الجمهورية الجزائرية الديمقراطية الشعبية
وزارة التعليم العالي و البحث العلمي

NATIONAL HIGHER SCHOOL FOR HYDRAULICS
"The MujahidAbdellah ARBAOUI"

المدرسة الوطنية العليا للري
"المجاهد عبد الله عرباوي"
ⴰⵖⵓⵔⵟⴰⵥ ⴰⵖⵓⵍⵏⴰⵡ ⵉⵎⵉⵏⵓⵅ ⵏ ⵜⵎⵓⵔⵡⵉⵜ

MEMOIRE DE FIN D'ETUDES

Pour l'obtention du diplôme d'Ingénieur d'Etat en Hydraulique

Option: **ALIMENTATION EN EAU POTABLE**

THEME :

Diagnosis and rehabilitation of the water treatment unit of the Reggane north development project (W.Adrar)

Présenté par :
DEMAGH Abdelmalek Islam

Devant les membres du jury

Nom et Prénoms	Grade	Qualité
DJOUDAR/HALLAL Dahbia	M.C.A	Président
TOUAHIR Sabah	M.A.A	Examinateur
DERNOUNI Youcef	M.A.A	Examinateur
DAHMANE Mouloud	M.C.B	Examinateur
HACHEMI Abdelkader	M.C.A	Promoteur

Session Juillet 2024

Acknowledgments

First and foremost, I would like to express my deepest gratitude to God for providing me with the strength, wisdom, and perseverance to undertake and complete this journey. Without His blessings, none of this would have been possible.

I would also like to acknowledge myself for the hard work, dedication, and resilience I have shown throughout this journey. This experience has been a significant personal and professional growth opportunity.

I am deeply grateful to my supervisor, Mister Elhachemi, for his invaluable guidance, support, and encouragement throughout this journey. His expertise and insights have been instrumental in shaping this work. I would also like to extend my heartfelt thanks to all the teachers who have supported me along the way, providing me with the knowledge and skills necessary to reach this milestone.

And of course, I am profoundly thankful to my family for their unwavering support, love, and encouragement throughout this journey. Their belief in me has been a constant source of motivation, and their sacrifices have made this achievement possible.

Finally, I would also like to express my sincere appreciation to the GRN technical staff for their assistance and support. Their expertise and dedication have been invaluable to the success of this project.

Dedications

This work is dedicated to everyone who ever believed in me and supported me along the way.

Family, friends, Colleagues… This is for you.

الملخص :

الماء هو مورد أساسي في الصناعة النفطية لعمليات مختلفة، بما في ذلك الحفر والإنتاج والمعالجة، حيث تتطلب هذه العمليات غالبًا درجات عالية من النقاء لتجنب مشكلات مثل التآكل وتكوين الرواسب. ولهذا السبب يجب أن تعمل وحدات معالجة المياه بأعلى كفاءة وأفضل طريقة ممكنة.

تتركز دراستنا على إجراء تحقيق شامل لوحدة معالجة المياه في مشروع تطوير شمال رقان من خلال مراقبة أدائها وإجراء تحليلات للمياه. أتاحت لنا هذه الدراسة تشخيص المشكلات ذات الصلة في الوحدة واقتراح عدة توصيات لإعادتها إلى حالتها التشغيلية الأصلية.

الكلمات الرئيسية: تحلية المياه، إزالة المعادن، التناضح العكسي، التحليل الكهربائي، الأغشية.

Résumé:

L'eau est une ressource essentielle dans l'industrie pétrolière et gazière pour divers processus, y compris le forage, la production et le traitement, avec des niveaux de pureté élevés souvent nécessaires pour éviter des problèmes tels que la corrosion et la formation de dépôts. C'est pourquoi leurs unités de traitement de l'eau doivent fonctionner de la manière la plus efficace et optimisée possible.

Notre étude se concentre sur une investigation approfondie de l'unité de traitement de l'eau du projet de développement de Regagne Nord en surveillant sa performance et en effectuant des analyses de l'eau. L'enquête nous a permis de diagnostiquer les problèmes pertinents de l'unité et de proposer plusieurs recommandations pour la remettre dans son état de fonctionnement d'origine.

Mots-clés : Dessalement, déminéralisation, osmose inverse, électrodéionisation, membranes.

Abstract:

Water is an essential resource in the oil and gas industry for various processes, including drilling, production and treatment, with high purities often being required to avoid issues such as corrosion and the formation of deposits. This is why their water treatment units should run in the most efficient an optimized manner possible.

Our Study focuses on conducting a thorough investigation of the Reggane north development project's water treatment unit by monitoring its performance and conducting water analysis. The aforementioned investigation enabled us to diagnosis the relevant issues of the unit and suggest several recommendations to get it back to its original working state.

Keywords: Desalination, demineralization, reverse osmosis, electrodionization, membranes.

Contents

List of Figures

List of Tables

List of drawings:

General introduction

In recent years our country and the world in general has been experiencing more droughts than ever, with the effects of water scarcity looking to be more pronounced and clearer with everyday that passes, And given the ever increasing global population, the demand for drinkable water will only grow.

Water availability is undeniably the most important problem the faces the human civilisation, not only for daily domestic use but also for industrial purposes. Water is an integral part in many industrial processes and it is often needed in massive volumes, whether it is for cooling machinery, as part of the fire protection system, to dilute different chemicals or for cleaning and washing purposes. Given the various use cases for water in such an environment, the fact that according to data from the United Nations World Water Development Report 2020, the industrial sector accounts for approximately 19% of global freshwater withdrawals is therefore unsurprising.

The oil and gas sector certainly is not the exception to the rule when it comes to water usage, but it presents us with a unique set of challenges that we need to overcome. Most oil and gas wells are located in arid locations, which is the case for Algeria as all of its natural gas and oil deposits are found in the Sahara desert, meaning that water scarcity is an incredibly big issue especially with the high demand of this industry coupled with the need to preserve the natural subterranean aquifers because of their non-renewable nature.

In order for us to face these challenges we need to use the most energy efficient and environmentally friendly techniques that provide us with the best quality water and avoid the over extraction of this precious resource.

The following work will consist of analysing the existing water treatment unit of the Reggane north development project and diagnosing the causes of any anomalies we might find and eventually suggesting an appropriate solution for them.

Chapter I

Presentation of the Reggane north development project

I.1 Introduction:

The Reggane north development project is a natural gas exploitation initiative run by groupement Reggane nord (GRN) which is a consortium lead by the Algerian SONATRACH with a share of 40% , and its international partners: REPSOL (29.25%), EDISON (11.25%) and RWE Dea (19.5%) (Hydrocarbons technology, 2018). This project aims at extracting the natural gas from the six gas fields found in the region and treating it in the gas treatment plant (GTP) to finally be export via a pipeline that is connected to the region's main gas transport system. The aforementioned gas fields are:

- Reggane
- Azrafil south-east
- Kahlouche
- Kahlouche south
- Tioulíline
- Sali

Figure I.1: GRN share holders

I.2 Site location:

The Reggane north project is located in the Wilaya of Adrar more precisely in the Daira of Reggane, which is constituted of two communes, Reggane and Sali found in a relatively densely populated region of the Sahara desert approximately 1500 km of the capital Algiers as demonstrated in Figure I.2.

The population of Reggane Daira is approximately 29271 inhabitants, according to the 2008 census data. Its total area is approximately 140981 square kilometers which includes inhabited and uninhabited land which implies a population density of 0.28 inh/km^2. It shares borders with several other communes, including Adrar to the north, Aoulef to the east, Bordj badji mokhtar to the south and the country of Mauritania to the west.

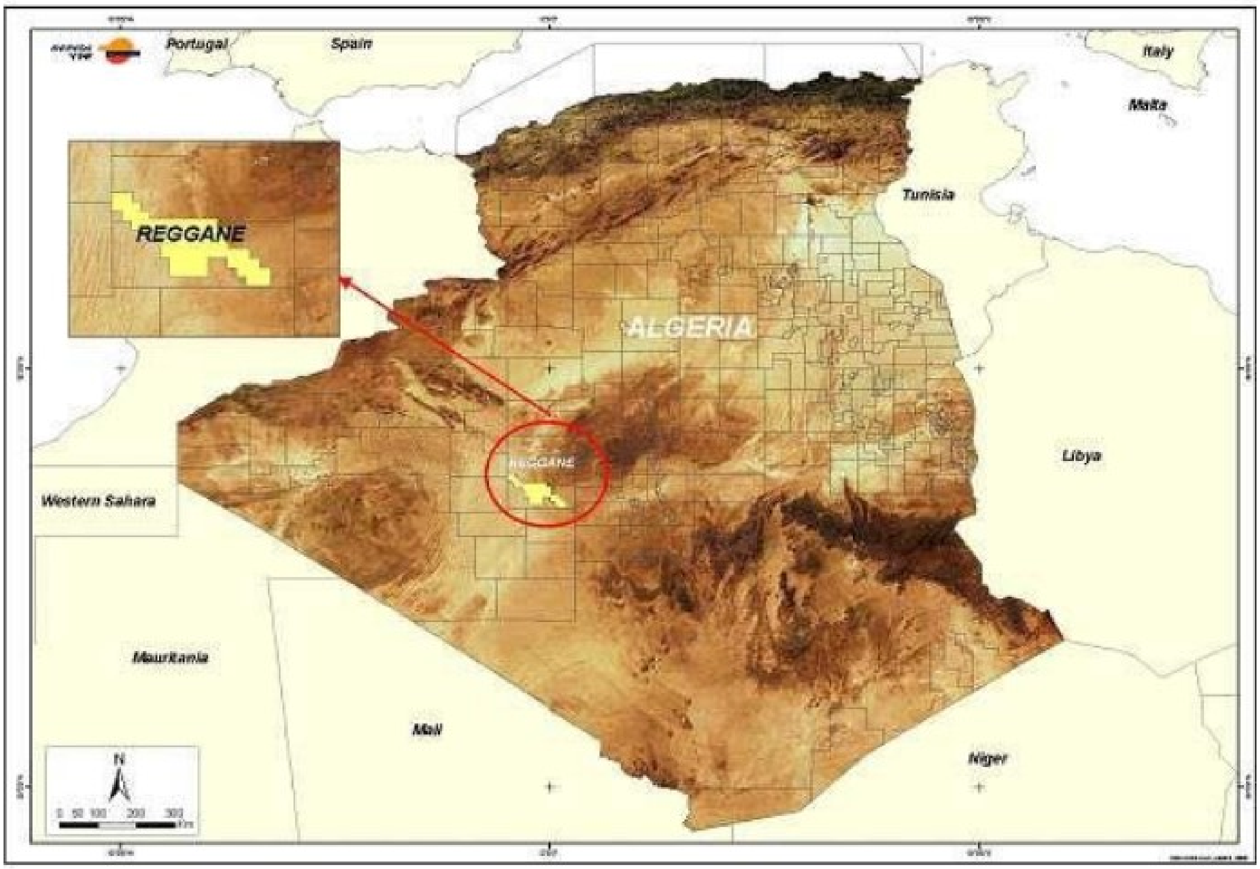


Figure I.2: Reggane basin location (Hydrocarbons technology, 2018)

I.3 Climate data:

Given the fact that Reggane is located in the middle of the Sahara desert, it experiences very low rainfall numbers and high temperatures and quite a high evaporation rate. All of these factors combined highlight the fact that this is one the harshest regions in the world in terms of climate.

The following data that has been collected throughout the period from 1997 to 2006 and was obtained at Adrar meteorological station which has the following coordinates:

- Latitude: 27º 49´ North
- Longitude: 00º 11´ West
- Altitude: 279 meters

I.3.1 Rainfall:

As Table I.1 demonstrates, the region receives very little rainfall with a maximum average precipitation of 4.7 mm recorded in April and a minimum of 0 mm recorded in July.

Table I.1: Average monthly precipitation (1997-2006)(Office national de la météorologie, 2006)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average (mm)	2,8	2,5	1,0	4,7	0,8	0,1	0,0	2,1	0,2	2,5	3,3	0,1

The maximum precipitation recorded in 24h in the sample period was 27.11 mm and was on 15-Apr-04.

I.3.2 Temprature:

The region experiences high temperatures throughout the year with averages that range from 12.6°C in the coldest month (January) to 38.5°C in the hottest month (July) as shown in Table I.2.

The absolute maximum temperature is 49,4 ºC, recorded on 11-Jul-02.
The absolute minimum temperature is -3,6 ºC, recorded on 29-Jan-05.
The mean annual temperature is 25,8 ºC.

Table I.2: Average dry bulb temperatures (1997-2006)(Office national de la météorologie, 2006)

	Min (°C)	Average (°C)	Max (°C)
Jan	5,5	12,6	22,9
Feb	6,0	15,5	25,7
Mar	9,2	21,1	29,7
Apr	18,3	25,8	33,8
May	21,6	30,5	36,8
Jun	29,2	35,5	41,1
Jul	33,8	38,5	42,1
Aug	29,0	37,2	41,6
Sep	23,9	33,3	38,7
Oct	17,9	27,3	34,0
Nov	9,9	19,0	26,2
Dec	7,0	13,7	22,9

I.3.3 Relative humidity:

Relative humidity present in the atmosphere is represented in Table I.3:

Table I.3: Relative humidity(Office national de la météorologie, 2006)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average (%)	39,4	31,5	20,1	17,6	15,2	11,9	10,0	13,6	20,1	28,9	34,1	41,1

I.3.4 Evaporation rate:

The evaporation rate as mentioned before is high due to high temperatures and the dry climate, and this is highlighted in Table I.4.

Table I.4: Evaporation rate (Office national de la météorologie, 2006)

Month	Total Average (mm/month)	Daily Average (mm/day)
Jan	204,6	6,6
Feb	243,6	8,7
Mar	362,7	11,7
Apr	429,0	14,3
May	530,1	17,1
Jun	588,0	19,6
Jul	675,8	21,8
Aug	638,6	20,6
Sep	510,0	17,0
Oct	390,6	12,6
Nov	252,0	8,4
Dec	195,3	6,3

I.3.5 Wind:

Wind is a very frequent and violent in this part of the country. It often points to the north-east as demonstrated in the wind chart in Figure I.3

Table I.5: Wind speeds (Office national de la météorologie, 2006)

	Average (m/s)	Max Average (m/s)
Jan	5,81	11,5
Feb	6,51	12,6
Mar	6,52	13,4
Apr	6,66	14,6
May	6,70	15,4
Jun	6,33	14,4
Jul	6,44	14,9
Aug	6,15	14,1
Sep	6,04	13,6
Oct	5,98	12,7
Nov	5,55	11,0
Dec	5,70	11,1

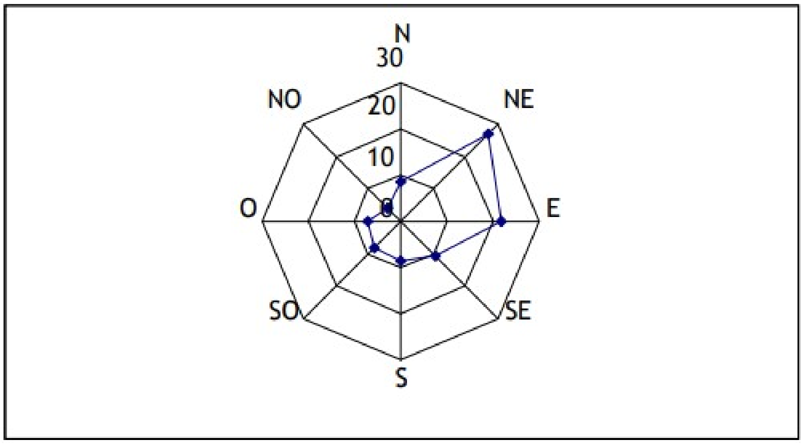


Figure I.3: Wind chart (Petrofac, 2014b)

The chart and table shown above both show that the win speeds are quiet high all throughout the year with it being mainly directed towards the east and the north-east.

I.3.6 Sand storms:

Sand storms are another climate phenomenon that happens often in our study area due to the high wind speeds (Figure I.5) and the data shown in Table I.6 reflects that.

Table I.6: Sand storm frequency (Petrofac, 2014b)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Total days	6	3	9	12	4	3	5	7	10	1	0	1

I.4 Geology:

The touat oasis is found in proximity to the site of the central processing facilities (CPF), it is located westward at an approximate distance of 8 to 12 km within the Reggane field. The oases are situated on a gentle slope beginning from the higher cretaceous plateau in the east, down to the zone of sebkha (evaporated-carbonate deposits) and sand dunes in the west.

Most of the land forms in this zone have been altered or influenced by anthropogenic activities. The most notable land form associated with the oases are the large dunes (some over 20 m high) created by construction palm frond fences perpendicular to the prevailing wind direction.

The plateau that forms the eastern third of the area is covered largely by stony desert with occasional duricrust (hard layer of some millimeters on or near the soil surface). Sand dunes are very infrequent and are poorly developed.

Central Processing Facilities and most of the gathering system for Reggane and Azrafil fields will be located in this area. This area is characterized by a flat sandy reg (areas covered by gravel and small stones coated with black-brown desert varnish). Some small hills can also be observed.

I.5 Hydro-geology:

Reggane field is located over the Continental Intercalaire (CI) Aquifer. CI is contained in Lower Cretaceous formations within a complex sequence of classic sediments of Mesozoic age. It extends over a surface of around 840.000 km2, along Algeria, Tunisia and Libya as shown in Figure I.4.

Groundwater is a valuable resource in the area and its use is managed carefully at local level. Groundwater is extracted either from deep wells drilled using modern techniques, through fouggara systems and from hand-dug wells.

Piezometric information indicates that groundwater in the project area flows to the southwest, towards the fouggara systems. Fouggara is the name given to an ancient combined system of water collection and distribution. The water for the fouggara is collected via a series of hand-dug wells on the CI plateau to the east of the oases. The wells are dug until the water surface is reached, and then linked at depth by hand dug tunnels.

Fouggaras have not been identified in the area selected for the Central Processing Facilities, but are very common in the areas of Sali and Tiouliline fields.

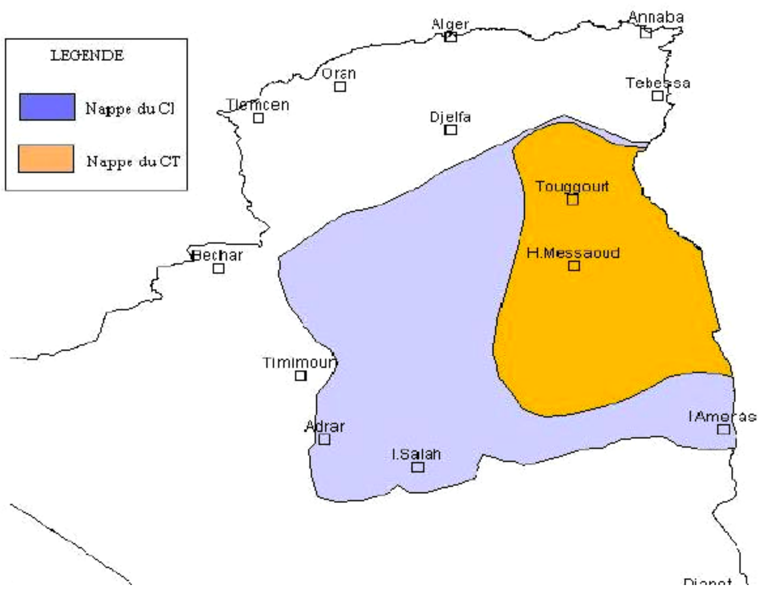


Figure I.4: Map representing the Continental Intercalaire aquifer(Ouali & Khellaf, 2006)

I.6 Conclusion:

In this chapter we gave an overview of the Reggane north development project and the geographical situation as well as climate and hydraulic data that can help us get a better grasp of the design parameters and conditions.

It was mainly concluded that Reggane resides in an extremely arid area with extremly harsh conditions, where precipitations are very rare and ambient temperatures are constantly high. These in addition to the prevalence of sand storms will pose several challenges in the design phase that need to be overcome.

Chapter II

Modern water demineralization techniques:

II.1 Introduction:

Water quality is of an utmost importance in industrial settings as it can interfere with the various processes found in the factory, as well as the different machines and units that maybe susceptible to damage caused by minerals or micro-particles carried by said water. It is for this reason that engineers may choose to demineralize the water they use.

Water demineralization refers to the removal of mineral ions and other impurities from water using various techniques such as ion exchange, nanofiltration and reverse osmosis. The aforementioned techniques produce a high quality water that can be used for domestic and industrial means. The specific technologies and methods used differ depending on the intended use case for the permeate water. These methods never ceased to advance and develop ever since their inception.

II.2 Traditional water demineralization techniques:

Throughout history, various techniques have been developed and refined to improve water quality and ensure its suitability for drinking, industrial processes, and other applications. In this section, we will explore some of the traditional water demineralization techniques that have played pivotal roles in water treatment practices. From distillation to ion exchange and chemical precipitation, these methods have been crucial in addressing water quality challenges and shaping the evolution of modern water treatment technology.

II.2.1 Distillation:

Distillation is one of the oldest water treatment methods and it has been used for centuries for the production of high quality water used for potability or otherwise. It consists of boiling raw or contaminated water and turning into vapor that is subsequently condensed and turned back into the liquid state. The aforementioned process separates non-volatile impurities such as heavy metals, organic material and hardness from the volatile gases such as water vapor. The volatile gases can later be separated by playing on their different boiling points thus getting a pure form of water at the end of the process.

The simplicity and efficacy of this process is the main reason that it has been used throughout antiquity with its popularity being at its highest in the late 19th to early 20th century.

The main problem with traditional distillation is its energy intensive nature due to the high heat demand to vaporise water. In fact the energy required to transform 1L of water into vapor is 2680KJ which is quite high. There are many types of distillation processes used in large scale settings that try to mitigate the energy consumption of this process. In the next section we'll go through a few of them.

II.2.1.1 Multiple effect distillation:

Multiple effect distillation is one of the oldest methods of demineralization as references and patents of it have existed since the 1840s and was and still is used as a method of thermal desalination.

According to Fadl A. Essa The MED process is the oldest desalination method. Thermodynamically, MED is the most inherent method as compared to all others. The MED process takes place in a series of evaporators. The basic principle involved in MED is reducing the ambient pressure at different points. There is no need to provide or supply extra heat after the completion of the first effect as this process automatically allows the seawater feed to undergo multiple boilings.

As the seawater reaches the first effect, the temperature of the seawater is raised to boiling point after being preheated in the tubes. Thereafter, to carry out rapid evaporation, seawater is sprayed onto the surface of an evaporator. The dual-purpose power plant is used to supply steam externally, and the tubes are heated. Condensation of steam occurs on the opposite side of the tube and forms a steam condensate. Steam condensate is again utilized as boiler feed water after it is recycled to the power plant.(Essa et al., 2022) Figure II.1 demonstrates a basic process diagram.

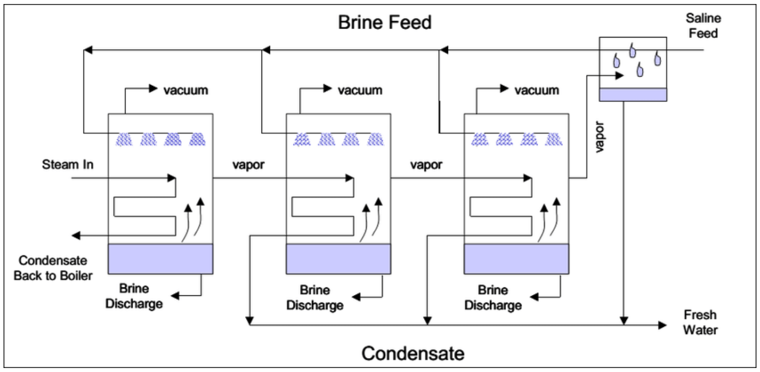


Figure II.1: Diagram of multiple effect distillation evaporator(Saadat et al., 2018)

II.2.1.2 Vapor compression distillation:

Vapor compression distillation is another thermal demineralization method that generates the heat energy needed for the process by using vapor compression as illustrated in II.2, It reduces the boiling point of water thus reducing the energy consumption by reducing the overall pressure of the system similar to MED. it is often used either in combination with other methods like MED or as a standalone method in smaller units.

