 28	07:15	12.1	14.4			
Nov 29	07:30	12.1	14.4			
Nov 30	09:00	12.1	14.4			
Dec 01	07:25	12.1	14.1			
	10:30	12.9	14.1			

The physical raw seawater analyses:

The Salt Density Index value measurement

The fouling potential of the raw seawater is measured using the Silt Density Index (SDI_{15}) value. The SDI_{15} value is measured by recording the time to filter a volume of 500 mL of water through a standard 0.45 µm filter at a constant given pressure of 30psi or 210kPA in a time interval of 15 minutes (t_e) between the initial time t_i and the final time t_f. The SDI_{15} is further calculated using the following formulae:

$$SDI_{15} = (100*(1-(t_i / t_f)/ t_e) \qquad (10.3)$$

Typically, good quality seawater feed for the membrane separation process should have a SDI_{15} lower than 5 [10.20]. Seawater feed with higher value indicating higher fouling potential requires the necessity of intensive pretreatment of seawater with micro-, nano- or ultra-filtration to prevent severe membrane fouling. Figure 10.10 illustrates the measured SDI_{15} values of the Production Well #1 during the pump test [10.19].

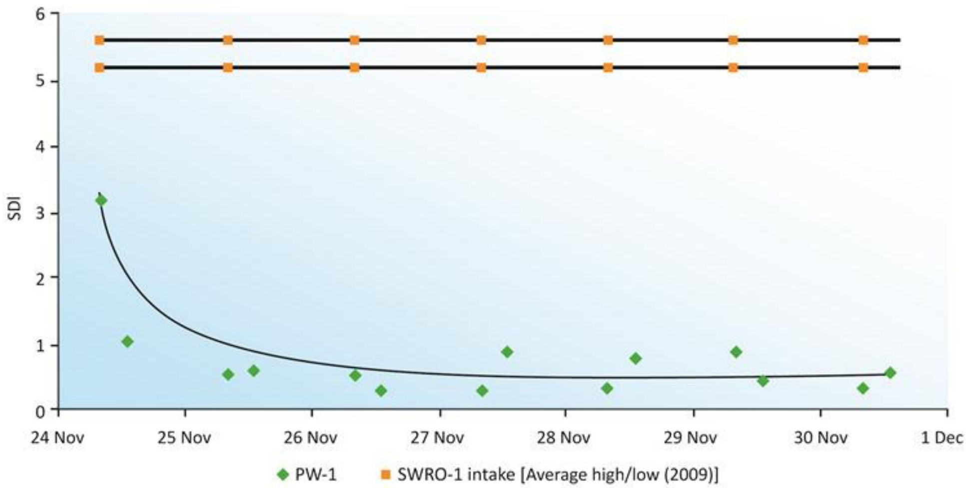


Figure 10.10: SDI_{15} values for the beach well raw seawater compared with the SWRO open intake at W.E.B. Aruba N.V. [10.19]

After approximately 1.5 days of natural filtration, the quality of the raw beach well seawater stabilized and SDI_{15} values as low as 0.3 were measured. The average value during the long-term pumping test was 0.54 compared with a value of 6 for the open intake of the existing SWRO indicating the effectiveness of the natural filtration capacity of the aquifer limestone. The picture in Figure 10.11 illustrates the SDI-filters used to compile the SDI-graph in Figure 10.10; filter #1 representing the SDI_{15} value of 3.16. The picture of the SDI_{15} filters clearly show that the filters of the beach well raw seawater remain relatively clear compared with the open intake seawater of the existing SWRO, which has a dark brown color indicating high fouling potential.

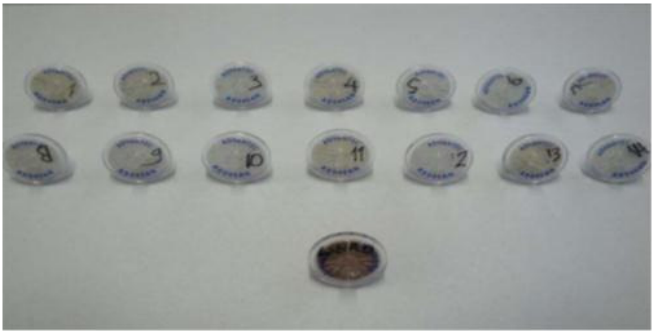


Figure 10.11: Picture of the SDI_{15}-filters of the beach well and open intake raw Seawater [10.19]

Turbidity measurements

Since 1900, turbidity is an important parameter used to assess the quality of a water source. It is a measure of the transparency of water in relation with suspended particles present in water influencing its clarity and quality. Once considered only as an aesthetic characteristic of drinking water, significant evidence exists that controlling turbidity is a competent safeguard against pathogens in drinking water [10.21]. In the membrane technology, it is an indication of the fouling capacity of the seawater feed and a characterization of the biofouling reduction capacity of the pretreatment system of the seawater feed. Typically, turbidity values lower than 1 *Nephelometric Turbidity Units* (NTU) indicates high quality seawater feed. Figure 10.12 illustrates the measured turbidity values for the beach well raw seawater samples compared to the SWRO#1 open intake system.

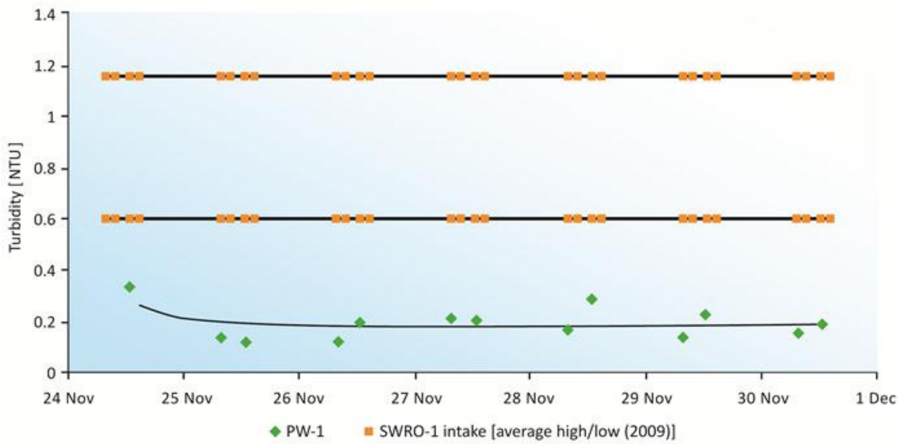


Figure 10.12: Measured turbidity values for beach well raw seawater compared to open SWRO intake [10.19]

As Figure 10.12 indicates, during the long-term pumping test very low values of turbidity were constantly measured averaging 0.18 NTU with lower values up to 0.12 NTU indicating the high quality of the natural filtered raw seawater feed. The turbidity of the beach well raw seawater is lower, compared with the SWRO#1 open intake seawater and approximately in the same range as the pretreated existing SWRO seawater feed.

Chemical analyses:

Dissolved oxygen measurement

Oxygen dissolved naturally in seawater through diffusion from air, by aeration or as a reaction product of the natural photosynthesis. It is a necessary chemical component for practical all life on Earth and a requirement to sustain an active aerobic microorganisms' environment. In the concentration range of 5-2 mg/L, it is critical for life forms and deadly below a concentration of 1-2 mg/L [10.22]. Therefore, the concentration of the Dissolved Oxygen (DO) in the raw seawater is a direct measure of the biologic load and the biofouling potential. Figure 10.13 illustrates the measured DO-value of the raw seawater of the beach well and the SWRO open intake system. During the long-term pumping test an average concentration of 3.21 mg/L is measured with low values up to 2.36 mg/L compared with typically concentration of 7-8 mg/L for natural seawater. The measured DO-values indicate the low aerobic biofouling potential of the natural filtered beach well raw seawater. As already indicated above, seawater feed for membrane desalination processes with low biofouling potential requires less intensive pretreatment system representing low operation cost.

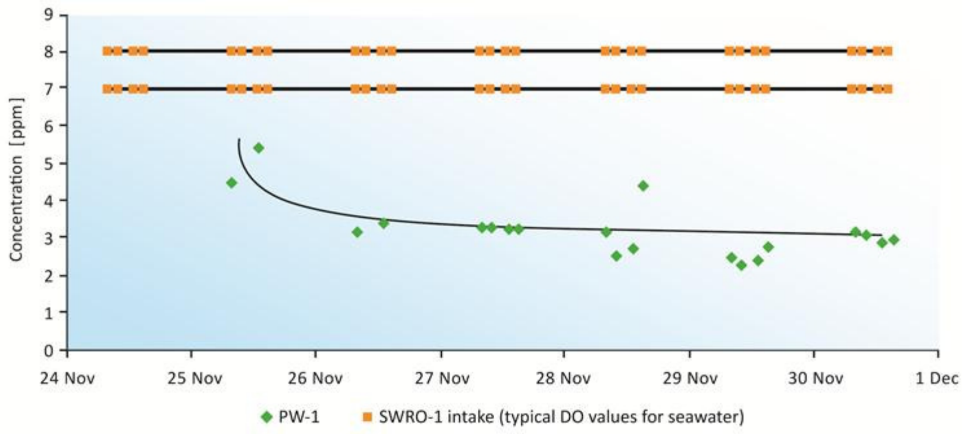


Figure 10.13: Measured Dissolved Oxygen levels during the pump test [10.19]

Dihydrogen sulfide (H_2S) measurement

Reverse osmosis technology has the capacity to remove dissolved salts however, dihydrogen sulfide being a gas at normal ambient temperature and pressure can pass freely through the permeable membrane surface. It is a colorless, flammable and toxic gas with an irritant smell of rotten eggs and can be detected by humans at levels as low as two parts per billion, (ppb). Dihydrogen sulfide is naturally produced in seawater or beach well water by bacterial decay of organic substances in anaerobic, oxygen deficient, environment. If present in the seawater feed further intensive post-treatment (gas scrubbing technology) is needed to remove this gas from the drinking water. The sampled beach well is tested with the Hach Hydrogen Sulfide test kit and no hydrogen sulfide is detected in the 0-0.55 mg/L concentration range. This confirms that the beach well raw seawater does not contain dihydrogen sulfide.

Chemical components of the beach well raw water

To specify further the quality of the raw beach well seawater feed an analyses of the chemical components is necessary. Table 10.7 illustrates the chemical composition of the beach well seawater indicating the suitability and high quality as seawater feed for the SWRO production unit.

Table 10.7: The Chemical composition of the beach well water [10.19]

Parameter	Unit	Value
Conductivity	µS/cm	48,883
pH	-	7.8
TDS	ppm	24,390
Total alkalinity	ppm	92
Turbidity	NTU	0.8
Phosphate (PO_4)	ppm	0.28
Calcium as CaCO3	ppm	549
Boron	ppm	4.3
Copper (Cu)	ppm	0.54
Magnesium (Mg)	ppm	1,300
Iron (Fe)	ppm	0.05
Hardness	ppm	6,716
Dissolved oxygen	ppm	8.71

Bacteriological analyses:

The Heterotrophic Aerobic Bacteria analyses

The SWRO#1 has experienced persuasive membrane biofouling with the seawater open intake system despite intensive pretreatment of the open intake seawater feed. Bacteriological analyses are therefore very important for the feasibility study of the beach well alternative intake. During the long-term pumping test, the Desalination Department performed indicative bacteriological analyses with the *Biological Activity Reaction Test*

(BART ™) for *Heterotrophic Aerobic Bacteria* (HAB) from Droycon Bioconcepts Inc. This test is based on the measurement of the ability of the total aerobic bacteria to respire while degrading the selected chemicals in the tester [10.23]. Aerobic bacteria can cause several problems in water, including slime formation, turbidity, taste and odor, corrosion, health risks and hygiene risks. Once attached on the SWRO membranes it can cause serious biofouling causing efficiency and production decay. As shown in Figure 10.14 the results of the bacteriologic analyses indicates that the tested beach well filtered raw seawater has tested positively for Heterotrophic Aerobic Bacteria with an approximate population size of 500,000 cfu/mL consisting approximately of a population of 140,000 cfu/mL of Iron related bacteria and 360,000 cfu/mL of slime forming bacteria. Iron related bacteria are difficult to enumerate because they use iron in their metabolism either by iron oxidation or by iron reduction [10.22].

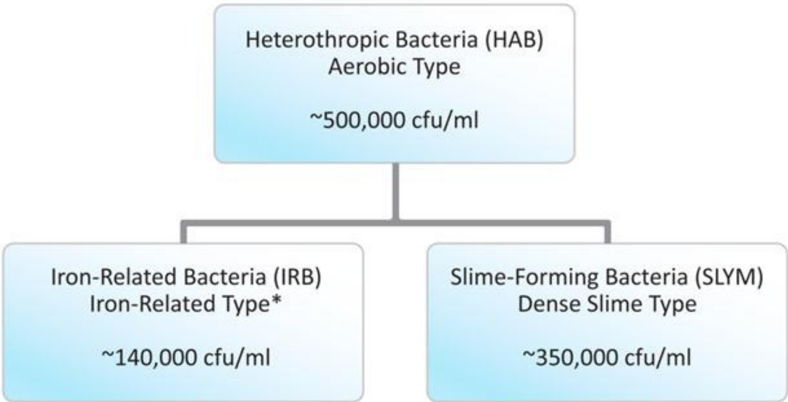


Figure 10.14: The beach well filtered raw bacteria content [10.19]

Using the BART ™ tester the Desalination Department performed further advanced bacteriological analyses to investigate the eventual presence of nitrifying bacteria, micro-algae, sulfate reducing bacteria, denitrifying bacteria. All samples tested negative for above-mentioned bacteria. In cooperation with the Government Laboratory, beach well seawater samples were analyzed confirming no presence of *Escherichia Coli* (E.Coli) and *Enterococcus Faecalis* (E. Faecalis).