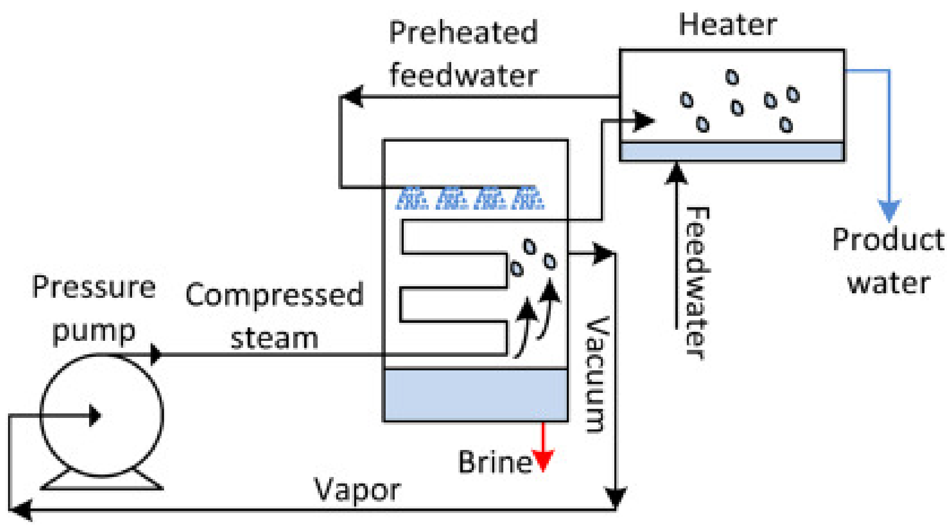


Figure II.2: Illustration of vapor compression distillation (Yousef & Hassan, 2023)

II.2.1.3 Multi-stage flash distillation:

Multi-stage flash distillation (MSF) is a prominent and widely employed desalination technique designed to convert seawater into fresh water by leveraging the principles of multiple stages of evaporation and condensation. The process begins with the heating of seawater, which is then introduced into a series of stages, each maintained at successively lower pressures. As the pressure decreases in each stage, the heated seawater flashes into steam at correspondingly lower temperatures. This steam is subsequently condensed on heat exchange surfaces to yield fresh water.

The MSF process is characterized by its high thermal efficiency, achieved through a cascading heat exchange mechanism. The heat released from the condensation of steam in one stage is utilized to preheat the incoming seawater in the subsequent stage, thereby conserving energy and reducing overall operational costs. This efficient use of thermal energy makes MSF an energy-efficient method for large-scale desalination.

MSF plants are typically robust and capable of producing large volumes of fresh water, which is essential for meeting the demands of regions with limited access to natural freshwater sources. The durability and scalability of MSF systems have made them a cornerstone in the infrastructure of many coastal areas, particularly in arid regions where freshwater scarcity is a critical issue.

Despite its advantages, MSF requires significant initial investment and maintenance due to the complexity of the system and the corrosive nature of seawater. However, advancements in materials and technology continue to improve the efficiency and lifespan of MSF plants. In summary, multi-stage flash distillation remains a vital technology for desalination, providing a reliable and efficient solution to the global challenge of freshwater scarcity.

II.2.2 Ion exchange:

Ion exchange (IX) refers to the chemical phenomenon where an insoluble resin attracts a certain ion from a solution while releasing an ion of a similar charge, this process occurs according to the affinity of certain ions to be captured by certain resins and this is calculated using a selectivity coefficient. It has been a widely used process in water and waste water treatment since the late 1800s until today.

IX is used in several facets of the water treatment industry but it is primarily used to treat waters with low mineral content, such as in the removal of specific toxic or harmful ions that may be found in certain waters or in water softening, which refers to the removal of calcium and magnesium ions from water. One of the biggest advantages for IX is the ability to regenerate the resins after their use by passing them through a solution that permits them to liberate the captured target ions and regain their original form.

IX resins can be classified based on two main categories, the first one being physical properties such as:

- Color,density and mechanical Resistance
- Particle size (0.04 - 1.2mm)
- Porosity (20% - 55%)

But more often than not we class resins based on their chemical properties and we distinguish the following classes:

- Strong-acid cation exchanger.
- Weak-acid cation exchanger.
- Strong-base anion exchanger.
- Weak-base anion exchanger

II.2.3 Chemical precipitation:

The process known as chemical precipitation has been in use for water and wastewater treatment for hundreds of years as one of the earliest recorded uses of it is a patent granted to De Boissieu in England in 1762 (Reynolds, 1933). It consists of transforming soluble metallic ions and certain anions from water or wastewater to an insoluble form called a precipitate which is subsequently discarded.

It is commonly used in water softening, the removal of heavy metals and phosphates. The major advantage of this process is the low capital cost compared to the previously mentioned processes and the simplicity of its operation. On the other hand it is not as effective in removing heavy metals and it raises several issues regarding the disposal of the resulting precipitate.

An example of this process is demonstrated by the addition of lime (Calcium oxide) which can be used in water softening a it reacts with the calcium ions, forming a calcium carbonate precipitate that can be discarded later.

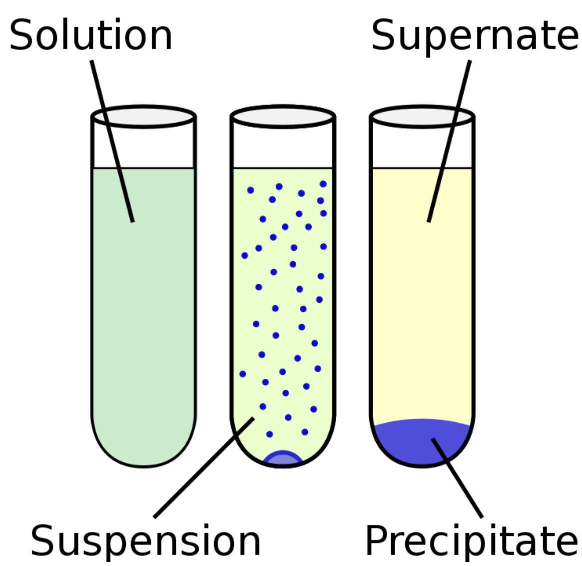


Figure II.3: Illustration of the chemical precipitation process (ZooFari, n.d.)

II.3 Pressure driven membrane-based demineralization techniques:

Membrane processes involve the use of semi-permeable membranes to separate impurities and contaminants from water. These membranes selectively allow certain substances to pass through while blocking others, based on differences in size, charge, or solubility. They rose to prominence in the water treatment industry in the late 1970s and the 1980s as a more efficient and cost effective solution for drinking water treatment especially in regions that experience water scarcity.

The following graph (Figure II.4) illustrates the growth in the use of membrane technology in the USA (USEPA 2001). This trend is continuing an exponential rise as numerous membrane facilities ranging from of 25 to 100 mgd [1] in capacity are either planned, in design or in operation (A.W.W. Association, 2005).

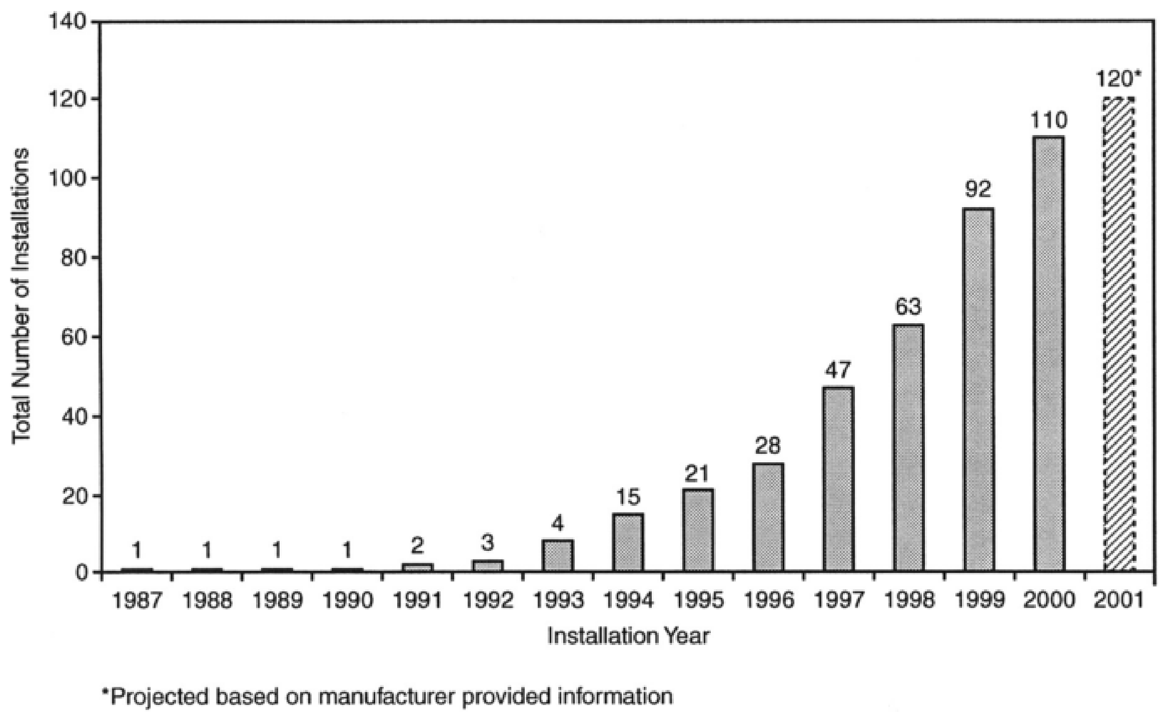


Figure II.4: The growth of the use of membrane processes (A.W.W. Association, 2005)

[1] million gallons per day

These processes can be categorised following several factors such as the driving force of the separation. In this section, as the title implies, we are going to treat the pressure driven kind of these membranes.

Figure II.5 demonstrates the separation capacities of different membrane processes according to the particle size.

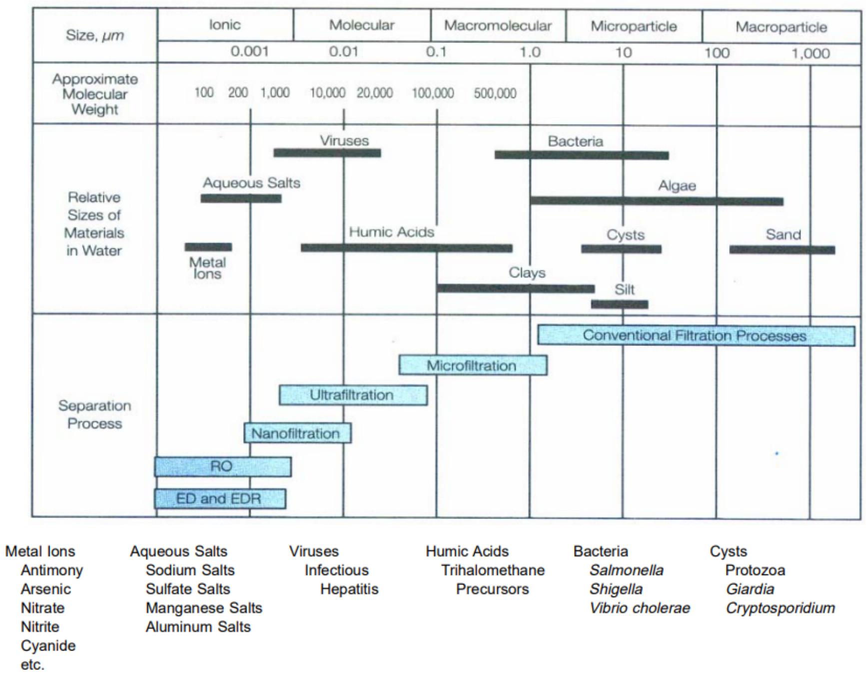


Figure II.5: Filtration capacity of different membrane processes (A.W.W. Association, 1995)

II.3.1 Microfiltration and Ultrafiltration:

Microfiltration (MF) and Ultrafiltration (UF) are membrane filtration technologies that permit the exclusion of particles that range from 0.1 to 0.2 μm for MF and more than 0.001 μm for UF via sieving mechanism that relies on the microscopic size of the membrane's pores.

The feedwater flows through the the membrane thus inducing the separation of undesirable particulates which are subsequently rejected in the the concentrate, while the filtrate/permeate is retained. The main driving force of the process can come of two different sources, either a pressurized feedwater source with the membranes installed in pressure vessels, called modules, or a partial vacuum in the filtrate flow stream caused by use of a filtrate pump or gravity siphon as seen in Figure II.6. The vacuum-driven processes are typically apply to MF and have membranes submerged or immersed in non-pressurized feedwater tanks.

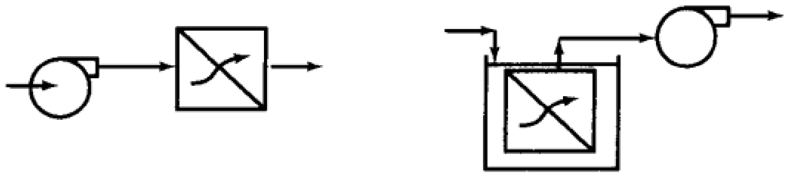


Figure II.6: Pressure-driven processes using feed or filtrate pumps (Baruth et al., 2005)

II.3.1.1 Pre-treatment requirements:

MF and UF membranes do not necessarily a complex pre-treatment process due to them not removing uncomplexed dissolved ions which induce scaling in other systems, therefore a simple PH adjustment is needed to get the water within the operating range of the membranes, as well as a pre-filtration system to remove larger particles (50 to 500 μm) that may damage the membranes. Other pre-treatment options may be explored depending on the desired filtrate/permeate quality. The following table (Table II.1) illustrates the needed pretreatment to achieve adequate removal for specific contaminants.

Table II.1: the needed pretreatment to achieve adequate removal for specific contaminants (A.W.W. Association, 2005)

		Pretreatments Needed for Substantial Removal	
Parameter		MF	UF
Particulate/Microbial	Turbidity	None	None
	Protozoa	None	None
	Bacteria	None	None
	Viruses	Coagulation	None
Organic	TOC	Coagulation/PAC	Coagulation/PAC
	DBP precursor	Coagulation/PAC	Coagulation/PAC
	Color	Coagulation/PAC	Coagulation/PAC
	T&O	Coagulation/PAC	Coagulation/PAC
	Pesticides	PAC	PAC
Inorganic	Iron and manganese	Oxidation	Oxidation
	Arsenic	Coagulation	Coagulation
	Hydrogen sulfide	Oxidation	Oxidation

II.3.1.2 Membrane applications:

As mentioned above, MF and UF membranes are particularly capable of removing turbidity and microbial contaminants, as it happens to be the main purpose for the conception of such membranes with the first small scale plants made for this purpose were inaugurated between 1991 and 1993 in the US and in 1988 in France. But as the water treatment industry developed and the water quality requirements became stricter, these low pressure membranes started being integrated with other processes to achieve a higher degree of treatment.

These integrated membrane systems employ low pressure membrane filtration (MF or UF) within the overall treatment process in different stages, therefore we can distinguish three different types:

- **Preliminary membrane treatment:** It refers to systems that use it as preliminary treatment to remove different particles and microbial contaminants.
- **Intermediate membrane treatment:** Processes in which membranes are used in the middle of the treatment cycle to remove coagulated particles that otherwise might have not been captured by the membranes.
- **Final membrane treatment:** It refers to systems where it is the last step in the treatment.

II.3.2 Nano-filtration and reverse osmosis:

Similar to MF and UF reverse osmosis (RO) and nano-filtration (NF) are pressure driven membrane processes with the distinction that they use non porous semi-permeable membranes that are selectively permeable to water and not to other chemical species, with RO membranes being almost completely impermeable to targeted contaminants (usually salts) and NF membrane having slightly higher permeability which results in the different separation levels of the two processes. NF rejects particles in the size range of 1 *nm* and a molecular weight greater than 200-400, while RO can remove particles in the range of 0.1 *nm* and a molecular weight greater than 100 (refer to FigureII.5).

Both these membrane processes utilise the principle of reverse osmosis which is the inverse of the natural mechanism that is osmosis, it consists of the transfer that happens between a dilute solution and a concentrated solution separated by a semi-permeable membrane in which the dilute solution passes through the membrane and joins the concentrated solution (this is the process with which plants absorb nutrients from the soil). Reverse osmosis refers to the phenomenon that happens when external pressure in excess of the osmotic pressure (height difference between the two solutions) is applied to the concentrated solution which prompts it to diffuse through the membrane thus reversing the original process.

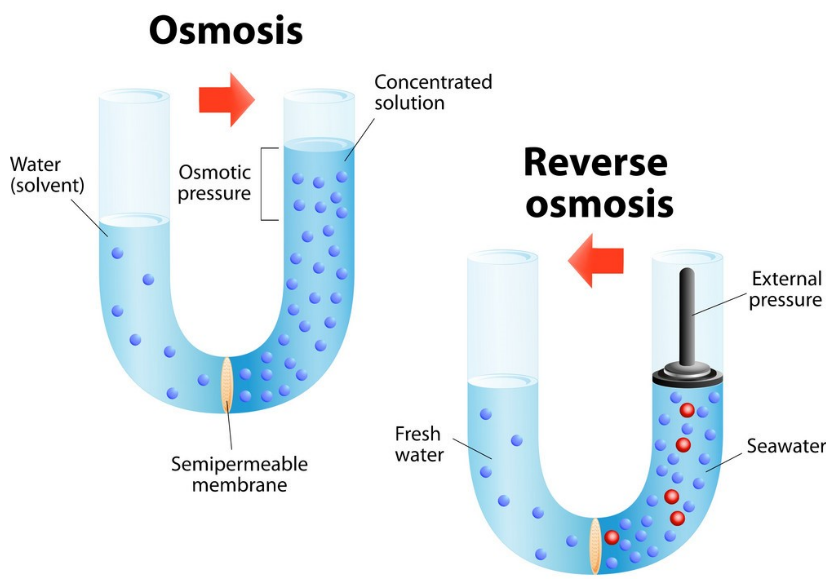


Figure II.7: Osmosis and reverse osmosis (Ma biologie, 2018)

RO and NF are therefore applied as a cross-flow filtration process where the raw water is continuously pumped through the membrane with a high pressure pump, which consequently splits it into a purified flow that is retained as the permeate and a a concentrate flow that either gets rejected or is treated further. FigureII.8 demonstrates this process.

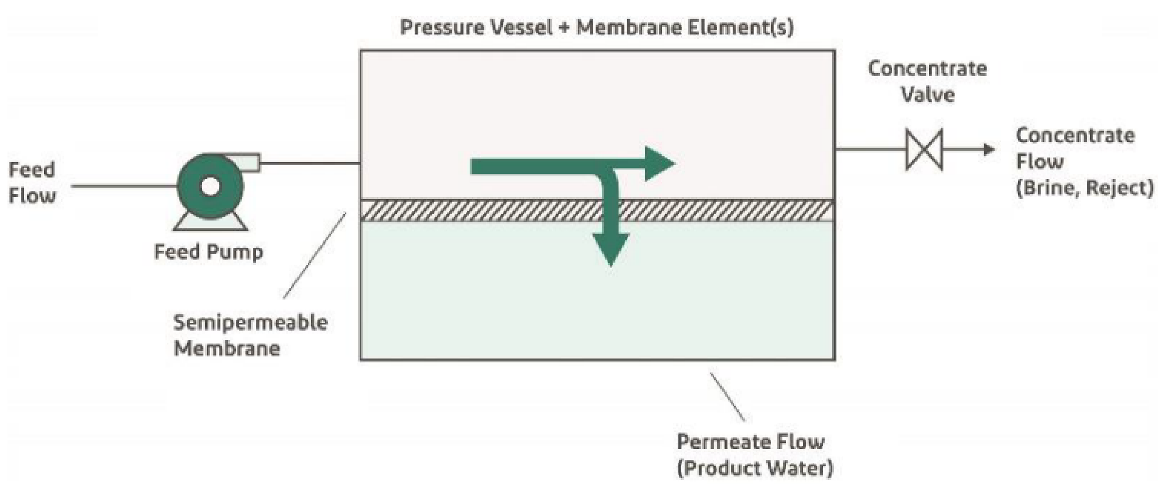


Figure II.8: basic reverse osmosis/nano-filtration process (DuPont, 2023)

II.3.2.1 Membrane applications:

The main application for NF and RO membranes is desalting, i.e. the reduction of TDS [2], although they're more than capable of removing all other types of other contaminants such as turbidity and pathogens... But the non porous nature of the membranes can the lead to the rapid fouling (formation of layers of silt or other particles on the surface of the membranes) of the membranes thus reducing their lifespan. As a result RO and NF are used for more fine applications and particles that can induce fouling such as turbidity are removed during the pretreatment phase.

Other applications include the removal of DBP[3] precursors such as organic materials which is very important due to the carcinogenic nature of those DBPs. Other applications include water softening, inorganic contaminants and pathogens.

II.4 Electro-chemical demineralization techniques:

Electro-chemical demineralization techniques are another type of membrane processes that differs from the ones mentioned above in the driving force of the separation, as they rely on an electrical current to drive produce pure water out of contaminated raw water. Another big distinction between these techniques and pressure driven ones is their inability to reject microorganisms due to the types of membranes that are used. We can distinguish two main treatment processes, electrodialysis (ED), and electrodialysis reversal (EDR).

II.4.1 Electrodialysis:

Electrodialysis is an electro-chemical membrane process that has the main objective of removing TDS from brackish water [4]. ED achieves that goal by electrically removing undesirable contaminants.

The basic setup consists of multiple alternating layers of cation-selective (only allows positively charged ions to pass) and anion-selective (only allows negatively charged ions to pass) electrically charged membranes arranged between two electrodes thus creating several water tight compartments separated by the membranes. A DC current is then applied through the electrodes thus attracting the anions to the anode (positive electrode) and the cations to the cathode, and given the alternation nature of the membranes and their impermeability to water, certain compartments collect all the anions and the cations while others are completely deprived of ions therefore creating pure water.

Figure II.9 demonstrates the basic principle of electrodialysis on a $NaCl$ solution, with (A) representing anion membranes and (C) representing cation membranes.