The Biofilm Monitor and Membrane Fouling Simulator analyses

The evaluation of the fouling potential of the natural filtered raw seawater of the limestone aquifer is further extended with a pilot installation containing a Biofilm Monitor to monitor the biofouling potential and an Early Warning System containing a Membrane Fouling Simulator to monitor the membrane fouling potential. As already described in Chapter 4 the biofilm monitor is designed by Kiwa Watercycle Research (KWR) to evaluate the biofilm forming potential of freshwater in drinking water distribution systems [10.24]. This device consists of a glass column filled with a set of glass rings with a specific outer surface that could capture and hold biofoulant materials. The amount of biomaterial on the glass rings is characterized by *Adenosine Tri Phosphate* (ATP) measurements. It is the first time that a biofilm monitor is used for the evaluation of the biofilm forming potential of the natural filtered raw seawater of the beach well. The Government Laboratory performed the ATP measurement by means of a luminometer, a device that measures transmitted light produced by two reagents in the sample water and converts it to '*Relative Light Emission*' (RLE) which has is a linear correlation with the ATP.

The Early Warning System (EWS) is a means to simulate and measure the fouling of an SWRO membrane. It contains devices to measure flow and pressure and a module to mimic the flow of seawater through a spacer. This part is called the Membrane Fouling Simulator (MFS) and it consists of an Aluminum-Plexiglas box container. It has an inlet and outlet for the seawater flow and connections for the pressure meter. Inside the box, a membrane and spacer can be placed. As the system runs, the pressure difference over the spacer will increase and this will be measured and registered by the monitor connected to the EWS [10.25]. The left hand picture of Figure 10.15 illustrates the pilot plant as designed and constructed at the Production Well #1.

a: provisional beach well monitoring   b: SWRO pilot beach well monitoring

Figure 10.15: The biofouling monitoring pilot installations at production Well#1

The ATP measurement in 2011 with the provisional pilot plant lasted for 8 days and the results show a fivefold increase in the biofilm-forming rate of 5pg ATP/cm^2 to 25 pg ATP/cm^2 as indicated in Figure 10.16. These measured values are still much lower than the measured values of higher than 5000 pg ATP/cm^2 with the seawater open intake of SWRO#1 [10.25]. Unfortunately, no membrane spacer's pressure drop could be obtained due to malfunctioning of the data logger, but the MFS spacer system was very clean during the whole test period of one month.

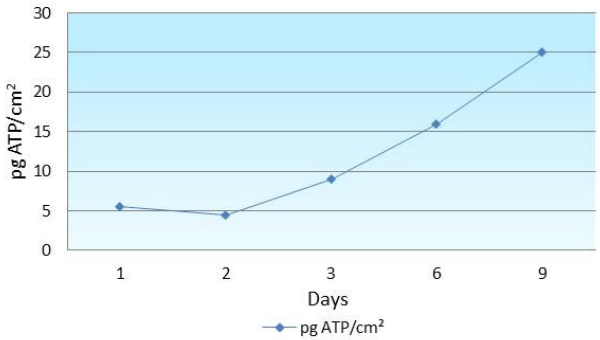


Figure 10.16: The biofilm-forming rate of the beach well raw seawater

The biofouling of the beach well raw feed water is further evaluated in the SWRO pilot unit shown in the right hand picture of Figure 10.15. As illustrated in Figure 10.17, the measured ATP values for a period of 21 days at a practically constant flow of 200 L/hr showed a biofilm rate increase from 3.53 to 25.6 pg ATP/cm^2 in the first two days. After the second day, the biofouling rate showed a practically constant trend with an average biofouling rate of 24.46 pg ATP/cm^{2}with a peak of 37.28 pgATP/cm^2, confirming the low biofouling potential in comparison with seawater [10.26].

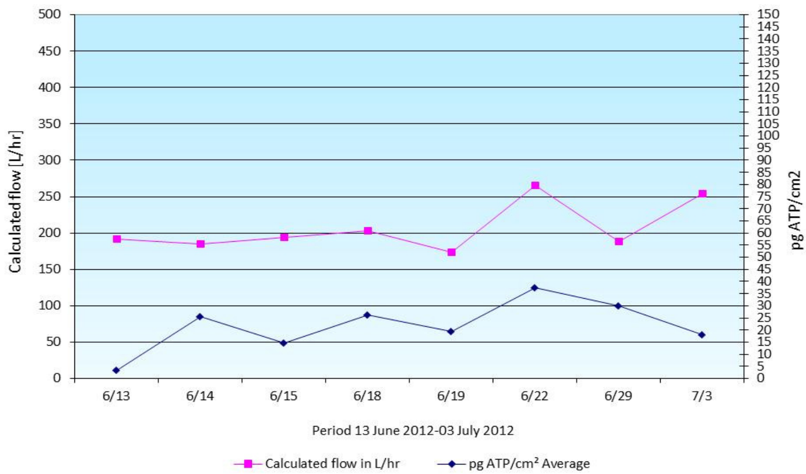
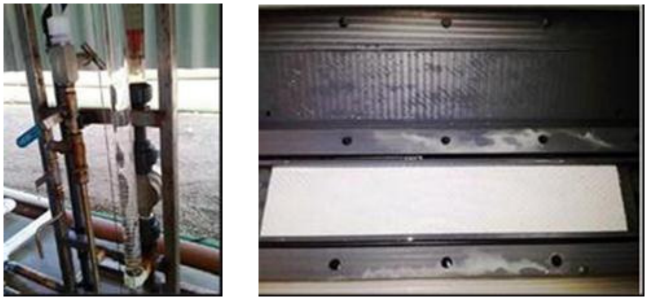


Figure 10.17: The biofilm-forming rate of the beach well raw seawater

As illustrated in Figure 10.18 the spacer and membrane material of the MFS and the rings of the biofilm monitor were at the end of the test still clean without visually any sign of biofouling. The picture of the test with seawater is also illustrated for comparison purposes.



Biofilm monitor Membrane Fouling System

a: beach well raw feed water

Biofilm monitor Membrane Fouling System

b: seawater raw feed water

Figure 10.18: Comparison of the beach well and seawater feed water biofilm monitoring

Figure 10.19 shows the measured pressure difference (ΔP) over the spacer in the Membrane Fouling Simulator, simulating in this manner the fouling potential of the beach well raw seawater in real SWRO membranes as explained in Chapter 4.

As Figures 10.19 illustrates, the measured pressure difference during 20 days was in the range of 15-40 mbar which is 200 percent lower than the measured pressure difference with the SWRO open intake system which was in the range of 200-500 mbar [10.25] indicating a much lower membrane fouling potential as compared with open intake seawater feed. The introduced parameter of the delta of the pressure difference (ΔP), the delta delta P, shows a straight line indicating that the membrane spacer's pressure difference is constant in time, which means no accumulation of biofouling in time.

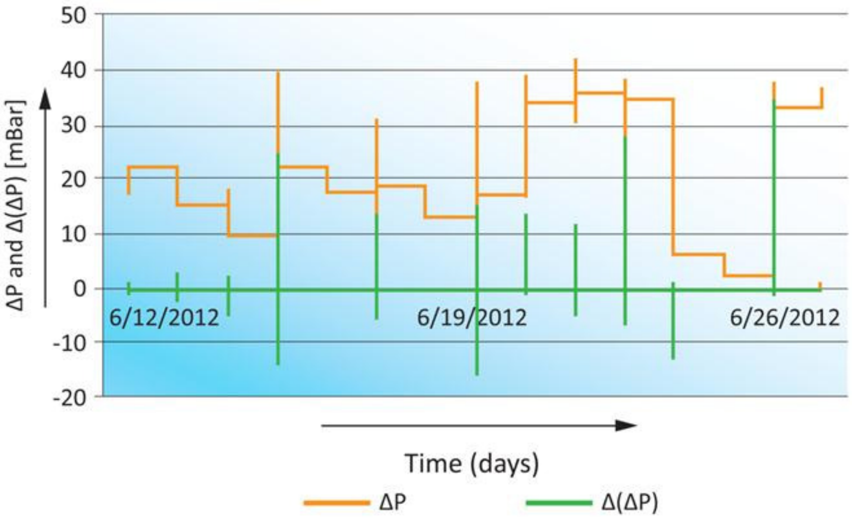


Figure 10.19: The measured pressure difference with EWS pilot installation [10.25]

The performed physical, chemical and bacteriological investigations as mentioned above have confirmed the superiority of the beach well seawater feed quality supporting the decision to go forward with implementation of beach well as seawater feed source for the SWRO desalination units to improve availability, reliability, sustainability and efficiency of the membrane technology. The only precaution is high aerobic bacteria counts, indicating the need for disinfection of the beach well prior to desalination.

10.5 Conclusions

1. The Desalination Department of W.E.B. Aruba N.V. has undoubtedly succeeded to be a worldwide pioneer in the implementation and support of the development of new innovative technology to improve seawater desalination efficiency.
2. The innovations and efficiency improvement initiatives of the Desalination Department to evaluate new economical technologies to improve desalination efficiency has undoubtedly stimulated and catalyzed, for the first time a structured intensive study based on the green field theory to evaluate new economical ways for power and water production at W.E.B. Aruba N.V., up to 2025. The results of this study are documented in the report “Energia Aruba 2025”.
3. The evaluation and the decision to implement beach well to guarantee a high quality feed water for the new SWRO technology at W.E.B Aruba N.V. is another success for the Desalination Department in its endeavor to reach out to excellence in efficient and sustainable seawater desalination.

4. Further scientific and pilot research is needed to develop improved Clean in Place technologies to inhibit or mitigate biofouling promoting sustainable SWRO desalination operation.

10.6 References

10.1. Oduber, L. H., Technical Department W.E.B. Aruba N.V., 2011.

10.2. Marchena, F. A., Vrolijk, V. R. J., Experience and New Challenges in Seawater Desalination at W. E. B. Aruba N. V., the 6th International Congress and Exhibition on Water, Renewable Energy and Health, Safety and Environmental, Aruba , November 2004.

10.3. Marchena, F. A., Hodgson, J. W., Reverse Osmosis A New Challenge in Seawater Desalination after seventy five years of successful Thermal Desalination, AWWA Seminar, Honolulu, Hawaii, May 2006.

10.4. Marchena, F. A., Hodgson, J. W., Harvey, W., Morrell, J. A., Maria, D. R., The Decision Process to Use Membrane Desalination after 75 years of successful Thermal Desalination, International Desalination Conference, Oranjestad, Aruba, June 2007.

10.5. DHV Consultants., Prefeasibility study: for RO Water Supply on Aruba: with focus on hotel Water Supply, Confidential Report W.E.B. Aruba N.V., July 2004.

10.6. DHV Consultants, Feasibility study for RO treatments in Aruba, Confidential Report W.E.B. Aruba N.V., May 2004.

10.7. Van der Veen, W., Vlaski A., et al., Energia Aruba 2025 Final Report., Confidential Report W.E.B. Aruba N.V., November 2005.

10.8. Ecovision N.V. Report, Two SWRO in Operation at W.E.B Aruba N.V.; Environmental Aspects, (in Dutch), November 2006.

10.9. Van den Brink, T., Assessment of The Environmental Risks associated Water Production using Reverse Osmosis on Aruba and Curacao, International Desalination Conference, Oranjestad, Aruba, June 2007.

10.10. Huiting, H., Kiwa N.V. Report, Seawater Desalination with Reverse Osmosis; Effects on Water Quality, January 2006.

10.11. Frank, R. A., An Economical Evaluation of the MSF, MED and the SWRO Technology, Internal Report W.E.B Aruba N.V., November 2005

10.12. Marchena, F. A., A Strategic Operation Philosophy for the New SWRO Technology, W.E.B. Aruba N.V. Internal Report, June, 2007.

10.13. Energia Aruba 2025, confidential report W.E.B. Aruba N.V.

10.14. Marchena, F. A., Prato, T., Resolution of Persuasive Biofouling Issues at W.E.B. Aruba N.V.'s Seawater Reverse Osmosis Plant., International Desalination Association Conference, Perth, Australia, September, 2011.

10.15. Marchena, F. A., SWRO #1: Findings and Proposals for Improvements, Internal Report W.E.B. Aruba N.V., July 2009.

10.16. Fritzmann, C., Lowenberg, J., et al, State-of-the-art of reverse osmosis desalination, Desalination 216 (2007), 1-76.

10.17. Ellms, J. W., Water Purification, 2nd Edition, McGraw-Hill Book Company, Inc., USA, April, 1928.

10.18. Schlumberger Water Services Inc., Reverse-Osmosis Desalination Plant Alternative Intake Investigation, Final Report for W.E.B. Aruba N.V., November 2009.

10.19. Cuba de, R. E., Wiersma, R. A., Long Term (168 hours) Pump Test of Production Well No.1, Internal Report W.E.B. Aruba N.V.

10.20. Degrémont Suez, Water Treatment Handbook, 7th edition, Volume 1, Lavoisier SAS, ISBN 978-2-7430-0970-0, France, 2007, 523.

10.21. EPA Guidance Manual, Turbidity Provisions, Chapter 7 Importance of Turbidity, USA, April, 1999.

10.22. http://www.state.ky.us/nrepc/water/wcpdo.htm

10.23. http://www.DBI.ca ., Droycon Bioconcepts Inc., BART™ Test for Heterotrophic Aerobic Bacteria, Canada, 2008.

10.24. Vrouwenvelder, J. S., et al, Manual Biofilm Monitor, KWR, Nieuwegein, The Netherlands, 2006.

10.25. Gudde, J. C. J., " Quantifying Serious fouling in the SWRO process at W.E.B. Aruba N.V., Internship Report Delft University of Technology and W.E.B. Aruba N.V., June 10, 2009.

10.26. Maduro, R. A., Internship Report, W.E.B. Aruba N.V.-De Haagsche Hogeschool, The Netherlands, June, 2012.

Chapter 11

Scientific and practical contributions and aspects that need further evaluation and research: a reflection

Reflection: a scientific art toward simply enlightening the twilight

Chapter 11

Scientific and practical contributions and aspects that need further evaluation and research: a reflection

Table of Contents:

11.1 Introduction

Fresh drinking water as we all know is the basic need for all living creature on Earth and fundamental for the quality of life. Although in abundance on Mother Earth, however due to the especially uneven rain fall and insufficient surface water and groundwater availability, many places are still in scarcity of save and healthy drinkable water resulting in severe poverty and an inhuman way of life. Desalination of seawater or brackish subsurface water is a viable option for the production of drinking water in arid areas but it is still a very expensive endeavor. Global research has constantly concentrated to improve efficiency to reduce operation cost. The last decades to diminish the environmental pollution caused by burning fossil fuel for the energy production, research concentrated extensively on development of innovative sustainable desalination technology based on alternative wind, geothermal, ocean or solar energy.

The Aruban application of efficient seawater desalination has solved the island's water shortage problem increasing the standard of life and the island's economy and prosperity. In view of the importance of the costly seawater desalination for the population and economy, a research has been performed to optimize the efficiency of the existing seawater desalination process. Awareness of the optimal operation efficiency as an important aspect of sustainability to effectively reduce energy consumption and consequently reducing operation cost and environmental pollution directed this research toward efficiency improvement of the existing desalination units, on the contrary to the global trend of modern sustainability research efforts.

The scope of this research is in essence primarily based on the successes of the application of the developed Continuous Desalination Efficiency Improvement Process in analogy with the EFQM performance improvement frame work. The basic concept is efficacy oriented operation and maintenance in desalination through effectively empowering and involvement of the experienced work floor personnel. In this research based on many years of practical experiences, the human aspect, the physicochemical aspect, the aspect of maintenance, the aspect of technology innovation and the application of new technology have been considered and established as the key efficiency improvement factors validating continuous desalination efficiency improvement.
In the previous chapters all these efficiency improvement aspects have been in depth evaluated and explained with respect to the endeavor of the Desalination Department of W.E.B. Aruba N.V. toward excellence in seawater desalination.
This chapter will give a reflection on the results achieved during this desalination efficiency improvement research and will elaborate further on the aspects that are not considered in this research and still need further investigation as necessary in a continuous desalination improvement process. This chapter is organized as follows. Section 11.2 gives an historical

reflection on the water supply and seawater desalination in Aruba. Section 11.3 elaborates on the results of this research and section 11.4 reflects on the contribution to science, the contributions to the desalination practice in Aruba and abroad and finally on the limitations and need for further research.
Finally to enlighten the envisioned future desalination improvements in Aruba, section 11.5 gives a conceptual design of a fossil fuel free membrane technology for combined water and power production to continue with the vision and passion of improving the desalination technology and wondering about still unknown technique and technology toward more efficient environmental friendly green sustainable seawater desalination.

11.2 The water supply and desalination on Aruba: a passionate reflection

Fresh water as we all know is the basic need and fundamental for the quality of life. On the Island of Aruba, due to the sub-tropical climate, fresh water can be in abundance in the rainy seasons. However (as indicated in Figure 11.1) most of the rain water flows back to the sea leaving the island in scarcity of drinkable water.

Figure 11.1: Rainwater flowing back to the sea leaving dry river beds behind

So, it is imaginable that centuries ago an Aruban native Arawak Indian during the seasons of water scarcity, walking on the white sand beaches, during fishing or in the evening admiring the reflection of the moonlight or the evening star on the seawater surface (as illustrated in Figure 11.2), may have wondered [11.1];

"If we could ever make fresh water from seawater, this will make my Oro Ubao a happier paradise"

As a consequence, the sea surrounding the island will not only be the source of food but also of the precious fresh drinking water.

Figure 11.2: Arawak Indians fishing and admiring the moonlight's reflection

Maybe walking away from the beach his thought stayed in the air swirling around for still many centuries and decades to come until his dream and vision became true.
He left us with his cave drawings (as illustrated in Figure 11.3) describing his ideas and maybe future perspectives as a precious heritage.

Figure 11.3: Aruban Arawak Indian cave drawings

In the course of time (as explained in detail in Chapter 2) his descendants continued to use surface water to foresee in their daily needs for fresh drinking water. They also learned to use the donkey as a sustainable environmental friendly grey energy for water transport from the *Tanki's*, the fresh water catching areas. Further on they learned to search for groundwater and dug wells and used wooden winches and wind mills to haul up the water. They learned to build houses with cisterns to catch rain water and discovered and applied primitive techniques for the water treatment. The cactus juice and some drops of seawater was used to clarify the muddy surface water, the *Cudi* (a calcite stone filter) to filter out colloidal particles and the *Purun* and the *Tinashi* (clay jars) to keep the water fresh and cool. The Cudi, Purun and Tinashi are illustrated in Figure 11.4.

a: the Cudi b: the Purun c: the Tinashi

Figure 11.4: The Cudi, Purun and the Tinashi

Finally in 1932 his dream and vision became true with the initiation of the first commercial seawater desalination activities on the island for municipal drinking water supply and in 1959, although for a very brief period, becoming the largest desalination facility in the world [11.2]. The desalination activities have followed since then the desalination market trend with the application of the MED technology from 1932 to 1983, followed by the MSF technology in 1964 till present and the new SWRO technology since 2008. Nowadays the desalination facility of Aruba is still known throughout the world as one of the first pioneering contributors to the seawater desalination applied technology and innovations for municipal drinking water supply and the most efficient thermal and membrane seawater desalination facilities for the production of one of the world's highest quality drinking water. The Aruban application of efficient seawater desalination has solved the water shortage problem increasing the standard of life and the island's economy turning the Arawak Indian's Oro Ubao into a one happy paradise.

Toward our future with sustainable green desalination, on the contrary to the global research and development of alternative desalination technology, the importance of continuous efficiency improvement especially in the present application of our costly conventional desalination technology is emphasized in the context of Efficacy, the efficiency improvement process through effective involvement and empowering of the work floor personnel [11.3]. The results of this desalination efficiency improvement research are highlighted in the following section.

11.3 The results of the continuous desalination efficiency improvement research

On the contrary to the global trend of research efforts in developing new alternative sustainable desalination technology, this research concentrates on the other important, sometimes forgotten, aspect of sustainability namely the operation and maintenance

efficiency improvement especially in the present application of the costly conventional desalination technology to effectively reduce energy consumption and consequently reducing operation cost and environmental pollution toward Green Desalination.
The research frame work is in main set up according to the developed and applied *Continuous Desalination Efficiency Improvement Process* (CDEIP) reaching out to excellence in Desalination. Considering the enabling importance of leadership in the context of efficacious motivation, effective involvement and empowering of the work floor personnel to best use partnership and resources to efficiently operate and maintain the desalination assets to guarantee the production of high quality drinking water at increased efficiency to all stakeholders' satisfaction, this research is primarily based on the principles of the performance frame work of the *European Foundation for Quality Management* (EFQM).

The main objectives of this research (as specified in Chapter 1) are:

"The specification and evaluation of the most important aspects in practical operations that influence sustainable efficiency in seawater desalination and to illustrate the effectiveness of a continuous desalination efficiency improvement process founded on these key efficiency improvement aspects."

"The illustration of the technologies and techniques developed and applied at the Desalination Department of W.E.B. Aruba N.V., validating and fortifying the developed continuous desalination efficiency improvement process to guarantee an environmental friendly and cost effective production and distribution of drinking water with a high chemical and bacteriological quality."

This goal oriented practical research has given on a scientific basis an answer to the main research question specifying the desalination efficiency improvement research process:

"What are the most important factors influencing desalination efficiency?"

The fundamental answer on this principle research question is based on many years of practical desalination experience exploring the possibilities to improve desalination efficiency. The experienced challenges at the Desalination Department pointed out the following factors as being the most important;
- The human factor
- The physical and chemical aspect
- The maintenance aspect
- The aspect of technology innovation
- The implementation of new technology

With the human factor and the abovementioned technical aspects specified as the determinative desalination efficiency improvement factors, the next important step of this research is answering the second research question to identify the most essential sub aspects;

“Given an efficiency improvement aspect, what are the sub aspects of importance to effectively improve efficiency?”

In this continuous desalination efficiency improvement research process only the important human factor and the physicochemical aspects are further specified in sub aspects.
With respect to the human factor the fundamental answer to this research question is an effective leadership strategy, work floor motivation and a strategic performance improvement program. This is also in accordance with the perceived challenges in practice at the Desalination Department considered as the most important sub aspects of the human factor to effectively involve and empower the work floor personnel toward desalination operation and maintenance efficiency improvement.

Regarding the technical aspects the fundamental answer to this question is given with respect to the physical chemical aspect which is the very import technical aspect greatly influencing efficiency. It is beyond any doubt that up to now there is no possibility for efficient, stable and sustainable saline water desalination and potabilization of the produced distillate without chemicals. The fundamental answer is based on the specified main important problems encountered in seawater desalination needing effective chemical treatment:

- Biofouling
- Scaling, fouling and corrosion
- Foaming
- Distillate post treatment

The abovementioned research questions are related to the first research objective to specify and evaluate the most important aspects in practical operations that influence sustainable efficient and stable operation in seawater desalination and to illustrate the effectiveness of a continuous desalination efficiency improvement process founded on these key efficiency improvement aspects.

The illustration of the importance of the human factor and the technical aspects for the continuous efficiency improvement process is based on the fundamental answer to the next research question:

“How can improvement of these factors of concern contribute to sustainable efficiency improvement?”

The developed technologies and applied techniques at the Desalination Department during this research founded on the basic concept of an efficacy oriented desalination operation and maintenance process have given a fundamental answer to this research question. The following summary is given of the applied technologies and techniques as described in detail in the previous subsequent chapters:

The human factor
In this research the socio-technical Passion and Fear motivational model and Human Attitude models have been developed in analogy with technological models as metaphors to cope with fear, resistance for change and to motivate to establish a creative work environment. To cope with resistance especially induced by company policy and rules the Mahatma Gandhi Leadership strategy is developed giving the opportunity to challenge rules but without violating any of them. The Efficacious Motivational Leadership approach is developed to effectively involve and empower the work force to improve desalination performance. The Desalination Hierarchy of Needs is developed and applied to sustain the motivational process.

The physicochemical aspects
Biofouling
The novel non oxidizing biocide, Clam Trol CT-2 ™ based on the quaternary amine technology has been applied to mitigate macro biofouling especially barnacles obstructing cooling seawater flow through the condenser tubes and micro biofouling forming biofilms on the heat transfer surfaces reducing heat transfer consequently decaying production and efficiency of the MSF evaporators. An improved Clean In Place (CIP) and a novel chemical free osmotic membrane cleaning process and a sanitation technique were developed and applied at the Desalination Department to mitigate membrane biofouling reducing SWRO production and efficiency.

Scaling, fouling and corrosion
Scaling and fouling due to high temperature decomposition of bicarbonates in the seawater also referred to as alkaline scale and deposition of corrosion products and under deposit corrosion have always affected desalination efficiency and stable operation. Aruba has played throughout its desalination history a major role in the development and application of different novel scale inhibition techniques as in the 1950s the ferric chloride (the first world wide scale inhibitor) and in the 1960s the first worldwide commercial application of

98% concentrated sulfuric acid. In 2004 the Desalination Department has significantly contributed to the development of the novel HT 15 ™ high temperature scale inhibition program that successfully eliminated the use of the 98% sulfuric acid. This is the first worldwide application of a high temperature scale inhibitor in MSF evaporation technology maintaining steadily a high performance.

Foaming

Excessive foam formation is inherent to the flashing process and affects efficiency and stable operation in MSF desalination. A novel approach based on the surface tension effect on flash evaporation is developed to optimize the dosing of the antifoam and the other surface active chemical additives. The experienced effect of production and efficiency decay in MSF evaporation due to overfeed of the antifoam is explained based on the stabilization of internal foaming in the recirculating brine. Up to now there is no acceptable explanation for this effect. An alternative for the foam stabilization mechanism in accordance with the natural flow from a high energy level to a low energy level is given in this research based on the hydrodynamic pressure of the interfacial surface of the foam.

The distillate post treatment

Distillate produced by thermal desalination and product water with a two pass SWRO is very soft and not potable and corrosive for the distribution network. Red water (iron corrosion) and blue water (copper corrosion) is caused if the post treatment is not optimized. Corrosion can on its turn cause leakages due to perforation of the distribution pipes.
The post treatment process of drinking water as applied at the Desalination Department consisted of the natural re-mineralization with coral stones and the application of a corrosion inhibitor. The introduction of the corrosion inhibitors pyrophosphate and zinc orthophosphate especially designed for the soft drinking water of Aruba, after an intensive research to improve quality of the drinking water, has eliminated the red and occasionally occurrence of blue water problem in Aruba since the application in 1990.

The maintenance aspect

To improve maintenance of the desalination asset a predictive maintenance approach is developed based on documentation of the experienced process failures and their effect on production. Key performance indicators and a heat balance were developed to monitor and predict efficiency decay and process failures. The Efficacy Oriented Maintenance approach has been developed in analogy with the Efficacious Motivational Leadership model based on the principle of Maintenance Conscience Operation and Operation Conscious Maintenance promoting an effective team and partnership between Production and Maintenance personnel at the work floor level.

The aspect of technology innovation

Throughout its desalination history Aruba has contributed to innovation in the desalination technology. Manufacturers have improved their designs due to valuable practical information gained from experienced and knowledgeable operations and maintenance personnel. Aruba has played since 1958 an important role in the development and practical application of the first worldwide successful high temperature scale inhibitors.
An innovative chlorine gas discharge hood assembly has been designed to empty a full liquid chlorine one-ton container with damaged discharge valves. A concept of a carbon dioxide degassing tower, a hybrid Osmosis Reverse Osmosis (ORO) desalination process and a novel environmental friendly chemical free osmotic cleaning process for SWRO-BWRO membranes have been designed and patented.