[2] Total dissolved solids

[3] Disinfectant by-products, they are formed from the reaction of disinfectants such as chlorine with organic material

[4] Brackish water is water that has TDS ranging between that of fresh water (500 mg/l) and seawater (10000 mg/l)

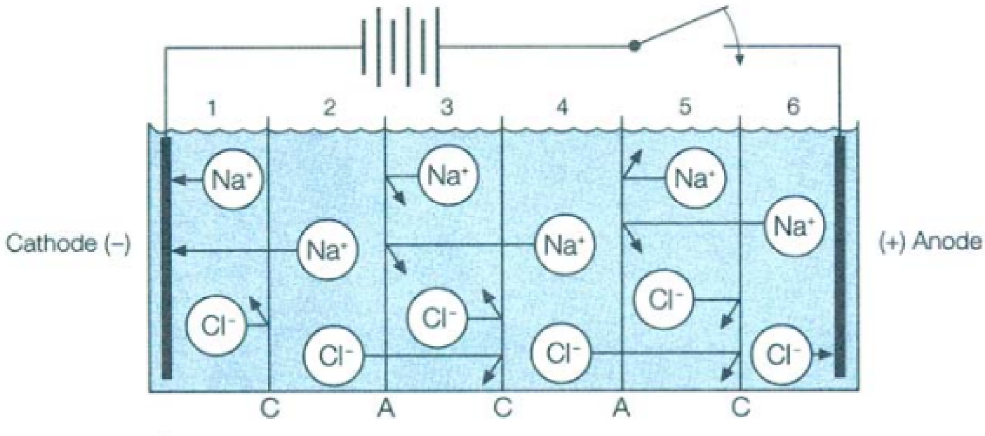


Figure II.9: Electrodialysis of a basic $NaCl$ solution (A.W.W. Association, 1995)

ED is quite an old technique that has been used especially in the industrial sector since the 1950s and its use has increased ever since with the advancements made in ion exchange membranes. The process can selectively target dissolved solids and achieve predetermined TDS levels with very high recovery rates with a relatively simple system as shown in the diagram in FigureII.10[5]

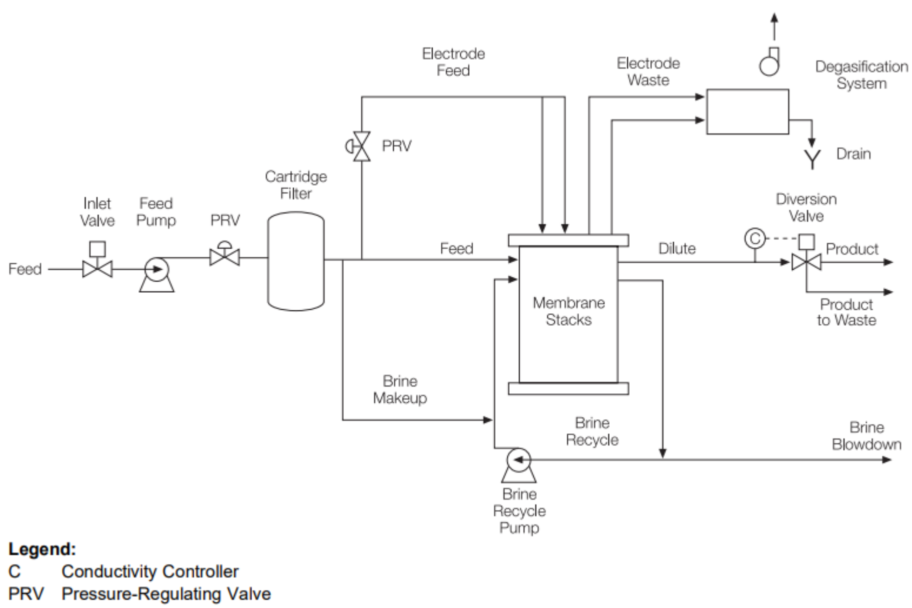


Figure II.10: Electro-dialysis system diagram (A.W.W. Association, 1995)

[5]Ionics inc

II.4.2 Electro-dialysis reversal:

Electro-dialysis reversal (EDR) applies the same principles seen in ED with changing one big aspect, ED systems are unidirectional, which means the ions always move in one direction, the anions towards the anode and the cations towards the cathode, which increases the chances for membrane fouling and the formation of scale, therefore continuous chemical use is necessary to increase the life of the ion exchange membrane. EDR on the other hand treats this problem differently and that with making the movements of the ions bidirectional by the reversal the polarity of the electrodes according to a certain time interval (usually twice to four times an hour) which reduces the foulability of the membranes and makes it so the system can function continuously without the need for the constant addition of antiscalants.

FigureII.11 represents an EDR system diagram, we can notice that it is identical to the ED system shown in Figure II.10 except for the addition of reversal valves.

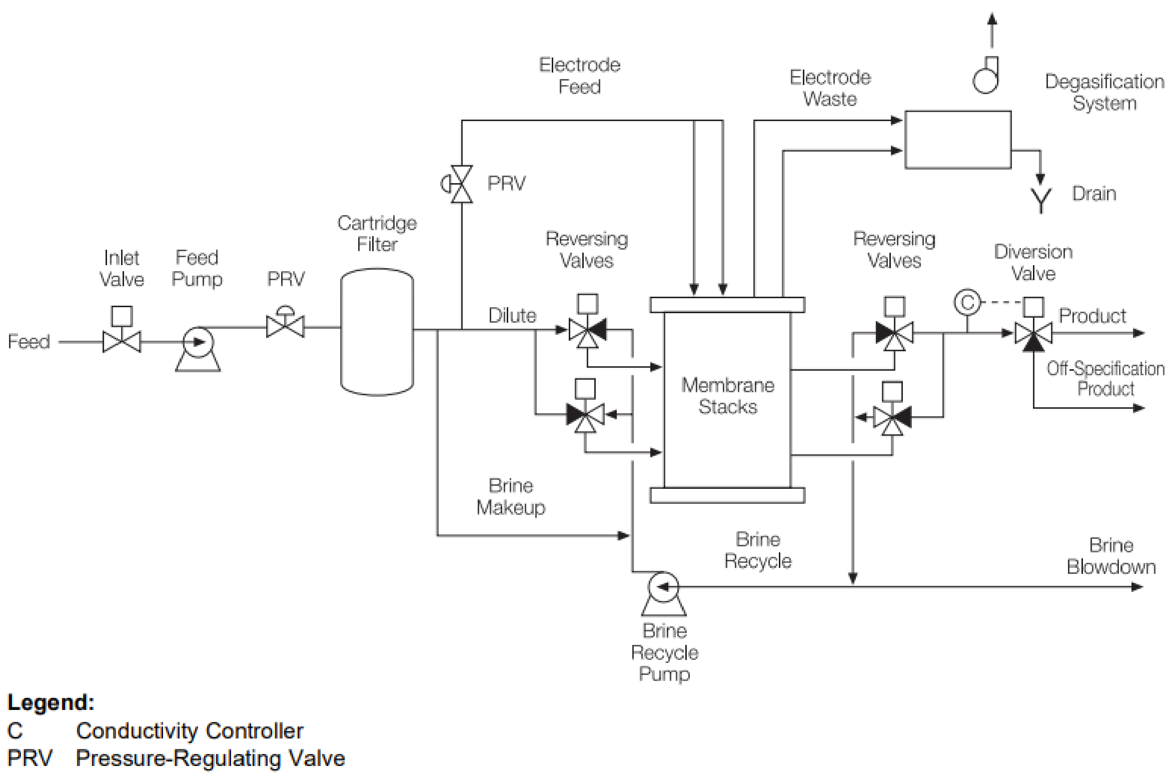


Figure II.11: Electro-dialysis reversal system diagram (A.W.W. Association, 1995)

II.5 Environmental and economic considerations:

In addition to technical effectiveness, environmental and economic considerations play pivotal roles in the evaluation and implementation of water demineralization techniques. Understanding the environmental impact, resource utilization, and economic feasibility of these processes is essential for achieving sustainable water management practices. In this section, we explore the environmental implications and economic aspects associated with water demineralization, examining factors such as energy consumption, chemical usage, waste generation, resource conservation, and cost-effectiveness.

Starting with energy consumption which directly correlates to the carbon footprint of the given demineralization technique, membrane techniques are all large energy consumers, and with the addition of other operational costs, coupled with the initial investment it is safe to say that despite the technical effectiveness, the costs of these systems might outweigh their benefits in certain cases. it is also noteworthy to add that comparing the prices of different membrane processes is a very complex task that depends on many variables so it should be looked at on a case by case basis.

Another factor worth examining is chemical use and disposal, as they can have a negative impact on both the economic and especially the environmental side. the safe handling and storage and eventual disposal of chemicals is essential as any accident could lead to the to lasting impacts of underground aquifers and the soil.

Although, the most important by-product of water demineralization is the concentrate water formed by the different techniques we discussed. It is essential that said concentrate is carefully and responsibly disposed of, whether it'd be with use of evaporation basins or the further treatment of it to lessen the toxic effects it may pose on the environment.

II.6 challenges and future perspectives:

Water demineralization techniques face several challenges that need to be addressed to ensure sustainable water management practices. High energy consumption remains a primary concern, particularly in processes like reverse osmosis and electrodialysis, necessitating efforts to reduce energy usage without compromising treatment efficiency. Additionally, environmental impacts such as chemical usage, waste generation, and carbon emissions pose significant challenges, highlighting the importance of minimizing adverse effects on ecosystems and natural resources.

Moreover, the cost and affordability of water demineralization technologies present barriers to their widespread adoption, underscoring the need for cost-effective solutions and innovative financing mechanisms. Keeping pace with technological advancements also poses challenges for water treatment facilities, requiring ongoing investment in personnel training, infrastructure upgrades, and operational adjustments.

Looking ahead, future perspectives offer opportunities for addressing these challenges and advancing water demineralization technologies. Advancements in membrane technology, such as nanocomposite membranes and bio-inspired materials, hold promise for improving treatment efficiency and reducing energy consumption. Integration of renewable energy sources into water treatment operations can enhance sustainability by lowering carbon emissions and reducing reliance on fossil fuels.

Process optimization techniques, coupled with real-time monitoring and control strategies, enable more efficient operation and minimize environmental impacts. Embracing circular economy principles, such as resource recovery and waste valorization, offers opportunities for transforming waste streams into valuable resources, contributing to resource conservation and cost savings.

Capacity building and knowledge sharing initiatives foster innovation and promote best practices, accelerating the adoption of sustainable water treatment solutions globally. By addressing these challenges and embracing future perspectives, the water treatment industry can advance towards more sustainable, efficient, and resilient water demineralization processes, ensuring access to clean and safe water for present and future generations.

II.7 Conclusion:

In conclusion, modern water demineralization techniques face challenges in energy consumption, chemical usage, waste generation, and affordability. However, opportunities for innovation exist, including advancements in membrane technology and integration of renewable energy sources. Embracing these advancements can enhance sustainability and efficiency in water treatment, ensuring access to clean water while safeguarding the environment.

Chapter III

Reverse osmosis:

III.1 Introduction:

As discussed previously, reverse osmosis (RO) is a membrane process that relies on the use of semi permeable membranes to separate dissolved solids such as ions from water. RO membranes have been a topic of research since the 1960s but the use of actual RO systems has only recently gained some steam and started overtaking distillation as the main demineralization technique in use whether it is for potable water production or for industrial purposes, Figure III.1 demonstrates that the use of membrane processes (RO being the most used) has been rising since the beginning of the new millennium and that they are consistently being used more than thermal techniques.

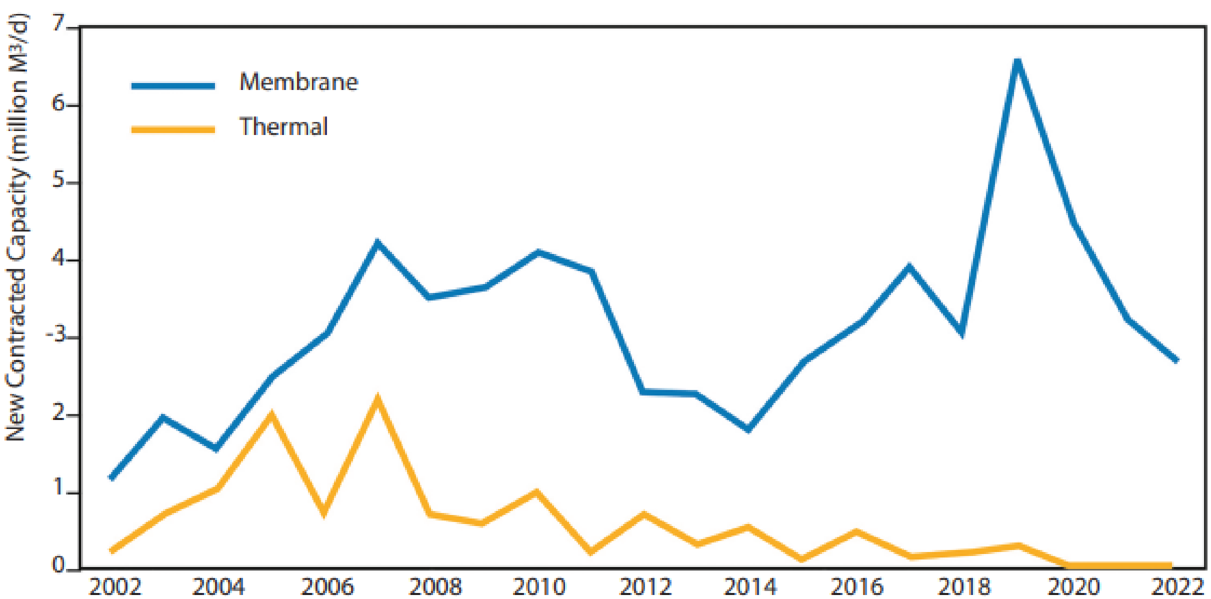


Figure III.1: Thermal desalination vs membrane techniques (Kucera, 2023)

In this chapter we will take a more in depth look at the technical details of reverse osmosis and we will identify its main characteristics.

III.2 Process fundamentals and description:

in this section we will discuss the founding principles of reverse osmosis systems as well as all the associated phenomenons and characteristics.

III.2.1 Reverse osmosis overview:

As we previously mentioned, reverse osmosis is the process in which the application of an external force (pressure) exceeding the osmostic pressure of the solution on a container of a concentrated solution separated from another one full of a dilute solution with a semi-permeable membrane results in the diffusion of the concentrated solution through the membrane while leaving out some of the solutes (dissolved solids).

Osmotic pressure is the force that needs to be overcome for RO to happen, it represents the difference in height of the two containers when at equilibrium. the VAN'T HOFF equation is used to calculate osmostic pressure and it goes as follows:

$$\Pi = \sum m_i \ R \ T \tag{III.1}$$

With:
Π: Osmotic pressure (Pa)
$\sum m_i$: The sum of molar masses of the chemical species present in the solution (mol/kg)
R: universal gas constant ($J \ K^{-1} \ mol^{-1}$)
T: Temperature (K)

The calculated value is subsequently multiplied by a factor of 2 to 3 for the RO process to be economically interesting.

It is also noteworthy to add that reverse osmosis use a cross-flow filtration method as opposed to a dead-end filtration which is commonly used in conventional filtration methods and micro-filtration. In dead-end filtration the water flows perpendicularly with the membrane or filter, with the latter forming a barrier that prevents the targeted contaminants from passing. It is a batch process in which the contaminants continue to accumulate on the surface of the membrane until it's completely blocked off and needs to be replaced.

On the other hand, in cross-filtration which is used in RO and UF systems, the water flows parallel to the membrane in tangential manner, with the feed water diffusing through the membrane thus creating two types of product water, the permeate which is deprived of the dissolved solids after passing through the membrane and the concentrate that doesn't flow through the membrane. RO uses this type of filtration due to its "self cleaning" nature that reduces the risk of the membrane's blockage and increases its life span. Figure III.2 demonstrates both filtration modes.

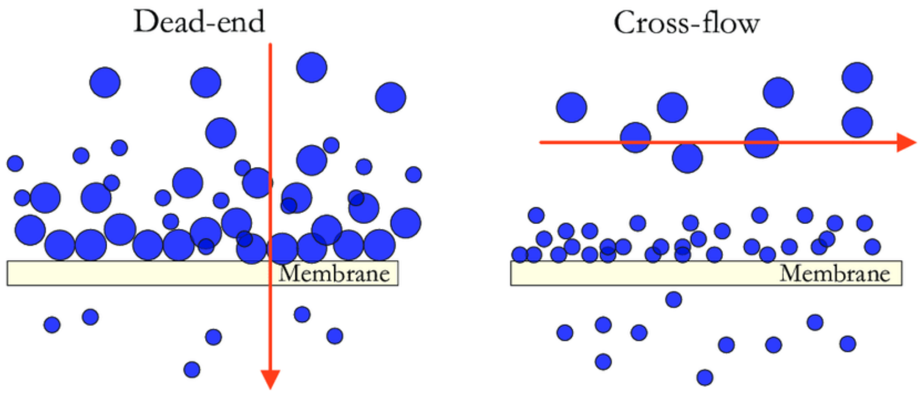


Figure III.2: Dead-end filtration and cross-flow filtration modes (Ruiz-García et al., 2017)

III.2.2 RO performance parameters:

The performance of an RO system can be evaluated with the use of certain parameters that give the observer insight on the efficiency and defining characteristics of the particular system configuration.

III.2.2.1 Recovery:

Recovery is the ration between the permeate flow and the feed water flow, presented as a percentage. It can be calculated using the following formula:

$$R = \frac{Q_p}{Q_f} \cdot 100 \tag{III.2}$$

Where:

R: Recovery (%)
Q_p: Permeate flow (m^3/d)
Q_f: feed water flow (m^3/d)

The recovery of RO systems usually ranges between 40 % to 90% with the most common recovery rate being 75 %. One of the useful information that can be concluded from the recovery is the concentration factor, it represents the ration between the concentration of dissolved solids in the concentrate and their concentration in the feed water (assuming that the membrane retains all dissolved solids). this means that a system with 75 % recovery has a concentration factor of 4 and a system with 80 % recovery has a concentration factor of 5.

III.2.2.2 Rejection:

Rejection represents the percentage of a dissolve solid that is rejected by the membrane and that doesn't diffuse through with the permeate. It can be calculated as follows:

$$Rejection = \frac{C_f - C_p}{C_f} \cdot 100 \tag{III.3}$$

where:

C_f : Concentration of a chemical species in the feed water.
C_p : Concentration of a chemical species in the permeate.

A corollary parameter to rejection should also be considered and that is salt passage, which is the inverse of rejection. salt passage represents the percentage of chemical species that the membrane allows to pass through with the permeate. It can be calculated with:

$$Salt\ passage = 100 - Rejection = \frac{C_p}{C_f} \cdot 100 \tag{III.4}$$

The rejection depends on a wide variety of factors the most important of them is the type of the membrane and the chemistry of the feed water. Other factors that can influence rejection are:

- Valance.
- Molecular weight.
- Physical state of the solute (example: gasses are not rejected by RO.)
- PH.

Another factor that should be considered in a choosing the recovery of an RO system is that increasing the recovery may seem intuitive as it decreases the volume of concentrate that needs to be discarded of treated, but another consequence of that increase is a higher concentration factor which means that chemical phenomenons such as scaling have a higher chance of happening, thus requiring a more robust pretreatment.

III.2.2.3 Flux:

Flux describes the quantity of a certain substance that passes through a predefined area of a membrane at a given duration. In RO we can calculate two different types of flux:

a. Water flux: Water flux is defined as the the volume of water that passes through a a given area of a membrane in a certain time ($m/d\ or\ l/m^2 \cdot h$). It can be calculated with the use of several transport models (discussed in the next section) but the most widely used in industry to the its relative simplicity is the Solution-Diffusion model that expresses water flux as follows:

$$J_w = K_w(\Delta P - \Delta\Pi) = \frac{Q_p}{A} \tag{III.5}$$

Where:

J_w: Water flux $(l/m^2/h)$
K_w: Water permeability coefficient, specific to each membrane $(l/m^2/h/bar)$
A: Effective membrane area
ΔP: Pressure difference across the membrane (bar)
$\Delta\Pi$: Difference of osmostic pressure across the membrane (bar)

Note: $\Delta P - \Delta\Pi = NAP$: Net applied pressure.

During the selection of membranes for the use for RO systems flux should not be directly used to compare membranes as different membranes are tested at different pressures which yields varying flux values. Instead, specific flux, also known as permeability should be used for the selection and it can be calculated as follows:

$$Specific\ flux = \frac{J_w}{NAP} \tag{III.6}$$

b. Solute flux: Solute flux represents the mass of a certain solute that passes through a given area of the membrane in a certain duration. At can be calculated according to the Solution-Diffusion model with:

$$J_s = K_s(C_m - C_p) \tag{III.7}$$

With:

J_s: Solute flux $(g/m^2/h)$
K_s: Solute permeability coefficient (m/h)
C_m: Concentration of a specific solute at the surface of the membrane
C_p: Concentration of a specific solute in the permeate

Note that the concentration of the solute in the feed water was not used due to it being less than the concentration at the surface of the membrane due to concentration polarization.

III.2.3 Concentration polarization:

As the the RO system functions in its cross-flow filtration configuration, solutes start to accumulate of the membrane's surface, creating deposits in the form of "cake". This will create a barrier to the flow thus decreasing the efficiency of the system as well as creating a boundary layer starting from the membrane's surface where the concentration of solutes is greater than on the bulk feed water. This phenomenon is called concentration polarization (CP) (because of the formation of a gradient of concentration) and can have many adverse effects of an RO system such as:

- A reduction in water flux due to the increased osmotic gradient caused by the higher concentration.
- Increased probability of scaling.

- Increased passage of solutes.

FigureIII.3 illustrates this phenomenon:

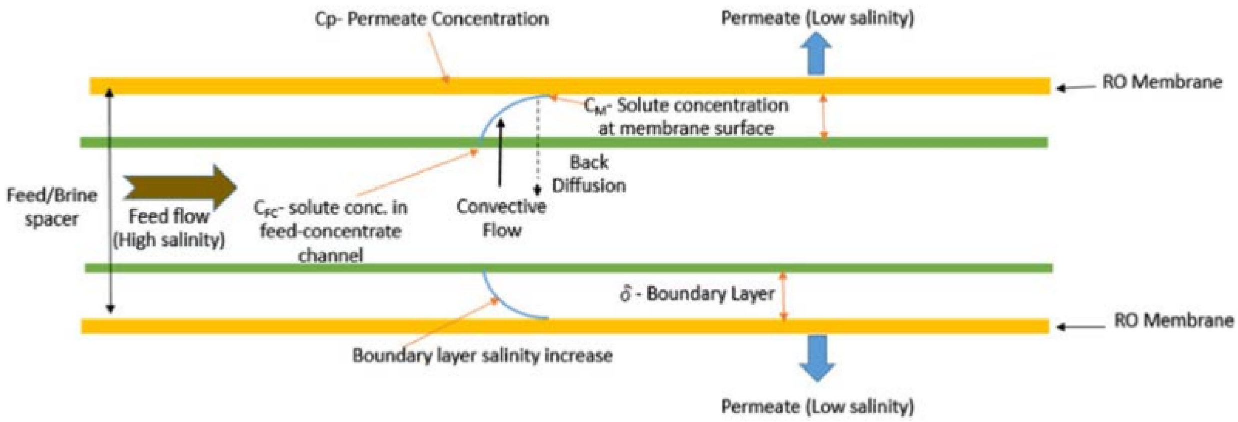


Figure III.3: Concentration polarization and the boundary layers (Zaidi & Saleem, 2022).

Evaluating CP is necessary due to its interference with a lot of other calculations. β is used for this task and it is evaluated as such:

$$\beta = \frac{C_m}{C_b} = exp(J_w \cdot \frac{\delta_{cp}}{D_s}) \quad \text{(III.8)}$$

Where:

β: Concentration polarization factor.
C_b: Solute concentration in the bulk of the feed water.
δ_{cp}: The thickness of the boundary layer.
D_s: Solute diffusion coefficient in the feed solution.

III.2.4 Fouling:

Fouling describes the phenomenon in which suspended solids and other organic or inorganic particulates form deposits on the surface of the membrane. This phenomenon has two main effects on a RO system, the first being an increase in the required operating pressure caused by the decrease in water flux, and the other one being an increased pressure drop.

Membrane fouling is one of the main issues currently facing RO technology as it hinders its operations and requires intensive pre-treatment to minimise its effects and increase the expected life of the often very expensive membranes.

TableIII.1 lists some of the water quality guidelines that restrict the propagation of fouling:

Table III.1: Generally-accepted water quality guidelines to minimize RO membrane fouling (Kucera, 2023)

Species	Measure	Value
Suspended Solids	Turbidity	<1 NTU
Colloids	SDI	<5
Microbes	Dip Slides*	<1,000 CFU/ml**
Organics	TOC Concentration	<3 ppm
Color	Color units	<3 APHA
Metals: iron, manganese, aluminum	Concentration	<0.05 ppm
Hydrogen Sulfide	Concentration	<0.1 ppm

To quantify the foulability of a a membrane the silt density index (SDI) is the industry standard, as it provides a good idea on whether the quality of the feed water permits the use of RO or further pretreatment is needed. SDI is measured using a physical test that uses the time needed for 500 ml of feed water to pass through a specific testing membrane first when the flow first starts then after 15 minutes in which the filter would have started to get plugged. Figure III.4 shows the apparatus used.

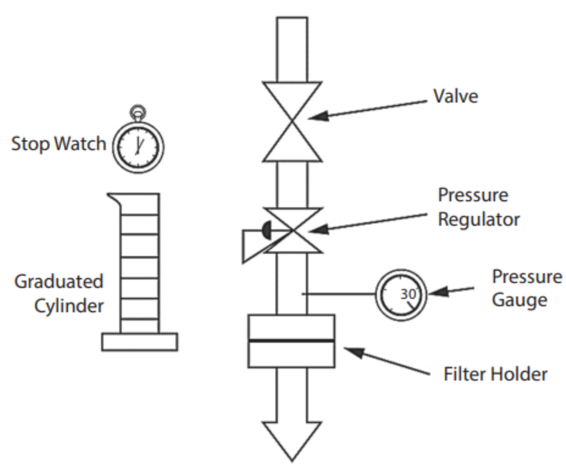


Figure III.4: SDI measuring apparatus at 30 psi (Kucera, 2023)

The following equating is subsequently used to evaluate the SDI value:

$$SDI_{15} = (\frac{1-(\frac{t_0}{t_f})}{15}) \cdot 100 \tag{III.9}$$

The maximum SDI value that can be calculated due the nature of the equation is 6.67, with an SDI of less than 5 being required by most membrane manufacturers (example: : Hydranautics require an SDI < 4), but the ideal SDI for the fouling potential to be at an acceptable level is less than 3.

III.2.5 Scaling:

As the feed water flows through the different elements of the membrane the solute concentration increases, and this increase may lead to the saturation of the feed water in different solutes, thus they precipitate and deposit on the surface of the membrane causing physical damage to the membrane and a reduction in water flux. This phenomenon is called scaling.

Scaling can be caused by numerous chemicals but the most common culprits are silica, calcium and barium scales. The precipitation occurs when the ionic product (IP) of the chemical species in question exceeds the solubility product at saturation of the same species (K_{sp}), with:

$$IP = [Anion]^a \cdot [Cation]^b \tag{III.10}$$

Similarly to fouling, there is a method to quantify the tendency of a water to form scale/be corrosive, and that is the Langelier Saturation Index (LSI), and it factors in several chemical parameters:

$$LSI = PH - PH_a \tag{III.11}$$

With:

$$PH_a = (9,30 + A + B) - (C + D) \tag{III.12}$$

Where:

$A = (Log_{10}[TDS] - 1)/10$, with [TDS] in ppm [1]
$B = -13,2 \cdot Log_{10}(°K) + 34,55$
$C = Log_{10}[Ca^{2+}] + 4$, with $[Ca^{2+}]$ in ppm
$D = Log_{10}[Alkalinity]$, with alkalinity in ppm

The LSI can only be used for brackish water with TDS below 4000 ppm, for higher concentrations the Stiff-Davis Saturation Index (SDSI) has to be used, and:

$$SDSI = Ph - PCa - Palk - K \tag{III.13}$$

Where:

$PCa = -Log_{10}[Ca^{2+}]$
$Palk = Log_{10}[Alkalinity]$
K: A constant based on the total ionic strength and temperature

[1] 1 ppm = 1mg/l

In RO applications, a positive LSI or SDSI suggests that the feed water is prone to calcium carbonate scaling. In such instances, pretreatment methods such as softening (using lime or ion exchange), or the application of antiscalants and/or acids are necessary. It's noteworthy that many membrane manufacturers advise maintaining an LSI of +1.8 or lower in the concentrate, particularly when employing antiscalant feed, to effectively mitigate scaling issues. Table III.2 demonstrates the meaning of different LSI values.

Table III.2: Langelier saturation index values (Kucera, 2023)

LSI	Condition
+3.0	Extremely severe scaling
+2.0	Very severe scaling
+1.0	Severe scaling
+0.5	Moderate scaling
+0.2	Slight scaling
0.0	Stable water (no scale)
–0.2	No scale, very slight tendency to dissolve scale

III.3 Transport models:

Transport models are used to define mathematical a mathematical relationship between the performance parameters of a membrane (water flux) and the operating conditions such as pressure and different concentrations, therefore simplifying the task of developing new improved membranes. Understanding the mechanisms with which water and solutes pass through the membranes is primordial for improving efficiency and decreasing operating costs.

We can separate the different existing transport models into three distinct categories based on the assumptions made by each model. In the following sections we will discuss each type of these models and give several examples for every one.

III.3.1 Homogeneous transport models:

Homogeneous Transport models are one of the first to be developed in the 1960s, they work on the assumption that the membranes are totally homogeneous in nature and are non-porous. One of these aforementioned models is the previously discussed Solution-diffusion model that also considers that water and the solutes are independent of each other and don't have any interactions between them.

In addition to the classical Solution-Diffusion model several modified versions have been developed that try to compensate some of its shortcomings.

III.3.1.1 Solution-Diffusion imperfection model:

This modified model builds on the basis of the classical Solution-Diffusion model and adds the assumption that the surface of the membrane is not perfectly homogeneous and that imperfections exist in the form of pores that allow some of the water to flow in addition to the already established water and solutes diffusion. Water flux can be calculated in this model using this equation (Zaidi & Saleem, 2022) :

$$N_w = J_w + K_3 \Delta P C_w \tag{III.14}$$

With:

N_w: Total water flux.
K_3: coupling coefficient.
C_w: Solvent concentration on the membrane feed side.

We can also calculate the solute flux similarly:

$$N_s = J_s + K_3 \Delta P C_R \tag{III.15}$$

With:

N_s: Total solute flux.
K_3: coupling coefficient.
C_w: solute concentration on the membrane feed side.

III.3.1.2 Extended Solution-Diffusion model:

The Extended Solution-Diffusion (ESD) model addresses the inconsistencies observed in the S-D model when ΔP approaches infinity. In instances where ΔP tends towards infinity, the S-D model predicts a maximum rejection of 100%, which is evidently never observed. To rectify this discrepancy, the ESD model introduces two additional terms concerning a specific solute, which were previously disregarded in the S-D model: one term incorporates the solute-to-water uptake ratio by the membrane, while the other term accounts for solute drag and a pressure diffusion factor.

III.3.2 Pore-Based Transport Models:

III.3.2.1 Preferential sorption-capillary flow porous model:

In 1970, Sourirajan introduced the Preferential Sorption-Capillary Flow (PSCF) model, which attributes separation to surface phenomena and fluid transport through pores. In this model, the membrane is viewed as microporous, with the barrier layer exhibiting specific chemical properties: repulsion towards solutes and affinity for the solvent. Consequently, a layer primarily composed of solvent is selectively absorbed within the pores and on the membrane's surface. The solvent is then propelled through the membrane's capillary pores under the pressure exerted by this solvent-rich layer. The water flux is calculated the with the same equation as in the standard Solution-Diffusion model, on the other hand the solute flux can be calculated with the following equation:

$$N_s = (\frac{D_{sm} \cdot K_s}{T}) \cdot (C_m - C_p) \tag{III.16}$$

where:

D_{sm}: solute diffusivity in membrane.
T: Effective membrane thickness.

III.3.2.2 Surface force-pore flow model:

Sourirajan and Matsuura introduced this model in 1981, which is viewed as a refinement of the PSCF model. It enables the characterization and specification of membranes based on pore size distribution, along with providing a quantitative assessment of the surface forces occurring between solvent-solute and the membrane wall within the transport pathway. In accordance with the Surface Force-Pore Flow (SFPF) model, the diameter of the pores significantly influences the separation factor, and the average separation factor can be derived from the distribution of pore sizes.

III.3.3 Irreversible thermodynamic models:

These models are not based on the membranes structures on relies thermodynamics concepts and complex mathematical theories to describe the phenomenon of reverses osmosis.

III.3.3.1 Kedem and Katchalsky model:

The Kedem and Katchalsky model, formulated in 1958 based on irreversible thermodynamics, conceptualizes the membrane as a black box. In this model, the membrane is assumed to be near equilibrium, with flow across it occurring at a very slow rate. The central tenet is the interdependency between the fluxes of components traversing the membrane. Introducing the Staverman reflection coefficient as a novel parameter, this model connects both solvent and solute fluxes. It explicates the solute and solvent fluxes in relation to osmotic and pressure differentials for solvent flux, and average concentration and osmotic variance for solute flux(Zaidi & Saleem, 2022).

The volume flow can be calculated as follows:

$$J_v = L_p \Delta P - L_p \sigma \Delta \Pi \tag{III.17}$$

With:

J_v: Volume flow.
L_p: Coefficient of filtration.

σ: coefficient of reflection.

While the solute flow is given as follows:

$$J_s = \omega \cdot \Delta\Pi - c(1-\sigma)J_v \tag{III.18}$$

With:

J_s: Solute flow.
ω: Coefficient of permeation.
c: Mean concentration, $c = \frac{C_1+C_2}{2}$.

III.4 Reverse osmosis membranes:

As previously discussed RO relies on the use of semi-permeable membranes that can allow the solvent (water) to pass while retaining a high volume of solutes (salts). The rejection rate, flux and salt passage are all highly dependent on the membrane's material, so choosing the appropriate membrane material for the specific requirements of our projects is essential. RO membranes can be classified into Two categories:

- Isotropic/symmetric membranes (These membranes have the same the same physical and structural properties throughout there thickness).
- Anisotropic/Asymmetric membranes.

Figure III.5 illustrates the cross-section of an asymmetric membrane:

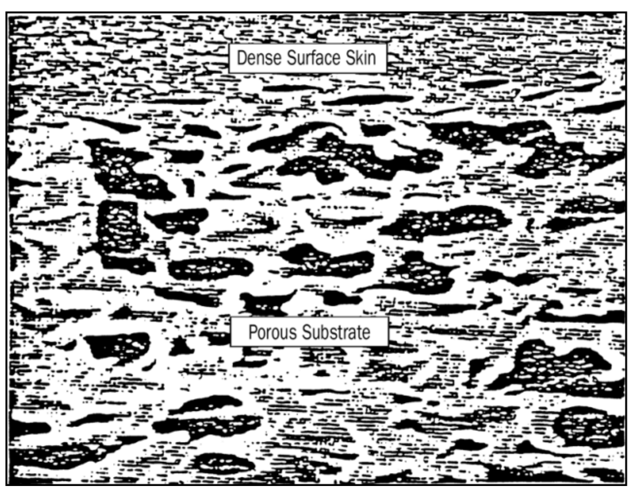


Figure III.5: Asymmetric membrane cross-section (A.W.W. Association, 2011)

We distinguish two commonly used membrane materials based of polymers, these are the Cellulose acetate membranes, and polyamide membranes.

III.4.1 Membrane materials:

III.4.1.1 Cellulose acetate membranes:

Cellulose acetate (CA) membranes are one of the first RO membranes to be made as they were developed in the 1960s, with the thickness of the active rejecting layer being around 0.2 μm while the entire membrane has a thickness of 100 μm with the supporting layer being micro-porous. The thinness of the membrane provided high flux for the time which helped reduce the estimated cost of an RO system. The overall structure of the membrane was homogeneous and asymmetric, meaning it was made out of the same polymer but different layers had different properties.

Figure III.6 illustrates the chemical structure of a CA membrane:

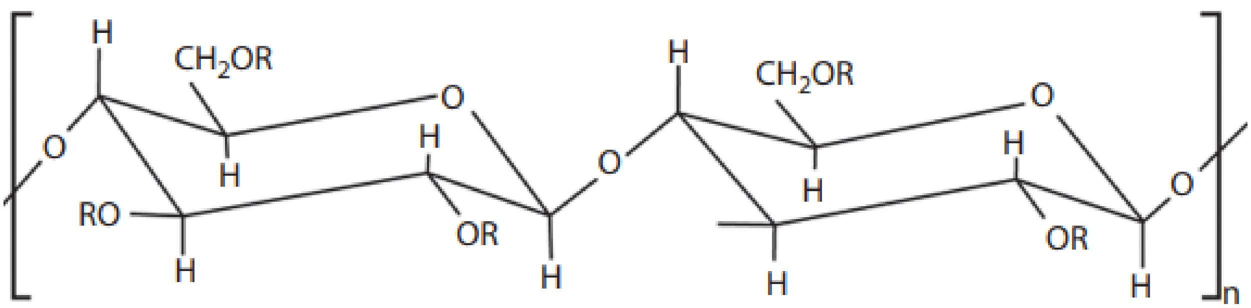


Figure III.6: Chemical structure of a cellulose acetate membrane (Kucera, 2023)

III.4.1.2 Polyamide and Composite Membranes

similarly with CA membranes, polyamide membranes are polymer based and they were specifically developed to improve upon the shortcomings observed with CA membranes.

The first polyamide membranes to be developed retained the homogeneous nature of the CA membranes while changing the material to linear polyamides also referred to as aramides. These membranes offered an improved salt rejection but suffered a big loss in permeability (flux) compared to the the traditional CA in addition to the higher sensitivity to chlorine and other oxidants.

But currently the most commonly used membranes are composite polyamide membranes also called "thin film composite" (TFC) membranes. As the name suggests TFC membranes are comprised of two polymers cast upon a supporting fabric. These types of membranes managed to solve some of the shortcomings of previous membranes but it still have some disadvantages such as higher pre-treatment requirements and a higher cleaning frequency.

Table III.3 compares CA membranes and polyamide membranes:

Table III.3: Comparison between cellulose acetate and polyamide membranes (Zaidi & Saleem, 2022)

Property	Cellulose Acetate membrane	Polyamide membrane
Membrane type	Homogenous asymmetric	Homogenous asymmetric, thin-film composite
Surface roughness	Smooth	Rough
Fouling tolerance	Good	Fair
Biological growth	Metabolizes membrane	Causes membrane fouling
Chlorine tolerance	Up to 1 ppm continuously	<0.02 ppm
Surface charge	Neutral	Negative (anionic)
Temperature tolerance	Up to 35°C	Up to 45°C
Feed pressure (brackish membrane)	200–400 psi	145–400 psi
pH range	4–6	2–12
Silica rejection (%)	~85	~96+
Salt rejection (%)	~95	~98+
Pretreatment requirements	Low	High
Organics removal	Low	High
Cleaning frequency	Lower (months to years)	High (weeks to months)

III.4.2 Membrane elements:

As previously discussed, having a large surface area for the membrane is essential to promote higher flux and better performance, and to achieve this goal the membranes are put in a compact form that can contain a large area of it, and these containers are called modules, with a single module being called an element, and several elements forming a train, and several trains form an RO system.

There are four types of module configurations with the first ones to be developed being the Plate and frame configurations and tubular configurations, but due to there relatively low density two additional configurations were introduced which are the spiral wound and hollow fine fiber configurations which are currently the most used in modern RO systems.

III.4.2.1 Plate and Frame Elements:

The plate and frame configuration, initially prominent in the early stages of reverse osmosis technology, gradually fell out of favor in favor of more compact spiral wound and hollow fiber configurations. In this setup, a selective membrane layer is sandwiched between two support plates, creating flow channels for fluid on both sides of the membrane. These plates can be stacked vertically to increase membrane surface area, facilitating parallel fluid flow across the membrane module, with Figure III.7 illustrating an example of such a module.

Despite being less commonly used today, plate and frame modules still find application where spiral wound or hollow fiber modules may not meet performance or reliability requirements, such as in the food processing industry and wastewater treatment.

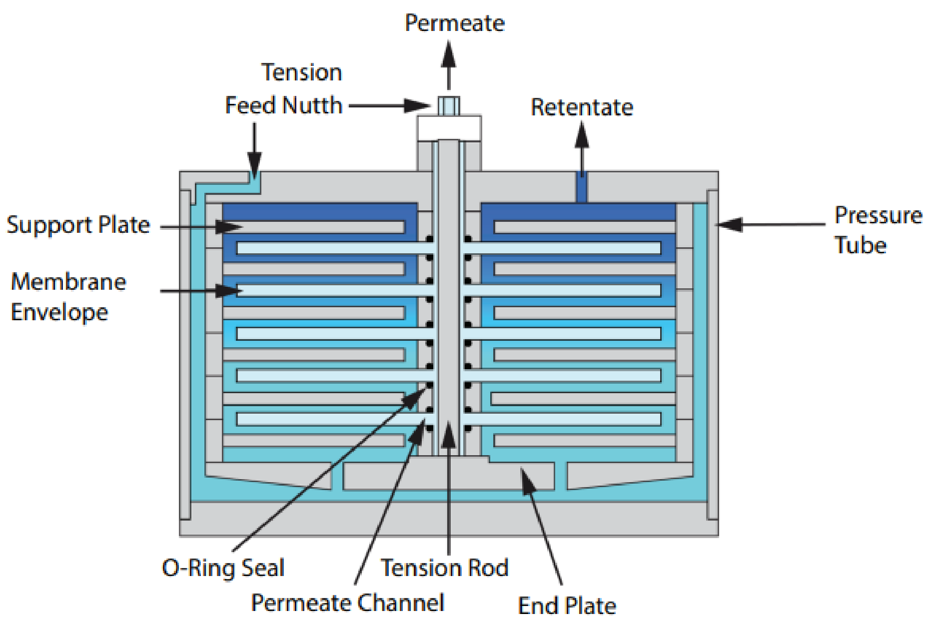


Figure III.7: Example of a plate and frame module (Kucera, 2023)

III.4.2.2 Tubular elements:

Tubular RO elements find extensive application in industries dealing with high-solids content, such as food or wastewater processing. These elements function akin to shell-and-tube heat exchangers, with the shell side acting as permeate and the tube side as feed. Typically ranging from 12 to 25 mm in diameter, the membrane tubes are arranged end-to-end within perforated sleeves. Compared to plate and frame elements, cleaning is relatively straightforward, and minimal pretreatment for suspended solids removal is necessary. However, similar to plate and frame elements, a substantial amount of hardware is needed for a relatively small membrane area, resulting in high element costs.

III.4.2.3 Hollow Fine Fiber Elements:

The hollow fine fiber elements are made of thin, hair-like fibers that have an outside diameter of 85-150 μm. These fibers are then assembled to form a bundle and subsequently placed in a cylindrical housing shown in Figure III.8. This configuration showcases a high density thus lowering the costs of the membranes. Conversely, It has the limitation of the existence of dead spaces in the module that don't exhibit good flow which increases the potential for fouling and depositions.

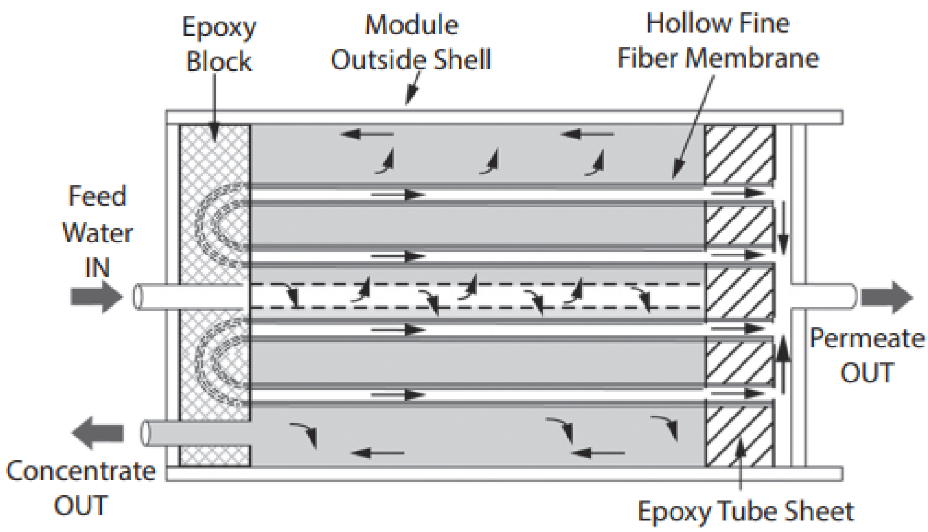


Figure III.8: Simplified example of a hollow fine fiber element (Kucera, 2023)

III.4.2.4 Spiral wound elements:

The spiral wound configuration stands out as the most widely adopted element for RO globally. It represents a balanced compromise among various factors including cost, manufacturing simplicity, packing density, susceptibility to membrane fouling, and ease of cleaning.

It is comprised of membrane sheets, feed channel spacers, and permeate spacers with these components being meticulously assembled, a process that has transitioned from manual to automated to ensure consistent quality and maximum membrane area utilization. Within the element, water flows longitudinally along the permeate tube, while permeate is collected through spiral channels created by the permeate spacers. Figure III.9 shows the basic construction of such a configuration.

The spiral wound modules present a lot of advantages compared to other configurations, with the most notable being:

- Low pressure drop in the permeate channel.
- Lowest concentration polarization.

- Least possible membrane contamination.
- Compactness.
- Higher-pressure durability.

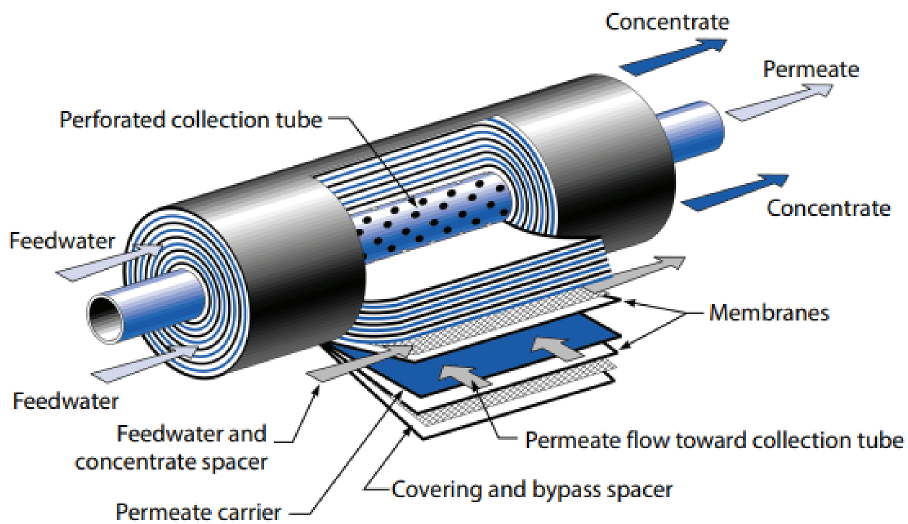


Figure III.9: Spiral wound module example (Kucera, 2023)

Finally, the following table compares different characteristics of each membrane module configuration:

Table III.4: Comparison of different module configurations (Kucera, 2023)

Property	**Plate-frame**	**Tubular**	**Hollow fine fiber**	**Spiral wound**
Approximate Packing Density (m^2/m^3)	150–500	20–375	500–5000	500–1250
Fouling Potential	Moderate	Low	Very High	High
Ease of Cleaning	Fair	Excellent	Poor	Poor
Manufacturing Cost/ Membrane Area	High	High	Low	Moderate

III.5 Reverse osmosis system components and flow configurations:

A reverse osmosis system is comprised of several components that interact with each other and work in parallel in a harmonious manner to produce water of an adequate quality in an efficient manner that reduces operating costs. we will discuss some of these components in this section.