The implementation of new technology

The application of new desalination technology in Aruba is historically in accordance with the global desalination market development to increase desalination efficiency. In 1964 the MSF technology is introduced to replace the less efficient MED technology. Due to high reliability, good operation experience the costly thermal evaporation was the preferred desalination technology for more than 75 years of desalination. A change was forced around 2004 because of the significantly increment in the water production cost due to rapid increases in fuel oil cost. The developments in the local market, a/o a number of the mayor hotels were considering the installation of their own SWRO units to reduce water cost and the increment in complaints from domestic consumers due to the increased cost of drinking water, contributed firmly to an intensive evaluation and the reintroduction of the SWRO membrane technology at W.E.B. Aruba N.V. as the main desalination technology. The heavy membrane biofouling experienced with the new SWRO technology led to the introduction of the beach well technology for the seawater intake at W.E.B. Aruba N.V. replacing the open seawater intake system applied since 1932.

The demonstration of the effectiveness of the developed technologies and applied techniques validating and fortifying the developed Continuous Desalination Efficiency Improvement Process to cope with the main second objective of this research is based on the fundamental answer to the next research question:

“What are the efficiency improvement results?”

The desalination performance improvement results obtained during this continuous desalination efficiency improvement research validating the developed Continuous Desalination Efficiency Improvement Process (CDEIP) are in summary as follows:

The human factor

As explained in details in Chapter 3, due to increased motivation and a creative work environment directed by leadership efficacy the frequency absenteeism of the desalination department has decreased substantially and consequently also the overtime. The efficiency of the desalination units is also increased. Based on motivation yearly cost savings have been achieved.

The physicochemical aspects

The applied biofouling and scale inhibitors have significantly increased desalination efficiency and stable operation due to decreased biofouling and effective scale inhibition. The awareness for the effective control of the antifoam additive dosing during shift is increased. The special developed corrosion inhibition program for the soft drinking water of Aruba has eliminated the occurrence of brown and blue water in the distribution system and has contributed to a low Non Revenue Water (NRW) and a low Infrastructure Leakage Index (ILI). The concentration of iron is decreased to a value lower than the maximal accepted concentration as stipulated by the World Health Organization (WHO). An extensive audit by Pan American Health Organization (PAHO) has acknowledged the high quality of the Aruba drinking water and has considered it as one of the world's highest quality drinking water [11.4]. Abovementioned results of the physicochemical aspects are in detail described in Chapter 4, Chapter 5, Chapter 6 and Chapter 7.

The maintenance aspect:

As described in Chapter 8, the introduction of the Efficacy Oriented Maintenance approach has significantly decreased pumps and process failures and has increased the accumulative performance ratio of the Multi Stage Flashing (MSF) evaporators from 8.7 to 9.3 in the period 2000 to 2008 reducing maintenance and operation cost. The importance of maintenance is also emphasized by the efficiency decay due to the neglect of maintenance of MSF evaporators as mandated by Senior Management to concentrate on the biofouling problem of the SWRO#1 since 2009. This EOM strategy has also promoted good maintenance and operation of the water distribution system achieving the lowest percentage Non Revenue Water in the region, an NRW of about 2.6-4.11 % comparing with 15 to 70% in the neighboring islands. The Infrastructure Leakage Index (ILI) of 0.51 indicates a well maintained water distribution system as compared with the other Dutch Caribbean Islands.

The aspect of technology innovation

The efficiency of the MSF evaporators has been optimized from a performance ratio of 9.0 to 11.5 by the manufacturer based on exchange of desalination practical experiences with the knowledgeable operation and maintenance personnel.

Three patents have been registered for the conceptual designs of a carbon dioxide degassing tower, a hybrid Osmosis Reverse Osmosis (ORO) desalination process and the conceptual design for the novel environmental friendly chemical free osmotic cleaning process for SWRO-BWRO membranes. These results are in detail described in Chapter 9.

The implementation of new technology
The implementation of the new SWRO membrane technology has significantly increased the overall efficiency of the desalination units. The performance ratio including the equivalent low pressure steam consumption of the SWRO technology (as indicated in Figure 8.31 of Chapter 8) has an increasing trend despite the decrease of the performance ratio of the MSF evaporators since 2009.

Finally as a reflection to the performed desalination efficiency improvement research, the contribution to science and operational practice and the limitations of this research and the need for further research with the intention to fortify and continuously broaden the existing practical and theoretical desalination knowledge are considered in the next section.

11.4 The contribution to science, practice and the need for further research: a reflection

Closing the discussion of this research the following last three reflection questions are answered for the distinguished performance improvement aspects of the Continuous Desalination Efficiency Improvement Process considering new acquired knowledge, new developed processes, what is not considered in this research and the need for further research based on the limitations. The last three research questions to be answered are:

“What is the contribution to science?”
“What is the contribution to the desalination operational practice in Aruba and abroad?”
“What is not considered in this research and what is important for further research?”

The fundamental answers to these questions for the distinguished desalination efficiency improvement factors are in summary as follows:

The human factor: (The Efficacious Motivational Leadership strategy)

Contribution to science
The main contribution to science of this part of the research is the development and application of a leadership and performance improvement framework on which basis clear performance improvements could be observed over a number of years.

New acquired knowledge during this research

- Effective performance improvement can be achieved by involvement and empowering of the work force enabling them to use their full potential and capacity of practical operational and maintenance knowledge and experience.
- The opportunity to challenge rules without violating any of them is an effective way to transform negativism into a change agent toward a positive mind set and team spirit.
- Fear has next to a negative effect of inducing the "comfort zone culture" also an important positive effect as a regulator and a control measure to manage implementation of innovations and new technology.
- The application of socio-technological models as metaphors to explain motivation and human attitude on the work floor level is effective to promote human performance improvements.

New developed processes in this research

- The Passion and Fear, the Human Attitude models are new developed metaphoric models based on known technological theories to understand and explain human behavior and used as motivation tools to improve harmony and team work on the work floor level.
- The Mahatma Gandhi leadership strategy and the Efficacious Motivational Leadership approach are new developed leadership tools to effective involve and empower the work force to reach out to improved performance.
- The Desalination's Hierarchy of Needs is developed as a motivational tool to support the performance improvement process of the desalination work force.

Contribution to the desalination practice in Aruba and abroad

The socio-technical performance improvement process has contributed to the establishment of a motivated creative work environment effectively improving desalination efficiency, interdepartmental communication, safety and good housekeeping and optimal engineered desalination and condensate and distillate processes.
The performance improvement of the Desalination Department resulted in a bench marking status worldwide for efficient application of the costly desalination technology for the production of drinking water according to chemical and bacteriological high quality standard.

The developed Human Attitude and Passion and Fear models, The Desalination's Hierarchy of Needs and the Mahatma Gandhi leadership strategy inducing the concept of Efficacious Motivational Leadership approach have discerningly supported the socio-technical continuous performance improvement process. These motivational tools resulted to be effective and had fortified the conviction of Efficacy, the effective empowering and involvement of the work floor personnel toward efficiency improvement of the costly desalination process.

Limitations of the research

The developed motivational models and the Efficacious Motivational Leadership approach and the Mahatma Gandhi leadership strategy are specifically developed for the Desalination Department and are not Company-wide applied.

No intensive study is performed to compare the Efficacious Motivational Leadership approach with well-established Leadership models and to further develop and validate this EML approach as a generalized scientific leadership model.

No intensive study is performed to evaluate the financial economic value of motivated personnel for a company in general and for the nation in particular, especially in an Island situation.

The need for further research

Based on the abovementioned limitations, further research is desirable to compare the EML approach with the common well know motivational theories as only an introductory study has been done in this research.

It is also important to perform research to evaluate the relation of the techno-economic aspects of motivated personnel for a company and the nation. Especially the coherence between motivated personnel and the contribution to the economic and financial state of a company and the economic growth of the nation especially in the case of the costly desalination process in the peculiar Island Situation is of interest.

More research is necessary to establish scientific founded guidelines for the estimation of the economic aspect of motivated personnel on cost reduction with respect to efficiency increment, absenteeism decrement, maintenance cost and training cost reduction.

The Physicochemical aspects: (biofouling)

Contribution to science

The main contribution to science of this part of the research is the development and application of a surface active non-oxidizing biocide to perform effectively under the stringent vacuum condition of a MSF evaporator and a sanitation and a novel online osmotic membrane cleaning procedure to effectively mitigate persuasive SWRO membrane biofouling.

New acquired knowledge during this research

- The surface active non oxidizing biocide performed well under stringent vacuum condition and elevated temperature as in an MSF evaporator with minor adjustment of the antifoam dosing.
- The application of the non-oxidizing biocide was also effective against micro-organism at low concentration dosage, keeping the heat transfer surfaces of the MSF evaporators practically free from biofilm formation. The common knowledge was that this non-oxidizing biocide was effective against macro organism as and barnacles.
- The developed sanitation procedure demonstrated to be effective for the mitigation of persuasive biofouling of membrane surfaces in combination with the osmotic membrane cleaning process.
- The developed osmotic membrane cleaning process has practically demonstrated that the use of special chemicals for the clean in place practices for the SWRO membranes can be eliminated and has given a simple cleaning method for BWRO membranes.
- The controlled osmosis process can be applied for membrane cleaning without any damage of the membranes. The common knowledge in SWRO practice is to prevent occurrence of osmosis to prevent damage of the SWRO and BWRO membranes.
- The developed osmotic membrane cleaning process has demonstrated that membranes that have undergone extensive chemical cleaning can be recovered practically as new. The common knowledge is that the life time of membranes is drastically reduced after severe chemical cleaning.
- The developed biofouling monitoring process using a biofilm monitor in combination with an Early Warning System resulted to be a simple but effective method for the evaluation of seawater biofouling potential for SWRO. The biofilm monitor was never before applied to evaluate biofouling of seawater.

New developed processes in this research

- The condenser fouling factor is a new developed effective practical key performance indicator based on operational experiences for the evaluation of biofouling of MSF evaporators and the efficacy of the applied non oxidizing biocide.
- The new total sanitation process of the SWRO system is developed with the application of pure distillate alternatively in combination with a special biodispersant. The biofouling mitigating effect of pure distillate was not known before.
- The chemical free osmotic SWRO and BWRO membrane cleaning process is developed and successfully applied. A patent is registered for this osmotic membrane cleaning process.

Contribution to the desalination practice in Aruba and abroad

The control of marine micro and macro biological fouling using non-oxidizing surfactants, such as the quaternary amines has been of very practical use for the desalination activities at W.E.B. Aruba N.V. by increasing the efficiency and production of the MSF evaporators.

Especially after years of negative experiences using the chlorine technology with respect to environmental and health hazard the usage of the biodegradable non-oxidizing biocide has convinced operation personnel of the use of chemicals as an effective way to control marine biological growth without introducing corrosion, safety, health and environmental hazard problems.

The successful application at W.E.B. Aruba N.V. has stimulated other islands in the Caribbean such as Curacao and Puerto Rico to apply the non-oxidizing biocide instead of the common application of chlorination in thermal desalination.

Limitations of the research

One of the problems experienced in the initial start-up of the trial is the excessive foaming of the surface active non-oxidizing biocide. This was not anticipated and the antifoam dosing was increased on trial and error basis to control foaming stabilizing operation during the biocide dosing.

No research is performed on the effect of the biocide on the mechanism of biofilm formation on the heat transfer surfaces and the kind of micro-organisms forming the matrix of the marine biofilm and the acclimatization potential of the micro-organism to the applied non-oxidizing biocide. This can be of importance to optimize the application of the biocide or the dosing frequency.

Doing research with a commercial production unit has its limitations in changing conditions because the main objective is production at high possible efficiency and production. This directed the research more in effective mitigation or elimination of biofouling based on the killing effect of commonly available biocides.

The effectiveness of the developed osmotic membrane cleaning process for SWRO and BWRO membranes could not thoroughly be evaluated due to the possibility of damaging all membranes in a commercial plant.

The need for further research
Further research on seawater desalination biocides should concentrate on the approach of the inhibiting efficacy of biocides instead of the killing effect, so to improve the environmental impact on marine life.

Further evaluation is also necessary for effectively mixing the antifoam and the non-oxidizing biocide in one solution for the optimal control of foaming during disinfection, so to improve operation stability.
The non-oxidizing biocide is a surface active component so causing foaming. For stable operation a lot of attention has to be put on adjusting the antifoam dosing to prevent carryover of the recirculation brine increasing the conductivity of the distillate. This has stimulated new research to evaluate the surface tension as a possible tool to optimize the chemical dosing in MSF evaporators and the development of an innovative concept for an on-line surface tension meter.

The need for drinking water especially in arid area has made seawater desalination as an important source of drinking water supply. It is up to now practically impossible for efficient seawater desalination without chemicals. From the environmental point of view worldwide intensified attention is put on the considerable impact of the brine and chemical discharge on the marine ecosystem [11.5]. A new preliminary research has been started for thoroughly evaluation and documentation of the possible environmental impact of all the chemicals applied in the desalination process at W.E.B. Aruba N.V. and to develop innovated solution to effectively eliminate any negative impact on the marine eco system [11.6].
New research should also be developed at W.E.B. Aruba N.V. with pilot plants to overcome the limitations of research with a commercial desalination unit. In this context a SWRO pilot plant is recently installed for new research for further evaluation and development of the osmotic membrane cleaning process and its effect on membrane integrity and the biofouling potential of the beach well’s naturally pre-filtered seawater. The intension is also to use the SWRO pilot for research toward the possibility of energy efficient green membrane desalination with minimal or without use of chemicals.