III.5.1 Cartridge filters:

Cartridge filters are an example of microfiltration technology discussed in the previous chapter. They serve the purpose of being the last line of defense for the RO system and the first point of entry of the feed water into the RO skid[2] as they prevent residues from the pretreatment process such as softening resins or sand filters to prevent any damage to the high pressure pumps and the membranes. It is noteworthy to add that their purpose is not supposed to be the reduction of turbidity or SDI as if they get used in this way this will result in very frequent filter changes and will thus increase operation costs. five micron filters are usually enough to comply with the operating conditions but finer filters could be used although it may result in more frequent replacements.

The following picture shows three different types of cartridge filters:

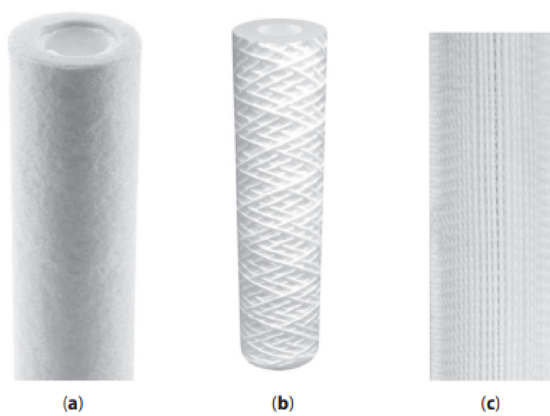


Figure III.10: Three types of cartridge filters (Kucera, 2023)

III.5.2 Pressure vessels:

Pressure vessels as their name indicates are pressure resistant housings made to accommodate multiple membrane elements (1 to 8). Their are various types of pressure vessels available in the market with different pressure specifications while the number of elements per pressure vessel depends on the desired recovery.

[2]An RO skid refers to the modular components of an RO system

III.5.3 High pressure Pumps:

High pressure pumps are responsible for the providing the necessary pressure for the feed water to overcome the osmostic pressure and initiate the reverse osmosis process, as well as any head loss and the proper resistance of the membrane.

Centrifugal pumps are the most used for this purpose and are either multi-stage or single stage with multi-stage pumps being generally used for seawater desalination due to their ability to reach extremely high pressures as opposed to single stage pumps which are quite limited in terms of pressure. But they are nevertheless used for brackish water demineralization.

designing these HP pumps has to be done while keeping in mind several considerations such as:

- The design should be done using the most unfavourable conditions (worst case scenario) to ensure proper operations.
- The design point of the pumps has to be 20% to 25% larger than than the required pressure at the lowest possible temperature.
- A soft-start for the motor is required to minimize the effect of water hammer.
- The pump should be located in such a place that simplifies its maintenance and doesn't induce cavitation.

III.5.4 Flow configurations:

III.5.4.1 Arrays and staging

The arrangement of several pressure vessels in a specific arrangement is referred to as an array , with every group of pressure vessels aligned in parallel being called a stage, train, or skid. an RO system can be comprised of multiple stages with every stage being comprised with multiple pressure vessels. RO arrays are describe using "a:b:c:..." notation. for example a 2:3:4 array means that their are 3 stages with the first one having 2 pressure vessels and the second having 3 and the last one having 4.

Taking the last array as an example, the concentrate of the the first stage is collected and used as the feed water for the second stage, and it's concentrate is subsequently used as the feed water of the final stage, while the permeate water of each stage is collected and mixed to achieve the desired specifications.

It is noteworthy to add that the recovery of the whole array is a function of the number of stages and the individual recoveries of each stage. For example, a two stage array with 50% recovery for each stage yields a total system recovery of 75%. FigureIII.11 demonstrates such an system.

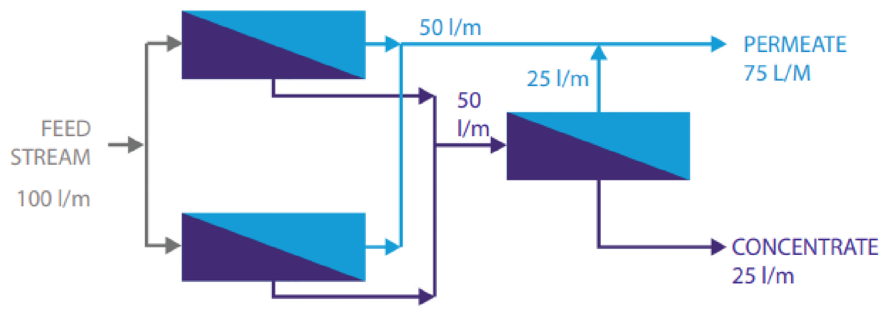


Figure III.11: A two stage, 75% recovery unit (Kucera, 2023)

III.5.4.2 Passes:

Certain application require water of an extremely high quality that may not be achieved by passing the feed water through a RO system once or through other post-treatment methods such as electrolysis, thus passing the permeate through another RO system may be necessary. Such systems are called Two pass systems.

These systems can reach high recoveries (up to 90%) as a result of the high quality the feed water. In addition, the concentrate is also usually recycled which lowers discharge costs and is more ecologically sound.

The following diagram represents an example of a two pass RO system:

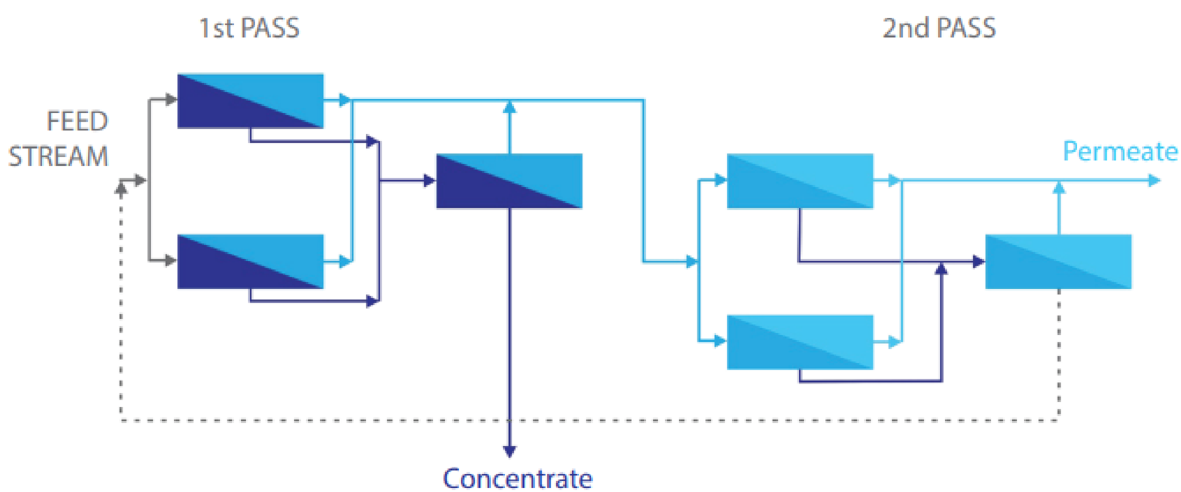


Figure III.12: Two pass RO unit (Kucera, 2023)

III.6 Pretreatment and water quality guidelines:

Reverse osmosis is a very sensitive process that heavily relies on the quality of the feed water,as with any reduction in the quality of the in-flowing water potentially provoking catastrophic results on the membrane elements and on the RO system as a whole.

In this section we will discuss some water quality guidelines for reverse osmosis systems and expose the pretreatment options used in modern reverse osmosis systems to obtain such qualities and prevent consequences like membrane fouling and scale formation.

III.6.1 Feed water quality guideline

The first step and arguably the most impotent one in the design of reveres osmosis systems is doing a chemical analysis on the raw water source, whether it is seawater, brackish water, or water from and underground aquifer.

The results of that analysis can determine the fouling potential for membranes and deposition, which have a big influence of the design of RO unit. The recommended parameters for water analysis are cation and anion composition in addition to other factors such as alkalinity, color, turbidity, PH, and organic content. Table ... illustrates an example of a chemical water analysis of five different sources while Table III.6 demonstrates some accepted water quality guidelines.

Table III.5: Example of the chemical analysis of five different water sources (DuPont, 2023)

Parameter	Unit	Well water[a]	Well water[b]	Lake water[c]	Surface water[d]	Pretreated tertiary effluent[e]
Calcium	mg/L	84	113	54	102	40 – 64
Magnesium	mg/L	6	2.7	23	11	—
Sodium	mg/L	36	23	87	20	150 – 200
Potassium	mg/L	3.3	2	6.6	4	—
Iron	mg/L	< 0.05	0.2	0.05	ND – 015	0.02 – 0.09
Manganese	mg/L	0.01	0.1	< 0.01	< 0.01	< 0.05
Barium	mg/L	0.07	0.1	0.09	—	0.01 – 0.1
Strontium	mg/L	0.7	1	1	—	0.2 – 1
Ammonium	mg/L	< 0.05	—	—	0.3	22 – 66
Aluminum	mg/L	0.02	—	0.02	ND – 0.15	0.03
Chloride	mg/L	45	52	67	33	150 – 500
Bicarbonate	mg/L	265	325	134	287	48.8 – 97.6
Sulfate	mg/L	24	8	201	56	120 – 160
Nitrate	mg/L	4.3	4	<1.0	15	40 – 60
Fluoride	mg/L	0.14	0.7	—	0.25	0.7 – 0.7
Phosphate	mg/L	< 0.05	0.6	0.01	1.2	6.1 – 12.2
Silica	mg/L	9	11	3.1	7 – 17	6 – 10
Hydrogen Sulfide	mg/L	—	1.5	—	—	ND
TDS	mg/L	478	377	573	400	500 – 1,300
TOC	mg/L	1.5	10	3.6	2.4	20 – 30 (COD)

Table III.6: Commonly acceptable water quality guidelines for reverse osmosis feed water and reject stream (Zaidi & Saleem, 2022)

Sl. no.	Species	Guideline value/range	Units
1	Chemical oxygen demand (COD)	<10	ppm
2	Color	<3	APHA
3	Organics (TOC)	<3	ppm
4	Silica (soluble)	140–200[a]	ppm
5	Microbes	<1000[b]	CFU/mL
6	Hydrogen sulfide	<0.1	ppm
7	Barium, strontium	<0.05	ppm
8	Calcium carbonate	<0[c]	LSI
9	Suspended solids	<1	NTU
10	Silt density index—Colloids	<5	1
11	Modified fouling index (0.45)	<4	1
12	Total organic carbon	<3	ppm
13	Oil and grease	<0.1	ppm
14	Assimilable organic carbon	<10	μg/L Ac-C
15	Manganese	<0.05	ppm
16	Ferric iron	<0.05	ppm
17	Ferrous iron	<4	ppm
18	Aluminum	<0.05	ppm
19	Temperature—PA membranes	<45	°C
20	Temperature—CA membranes	<30	°C
21	Chlorine, free-PA membranes	<0.02	ppm
22	Chlorine, free-CA membrane	<1	ppm
23	pH—PA membranes	2–12	pH units
24	pH—CA membranes	4–6	pH units

[a]*In reverse osmosis concentrate stream, changes as functions of temperature and pH.*
[b]*In reverse osmosis concentrate stream.*
[c]*In reverse osmosis concentrate stream, and could be till 2.0–2.5 on the basis of the type of antiscalants used.*

III.6.2 Pretreatment techniques:

The objective of pretreatment of the RO feedwater is to control its quality and stabilise it at accepted levels. Doing this ensures the integrity of reverse osmosis membranes and the effective operation of the whole system.

Most RO troubles originate in this phase because of how important it is to the functioning of the unit, any dysfunction in one of it's components would lead to a chain reaction of problems that put the whole system at risk.

There are several pretreatment techniques available commercially and it is the designers job to choose the appropriate ones depending on the quality of the raw water and the desired output quality.

III.6.2.1 Conventional pretreatment:

Traditionally the pretreatment of RO systems utilises two types of techniques, physical treatment, and chemical treatment to improve the quality of the feed water to the RO membranes and disallow any fouling or scaling. these techniques are employed as follows

Coarse particulate removal: In this step all larger diameter particles are removed from the raw water using coarse strainers such as bar racks.

Chlorine disinfection: The objective of this step is to kill any living organisms such as bacteria or viruses that maybe found in the water.

clarification and floculation: In this step finer sands and silt that cannot be removed using other filtration techniques are removed.

Media filtration: Using Sand or anthracite filters, activated carbon grains can also be used in this step.

PH adjustment: As discussed before PH is an important factor that can contribute to the degradation of RO membranes so adjusting it before it enters the unit with chemicals such as caustic soda is essential.

Scale inhibitor: Scale inhibitors are another type of chemical used in pretreatment. As the name implies it is used to reduce the scaling potential of the water (reduces the LSI) thus protecting the membranes.

Dechlorination: Although chlorination is necessary for disinfection purposes, free chlorine is very damaging for RO membranes, so removing it is necessary via dechlorination chemicals.

III.6.2.2 Membrane technique in pretreatment:

Pressure driven process previously discussed in this thesis (MF and UF) can also be used in the pretreatment phase of RO systems, and this is what the the industry is trending towards, as it provides a higher filtration level and stable and high flux for long periods even with variation in the quality of the raw water. Coarse particulate screening is needed as a prefiltration measure although in contrast with conventional pretreatment mentioned above, Pressure driven membrane don't need as much chemical treatment, therefore the chemical dosing costs are significantly lower which makes it both a more cost effective and efficient solution, but also an ecological one.

III.7 Post-treatment:

There are no standard post treatment procedures for RO systems as the quality of the product water is dependent on it's eventual use, so the post-treatment techniques employed differ from one station to another.

The most common treatment options are:

- Disinfection: By added chlorine or using UV rays to kill any potential bacteria or viruses the product water eventually comes in contact with.
- PH adjustment: Probably the most common post-treatment as the PH needs to be adjusted to meet the norms of usage.
- Remineralization: generally employed for water destined for human consumption, it can consist of mixing the product water with a portion of the raw water.
- Continuous electrodeionization: used to further demineralize the water and produce very pure water generally used in cooling systems in big industries.

III.8 Troubleshooting reverse osmosis system issues:

Reverse osmosis systems fall victim to many problems that can arise due to various reasons but they often result in membrane fouling or scaling which in turn leads to a decrease in permeate water quality eventually the complete degradation of the membrane and the need to replace them.

This makes troubleshooting RO systems a very important task that can help us determine potentially harmful conditions that are effecting the unit's performance, and duly repair them to bring the unit back to its optimal operating conditions.

III.8.1 Monitoring and data collection:

Monitoring the RO system's performance is an essential step in identifying any potential problems that may arise due to one or several variable factors.

All RO systems are equipped with high precision monitors and sensors that collect the information straight out of the unit, but additional manual measurements have to be taken to confirm the precision of the numerical data as the sensors may need calibration after a certain operational time. The following are the minimum data collection requirements for every RO system:

- Flow rate in the permeate and concentrate side
- Pressure in all steps of the system (feed, permeate, concentrate and interstage).
- Conductivity/TDS in the feed, concentrate, and permeate.

Although these parameters may be enough to run a rudimentary RO unit, it is better to collect and monitor additional data such as ORP[3], PH, temperature, SDI_{15}, LSI... All of these information can provide valuable insight on the performance of the RO unit at hand as all of them have a big impact on optimal operations, for example, Figure ... demonstrates the effect of temperature on salt rejection:

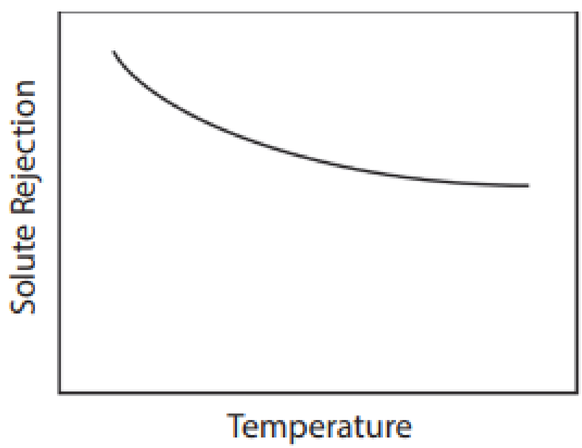


Figure III.13: solute rejection as a function of feed water temperature with constant feed pressure and solute concentration (Kucera, 2023)

III.8.2 Data normalization:

As we've seen in the previous chapters, the performance of RO systems is influenced by many parameters that can vary during operations and can lead to both drops and up trends in performance. This fact leads to the interpretation of trended data being very challenging due to the many factors that could be the cause of any change.

[3] OX-RED potential

To overcome this challenge normalization is used which is a data analysis method that serves to eliminate the effect of parameters such as temperature and by comparing the current data of the system to a baseline usually being the collected data during the startup at normal conditions. This makes it so any observed change in the normalized data being due to either membrane fouling, scaling or general degradation and not any other factors such as temperature and variations in feed concentration.

The equations for normalized permeate flow (NPF) and normalized solute passage (NSP) are described below(ASTM, 2013):

$$NPF = \frac{(Pfs - (\frac{\Delta Pfbs}{2}) - Pps - \pi fbs + \pi ps) * (TCFs)}{Pfa - (\frac{\Delta Pfbs}{2}) - Ppa - \pi fba + \pi pa} \tag{III.19}$$

And:

$$NSP(\%) = (\frac{EPFa}{EPFs}) * (\frac{STCFa}{STCFs}) * (\frac{Cfbs}{Cfba}) * (\frac{Cfa}{Cfs}) * SP(\%) \tag{III.20}$$

with:

Q: Flow rate.
P: Pressure, Kpa.
ΔP: Differential pressure.
π: Osmotic pressure.
TCF: Temperature correction factor, °C.
SP: Solute passage percentage.
EPF: Average element permeate flow.
$STCF$: solute transport temperature correction factor, °C.
C: Concentration.

while the letters in lowercase representing the following:

a: Actual condition.
s: Current condition.
f: Feed
fb: Feed-brine average
p: Permeate.

Trending these normalized data can allow operators when to properly schedule cleanings and maintenance for the system as any noticeable drop (usually 10% to 15%) or increase in these parameters.

III.8.3 Possible RO issues and their causes:

RO systems are susceptible to many issues that can effect their general performance with those issues having many possible causes. Figure III.14 shows the the failure mechanisms of 99 autopsied seawater membrane elements collected by the international desalination association (IDA).

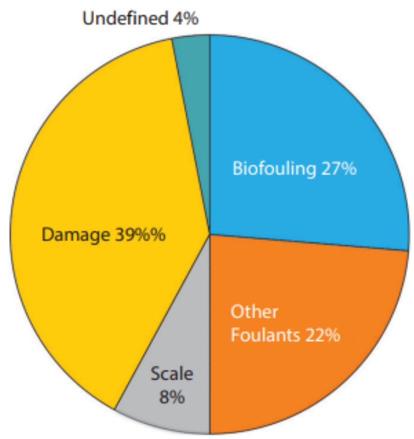


Figure III.14: Failure mechanisms from 99 autopsied seawater membrane elements (Kucera, 2023)

As you can notice the vast majority of membranes exhibit signs of damage which could be caused by a multitude of sources that we will promptly discuss. the different performance issues that RO systems face are as follows:

III.8.3.1 Loss in permeate quality:

An increased permeate concentration is especially concerning for industries that require a high purity water such as the pharmaceutical industry or precision electronics manufacturing, thus any increase in permeate quality can lead to severe consequences. the following are some probable causes for this with some being acute (due to sudden changes in operating parameters) or chronic (bigger issues that manifest with time):

- Increased feed concentration (TDS).
- Higher feed temperature.
- Hardness scaling.
- Membrane damage.
- Feed pressure decrease.

III.8.3.2 Variable permeate flow:

This could also be a cause of variations in feed temperature and membrane fouling as it directly affects the water and solute flux.

III.8.3.3 High system differential pressure:

Is represents the difference between feed pressure and brine pressure. any increase in differential pressure can be attributed to many causes such as mechanical issues, fouling, scaling...

As for the causes of these issues, as previously mentioned they can be many, for example:

- Mechanical issues: leaking valves, uncalibrated instrumentation, badly installed equipment...
- Improper system design.
- Operational problems such as increasing permeate flow and not conducting regular cleanings.
- variations in feed water quality either due to changing water sources or pretreatment issues.
- Membrane fouling, scaling, or general damage can also be the cause of many RO system problems.

III.8.4 Troubleshooting techniques:

III.8.4.1 Mechanical and visual inspection:

The first step of any troubleshooting procedure should be a mechanical inspection of all of the system components, as the problem may be as simple as a leak in a valve or visible biological growths around the pipes or pressure vessels or the filters needing to be backwashed properly. Doing this may help fix the issue at hand without the need for conducting more extensive research.

III.8.4.2 Water analysis:

Certain parameters should be regularly monitored, such as SDI_{15} and free chlorine and be recorded as they can give valuable information on the state of the pretreatment systems, but when experiencing performance drops additional tests may be needed such as bacterial analysis and general mineral composition of water. Doing so can give us a good idea about the real effeciency of every step of the pretreatment process.

III.8.4.3 System projections:

Using projection software and comparing the design projections with ones conducted using current data can be a good way of analysing where the mishaps in the system are and if any modifications are needed.

III.8.4.4 Profiling and probing:

Profiling and probing are two methods that are usually done in parallel with each other, with profiling involving the measurement of conductivity and temperature of each pressure vessel separately and observing if any pressure vessel exhibits abnormal values. While probing, as the name suggests refers to the operation in which a probe (a tube) is inserted in one of the pressure vessels and the conductivity being measured at different lengths of the pressure vessel, which can gives an idea of the state of each individual membrane element and whether scale or fouling is apparent.

III.8.4.5 Normalized data analysis:

This is one of the best ways of troubleshooting an RO system as it doesn't require many resources except the continuous monitoring of the system. As previously discussed fluctuations in normalized data can be interpreted as the membranes being either fouled, scaled, or damaged, with NPF being the first parameter to show any changes monitoring it can give great insight, with the following graph showing the different possibilities for it:

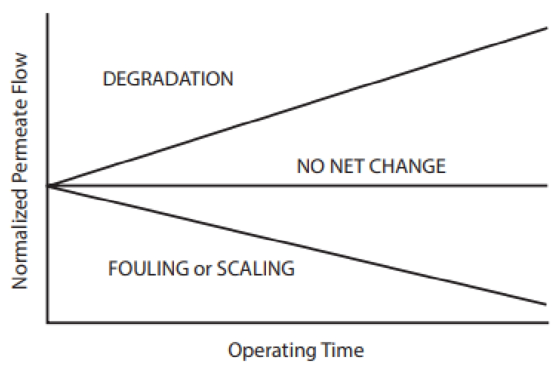


Figure III.15: NPF variations and the different explanations (Kucera, 2023)

III.8.4.6 Membrane autopsy:

An autopsy of the membranes is the last resort when it comes to troubleshooting RO systems as it is a destructive method that renders the membranes unusable after it's done. It consists of conducting visual inspections and several tests and analysis to determine the source of the problem. Some of the problems that may be found using this method is membrane telescoping, signs of damage, fouling deposits, scaling...

III.8.5 Preventative measures:

The best way to deal with RO system issues is to avoid them all together, or at least to make the process of localising them as easy as possible for the operator. This can be done by following the steps:

- Conducting regular water analysis (SDI_{15}, turbidity, free chlorine, cations and anions…
- Monitoring and recording data of the RO system and creating a data base and trends from normalized data.
- Cleaning and flushing the membranes depending the interpretation of normalized data trends.
- Calibrating and regularly inspecting instrumentation to ensure proper data collection and operations.
- Replacing the cartridge filters and backwashing the media filters when necessary.

III.9 Conclusion:

Finally, in this chapter we exposed the intricate details of reverse osmosis while exploring all the theories behind it and all the complexities that are present in this water demineralization process. By understanding its principles and factors affecting performance, we see RO as a powerful solution for clean water needs. Moving forward, this knowledge paves the way for continued advancements in RO technology to meet the world's increasing demand for freshwater.

Chapter IV

Diagnosis of the existing unit:

IV.1 Introduction:

In this chapter we will delve into the crux of this thesis as we will be diagnosing the water treatment unit of the Reggane north development project as it has been exhibiting some issues. But before we start with the troubleshooting procedure we have to familiarise ourselves with the unit itself and it's purpose.

IV.2 Description of GRN's water treatment unit:

As we exposed previously the purpose of the Reggane north development project is the exploitation of natural gas reservoirs found in the region. This process happens in the central production facilities (CPF) located inside the GRN complex.

Water is very important part of the gas treatment process as it's not only used for general use (sanitary and consumption) but also for fire water and for use in the heating medium and the regeneration and dilution process for the amine (used for capturing acid gases from the natural gas). Therefore the water treatment utility unit was designed to meet the high quality product specifications.

The process starts by the extraction of water from two wells situated outside of the CPF (REG-5 well and SALI-2 well) which is subsequently passed through a de-sander to remove coarse sand particles. the next step is pumping the water to the raw water tank which has a capacity of 471 m^3 while the pumps operate with a flowrate of 15 m^3/h and a head of 46.3 m (4.6 $Barg$) with the addition of Biocide and chlorine for disinfection purposes. The raw water tank then feeds the service water treatment package, which consists of a conventional pre-treatment system (Sand filters, chemical injections, cartridge filters) that serves the purpose of removing suspended particles and getting the quality of the water to an acceptable level that would not damage the RO membranes (RO1). After passing through the membranes the water is fed to a service water tank that has a capacity of 1295 m^3.

A portion of the service water is then routed for use by the domestic users, eye wash stations, the laboratory, and to fill fire fighting tanks; while around 4 m^3/h is used to feed the demineralized water package which consists of another reverse osmosis train (RO2), continuous electrodeionization (CEDI) train, and a deoxygenation unit (DEOX). The final product water is stored in a pressurised demineralized water tank (blanketed with fuel gas) and used to feed the heating medium system for amine regeneration and other industrial processes. The following black diagram summerises all the previous talking points:

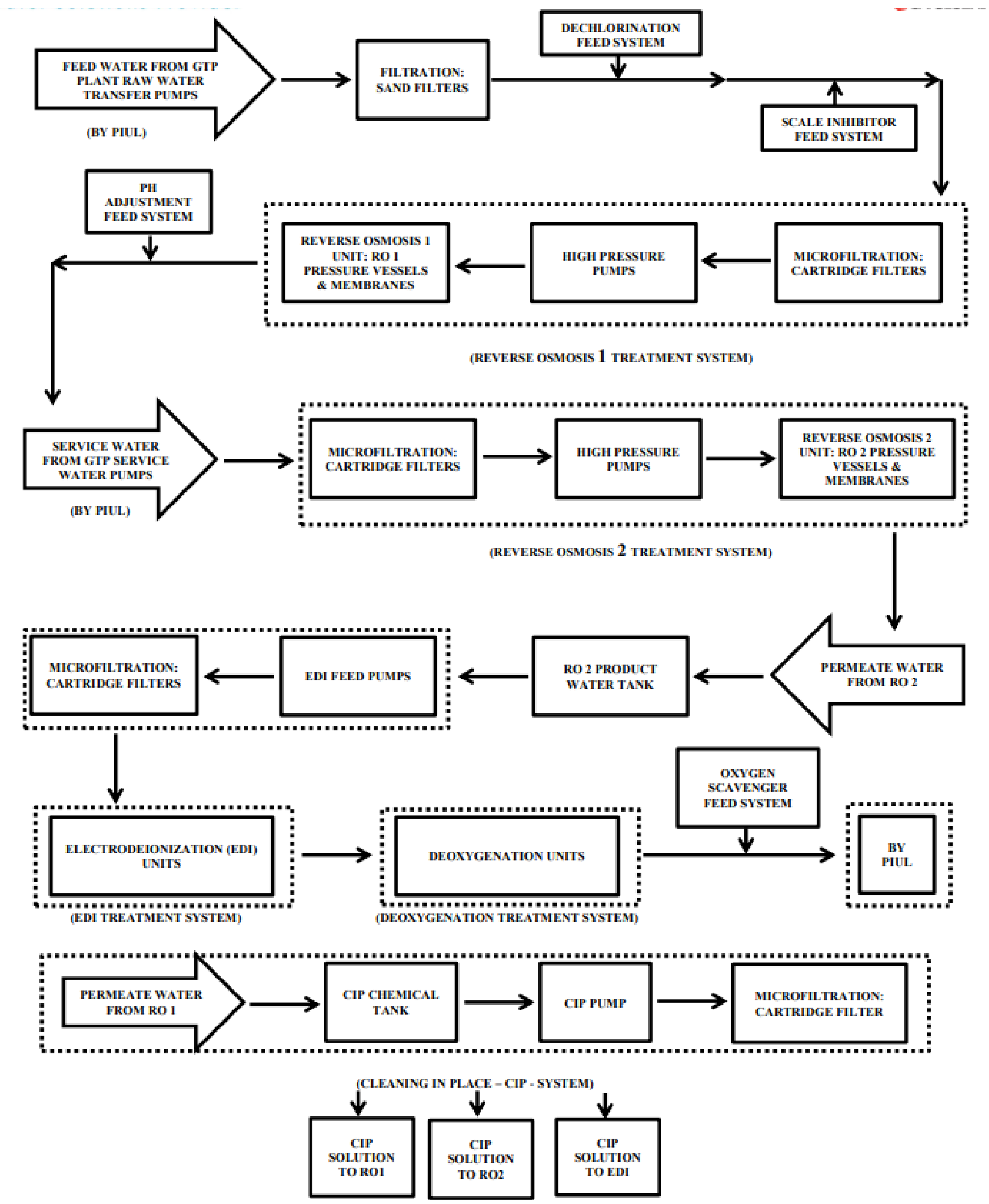


Figure IV.1: Water treatment unit block diagram (EMCO engineering LTD, 2014)

IV.2.1 Inlet water specifications:

The unit was designed based on the water analysis of REG-5 well and SALI-2 well in addition to the feed water analysis[1] with everything being detailed bellow:

Table IV.1: REG-5 well analysis (Petrofac, 2014a)

PARAMETRES PHYSICO-CHIMIQUES			RESULTATS	MINERALISATION GLOBALE			RESULTATS
pH			7.04	Calcium	Ca^{++}	mg/l	154
Conductivité, ms/cm			2.84	Magnes.	Mg^{++}	mg/l	86
Turbidité eau brute, NTU			0.00	Sodium	Na^{+}	mg/l	260
Turbidité eau déc., NTU			0.00	Potassium	K^{+}	mg/l	20
Résidu sec a 110 °, mg/l			1700,00	Chlorure	Cl^{-}	mg/l	495
Température °C			-	Sulfate	SO_4^{--}	mg/l	420
PARAMETRES DE POLLUTION			**RESULTATS**	Bicarbon.	HCO_3^{-}	mg/l	168
				Carbonate	CO_3^{--}	mg/l	0
Oxygène Dissous		mg/l	-	Silice	SiO_2	mg/l	6,10
Ammonium	NH_4^{+}	mg/l	0,02	TH		°F	73
Nitrite	NO_2^{-}	mg/l	0,05	TAC		°F	14
Nitrate	NO_3^{-}	mg/l	65,00	TA		°F	0
O.phosphate	PO_4^{-}	mg/l	0,00	Minéralisation		mg/l	1637
Mat.Ox (mil. Ac.)		mg/l O_2	1,80	Somme des ions		mg/l	1668
Fer en		mg/l	-	Manganèse en		mg/l	-

Table IV.2: SALI-2 well analysis (Petrofac, 2014a)

PARAMETRES PHYSICO-CHIMIQUES			RESULTATS	MINERALISATION GLOBALE			RESULTATS
pH			7.09	Calcium	Ca^{++}	mg/l	153
Conductivité, ms/cm			2.70	Magnes.	Mg^{++}	mg/l	88
Turbidité eau brute, NTU			0.00	Sodium	Na^{+}	mg/l	260
Turbidité eau déc., NTU			0.00	Potassium	K^{+}	mg/l	20
Résidu sec a 110 °, mg/l			1700,00	Chlorure	Cl^{-}	mg/l	420
Température °C			-	Sulfate	SO_4^{--}	mg/l	460
PARAMETRES DE POLLUTION			**RESULTATS**	Bicarbon.	HCO_3^{-}	mg/l	159
				Carbonate	CO_3^{--}	mg/l	0
Oxygène Dissous		mg/l	-	Silice	SiO_2	mg/l	14,50
Ammonium	NH_4^{+}	mg/l	0,00	TH		°F	73
Nitrite	NO_2^{-}	mg/l	0,00	TAC		°F	13
Nitrate	NO_3^{-}	mg/l	83,00	TA		°F	0
O.phosphate	PO_4^{-}	mg/l	0,00	Minéralisation		mg/l	1674
Mat.Ox (mil. Ac.)		mg/l O_2	8,20	Somme des ions		mg/l	1663
Fer en		mg/l	-	Manganèse en		mg/l	-

We can see that the well water analysis is similar for both wells which is explained by the fact that the source aquifer is the same for them both (Albien aquifer), We can also ses that the water is very hard with 73°F which classifies it as an extremely hard water according to the world health organisation's (WHO) standards, while the TDS is around 1700 ppm

[1]ANRH, Adrar

Table IV.3: Feed water analysis (ANRH, 2014)

PARAMETRES PHYSICO-CHIMIQUES	RESULTATS	NORMES DE POTABILITE	MINERALISATION GLOBALE	RESULTATS	NORMES DE POTABILIT
PH	7,58	≥ 6,5 et ≤ 9	Calcium Ca++ mg/l	76	200,00
Conductivité ms/cm	1,76	2,80	Magnes. Mg++ mg/l	53	150,00
Turbidité eau brute NTU	0,50	5,00	Sodium Na + mg/l	200	200,00
Turbidité eau déc. NTU	-		Potass. k+ mg/l	33	12,00
Residu sec à 110° C mg/l	1080,00	1500,00	Chlorure Cl- mg/l	255	500,00
Temperature °C	-	25,00	Sulfate SO4-- mg/l	340	400,00
PARAMETRES DE POLLUTION	RESULTATS		Bicarbon. HCO3- mg/l	159	-
			Carbonate CO3-- mg/l	0	-
Oxygène Dissous mg/l	-		Silice SiO2 mg/l	-	-
Ammonium NH4+ mg/l	0,005	0,50	TH ° F	40	-
Nitrite NO2- mg/l	0,020	0,20	TAC ° F	13	-
Nitrate NO3- mg/l	42,00	50,00	TA ° F	0	-
O.phosphate PO4- mg/l	0,520	0,50	Minéralisation mg/l	1091	-
Mat. Ox.(mil. Ac.) mg/l O2	1,70	5,00	Somme des ions mg/l	1157	-
Fer mg/l	-	0,30	F- mg/l	-	-

We notice that the hardness of the water drops but it is still quite hard, while the TDS also dropped to around 1000 ppm.

Table IV.4 refers to a bacterial analysis conducted on water of different parts of the process, with this analysis testing for both aerobic and anaerobic bacteria that cause corrosion. We notice that GAB and BF bacteria reach extreme levels in the raw and service water which justifies the use of the biocide.

IV.2.2 Pretreatment system:

This conventional pretreatment system is comprised of several steps that all start with one very important instrument, a temperature transmitter installed at the feed side of the system that will send a signal to the intake valves into the RO1 unit if a water temperature exceeding 40°C is detected.

IV.2.2.1 Sand filters and back-wash pumps:

The first step of the pretreatment unit is the sand filters which serve to capture all suspended solids, the media used is two layers of differently sized gravel and a final layer of sand. The system is disposed of two identical sand filters with one working as duty and the other is in standby so they can be used in alternating fashion which will increase their lifespan, this also counts as a security measure so that if any problems arise with either one the other one will always be available and will ensure continuous filtration.

On the other hand the backwash pumps can start automatically or manually to unclog the filters in one of three cases:

Table IV.4: Bacterial analysis results (MI SWACO, 2022)

…n des Installations evaluées	Concentration bacetrienne (germes/ml)/type de corrosion bacetrienne								
	BSR	BTR	SOB ANA	APB	GAB	BF	SOB A	Niveau de corrosion bacetrienne	Nature de la corrosion bactérienne
WATER WELL CPF 802	0	10	0	10	10[illegible]	10	10	Elevee	corrosion bactérienne aérobie
WATER WELL CPF 801	0	10	0	10[illegible]	10[illegible]	10[illegible]	10		
RAW WATER TANK	0	0	0	0	10[illegible]	10[illegible]	10	Severe	
SERVICE WATER TANK	0	0	0	10	10[illegible]	10	10		
DEMINE WATER TANK	10	0	10	10[illegible]	10[illegible]	10[illegible]	10		
FIRE WATER TANK 141 A-TK-901 A	10[illegible]	10[illegible]	0	10[illegible]	10[illegible]	10[illegible]	10		
FIRE WATER TANK 141 A-TK-901 B	10[illegible]	0	0	10	10[illegible]	10[illegible]	10		
FIRE HAYDRANT 141 A-HYD-901 B	10	10	0	10	10[illegible]	10[illegible]	10		
FIRE HAYDRANT 141 A-HYD-904 A	10	0	0	10	10[illegible]	10[illegible]	10		
FIRE HAYDRANT 141 A-HYD-903 Z	10	10	10	10	10[illegible]	10[illegible]	10		
FIRE HAYDRANT 141 A-HYD-902 C	10	10[illegible]	0	10	10[illegible]	10[illegible]	10		
HEATHING MEDIUM INCINERATEUR	0	10[illegible]	10	0	10	10[illegible]	10[illegible]		Corrosion bactérienne mixtes aéro-anaérobie
HEATHING MEDIUM OUTLET GTG'S	0	10[illegible]	0	0	0	10[illegible]	10[illegible]		
HEATHING MEDIUM BALLON D'EXPANSSION	0	10[illegible]	0	0	10	10[illegible]	10[illegible]		
RG 11	10[illegible]	10	0	10[illegible]	10[illegible]	10[illegible]	10		corrosion bactérienne aérobie
AZSE 04	0	0	10	0	10[illegible]	10	10	faible	Corrosion bactérienne aérobie
AZSE 10	0	0	10	0	10[illegible]	10	10		
CPF scrapr receiver RG	0	0	0	0	10[illegible]	0	10		
CPF scrapr receiver AZSE	0	0	10	0	10	10	10		
CPF SLUGCATCHER	0	0	10	0	10[illegible]	10[illegible]	10	Elevee	Corrosion bactérienne mixtes aéro-anaérobie

1. The differential pressure across the filters exceeds 0.7 bar.
2. The operator manually initiates the back-wash cycle via the control panel.
3. If the filters complete 24h of service.

The technical information for sand filters and the back-wash pumps is as follows:

Sand filters:

- **Manufacturer:** EMCO ENGINEERING
- **Vessel shape:** Vertical cylinder
- **Diameter (outer):** 1250 mm
- **Shell height:** 1500 mm
- **Overall height:** 2660 mm
- **Operating flow:** 15.76 m^3/h
- **Operating pressure:** 3.5 bar
- **Media:** Gravel (5x8mm and 3x5mm) and sand (0.5x1mm)

Back-wash pumps:

- **Manufacturer:** GRUNDFOS
- **Type:** Centrifugal Horizontal End Suction.

- **Operating flow:** $34\ m^3/h$
- **Operating pressure:** 5.83 bar

The sand filters and back-wash pumps pumps are also equipped with pressure gauges and flow-meters with their accompanying transmitters to monitor and allow the automation of the start-up and shutdown of the systems as well as their backwash. Figure IV.2 illustrates the backwash filters in GRN's CPF:

Figure IV.2: Sand filters (2 may 2024, GRN)

IV.2.2.2 Dechlorination system:

The purpose pf the dechlorination system is to eliminate any residual chlorine from the water after it passes through the sand filters as the RO membrane' maximum allowable chlorine concentration is 0.1 ppm with the preferable concentration being 0 ppm.

The system consists of a cylindrical chemical storage tank (500 mm Diameter and 1250 mm height) equipped with a mixer, Two dosing pumps operating as one duty and one standby for the same philosophy stated above for the sand filters, and multiple transmitters and instruments to monitor the unit. The dechlorination chemical used is a sodium metabisulfite solution with an adjustable dose depending on the incoming chlorine levels.

IV.2.2.3 Scale inhibitor system:

The scale inhibitor system is identical to the the dechlorination system except for the injection point which is just at the inlet of the RO1 unit and also evidently the chemical at use which is VITEC 3000 with a dose of around 2 mg/l.

Figure IV.3 illustrates the entirety of the chemical feed system including the PH adjustment system which will be discussed subsequently

Figure IV.3: Chemical feed system (2 may 2024, GRN)

IV.2.3 RO1 unit:

RO1 unit is the reverse osmosis unit that's responsible for producing service water. It consists of two identical reverse osmosis trains working as one duty and one standby. It is a 1:1 system that utilises spiral wound brackish water membranes and has a recovery rate of 75% with a permeate flow of 11.82 m^3/h and a feed flow of 15.76 m^3/h.

The entire skid is comprised of several components: The cartridge filters, high pressure pumps (HPP), Pressure vessels, RO membranes.

IV.2.3.1 RO1 cartridge filters:

Each RO1 has its own microfiltration cartridge filters installed on the feed side of the unit to prevent any suspended solids from entering and damaging the membranes. The associated transmitter send an alarm to the operators if the differential pressure across the filters exceeds 0.7 bar which would mean the filters are clogged. The following are some technical information on the cartridge filters:

- **Manufacturer:** AQUA PURIFICATION.
- **Model number:** 5V30-316L.
- **Operating flow:** 15.76 m^3/h.
- **Operating pressure:** 2.5 bar.
- **Diameter:** 260 mm.
- **Height:** 1038 mm.
- **Filter element quantity:** Five.
- **Pore size:** 5 micron

IV.2.3.2 RO1 HP pumps:

They are located downstream of the cartridge filters and serve the purpose of providing the needing the driving pressure to ensure the proper functioning of the RO1 membranes:

- **Manufacturer:** GRUNDFOS.
- **Model number:** CRN 15-14.
- **Type:** Centrifugal Vertical Multi-Stage In-line.
- **Number of stages:** 14 stages.
- **operating flow:** 15.76 m^3/h.
- **operating pressure:** 16.6 bar @ 10°C, 10.7 bar at 30°C.

The follow figures illustrate GRUNDFOS CRN 15-14 high pressure pumps components, and operating curve respectively:

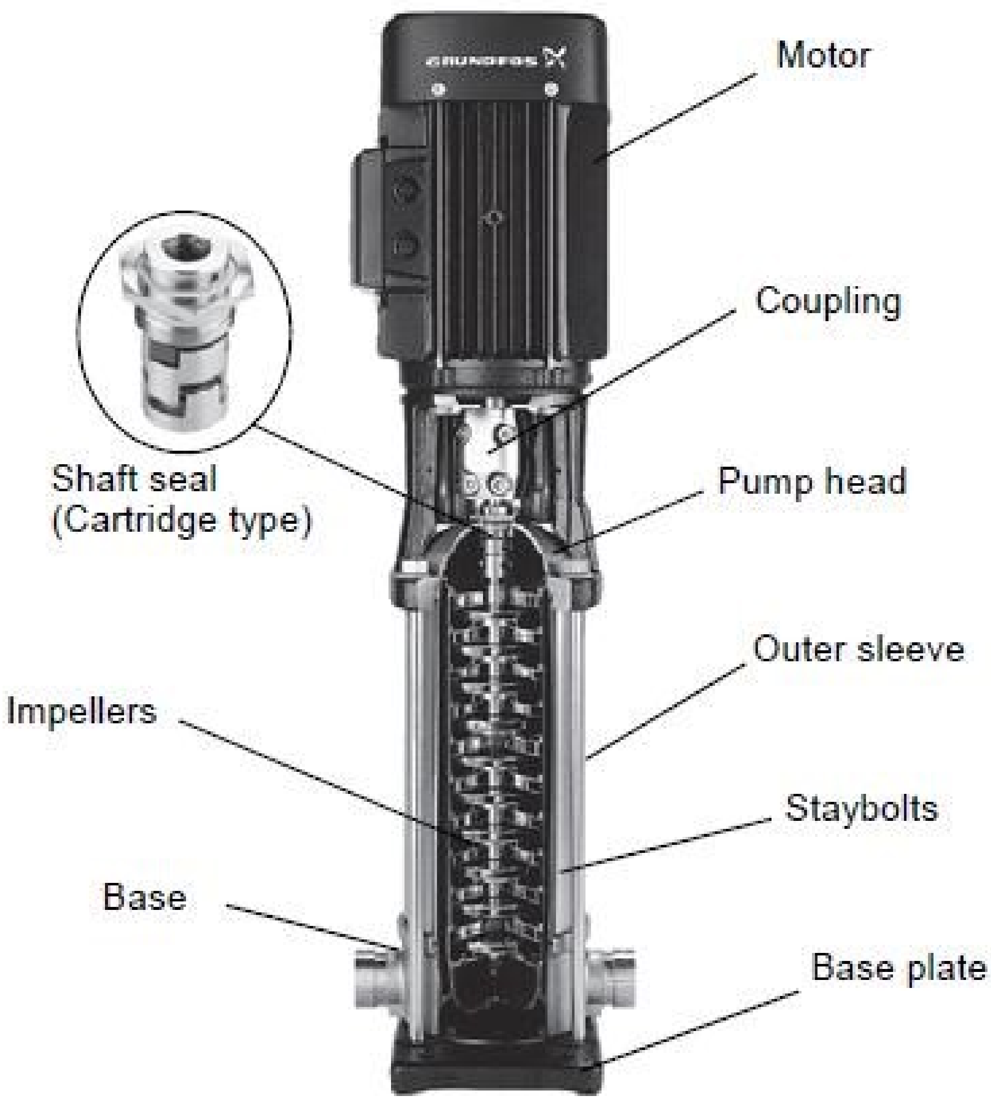


Figure IV.4: RO1 high pressure pumps (Grundfos, 2024)

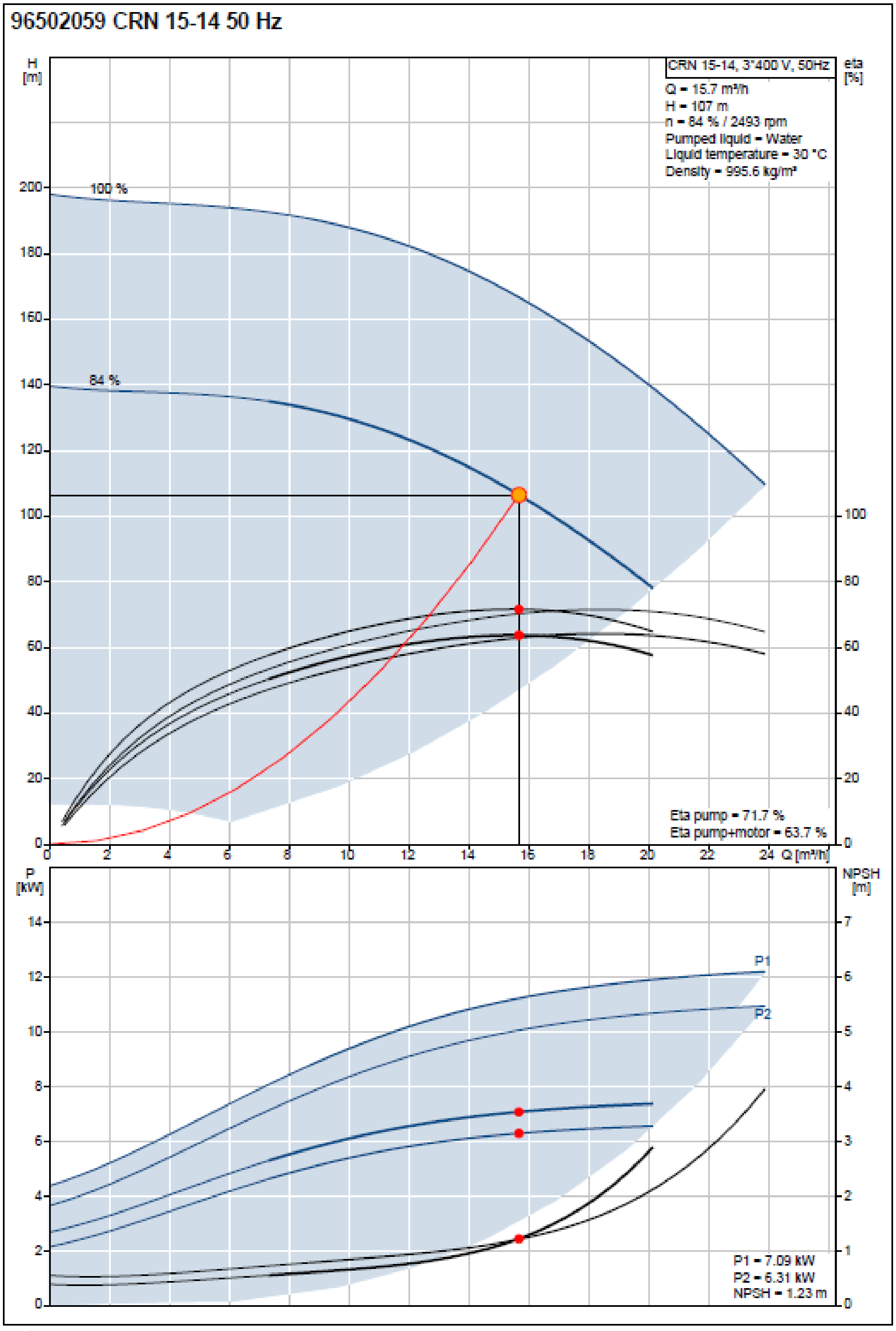


Figure IV.5: RO1 high pressure pumps performance curve (Grundfos, 2024)

IV.2.3.3 RO1 pressure vessels:

As previously mentioned RO1 has two trains of 1:1 reverse osmosis systems which means it consists of four pressure vessels in total, each one housing 6 membranes. The pressure vessels have to be able to resist the incoming pressure from the high pressure pumps and properly house the membranes without allowing any leaks, with the two trains functioning in an alternating manner every six hours of continuous operation or if one of them is faulty. The information of the pressure vessels used is as follows:

- **Manufacturer:** PROTEC;
- **Model number:** PRO-8-600-SP-6.
- **Type:** Side Ported.
- **Material of construction:** Filament Wound, Epoxy FRP
- **Inner diameter:** 7.95 ± 0.0059 inch.[2]
- **Outer diameter:** 8.54 inch.
- **Membrane element:** HYDRANAUTICS ESPA2-LD.