The Physicochemical aspects: (scaling, fouling and corrosion)

Contribution to Science
The main contribution to science of this part of the research is the development and application of an effective high temperature threshold scale inhibiting program to effectively control scaling, fouling and corrosion in MSF evaporators maintaining steadily high efficiency. This scale inhibiting program has also eliminated the safety, health and environmental high risk potential of the concentrated sulfuric acid dosing.

New acquired knowledge during this research

- The possibility of elimination of sulfuric acid with 100% dosing of a threshold antiscalant under the severe MSF evaporation condition with an efficiency higher than with sulfuric acid dosing. The common practical knowledge is that combined acid-threshold dosing with regular on-line acid cleaning to restore efficiency is the alternative for acid dosing.
- The inefficiency of threshold inhibitors available on the market was due to poor magnesium hydroxide scale control at elevated temperature, high concentration cycle and pH. The common knowledge was that effective scale control in thermal desalination can be obtained by controlling calcium carbonate formation.
- The effectiveness of a threshold scale inhibitor can only be obtained in combination with a need dosing of an effective dispersant in the high temperature section in MSF evaporators.
- The possibility of an automatic operation control of the redundant chemical feed pumps with the pace setter dosing system. Without this possibility the scale program was not practical applicable without the risk of scaling and damaging the MSF evaporator.
- The importance of a bench scale pilot plant for dynamic testing of scale inhibitors to sustain static beaker tests. Usually, beaker test with scale inhibitors under severe conditions is considered sufficient for efficacy evaluation.

New developed processes in this research

- The scale control program based on new developed polymeric phosphonate in combination with an effective dispersant for calcium carbonate, magnesium hydroxide and calcium sulfate scale inhibition in a two injection point to control scaling maintaining a higher than acid like performance.
- The Performance Decay Indicator (PDI) for evaluation of scale control effectiveness.

Furthermore, the successful evaluation of the new HT 15^{TM} program under the severe condition of high temperature, alkaline pH and high concentration factor of the MSF evaporators demonstrate that in general this program is suitable for application in practically all thermal desalination evaporators.
The applied approach for the development of the new additive technology in this research from bench scale to pilot plant to real application using scientific sound physicochemical theories is in general applicable for the successful development and application of a new effective product in a team work promoting the necessary effective collaboration between scientist, technologist and operational personnel.

Contribution to the desalination practice in Aruba and abroad

The development of the new high temperature additive has a tremendous practical importance by eliminating the use of concentrated sulfuric acid which has improved the operation safety, eliminating environmental and health hazards presented by the use of 98% concentrated sulfuric acid. The successful trial has also promoted motivation and fortified internal and external team work and the change of company policy accepting trial with new non-proven technology to support research and development of innovative technologies.

The success at W.E.B. Aruba N.V. with the new scale inhibition program has stimulated the application at other desalination plants such as in Curacao and Puerto Rico and in the Middle East.

Limitations of the research
The dispersant PDC 9323 ™ and the Clam Trol CT-2 ™ have both a high foaming tendency. The antifoam adjustment has been done on trial and error basis. No research has been performed with the Single Stage Flash Distillation Unit (SSFDU) bench scale pilot plant to optimize antifoam dosage.

This research has also not addressed the compatibility of the antifoam with the antiscalant chemicals to evaluate possible stable mixing to improve foam control and antifoam dosage. No further research has been performed to investigate the mechanism of the scale formation without a second injection of the dispersant PDC 9323 ™ in the higher temperature vessel for the development of a single component antiscaling program.

Need for further research
Important for future evaluation and research is a thoroughly evaluation of the fact that single dosing does not work effectively to promote the development of a blend solution for an effective single high temperature additive dosing.

Research to evaluate the compatibility of the antifoam agent with the additive chemicals in MSF evaporator is essential to control the foaming potential of the additives promoting stable operation with minor adjustment of the antifoam dosing.

Further research to evaluate the influence of precursors of the precipitated components on the scaling potential is recommended to further improve the efficacy of the inhibitor to optimize chemical treatment cost.
Many salts are supersaturated in seawater however they do not precipitate maybe due to ionic effects and natural dispersants and precipitation inhibiting natural components. It is recommended to perform further research on this special property of seawater as basis for the development of innovative scale controlling components.

The Physicochemical aspects: (foaming)

Contribution to science

The main contribution to science of this part of the research is the development of a simple theoretical explanation for the surface tension influence on the flash evaporation process, for the foam stabilization process and for the in practice experienced effect on production, quality and efficiency decrease of the respectively overfeed and underfeed of antifoam. The surface energy of the brine recirculation as a possible monitoring and control measure for the antifoam dosing is also an important contribution.

New acquired knowledge during this research

- In this research based on a simple theoretical approach the important influence of the surface tension effect on flashing evaporation is demonstrated taking into consideration the curved surfaces of vapor bubbles. Common practical knowledge was that there is no relationship between surface tension and evaporation due to the usual misconception assuming that evaporation takes place from a flat water-vapor surface.
- Based on the molecular interaction of antifoam and surfactant molecules in the interfacial surface a simple explanation is formulated for the in practice observed effect of antifoam dosage on product quality, production and efficiency. There was up to now no satisfactorily explanation for this phenomenon.
- The description of the foam stabilization process based on the difference in hydrodynamic pressure in the interfacial surface permits liquid to flow from a high energy level toward a lower energy level according to the common thermodynamic law on the contrary to other theories.
- The surface tension resulted to be an effective measure to control the antifoam dosing in combination with the surface active chemical additive in MSF evaporators. The right antifoam dosage is always calculated by the trial and error method.

New developed processes and models in this research

- In this research theoretical models were developed contributing to the simple explanation and comprehension of the surface tension effect on flash evaporation, and the experienced foaming and antifoaming phenomena in practice.
- Furthermore, a novel method is developed for the control of the antifoam dosing based on the surface tension of the recirculating brine in MSF evaporators. Also a conceptual design for on-line measuring of the surface tension is proposed in this research.

It is worth mentioning that the physicochemical molecular interaction of surfactants and antifoams in the stabilization and destabilization process of foam is a very complex interfacial surface theoretical science. In this context, the theoretical point of view from which the subject appears in its greatest simplicity proves to be invaluable to comprehend the fundamental basic mechanisms governing the experienced practical phenomena in the applied thermal desalination technologies.

Contribution to the desalination practice in Aruba and abroad
The acknowledgement of the importance of the surface tension effect on flashing evaporation has founded a firm comprehension of important basics of the foaming processes taken place in the MSF evaporators.

The developed theory for a simple but firm explanation for the diminishing product quality, production and efficiency decrease in the case of underfeeding and overfeeding of the antifoam in MSF evaporators, has contributed to significant improvement of the control on the antifoam dosage during daily shifts.

The developed surface tension approach to optimize additive dosing in MSF evaporators and other thermal desalination technology is a promising novel technique improving practical desalination efficiency.
The developed theory has also contributed to the correct explanation of experienced operational foaming problems with thermal desalination unit abroad such as the Aqua Chem evaporator in Malaysia as elaborated on in Chapter 6.

Limitations of the research
A simple explanation of the experienced foaming phenomena in MSF operation was one of the objectives of this research. The fundamental theoretical explanation and description of the antifoam effect in the MSF evaporation process was due to the complexity of the subject out of the scope of this research.

In this research only preliminary surface tension measurements were performed with a bubble type tensiometer to evaluate the feasibility of the surface tension based control system. The design of the online surface tension control system for the antifoam dosing was not part of this research.

The need for further research
In accordance with the considered limitations further research is needed to improve and standardize the novel surface tension method for the control of the additives dosing and to develop the on-line surface tensiometer. In combination with the computer controlled chemical dosing system, the surface tension method can be developed as an efficient automated foam control system. The membrane integrity testing method should be evaluated for applicability as an on-line surface tensiometer.

The Physicochemical aspects: (The distillate post treatment)

Contribution to Science

The main contribution to science of this part of the research is the development and application of a novel pyrophosphate and zinc orthophosphate corrosion inhibition program for soft (low hardness) drinking water produced by thermal and membrane desalination technology effectively eliminating the occurrence of brown water and blue water due to iron and copper corrosion in the water distribution system.

New acquired knowledge during this research

- This research has increased the theoretical understanding of the corrosion aspects of soft drinking water produced by thermal and membrane desalination technologies. Common corrosion inhibition knowledge and research was essentially based on the corrosion aspects of drinking water produced by treated natural groundwater and surface water with high calcium carbonate buffering capacity.
- New insights in the occurrence of blue water in the distribution system are obtained in this research highlighting the possible mechanism of copper corrosion in soft drinking water with low calcium carbonate buffering capacity and alkaline pH. The irregularly and infrequently release of blue water copper particulates in locally acidic conditions was before not well understood.
- A thorough theoretical understanding is acquired for the practical experienced higher occurrence of brown water in Aruba in the period of the Aquanova MSF evaporators producing low quality water. The chloride catalytic acceleration of under deposit iron corrosion in soft drinking water was not known.
- The performed analysis on the cement lining indicates that even though leaching out and consequently high pH occurrence is experienced, no significant degradation of the cement lining is observed. Despite the leaching process the cement lining retained its iron corrosion protection capacity.

New developed processes in this research

- The pyrophosphate and zinc orthophosphate is a corrosion inhibition and iron removal program for soft drinking water specifically designed for the practically scaled old water distribution network of Aruba in the 1990s.
- In this research a preliminary investigation approach is developed for the evaluation of the irregularly occurrence of copper corrosion with the objective to develop an effective copper corrosion inhibition program and theoretical comprehension of this phenomena.

The developed corrosion inhibition program is in general applicable in all water distribution systems handling soft drinking water to improve water quality and water distribution network integrity.

Contribution to the desalination practice in Aruba and abroad

The application of the pyrophosphate and zinc orthophosphate corrosion inhibition program has contributed to the solution of red water occurrence in Aruba and was an improvement of the conventional hexametaphosphate treatment program reducing the enormous complaints of the population before 1990.

The successful application of the pyrophosphate and zinc orthophosphate corrosion inhibition program establishing a high water quality with good corrosion characteristics has stimulated improved maintenance and operation of the distribution system which contributed to achieve a low NRW and a low ILI value.

Furthermore, the successful application of this corrosion inhibition approach has stimulated the other Dutch Caribbean Islands to use pyrophosphate to improve the carbon dioxide enhanced re-mineralization. Despite the increased hardness and calcium carbonate buffering of the drinking water regularly red water is experienced.

The low NRW percentage and ILI value of Aruba have received a lot of attention in the region and worldwide recognition for the production of high quality drinking water and a well maintained and operated drinking water distribution network.

Limitations of the research

Evaluation of increased calcium carbonate buffer capacity in combination with pyrophosphate and zinc orthophosphate to mitigate leaching out of the cement lining creating locally high pH was out of the scope of this research.

Investigation of biofilm formation in the distribution system and the effect of pH and trace elements such as calcium (Ca), magnesium (Mg) are also not considered in this research.

Due to time constrains the preliminary investigation of the ILI for Aruba and the other Caribbean Dutch Islands could not continue. To further decrease water loss in the water distribution network especially during disinfection a zero discharge disinfection program should be evaluated which is also out of the scope of this research.

Research is often limited because of “evaluation inflexibility” dealing with commercial production units and water distribution system. Changing operation conditions is usually prohibitive.

The need for further research

Based on the abovementioned limitations further research is desirable for the following investigations concerning the quality of the drinking water.

An aspect that needs further evaluation and research is increasing the hardness with carbon dioxide acidified distillate in combination with the existing corrosion inhibition program to lower the pH to nearly neutral conditions as recommended by PAHO, as a means to further improve the high quality of the Aruba Drinking water.

It is also important to further evaluate the copper corrosion in soft water to develop an effective inhibition program for the total elimination of the occurrence of blue water.

Also the effect of increasing the pH and other chemical componens as Ca and Mg on the Legionella biofilm formation in sub-tropical drinking water system is an aspect for further research.

A research project is proposed to evaluate the applicability of ultra and or nano-filtration when disinfecting the system with the possibility of back recirculation of the filtered water into the distribution system to approach zero discharge operation.

It is important to extend the ILI calculation to incorporate the Caribbean region for comparison purposes.

To increase flexibility of research a pilot test rack is designed and constructed to evaluate further improvement of the chemical conditioning and the biofilm potential of the drinking water. The pilot test rack is illustrated in Figure 11.5 [11.7].

Figure 11.5: A picture of the pilot installation for the drinking water conditioning

The maintenance aspect:

The contribution to Science

The main contribution to science of this research is the development and application of a maintenance approach on which basis clear technical performance improvements could be observed over a number of years.

New acquired practical knowledge during this research

- The Operation Conscious Maintenance and the Maintenance Conscious Operation strategy is an effective tool to cope with the existing rivalry between the operation and maintenance department.
- The Operation Conscious Maintenance and the Maintenance Conscious Operation concepts were very effective in developing a work floor predictive preventive maintenance approach.
- Involvement and empowering of the knowledgeable Operations and Maintenance work floor personnel to direct the right way to do the job right has reduced desalination failures and has improved performance efficiency.
- Customized company specific maintenance program with effective involvement and empowering of the work floor personnel is very effective, less complex and implementable without time constrains.

New developed processes in this research

- In this research the Efficacy Oriented Maintenance approach has been developed based on the concept of effective involvement and empowering of the operational and maintenance work floor team and successfully applied to increase operational and maintenance performance leading to improved maintainability of the desalination asset reducing pump and process failures and production waste.

Contribution to the desalination practice in Aruba and abroad

The Efficacy Oriented Maintenance approach has established a structured work relationship between line management and the work force effectively eliminating the cultural rivalry between Operations and Maintenance in practice.

The well-maintained status of the desalination assets obtained after the introduction of the Efficacy Oriented Maintenance and the experienced decrease in pump and process failures and an increase in desalination efficiency have undoubtedly established in practice the foundation for the involvement and empowering of the work floor personnel.