Note that the pressure vessels are designed to house a specific type of membrane (ESPA2-LD).

IV.2.3.4 RO1 membranes:

Their are six Composite Polyamide and Polyvinyl Derivative (PVD) spiral wound RO Membrane Elements in each pressure vessel as per the design documents and they have the following specifications:

- **Manufacturer:** HYDRANAUTICS.
- **Model number:** ESPA2-LD.
- **Type:** Low Fouling Spiral Wound.
- **Membrane material:** Composite Polyamide.
- **Active area:** 37.1 m^2.
- **Salt rejection:** 99.6%.
- **Diameter:** 7.89 inch.
- **Length:** 40 inch.
- **Operating flow:** 15.76 m^3/h
- **Operating pressure:** 16.6 bar

[2] 1 inch = 2.54 cm

IV.2.3.5 RO1 post-treatment system:

The RO1 unit is also equipped with a PH adjustment system that automatically injects caustic soda to increase the PH back to the operating range (7.5 to 8.5). although the system is again identical to the previous dosing pumps.

Figure IV.6: Real life picture of the RO1 unit. (2 may 2024, GRN)

IV.2.4 RO2 unit:

The RO2 unit is the first step in the demineralized water package which consists of CEDI and DEOX units on top of RO2.

RO2 can be considered as a second pass to RO1 as it uses a portion of the flow of the service water (3.62 m^3/h) I.e., RO1 permeate. It is also a two stage system (1:1) but has an increased recovery of 77% therefore producing 2.72 m^3/h of high purity permeate water while its reject is recycled into the raw water tank.

IV.2.4.1 RO2 cartridge filters:

The operate using the same principle as the ones installed in RO1. These are their specifications:

- **Manufacturer:** AQUA PURIFICATION.

- **Model number:** 4V10-316L.
- **Operating flow:** 3.62 m^3/h.
- **Operating pressure:** 4.5 bar.
- **Diameter:** 260 mm.
- **Height:** 530 mm.
- **Filter element quantity:** Four.
- **Pore size:** 5 micron

IV.2.4.2 RO2 HP pumps:

The RO2 high pressure pumps have the following specification (Figure IV.7 illustrates their performance curve):

- **Manufacturer:** GRUNDFOS.
- **Model number:** CRN 5-20.
- **Type:** Centrifugal Vertical Multi-Stage In-line.
- **Number of stages:** 20 stages.
- **operating flow:** 3.62 m^3/h.
- **operating pressure:** 12 bar @ 10°C, 5.5 bar at 30°C.

IV.2.4.3 RO2 pressure vessels:

- **Manufacturer:** PROTEC;
- **Model number:** P PRO-4-300-EP-6.
- **Type:** End Ported.
- **Material of construction:** Filament Wound, Epoxy FRP
- **Inner diameter:** 4.015 ± 0.004 inch.
- **Outer diameter:** 4.33 inch.
- **Membrane element:** HYDRANAUTICS ESPA2-LD4040.

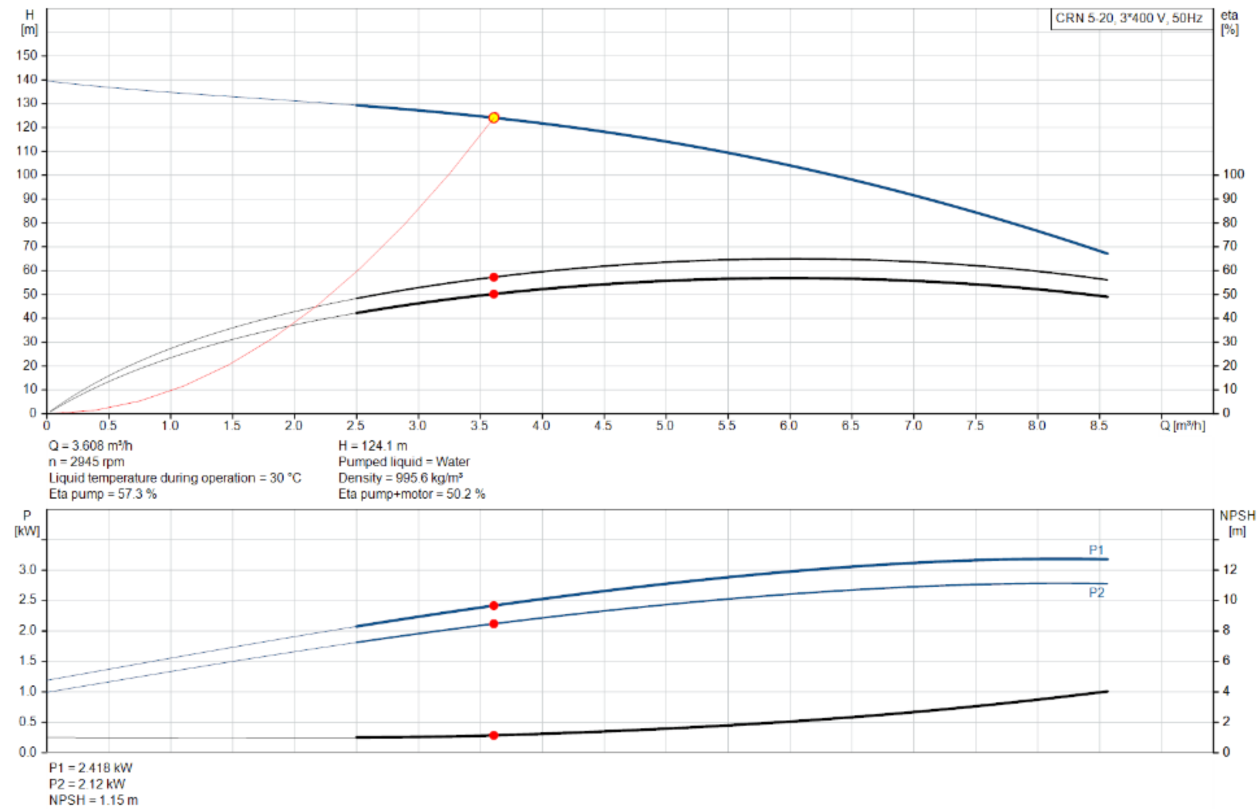


Figure IV.7: RO2 high prssure pump performance curve

IV.2.4.4 RO2 membranes:

- **Manufacturer:** HYDRANAUTICS.
- **Model number:** ESPA2-LD4040.
- **Type:** Low Fouling Spiral Wound.
- **Membrane material:** Composite Polyamide.
- **Active area:** 7.43 m^2.
- **Salt rejection:** 99.6%.
- **Diameter:** 3.95 inch.
- **Length:** 40 inch.
- **Operating flow:** 3.62 m^3/h
- **Operating pressure:** 16 bar

The following image illustrates the RO2 unit:

Figure IV.8: Real life picture of the RO2 unit (2 may 2024, GRN)

IV.2.5 CEDI unit:

The CEDI is the first step in the post-treatment of the RO permeate and the penultimate step in the overall water treatment unit. This EDI unit comprises numerous flow compartments created by alternating cation and anion exchange membranes. Feed water entering the modules is distributed throughout the product compartments and then transferred to the reject compartments for disposal. Both compartments are filled with resin. As the water in the product compartments becomes ion-free, the DC voltage splits water into hydrogen and hydroxyl ions, which in turn regenerate the ion exchange resins.

The water passing through the product compartment is deionized to pure water, while the remaining water flows into the reject compartments. This reject water carries away concentrated salts and small amounts of gases formed on the electrode surfaces. the technical characteristics of the unit are as follows:

IV.2.5.1 Feed pumps:

- **Manufacturer:** GRUNDFOS.
- **Model number:** CRN 3-12.
- **Type:** Centrifugal Vertical Multi-Stage In-line.

- **Number of stages:** 12 stages.
- **operating flow:** 2.79 m^3/h.
- **operating pressure:** 5.93 bar.

IV.2.5.2 Cartridge filters:

- **Manufacturer:** AQUA PURIFICATION.
- **Model number:** 4V10-316L.
- **Operating flow:** 2.79 m^3/h.
- **Operating pressure:** 5.9 bar.
- **Diameter:** 260 mm.
- **Height:** 530 mm.
- **Filter element quantity:** Four.
- **Pore size:** 1 micron

IV.2.5.3 EDI modules:

- **Manufacturer:** IONPURE.
- **Model number:** IP-LXM18Z-1.
- **Operating flow:** 2.58 m^3/h.
- **Operating pressure:** 2.9-7 bar.
- **Recovery:** 95%.

The following figure illustrates the CEDI unit:

Figure IV.9: CEDI unit real life picture (2 may 2024, GRN)

IV.2.6 DEOX unit:

This unit is consisting of a membrane degassing unit which contains membrane contactors consisting of thousands of micro porous polypropylene hollow fibres knitted into array that is wound around a distribution tube. The separation principle of Membrane Contactors using micro porous membranes is totally different from other membrane separations such as RO systems. Sweep gas technique is used for removing oxygen dioxide from the liquid stream. In this process the gas which is in the lumen side of membrane contactor flows counter-current to the water flow. For oxygen removal, Nitrogen as sweep gas is used. When using this technique, the liquid steam becomes saturated with the sweep gas, and nitrogen and oxygen are evacuated through a vacuum pump to a safe place.

The water from the EDI unit is introduced into the De-oxygenation Membrane Contactor units and counter-currently Nitrogen is introduced from the Nitrogen distribution header to sweep the oxygen dioxide from the water to get High purity water as product. Two de-oxygenation vacuum pumps are also provided to operate along with the sweep gas to optimise the removal of oxygen from the water. The high purity water is collected in Demineralized Water Storage Vessel.

The DEOX unit consists of the following components:

IV.2.6.1 Membrane contactors:

- **Manufacturer:** LIQUICELL.
- **Model number:** IP-LXM18Z-1.
- **Operating flow:** 2.5 m^3/h.
- **Operating pressure:** Vacuum bar.
- **Product oxygen content:** $<$ 10ppb.

Figure IV.10 is a real life picture of the DEOX unit:

Figure IV.10: Real life picture of the DEOX unit (2 may 2024, GRN)

IV.2.7 Product quality specifications:

Each previously mentioned unit has unit has its own desired outlet specifications that need to be met. Each unit's outlet quality affects the proceeding unit as it comprises its feedwater, therefore maintaining the desired quality is essential for proper operations and to avoid any problems.

IV.2.7.1 Pretreatment system outlet characteristics:

The conventional pretreatment system has to produce water with a turbidity less than 0.1 NTU and free chlorine content of 0 ppm

IV.2.7.2 RO1 outlet specifications:

The outlet of the RO1 unit should meet the following specifications:

- **Permeate flow:** 11.82 m^3/h.
- **PH:** 8.1-8.4
- **TDS:** 200 mg/l
- **Conductivity:** <125 $\mu S/cm$.

IV.2.7.3 Demineralized water package outlet specifications:

- **Permeate flow:** 2.45 m^3/h.
- **PH:** 6.5-7.5.
- **TDS:** <0.1 mg/l
- **Conductivity:** < 0.2 $\mu S/cm$.
- **Oxygen:** < 10 ppb[3].

IV.3 Diagnosis of the pretreatment system:

IV.3.1 Current product water characteristics:

The first thing to be examined is the quality of the raw water before and after going through the pretreatment system, because they can give us good insight on the the functioning of the system.

The raw water is tested on a weekly basis (PH, conductivity, TDS) and as per the weekly analysis reports provided by the company laboratory the previously mentioned parameters average 7.3, 1000 $\mu S/cm$ and 1600 mg/l respectively.

Unfortunately, no type of analysis is conducted on the raw water after passing through the pretreatment system.

[3] ppb = parts per billion

IV.3.2 General history of the system:

According to the technical staff, biocide injections have ceased for months due to running out of the chemical agent being used. This presents a big problem that can affect not only the RO membranes and induce biofouling, but also the piping of the whole unit due to the high presence of corrosion inducing bacteria as per Table IV.4.

It is also noteworthy to add that the strainer by the water wells is no longer functional as in the last cleaning in 2023 it was found to be heavily clogged with sand and silt with a lot of parts showing signs of damage which hasn't been addressed since then, Therefore causing more sediments to enter into the raw water tank.

Figure IV.11: Picture of depositions inside the raw water tank during the last cleaning (2022)

IV.3.3 Mechanical inspection:

During the mechanical and the visual inspection of the pretreatment system several anomalies were noted, specifically with the chemical dosing pumps :

- Scale inhibitor pumps working simultaneously while they should work as one duty/one standby.
- Scale Dechlorination pumps working simultaneously while they should work as one duty/one standby.
- Stroke of both sets of pumps not working, meaning there was no actual dosing and that pumps were working at full capacity all the time.

These issues can have a catastrophic impact on the whole unit and especially the RO membranes, as scale inhibator overdosing can cause depositions and fouling of the membranes (Ismail et al., 2019) with overdosing dechlorination agents having similar effects. In addition to damage caused to the system this also significantly increases the cost of chemicals usage.

IV.4 Diagnosis of the service water package (RO1):

IV.4.1 Current product water characteristics:

Examining the operations of an RO unit requires collecting certain data over a long period of time as discussed in the previous chapter. GRN's unit is no different.

Starting with the product water conductivity and TDS. The following two graphs show the evolution of permeate conductivity and TDS of the RO1 unit's train 1 (train 2 completely offline and only works 5 minutes a day to preserve the quality of the membranes) in two different time periods.

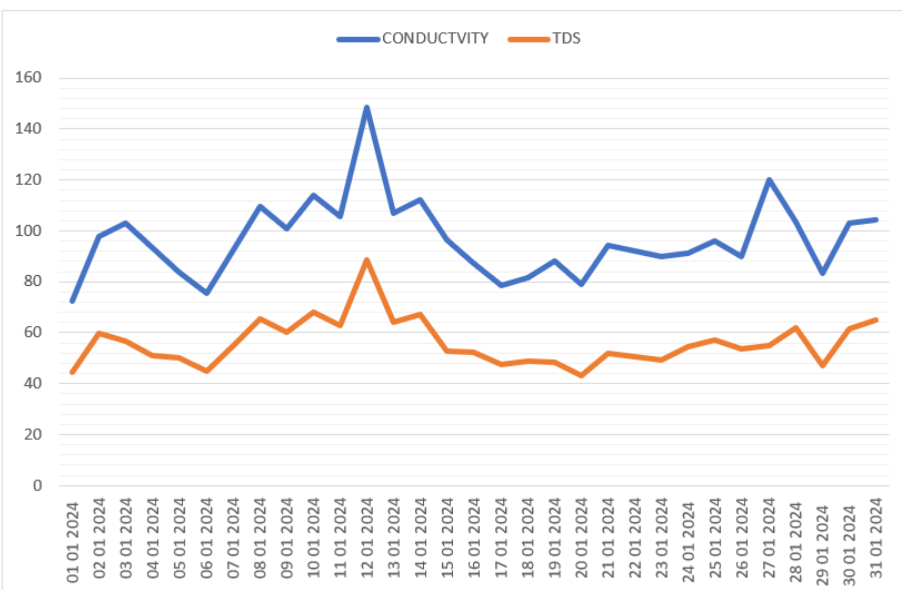


Figure IV.12: Conductivity and TDS trends of RO1 train 1 permeate in the month of January.

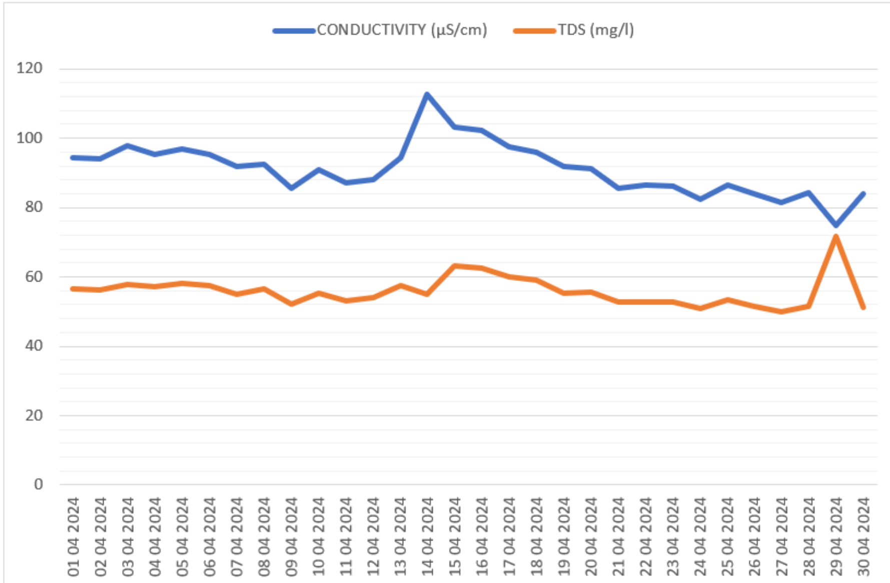


Figure IV.13: Conductivity and TDS trends of RO1 train 1 permeate in the month of April.

Figure IV.12 demonstrates that the conductivity and TDS of RO1 fairly invariable with the averages being 96.63 $\mu S/cm$ and 56 mg/l respectively with the values ranging between 148.4 and 72.3 $\mu S/cm$ and 88.5 and 43.21 mg/l which means that in January the RO1 unit produce permeate water in accordance with the set specifications (< 125 $\mu S/cm$ and 200 mg/l). On the other hand Figure IV.13 illustrates the trend of those same parameters after four months of continuous operations. It is evident that both the average conductivity and TDS values have gone up to 116 $\mu S/cm$ and 70 mg/l respectively which represents a 20 % drop in permeate quality.

IV.4.2 General history of the unit:

RO1 membranes were changed for both trains by the vendor (EMCO) for the first time in August 2019 with both trains producing acceptable values during the commissioning[4], with the vendor giving recommendations to conduct regular cleanings for the membranes (every six months) and ensuring proper storage conditions for the membranes.

Unfortunately cleaning were never conducted for unit which lead to continuous degradation of permeate quality which in turn required changing the membranes yet another time in January 2023. According to the technical staff during this procedure several anomalies were noted:

- After opening the unit it was found that the membranes that were ordered (Figure IV.14) did not match with the membranes that were already installed in the unit (Figure IV.15).

[4]EMCO service report 15 Aug 019

- Certain membrane modules were slightly larger in diameter than the previous ones which lead to them being forced inside the pressure vessels.
- The discharge pressure of the high pressure pump of RO1 train 2 was set at 20 bar which lead to several membranes exhibiting signs of physical damage as shown in Figure IV.16.

Figure IV.14: New (Current) RO1 membranes

Figure IV.15: Used RO1 membranes

Figure IV.16: Physical damage due to high pressure exposure on the used membranes

Finally, cleaning operations are yet to happen since this latest change in membranes.

The accumulation of all of these anomalies has lead to results which are less than expected as well as the complete dysfunction of Train 2 of the RO1 unit.

IV.4.3 Specification anomalies:

As previously mentioned, the required outlet specifications for RO1 permeate is $< 125\ \mu S/cm$ and < 200 mg/l. Given the fact that these specifications represent the same water characteristic (salinity) it is safe to assume that a simple conversion between the two was done to obtain both specs.

The issues is that Conductivity is always greater than TDS except in rare cases that do not apply here as the conversion between the two is done using the following equation:

$$TDS = K \cdot EC \tag{IV.1}$$

With K being a the conversion factor that varies in a range between 0.5 and 0.89 (Rusydi, 2018).

After further inspection of design documents, the actual specifications of the service water (RO1 permeate) is a TDS of 200 mg/l (Petrofac, 2014a) meaning the spec for conductivity is not accurate.

IV.4.4 Operating parameters:

Unfortunately there is no history for collected operational data. The following is data that was collected on 26/04/2024 at 8 am:

- **Feed conductivity:** 1805 $\mu S/cm$
- **Cartridge filter ΔP:** 0.160 bar.
- **ORP[5]:** 150 mv.
- **Feed temperature:** 29.3 °C.
- **Feed flow:** 14 m^3.
- **Permeate flow:** 11 m^3.
- **Reject flow:** 3.1 m^3.
- **Recovery:** 79%.
- **Discharge pressure:** 12.77 bar.
- **Membranes ΔP:** 4.28 bar.

Several anomalies can be noticed based on these data, mainly the fact that the recovery of the unit is higher than the design recovery of 75%, with the feed and permeate flows being lower than what they're supposed to be (14 m^3 as opposed to 15.76 m^3 for the feed side and 11 m^3 as opposed to 11.82 m^3 for the permeate). Another anomaly can be seen with the discharge pressure as it is considerably higher than the design pressure for the given feed temperature.