After the application of the Efficacy Oriented Maintenance the awareness for safety, good housekeeping and environmental aspects has increased drastically resulting in a worldwide acknowledgement for the well-kept desalination facility of W.E.B. Aruba N.V. The successes attained at the Desalination Department of W.E.B. Aruba N.V. have stimulated interest for the possible introduction and application of the principles of the Efficacy Oriented Maintenance at the Desalination Departments in the neighbouring Dutch Islands.

Limitations of the research
The developed Efficacy Oriented Maintenance is specifically developed for the Desalination Asset's maintenance and is not Company-wide applied.

In this research no intensive study is performed to compare the Efficacy Oriented Maintenance approach with well-established maintenance models and to further develop and validate this approach as a generalized maintenance model.

The need for further research
Further research is desirable to compare the Efficacy Oriented Maintenance with other maintenance concepts especially the new generation of customized maintenance concepts.

It is also important to perform further research to evaluate the relation improvement, the support and acceptance of the desalination improvement's aspects of the Efficacy Oriented Maintenance concept by all stakeholders as also in this case only an introductory study has been performed.

More research is necessary to establish scientific founded guidelines for the introduction of the Efficacy Oriented Maintenance at other Desalination facilities in the Dutch Caribbean, forming the basis for a frame work for the application at other companies.

The aspect of innovation:

The contribution to science
The main contribution to science of this part of the research is the development of patented novel conceptual designs for desalination process promoting effective green desalination without the use of chemicals and the environmentally polluting fossil fuels as energy source.

New acquired knowledge during this research
- In this research the acquired knowledge to use especially the osmosis process in a hybrid combination with the common seawater desalination technologies sets the first steps in the direction to believe in the possibility of stable green seawater desalination operation

without the use of chemicals. The common firm knowledge is that efficient stable seawater desalination is impossible without chemicals.

- The chemical free osmotic membrane cleaning process has shown, on the contrary to common knowledge, that membranes can withstand frequently applied intensive chemical cleaning without diminished membrane integrity and life time.
- Fossil fuel free production of water and power is possible in membrane hybrid configuration of the membrane processes based on Electro-Dialysis Reversal, SWRO and BWRO.

New developed processes in this research

- In this research the conceptual designs of the hybrid fluidized bed-tray heat exchanger, the hybrid Osmosis Reverse Osmosis (ORO) membrane desalination process and the on-line osmotic membrane cleaning process have been developed to promote Green Desalination to reduce fossil fuel consumption and to eliminate the chemical environmental impact of seawater desalination.
- A scientific approach is introduced and accepted by management to promote pilot plant application to perform research for evaluation and further development of innovative ideas and conceptual designs. It has opened the door for a scientific approach accepting pilot plant studies and has stimulated acceptance of academic support through internship students.

Contribution to the desalination practice in Aruba and abroad

The developed chlorine disposal process has demonstrated the value of the human aspects to face challenging projects with high safety and environmental risk potential promoting teamwork to achieve a common goal set forth. The practical value for W.E.B. Aruba N.V. is not only eliminating a potential risk on its premises but also the dedication to face a problem and seek for practical economical solution instead of procrastination. An important initiative in this project is also the establishing of the contact with the other Water Production Companies in the Dutch Antilles on a technological level to interchange knowledge and experience inducing the first thoughts and desires to establish a more firm relationship leading to the establishment of the Caribbean Desalination Association (CaribDA) in 2009.

The successful disposal of the damaged one-ton containers has proven and increased the self-confidence that we have the technological knowledge to design, implement and successfully carry out a process to solve a high risk problem.
The innovations developed by working together with the work floor has stimulated the motivation, creativity and job satisfaction consolidating the human aspects to excel in efficient desalination continuously seeking for practical improvements.

The practical application of the on-line osmotic membrane cleaning process resulting in the decrease of the average energy consumption lower than the design value of 4.0 kWh per cubic meter produced permeate is considered by the manufacturer of the existing SWRO at W.E.B. Aruba N.V. as a worldwide success and granted the “Proof not Promise” Award.

The aspect of implementation of new technology:

Contribution to Science

The main contribution to science of this part of the research is the application of the Green Field method, the Multi Criteria Analyses and the System Approach for the extensive evaluation of the implementation of new technology. The application of simple preliminary pilot plant testing has also contributed to support the implementation of new technology.

New acquired knowledge during this research

- The membrane fouling simulator and the biofilm monitoring system resulted to be effective for the biofouling evaluation for raw seawater from beach well and open intake. The biofilm monitor was previously, only used for drinking water biopotential monitoring.
- The evaluation according to the Green Field methodology, Multi Criteria Analysis and System Approach has proven to be a sound method for the implementation of new technology. This process has undoubtedly confirmed the importance of and reintroduced the scientific approach as a basic process to solve practical problems.

New developed processes in this research

- In this research the evaluation process based on scientific technologic approach with pilot plant study to evaluate biofilm forming potential and the membrane fouling potential of SWRO feed water with the Early Warning System and the biofilm monitor was developed.
- The scientific approach was so evident that during negotiation of the SWRO#2 with perseverance of the Desalination Department a SWRO pilot plant was acquired to investigate the biofouling more profoundly and to create the possibility to evaluate new membrane technology and to simulate practical operational conditions to optimize operation of the commercial SWRO.

Contribution to the desalination practice in Aruba and abroad

The experiences of W.E.B. Aruba N.V. with implementation of innovative technologies have sustained worldwide the practical improvement of the desalination technology through exchange of practical operation and maintenance experiences with manufacturers.

The sustainability and efficiency worldwide has increased due to involvement of the Desalination Department of W.E.B. Aruba N.V. in the development of cost-effective high temperature antiscalants during the years solving one of the major problems in high temperature seawater desalination.

The structured sound evaluation process toward the introduction of the membrane technology has created a confident teamwork relation between international desalination consultants and internal desalination experts of W.E.B. Aruba N.V. and created again confidence for innovative technology after the negative experiences with the application of new desalination technologies in the 1980s.

Further, the evaluation of beach well as an alternative seawater intake to mitigate biofouling has promoted systematic practical research approach proving the importance of the continuous desalination improvement process based on the Engineering Design process and the Deming improvement circle. In practice most of the time the practical approach is over-emphasized underestimating the mere importance of the theoretical comprehension of nature enhancing the understanding of the processes in practice.

Limitations of the research

The evaluation of the membrane fouling rate and process based on membrane autopsy, membrane spacer’s pressure difference for comparison with the Early Warning System and the biofilm monitor was out of the scope of this research.
In this research, the development of a W.E.B. Aruba N.V. specific structured model for application of new technology based on the applied intensive evaluation process for the implementation of the new SWRO technology was not considered.

The need for further research

The biofouling potential of the beach well’s natural filtered seawater feed will be further investigated in the pilot plant extended with a membrane module to evaluate especially the aspects of viable but not cultivable bacteria.

Further research to correlate the findings of the Early Warning System and the Biofilm Monitor is essential for a more structured prediction of the membrane fouling process and to improve membrane cleaning frequency.

It is important to perform long term monitoring of the beach well water quality to develop an effective disinfection and chemical cleaning process of membranes to further improve the sustainability of beach well-feed-SWRO.

Further research to qualify and quantify the micro-organism encountered in the natural filtered raw seawater will certainly improve the chemical cleaning of membranes mitigating biofouling and improving desalination efficiency.

To conclude this chapter a reflection is given in the following section of the envisioned future excellence in green desalination.

11.5 A passionate reflection of future green desalination in Aruba

As we all know there is no present without a past and there will be no future without a present. In this context this desalination efficiency improvement research can be considered as a successful important step contemplating the past for lessons learned to improve the present desalination and to pave the way toward a prosperous green desalination future. To passionately envision and reach out for a future with green desalination next to knowledge and experience also passion and patience, perseverance, persistency and especially imagination plays an important role.
Going back to the Arawak story, maybe Aruban archeologists may still have problems interpreting the cave drawings but for an Aruban desalter it may mean (as Figure 11.6 illustrates):

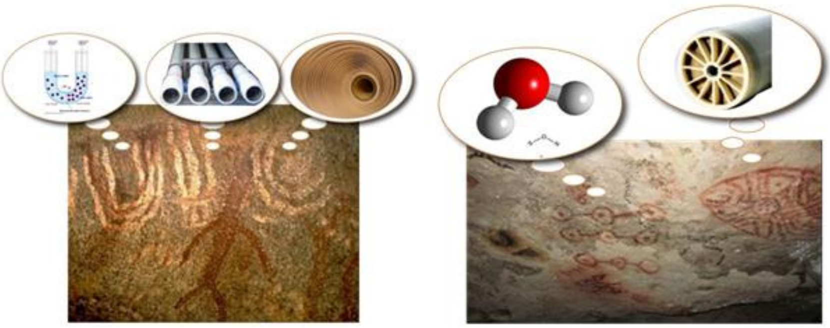


Figure 11.6: A desalination interpretation of the Arawak's cave drawings

That the Arawak Indian had figured out how to desalinate seawater after all and that he did know about the water molecular structure and the anti-telescoping device or that he may have envisioned this future desalination technology.

So with this Arawak's passion we can envisage a green desalination future without the use of chemicals and a green membrane power and water production unit without the use of fossil fuel to produce energy and further of imminent importance desalination at the thermodynamic minimum required energy of 0.7 kWh/m^3 produced fresh water.

This innovation in sustainable green desalination technologies (as discussed in detail in Chapter 9) are illustrated in Figure 11.7 and Figure 11.8.

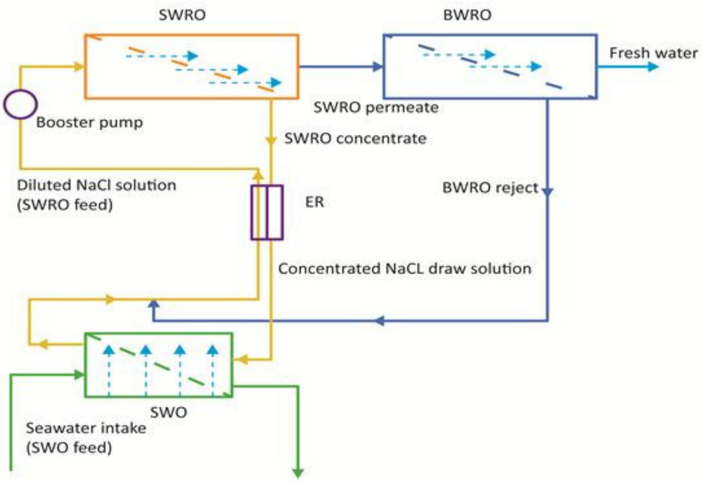


Figure 11.7: The hybrid Osmosis Reverse Osmosis (ORO) process

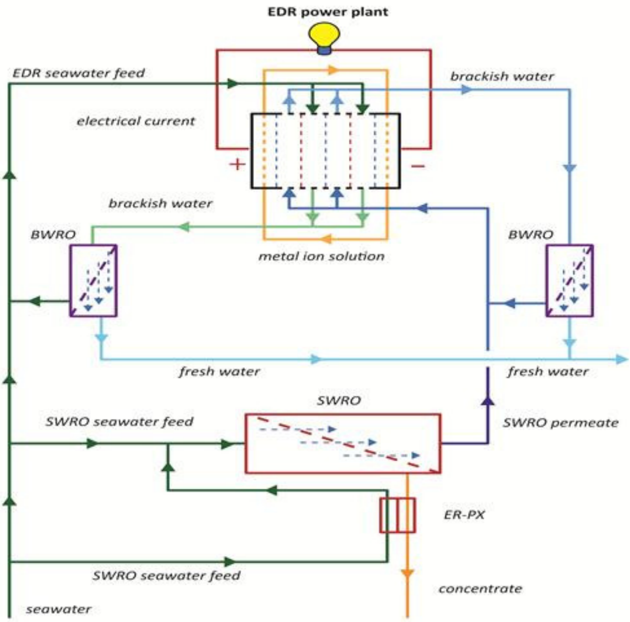


Figure 11.8: A green membrane Water and Power production concept

11.6 Concluding remarks

In this desalination efficiency improvement research the imminent importance of leadership efficacy, efficiency improvement through effectively involvement and empowerment of the work force is undoubtedly proven by means of the significantly decrease of frequent absenteeism and increased yearly operation cost savings mainly due to motivation, the increased desalination efficiency and the decreased pump and process failures and reduced production waste, as the solid foundation of the Continuous Desalination Efficiency Improvement Process.

Following the obtained research results, the main conclusion that can be drawn is that all the objectives of this research have been met by demonstrating the effectiveness of the efficiency improvement factors primarily specified based on years of practical desalination experiences. In this context the developed socio-technical metaphoric models, developed and applied technologies and techniques with respect to the human and technical improvement factors have validated and fortified the developed Continuous Desalination Efficiency Improvement Process toward Desalination Excellence.

Besides the novel developments the most important contribution to science is the proof in practice of the fundamental concept of science, the comprehension of nature in the total beauty of simplicity to fortify and broaden the existing practical and theoretical desalination knowledge.

Combining practical knowhow and experience and academic research will optimally benefit the scientific research process of developing an innovative idea, bench scale lab testing, pilot plant testing, up scaling and finally “real life” practical operational testing developing new innovative ideas for improvement. So, in general this research can also be considered as practical empirical analysis supporting the analytical analyses in the scientific development process as indicated in Figure 11.9.

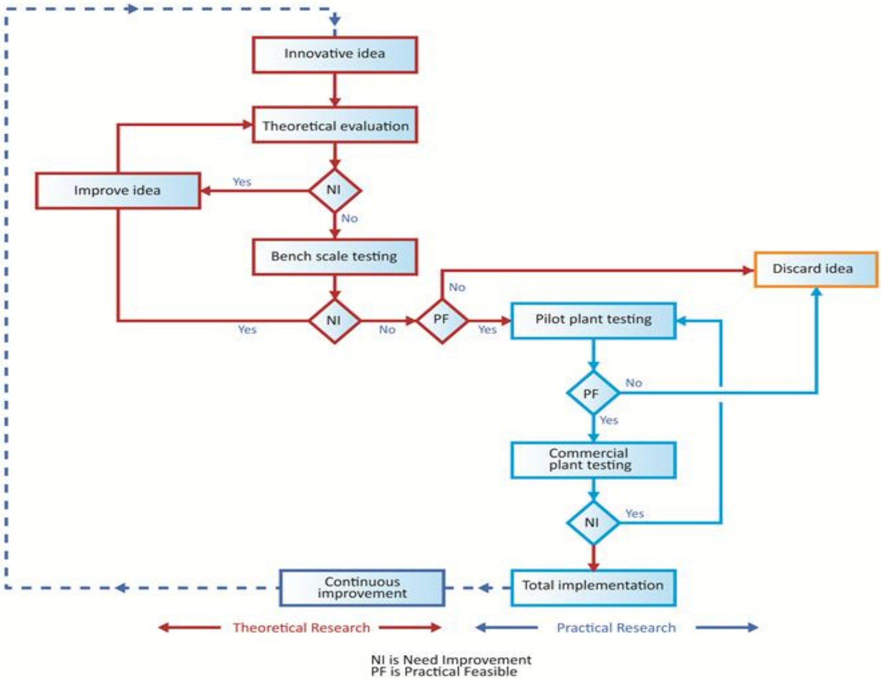


Figure 11.9: The practical support of the scientific development process.

Research in real practical production systems is of invaluable importance to attain practical knowledge for the support of theoretical and small bench or pilot plant scale experimental research inductive for the setup of general scientific models.

The importance of real time practical research can be highlighted by the experienced obstacles during the development of the novel high temperature antiscalant as explained in Chapter 5. The first developed antiscalants were tested on lab scale in beaker test under more severe circumstances than practical MSF evaporation, however the product failed because the dynamic practical process is overlooked inducing the necessity to design and build a pilot plant. Even though the product is upgraded in the pilot plant the application in a real plant indicated the necessity of the application of the two injection point system and the upgrading of the automatic chemical dosing system to increase redundancy.

The general main conclusion that can be drawn is that despite the intensive dedication and successful performed work to increase efficiency at the Desalination Department, Seawater Desalination Excellence demands the continuously search for efficiency improvement and for innovative efficient desalination technologies.

This desalination efficiency improvement research still needs to continue with further scientific investigation to fortify and broaden the existing practical and theoretical desalination knowledge to passionately envision the continuous improvement of the existing desalination technology and searching for still unknown technique and technology toward more efficient green seawater desalination.

The final concluding remark is that this research has proven in accordance with the EFQM performance frame work that Desalination Excellence is reachable through leadership efficacy as a main enabler to motivate and effectively involve and empower the work force to optimal use partnership and resources to effectively operate and maintain the Desalination assets to the satisfaction of all stake holders.

11.7 References

11.1. Marchena, F. A., 80th Celebration of Desalination on Aruba, CaribDA 2012 Conference and Exhibition, June 19-22, 2012, Oranjestad, Aruba.
11.2. Birkett, J. D., Marchena, F. A., Early Desalination in the Caribbean and its Adoption in the Netherlands Antilles, CaribDA 2012 Conference and Exhibition, June 19-22, 2012, Oranjestad, Aruba.
11.3. Marchena, F. A., Efficacy Oriented Operations and Maintenance: An Important Step Toward Sustainable Conventional and Green Desalination Technology, Conference and Trade Fair "Our Future with Green Energy”, Oranjestad, Aruba October, 2010.
11.4. Muñoz Elguera, A., Assessment of Water Quality Monitoring and Control in Aruba and Recommendations for Health Risk Reduction, PAHO/OMS Report, June, 2008.
11.5. Höpner, T., Lattemann, S., Seawater Desalination: Impacts of Brine and Chemical Discharge on the Marine Environment, ISBN 0-86689-062-9, Balaban Desalination Publications, L’Aquila, Italy, 2003.
11.6. Lue, N. G. K., Seawater Desalination; Impacts of Chemical Discharge on the Marine Environment, Internship report W.E.B. Aruba N.V.- Avans Hogeschool, August, 2011
11.7. Fernandez Segrera, F. G., The Design and Construction of the Water Conditioning Pilot Installation, Internship Report, W.E.B. Aruba N.V.-UNA, February 2010.

List of definitions

Accumulative performance ratio:
The ratio of the accumulative distillate produced to the accumulative low pressure steam consumed in an MSF evaporator in a period of concern.

Adhesion:
Adhesion is the intermolecular force of attraction that causes two different substances to join.

Alveolus:
Alveolus is any of the tiny air-filled sacs arranged in clusters in the lungs, in which the exchange of oxygen and carbon dioxide takes place.

Antifoaming:
Antifoaming refers to the process of inhibiting or modifying the formation of foam.

Antiscalants:
Antiscalants are chemical additives that inhibit or delay precipitation and subsequent scale formation.

Approach:
Approach is a method used in dealing with a situation or accomplishing a goal.

Availability:
Availability is the probability that a system is operating satisfactorily at any point in time, excluding times when the system is under repair.

Bathymetry:
Bathymetry is the science of measuring and mapping the depths of oceans and seas.

Cohesion:
Cohesion is the intermolecular attraction by which the elements of a body are held together.

Conjunctiva:
Conjunctiva is the mucous membrane lining the inner surface of the eyelids and covering the front part of the eyeball.

Copolymer:
Copolymer is a chemical compound produced by copolymerization of two or more monomers

Defoaming:
Defoaming refers to the process of reducing foaming after it has developed.

Desalination:
The process of removing dissolved salts from seawater or brackish water.

Dispersants:
Dispersants are chemical additives, either a liquid or gas, used to disperse small particles in a medium.

Efficacy:
Efficacy is the ability to produce a desired or intended result with the involvement and empowering of the work force.

Efficiency:
Efficiency is the ratio of the useful work performed by a machine or in a process to the total energy expended or heat taken in

Ergonomy:
Ergonomy is the science of adapting the job and/or the equipment and the human to each other for optimal safety and productivity.

Entropy:
Entropy is a thermodynamic quantity representing the unavailability of a system's thermal energy for conversion into mechanical work, often interpreted as the degree of disorder or randomness in the system.

Equivalent Performance Ratio:
The performance ratio based on the calculated electrical equivalent low pressure steam consumption of a SWRO unit.

Exopolymer:
Exopolymers are biopolymers that are secreted by micro-organisms into the environment (i.e. external to the organism), including the biofilms produced by bacteria to anchor them and protect them from environmental conditions.

Flashing:
Flashing is the partial evaporation that occurs when a saturated liquid stream undergoes a reduction in pressure by passing through a throttling valve or other throttling device.

Fluidization:
Fluidization is a process similar to liquefaction whereby a granular material is converted from a static solid-like state to a dynamic fluid-like state.

Green Field Method:
The Green Field evaluation method is based on the assumption that most, if not all existing current assets is not available in the considered future period of time to allow proposition of new technology without being constrained by current configuration.

Heterotrophic organism:
Heterotrophic organisms are micro-organisms that require living or dead organic materials as its principal source of nutrients.

Interfacial surface:
Interfacial surface is the surface that separates two non-miscible phases.

Integrity:
Integrity is the ability to always act with moral soundness, honesty and free from corruptive influence or motive and is the absolute dedication to truth and the rigid adherence to a code or standard of values assuring that information will not be accidentally nor maliciously altered or destroyed.

Leptothrix:
Leptothrix is a genus of sheathed bacteria; single cells are motile by means of polar or sub polar flagella, and sheaths are encrusted with iron or manganese oxides.

Membranes:
Membranes are polymeric material consisting of a thin selective layer supported by a permeable no selective material which provides mechanical strength that separates the seawater from the fresh water.

Model:
A model is a schematic description of a system, theory, or phenomenon that accounts for its known or inferred properties and may be used for further study of its characteristics.

Nephelometry:
Nephelometry is the technique of comparing diffused light at an angle of 90^o to transmitted light to measure turbidity.

Osmosis:
Osmosis is the natural distribution of liquid with a low concentration flowing through a membrane into an area with a higher concentration resulting in the concentrations being equal on both sides.

Performance ratio:
The ratio of the amount of distillate produced to the amount of low pressure steam consumed in MSF evaporation.

Polymer:
Polymer is a chemical substance made up of a large number of smaller molecules that link together to form larger molecules.

Pulmonary edema:
Pulmonary edema is an abnormal accumulation of fluid in cells and tissues of the lung resulting in swelling.

Retrograde solubility:
Retrograde solubility is the reversed or decreasing solubility of chemical components with increasing temperature.

Semi permeable:
A semi-permeable membrane selectively lets only particular components pass through it.

Stoichiometric:
Stoichiometric describes a quantitative relationship, usually expressed as the ratio between two or more chemical substances undergoing a physical or chemical change; the point at which the chemical reaction ends or stabilizes.

Threshold inhibition:
Threshold inhibition is classified where sub-stoichiometric quantities of the inhibitor agent are necessary to perform the inhibition action such as scale inhibition through dispersion, sequestration and crystal distortion.

Transmissivity:
Transmissivity is the aquifer characteristic that measures its ability to receive and give up water as pressure changes.

Turbidity:
Turbidity is a measure of the colloidal content whether of mineral or organic origin disturbing the water clearness.

Viscosity:
Viscosity the internal friction of a fluid which makes it resists flowing past a solid surface or other layers of the fluid.

List of abbreviations and symbols

Abbreviations:

ADBAC : Akyldimethylbenzylammonium Chloride
AFE : Approval For Expenditure
ANSI : American National Standards Institute
APT : Aquifer Performance Test
ATP : Adenosine Tri Phosphate
AWG : Arubaanse Wettelijke Guldens (Aruban legal Currency)
AWWA : American Water Works Association

BART : Biological Activity Reaction Test
BCM : Business Centered Maintenance
BEM : Business Excellence Model
BOO : Build Own Operate
BWRO : Brackish Water Reverse Osmosis

CARL : Calculated Annual Real Losses
CBM : Condition Based Maintenance
CBPM : Chemical Based Preventive Maintenance
CCD : Closed Circuit Desalination
CCF : Critical Cross Flux
CDEIP : Continuous Desalination Efficiency Improvement Process
CE : Cavitation Eduction
CFE : Controlled Flash Evaporation
CI : Corrosion Index
CIP : Clean In Place

CIS	: Client Information System
CMMS	: Computer Maintenance Management Systems
COPM	: Culture Oriented Participating Management
CSF	: Critical Success Factor
DBT	: Dynamic Beaker Test
DGC	: n-dodecylguanidine hydrochloride
DO	: Dissolved Oxygen
DOM	: Design Out Maintenance
EAM	: Enterprise Assets Management
E.Coli	: Escherichia Coli
ECP	: Extra Cellular Polysaccharides
ED	: Electro Dialysis
E. Faecalis	: Enterococcus Faecalis
EFQM	: European Foundation for Quality Management
EDI	: Electrodeionization
EDP	: Engineering Design Process
EDR	: Electro Dialysis Reversal
EDTA	: Ethylenediaminetetra-acetetic acid
EDXA	: Energy Dispersive X-ray Analysis
EML	: Efficacious Motivational Leadership
EOM	: Efficacy Oriented Maintenance
EO-PO	: Ethylene Oxide-Propylene Oxide
EWS	: Early Warning System
FMEA	: Failure Mode and Effect Analysis
FMECA	: Failure Mode and Effect and Criticality Analysis
FO	: Forward Osmosis
FTIR	: Fourier Transform Infrared
GE WPT	: General Electric Water and Process Technologies
GI	: General Inspections
GMWPP	: Green Membrane Water and Power Production
GOR	: Gain Output Ratio

HAB	: Heterotrophic Aerobic Bacteria
HMI	: Human Machine Interface
HTA	: High Temperature Antiscalant
ICP	: Induced Coupled Plasma
IDT	: Inventory Decision Tree
ILI	: Infrastructure Leaking Index
ISO	: International Organization for Standardization
IP	: Internal Passion
IWA	: International Water Association
LCC	: Life Cycle Costing
LSI	: Langelier Saturation Index
MAC	: Maximal Accepted Concentration
MCA	: Multi Criteria Analysis
ME	: Motivational Energy
MED	: Multi Effect Distillation
MFS	: Membrane Fouling Simulator
MIC	: Microbiologically Induced Corrosion
MMF	: Multi Media Filters
MPY	: Mills Per Year
MSF	: Multi Stage Flashing
MVD	: Mechanical Vapor Compression
NTU	: Nephelometric Turbidity Units
NSF	: National Sanitation Foundation
NRW	: Non Revenue Water
OECD	: Organization for Economic Cooperation and Development
OR	: Operation Research
ORO	: Osmosis Reverse Osmosis
PAHO	: Pan American Health Organization
PDCA	: Plan Do Check Act
PDI	: Performance Decay Indicator
PRO	: Pressure Retarded Osmosis
PF	: Passion and Fear
PM	: Preventive Maintenance

PO	: Purchase Order
PPM	: Parts per Million
PR	: Purchase Request
PX	: Pressure Exchanger
QMS	: Quality Management System
RBM	: Reliability Based Maintenance
RCM	: Reliability Centered Maintenance
RFQ	: Request for Quotation
RO	: Reverse Osmosis
ROI	: Return on Investment
ROR	: Re-Order Report
RSI	: Ryzner Stability Index
SCAS	: Semi Continuous Activated Sludge
SDI	: Silt Density Index
SEM	: Scanning Electron Microscopy
SHMP	: Sodium hexamethaphosphate
SM	: Scheduled Maintenance
SRB	: Sulfur Reducing Bacteria
SSFDU	: Single Stage Flash Distillation Unit
SWRO	: Seawater Reverse Osmosis
TAPPI	: Technical Association of the Pulp and Paper Industry
TBT	: Top Brine Temperature
TDS	: Total Dissolved Solids
TEE	: Total Equipment Effectiveness
TEM	: Thermo Economic Model
TIC	: Total Inorganic Carbon
TMEGD	: Thermodynamic Minimum Energy Green Desalination
TPM	: Total Productive Maintenance
TVC	: Thermo Vapor Compression
UARL	: Unavoidable Annual Real Losses
UBM	: Used Based Maintenance
USEPA	: United States Environmental Protection Agency
UV	: Ultra Violet

VC	: Vapor Compression
VBNC	: Viable but not Cultivable
VFD	: Variable Frequency Drive
W.E.B. Aruba N.V.	: Water- en Energiebedrijf Aruba (W.E.B.) N.V.
WHO	: World Health Organization

Symbols:

C	: concentration	[kg/m^3; kmole/m^3]
g	: gravity acceleration	[m/s]
h	: height	[m]
k	: gas constant	[J/(^{o}K mole)]
L	: length	[m]
m	: mass	[kg]
P	: pressure	[N/m^2]
R	: universal gas constant	[J/^{o}K]
r	: radius	[m]
S	: entropy	[J/(mole ^{o}K)]
T	: temperature	[^{o}C]
T	: absolute temperature	[K]
U	: internal energy	[J]
V	: volume	[m^3]
V_m	: molar volume	[m^3 /mole]
⍰	: contact angle	[rad]
γ	: surface tension	[N/m]
ρ	: specific density	[kg/m^3]
η	: dynamic viscosity	[Ns/m^2]
μ	: molar thermodynamic potential	[J/(mole)]

Electrical symbols:

V	: electrical voltage	[V]
R	: electrical resistance	[Ω]
i	: electrical current	[A]
G	: electrical conductance	[Ω^{-1}]

Subscripts:

v	: vapor phase
l	: liquid phase
s	: solid phase

Academic Output

Patents:

Marchena, F. A., Franken, N. N., Bureau of Intellectual Property Aruba, Octrooi nummer 010910.22, W.E.B. Aruba N.V., Trapsgewijze CO2 desorptie uit zeewater met behulp van stoom of damp als hulpfase ter voorkoming van scale vorming in MSF-verdampers.

Marchena, F. A., Franken, N. N., Bureau of Intellectual Property Netherlands Antilles & Octrooi Centrum Nederland, Octrooi nummer 1025361, W.E.B. Aruba N.V., Trapsgewijze CO2 desorptie uit zeewater met behulp van stoom of damp als hulpfase ter voorkoming van scale vorming in
MSF-verdampers.

Marchena, F. A., Vrolijk, V. R. J., Een Innovatief hybride Osmose en Reverse Osmosis (ORO) ontzoutingsproces voor de productie van drinkwater. Octrooi 1035431, Octrooibureau Nederland, 03 november 2009.

Marchena, F. A., Vrolijk, V. R. J., Een Innovatief hybride Osmose en Reverse Osmosis (ORO) ontzoutingsproces voor de productie van drinkwater. Octrooi OCT, Bureau of Intelectual Property Aruba, June 29, 2007.

Marchena, F. A., Wever, R. P. M., et al., Een innovatieve milieuvriendelijke chemicaliën vrije osmotische reinigingsproces voor het in bedrijf reinigen van SWRO- en BWRO membranen. Octrooi 1038485, NL Octrooicentrum, 18 februari 2013.

Marchena, F. A., Wever, R. P. M., et al., Een innovatieve milieuvriendelijke chemicaliën vrije osmotische reinigingsproces voor het in bedrijf reinigen van SWRO- en BWRO membranen, Octrooiaanvrage OCT-01/100824.02, August 2010, Bureau of Intelectual Property Aruba, patent pending.

Technical papers:

Marchena, F.A., Alberts, V. A., et al., A Strategic Quality Program: Basic efficiency Control for Brine Recirculating MSF-plants, Caribbean 2002 Conference, Oranjestad, Aruba, June 2002.

Post, R. M., Marchena, F. A., et al., A New Method for Controlling Marine Growth in Desalination Plant Intake Systems, Caribbean 2002 Conference, Oranjestad, Aruba, June 2002.

Post, R. M., Marchena, F. A., et al., Water treatment Technology for Desalination Systems-A Decade of Experience inhibiting Corrosion and "red water" in drinking water systems, Caribbean 2002 Conference, Oranjestad, Aruba, June 2002.

Post, R. M., Marchena, F. A., et al., An Alternative Method for Disinfecting desalination Plant Intake Systems, 2nd Expo/Congress Water 2003, January 29-31, Curacao N.A.

Marchena, F. A., Vrolijk, V. R. J., Experience and New Challenges in Seawater Desalination at W.E.B Aruba N.V., The 6th International Congress and Exhibition on Water, Renewable Energy and Health, Safety & Environment, Oranjestad, Aruba, November 2004.

Marchena, F. A., Angela, A. E., The Quality of Potable Water and the Distribution System in Aruba: chemical aspects, The 6th International Congress and Exhibition on Water, Renewable Energy and Health, Safety & Environment, Oranjestad, Aruba, November 2004.

Marchena, F. A., Uytiepo, B. A., Maria, D. R., New Antiscalant Technology to Replace Acid Dosing in MSF plants, International Desalination Association Conference: SP05-198, Singapore, September 2005.

Marchena, F. A., Hodgson, J. W., Reverse Osmosis A New Challenge in Seawater Desalination after seventy five years of successful Thermal Desalination, AWWA first Desalination Seminar, Honolulu, Hawaii, May 2006.

Wessels, L. P., Marchena, F. A., et al., Improved cleaning of spiral wound membranes and forward osmosis reduces cost of seawater desalination, International Desalination Conference, Aruba, June 2007.

Marchena, F. A., Hodgson, J. W., Harvey, W., et al., The Decision Process to Membrane Desalination after 75 Years of Successful Thermal Desalination, International Desalination Conference, Aruba, June 2007.

Marchena, F. A., Uytiepo, B. A., Maria, D. R., Successful Novel Antiscalant to Replace Acid Dosing in MSF Evaporators in W.E.B. Aruba N.V., International Desalination Conference, Aruba, June 2007.

Marchena, F. A., Uytiepo, B. A., Maria, D. R., Plant Experience on New Antiscalant Technology for MSF Plants, International Desalination Association Conference: MP07-264, Maspalomas, Gran Canaria-Spain, October 2007.

Marchena, F. A., Uytiepo, B. A., Maria, D. R., Optimizing Antifoam in Additive Dosed MSF plants, International Desalination Association Conference: MP07-265, Maspalomas, Gran Canarias-Spain, October 2007.

Marchena, F. A., Hodgson, J. W., Experiences and Challenges of Aruba and the Netherlands Antilles in Seawater Desalination, Wetsus Congress, Leeuwarden, The Netherlands, September 2008.

Marchena, F. A., Bulbaai, R. R., Experiences and Challenges of Aruba and the Netherlands Antilles in Seawater Desalination; the Importance of a Water Technology Chair at the University of the Netherlands Antilles, UNESCO IHP LAC Conference “Water and Education”: Asuncion, Paraguay, December 2008.

Marchena, F. A., Efficacy Oriented Maintenance: A Total Productive Work Floor Maintenance Program to Increase Desalination Efficiency, Proceedings of the 2nd Conference of Caribbean Desalination Association, Grand Cayman, Cayman Islands, June, 2010.

Marchena, F. A., Efficacy Oriented Operations and Maintenance: An Important Step Toward Sustainable Conventional and Green Desalination Technology, Conference and Trade Fair "Our Future with Green Energy”, Oranjestad, Aruba October, 2010.

Prato, T., Marchena, F. A., Resolution of Persuasive Biofouling Issues at W.E.B. Aruba N.V.'s Seawater Reverse Osmosis, International Desalination Association Conference, Perth, Australia, September, 2011.

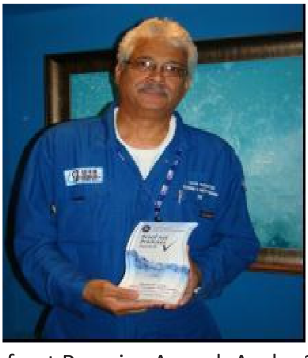
Birkett, J. D., Marchena, F. A., Early Desalination in the Caribbean and Its Adoption in the Netherlands Antilles, CaribDA 2012 Conference and Exhibition, June 19-22, 2012, Oranjestad, Aruba.

Marchena, F. A., 80th Celebration of Desalination on Aruba, CaribDA 2012 Conference and Exhibition, June 19-22, 2012, Oranjestad, Aruba

About the author

Filomeno A. (Boey) Marchena was born on December 14th, 1953 in Mabon on the Island of Aruba. In 1971 he graduated from the secondary school Colegio Arubano and in 1988 he finished his Master of Science studies in the Chemical Engineering at the Delft University of Technology. His Master of Science thesis entitled “Some Theoretical Aspects of the Mercury Porosimetry” was supervised by Prof. Dr. J. J. F. Scholten of the Faculty of Chemical Technology and Inorganic and Physical Chemistry. He started his professional career in 1989 as a Technical Support Engineer at W.E.B. Aruba N.V., the Water and Power production company of Aruba and was promoted in 1997 as the Desalination Superintendent. In 2008 he was nominated by the Government of Aruba as the Focal Point of Aruba for the UNESCO International Hydrological Program of Latin America and Caribbean. He started his PhD research project on efficiency improvement in desalination processes as an external doctorate candidate at the University of Twente under supervision of Prof. Dr. Ir. Johannes I. M. Halman, Head of the Chair Technology Innovation and Risk Management and the co-supervisor Prof. Dr. Ir. Jan Peter van der Hoek MBA, Head of the Chair Drinking Water Supply Section Sanitary Engineering at the Delft University of Technology. He acted Division Manager Operations at W.E.B. Aruba N.V. from December 2010 to March 2012. This desalination efficiency improvement research at W.E.B. Aruba N.V., has been granted with four prestigious awards by GE Water and Process Technologies and three patents.

Ecomagination Award, Singapore 2005



Proof not Promise Award, Aruba 2011

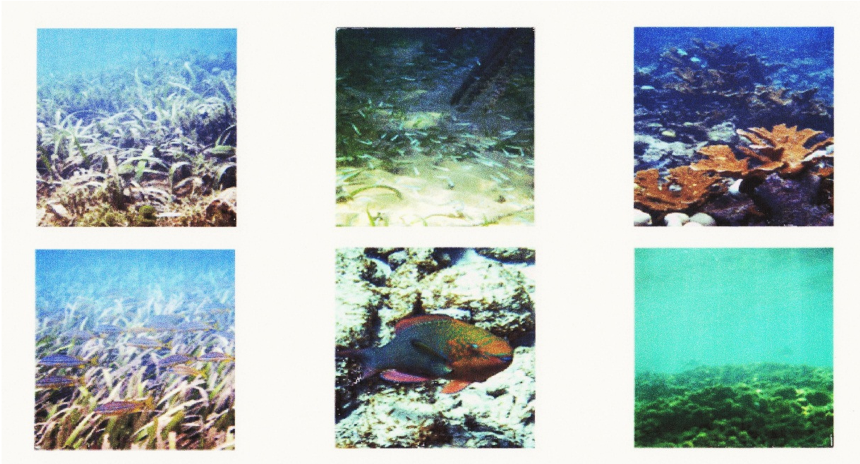
Epilogue

Since the early days of discovery by the Spanish Conquistadores and considered as *"Isla Inutil"* (Useless Island), Aruba grew from a poor semi-arid Island with practically no sufficient natural fresh water resources to a worldwide well known touristic island in the Caribbean with a high living standard and booming economy mainly due to the availability of the world highest chemical and bacteriological quality drinking water. In the period before commercial seawater desalination the main drinking water supply was well water, surface water and rainwater collected in cisterns in the rainy seasons. Also primitive water treatment techniques were applied to remove suspended particles and to clarify the water removing colloidal particles.
Aruba, one of the first pioneers in seawater desalination in the period of 1898-1917 for the production of process water at the Aruba Gold Mining Company and in the 1959 for a short period the largest seawater desalination facility in the world has earned a worldwide reputation for the support of innovative developments in the desalination technology and for the efficient thermal and membrane drinking water production facility at W.E.B. Aruba N.V.

In Aruba, we took a long journey from primitive water supply to a sophisticated modern water production and distribution company continuously envisioning excellence in desalination to efficaciously improve efficiency to guarantee our population and to support our economy with the hundred percent supply of safe and high quality drinking water at optimal production cost.

At W.E.B. Aruba N.V., we have taken the first steps toward alternative technology using wind energy and reciprocating engines for power production to reduce fossil fuel combustion to promote the environmental protection. The intention is to increase the application of alternative technology with solar energy and biodiesel produced of waste for the production of power in the very near future.

Also, we enthusiastically envisage the journey to future green sustainable efficient seawater desalination technology: (1) the Combined Membrane Water and Power Production; without (2) the use of fossil fuel; and (3) without chemicals. The most important futuristic ambitioned seawater desalination technology is the Thermodynamic Minimum Energy Green Desalination (TMEGD) as a viable option for the solution for the water shortage in the world and most important with the mindset to protect our environment especially the seawater eco system.



The main objective of this thesis is to illustrate and emphasize the guiding principles of the human aspect, the physicochemical aspects, and the aspect of innovation, maintenance and the application of new technology toward sustainable optimal efficient seawater desalination as we have practiced on the Aruban journey reaching out to Excellence in Green Seawater Desalination, so we can proudly say:

WE stand for **W**ater **E**xcellence