These issues can all contribute to reducing the age of the membranes and can even cause physical damage to them.

In addition to the previously mentioned issues it is important to add that due to the climate of Reggane being extremly arid with the ambient temperature regularly exceeding 45°C, the temperature of the feed water is often extreme (if it reaches 40°C the unit trips and does not automatically start to not damage the membranes) which means the membranes are usually exposed to higher than usual temperature which also contributes in the reduction of the membranes' age.

Figure IV.17 illustrates the trend of average RO1 feed temperatures for the month of April:

[5]ORP: OX-RED potential

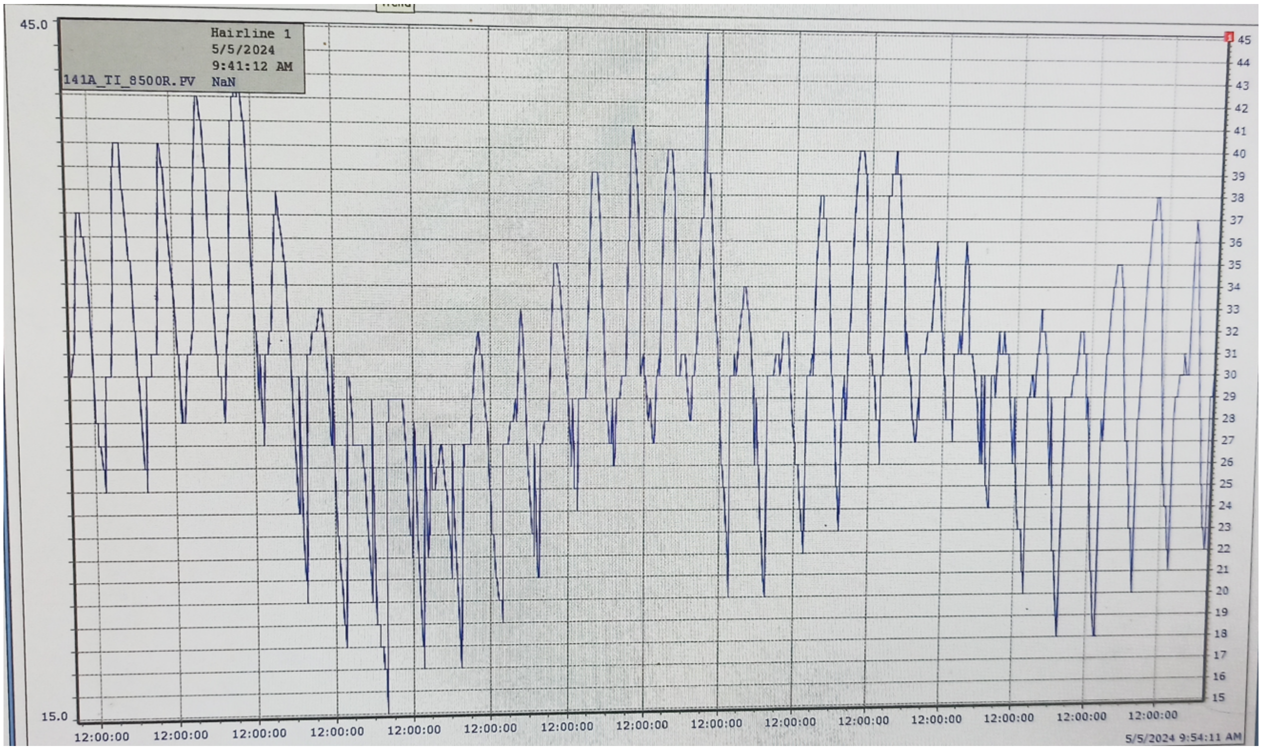


Figure IV.17: RO1 feed temperatures for the month of April.

IV.4.5 Design anomalies:

This unit was design using the projection software provided by the membrane manufacturer Hydranautics, IMSDesign. After examining the projections provided by the vendor of the unit one issue can be noticed which is that membranes used for the projections and therefore to design the high pressure pumps and all other components for the RO1 skid (ESPA2-LD) are not the same membrane models that were used before the last membrane change (CPA7-LD).

This would usually not cause any problems if the membranes are equivalent which is not the case for these two models. As per the technical information provided in the manufacturer's website[6], ESPA2-LD membranes have the property of being energy efficient, meaning they require less pressure to drive the separation process as opposed to other membrane models such as CPA7-LD.

This means that the high pressure pumps currently installed cannot provide enough pressure to provide the projected results unless the proper membranes are used (ESPA2-LD).

This issue has been solved by going back to the required membranes but the RO1 skid has already been damaged due to overworking the pumps for so long.

[6]https://membranes.com/solutions/products/ro/

The following is a comparison between projection results done using both types of membranes which illustrate a big difference in required feed pressure at the worst case scenario for the pump (10°C):

CPA7-LD

Permeate Throttling (Variable)

Project name	RO1			Page : 1/4
Calculated by	me		Permeate flow/train	11.82 m3/h
HP Pump flow		15.76 m3/h	Raw water flow/train	15.76 m3/h
Feed pressure		20.2 bar	Permeate recovery	75.00 %
Feed temperature		10.0 °C(50.0°F)	Element age	3.0 years
Feed water pH		7.00	Flux decline %, per year	5.0
Chem dose, mg/l, -		None	Fouling factor	0.86
Specific energy		0.94 kwh/m3	SP increase, per year	7.0 %
Pass NDP		16.0 bar	Inter-stage pipe loss	0.207 bar
Average flux rate		26.5 lmh		

ESPA2-LD

Permeate Throttling (Variable)

Project name	RO1			Page : 1/4
Calculated by	me		Permeate flow/train	11.82 m3/h
HP Pump flow		15.76 m3/h	Raw water flow/train	15.76 m3/h
Feed pressure		20.2 bar	Permeate recovery	75.00 %
Feed temperature		10.0 °C(50.0°F)	Element age	3.0 years
Feed water pH		7.00	Flux decline %, per year	5.0
Chem dose, mg/l, -		None	Fouling factor	0.86
Specific energy		0.94 kwh/m3	SP increase, per year	7.0 %
Pass NDP		16.0 bar	Inter-stage pipe loss	0.207 bar
Average flux rate		26.5 lmh		

Figure IV.18: Comparison between projection results done using both types of membranes

It is also noteworthy that the feed pressure suggested by the projection software was directly used for selecting the HP pumps while most sources require it to be increased by 20 to 25% as a security measure.

IV.5 Diagnosis of the RO2 unit:

IV.5.1 Current product water characteristics:

Similarly with RO1, the RO2 unit is also running with one train (train 2). Figure IV.19 demonstrates the graph of the conductivity and TDS measurements done at the laboratory of GRN for the permeate water of the RO2 unit during the month of January, we notice that the graph is quite stable with an average conductivity of $66.44\mu S/cm$ and average TDS of 39.53 mg/l with both values being extremely off the expected specifications of 0.2 $\mu S/cm$ and 0.1 TDS respectively.

On the other hand figure IV.20 demonstrates the graph of the conductivity and TDS measurements done at the laboratory of GRN for the permeate water of the RO2 unit during the month of January, we notice that the graph is quite stable with an average conductivity of 79.24 $\mu S/cm$ and average TDS of 47.87 mg/l with both values being extremely off the expected specifications of 0.2 $\mu S/cm$ and 0.1 TDS respectively.

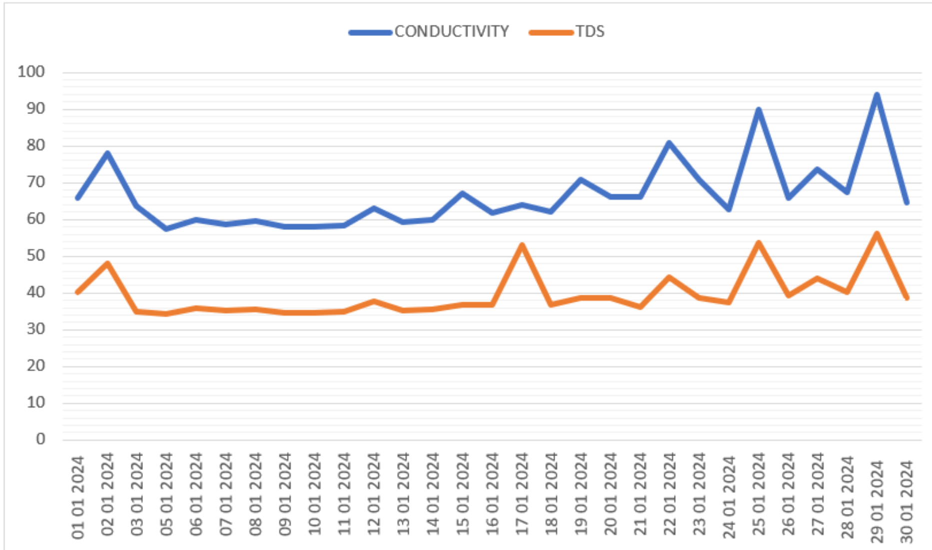


Figure IV.19: Conductivity and TDS trends of RO2 train 2 permeate in the month of January

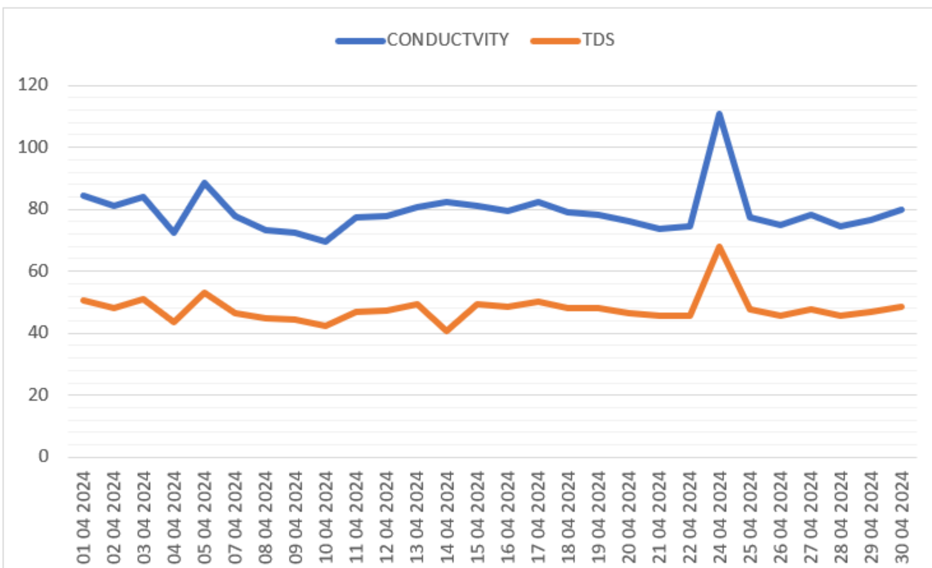


Figure IV.20: Conductivity and TDS trends of RO2 train 2 permeate in the month of April

Comparing the two graphs we notice that the average values for both the conductivity and TDS exhibited a 20% increase which is consistent with the RO1 unit. this mean that the membranes have been degraded considerably in a short period of time (4 months).

IV.5.2 General history of the unit:

This unit has similar history with the RO1 unit as their membranes were changed in the same occasions and it also never be subjected to cleaning protocol.

The following are some anomalies that were found during the last membrane replacement:

- Pressure vessel end caps in train 2 damaged and broken(Figure IV.21).
- RO2 used membranes showed signs of fouling (Figure IV.22)
- During the installation of the new membranes they did not fit properly so they were forced in and even hit with hammers. (eye witness accounts)
- Signs of telescoping on the used membranes.

Figure IV.21: Damaged RO2 end cap.

Figure IV.22: Used RO2 membrane with reddish deposits.

As previously mentioned the RO2 train 2 is currently still dysfunctional and exhibits leaks on feed side and the accumulation of deposits and biological growth. The following is a recent picture of RO2 train 2:

Figure IV.23: Current status of RO2 train 2.

Finally, in an effort to decrease the damage done to RO2 unit the cartridge filters used were changed from 5 micron filters to 1 micron filters and this has lead to very frequent changes in filters.

IV.5.3 Specification anomalies:

Similarly with the RO1 unit RO2 also has an issue with the specifications set for it but not in the same way.

The specifications for RO2 used by the technical staff are 0.2 $\mu S/cm$, which is extreme for a reverse osmosis system. But after further inspection of user manuals for the unit (EMCO engineering LTD, 2014) it was concluded that the specifications that are thought to be for the RO2 unit are actually supposed to be for the whole demineralized water package (RO2 + CEDI + DEOX) and not just for RO2.

This means that the actual specifications for the RO2 unit should be the maximum allowable values for the subsequent unit (CEDI).

IV.5.4 Operational data:

Similarly with the RO1 unit, no history of data is available so the following are data collected on 26/04/2024 at 9 am:

- **Feed conductivity:** 125 $\mu S/cm$
- **Cartridge filter ΔP:** 3.61 bar.
- **Feed temperature:** 29.7 °C.
- **Feed flow:** 3.5 m^3.
- **Permeate flow:** 2.7 m^3.
- **Reject flow:** 0.9 m^3.
- **Recovery:** 77%.
- **Discharge pressure:** 11 bar.
- **Membranes ΔP:** 5.1 bar.

Based on these data it is concluded that the differential pressure for both the cartridge filters and the membranes is very high which indicates blockage in both cases. The following are the trends of both parameters for the month of April:

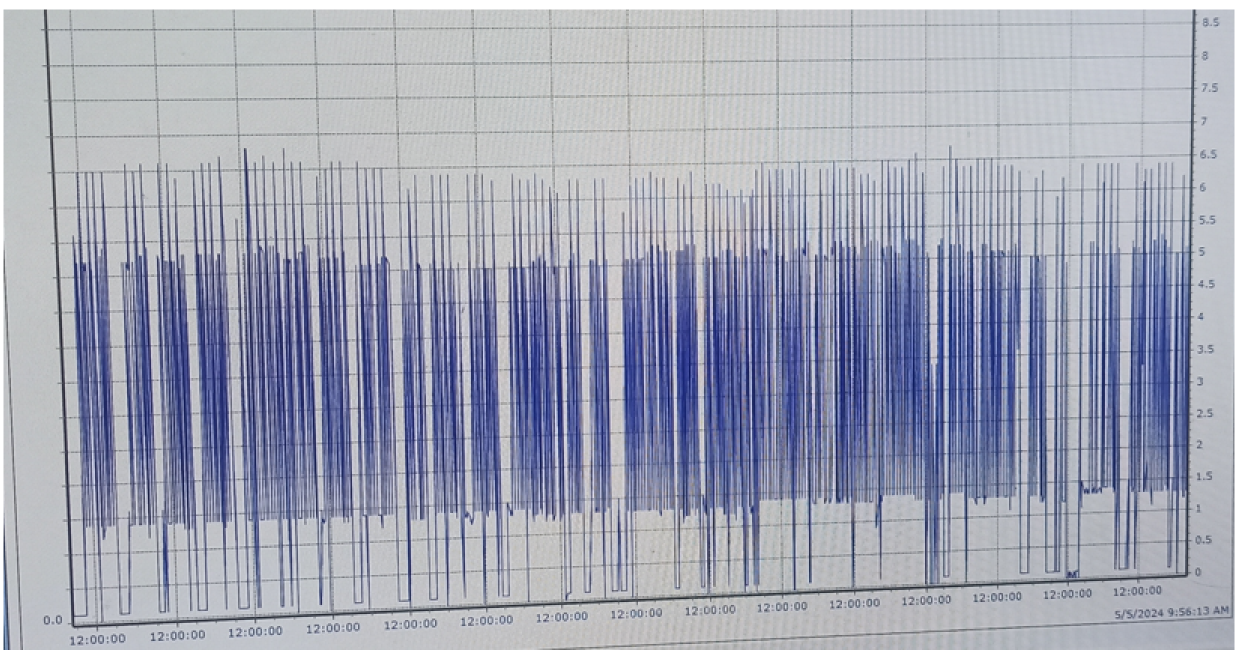


Figure IV.24: Pressure drop trend for RO2 membranes

It is noticed that the pressure drop for the membranes fluctuates a lot due to difference between start-up and shutdown states but the average values is around 3.5 bar.

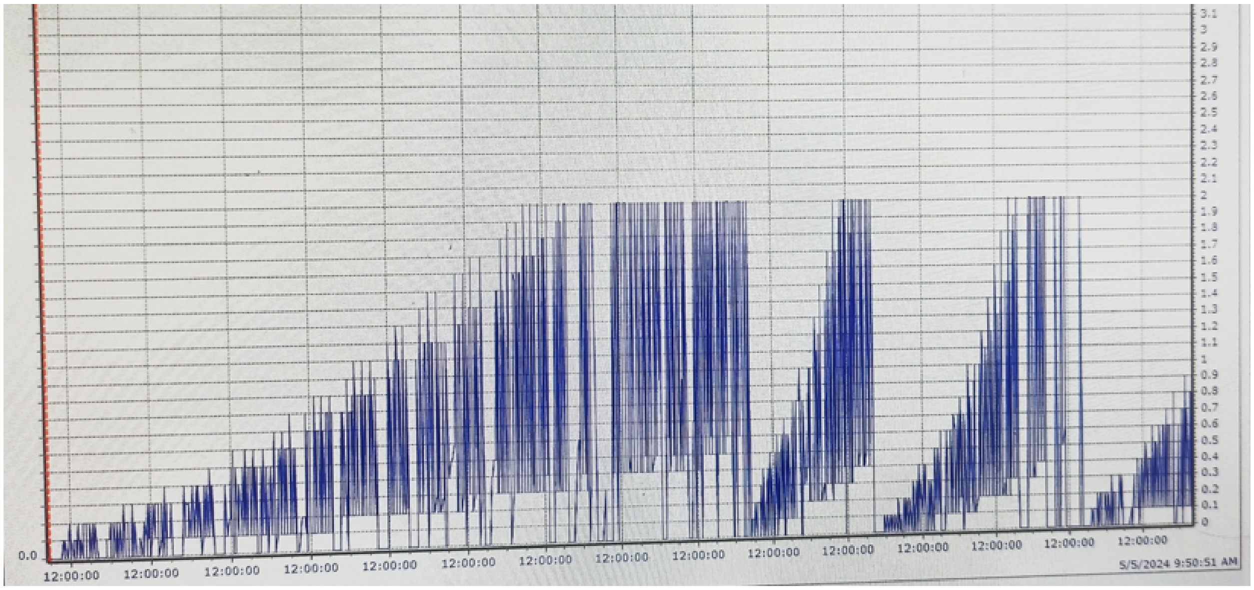


Figure IV.25: Pressure drop for the RO2 cartridge filters.

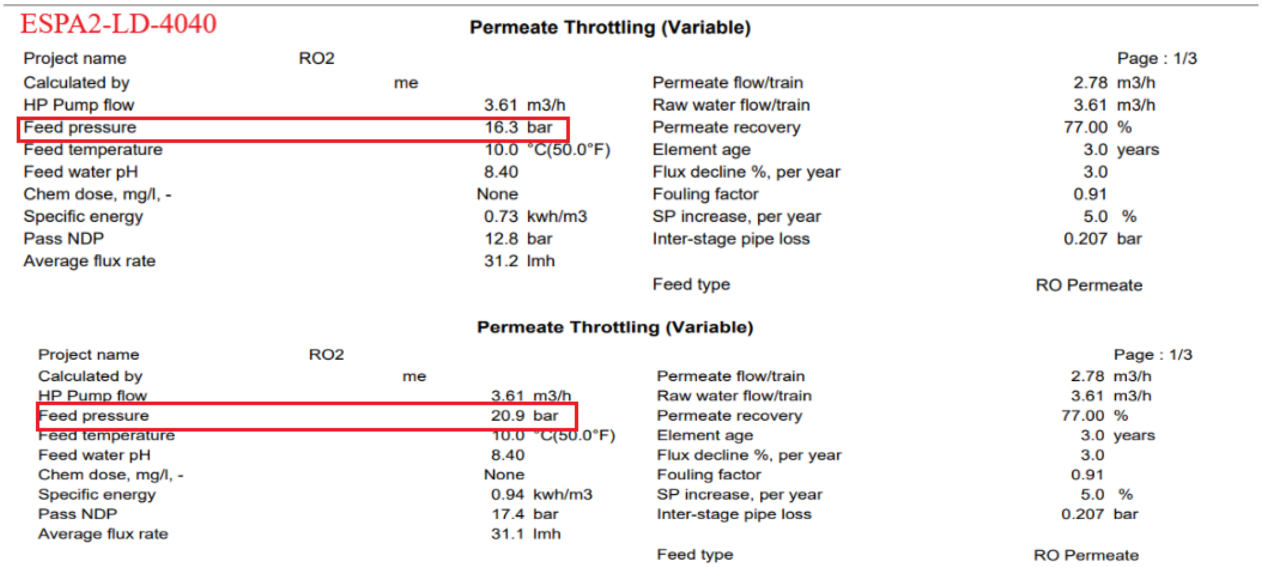
Figure IV.25 shows that as opposed to the membranes the pressure drop values increase gradually with time until a filter replacement is needed. It is clear that before replacing the 5 micron filters by 1 micron filters they lasted longer (around two weeks) while currently they only last around 3 days which increases the operational costs significantly.

IV.5.5 Design anomalies:

Examining the user manuals and design projections demonstrates the same design problem seen on RO1, except for the fact that unlike the RO1 unit, this issue still persists at this very moment.

The projections that were used to design the HP pumps and pressure vessels as well as get the expected permeate quality for the unit use Hydranautics membrane model ESPA2-LD-4040, but the unit was delivered with and still uses CPA7-LD-4040 membranes which require higher feed pressure to achieve the desired results. Figure IV.26 demonstrates the design projections at 10°C (worst case scenario for the pumps) using both types of membranes.

Another potential anomaly that was noted is that the feed water quality used to design RO2 is the permeate quality given by RO1 unit (TDS of 10 mg/l at 10°C and 21 mg/l at 30°C) which is highly unrealistic given the fact that the permeate quality experiences a lot of degradation with time even in ideal conditions, a better approach would've been to use the maximum allowable TDS for RO1 for the feed quality for RO2 as it would've allowed getting a better projection.



ESPA2-LD-4040

Permeate Throttling (Variable)

Project name	RO2		Page : 1/3
Calculated by	me	Permeate flow/train	2.78 m3/h
HP Pump flow	3.61 m3/h	Raw water flow/train	3.61 m3/h
Feed pressure	16.3 bar	Permeate recovery	77.00 %
Feed temperature	10.0 °C(50.0°F)	Element age	3.0 years
Feed water pH	8.40	Flux decline %, per year	3.0
Chem dose, mg/l, -	None	Fouling factor	0.91
Specific energy	0.73 kwh/m3	SP increase, per year	5.0 %
Pass NDP	12.8 bar	Inter-stage pipe loss	0.207 bar
Average flux rate	31.2 lmh		
		Feed type	RO Permeate

Permeate Throttling (Variable)

Project name	RO2		Page : 1/3
Calculated by	me	Permeate flow/train	2.78 m3/h
HP Pump flow	3.61 m3/h	Raw water flow/train	3.61 m3/h
Feed pressure	20.9 bar	Permeate recovery	77.00 %
Feed temperature	10.0 °C(50.0°F)	Element age	3.0 years
Feed water pH	8.40	Flux decline %, per year	3.0
Chem dose, mg/l, -	None	Fouling factor	0.91
Specific energy	0.94 kwh/m3	SP increase, per year	5.0 %
Pass NDP	17.4 bar	Inter-stage pipe loss	0.207 bar
Average flux rate	31.1 lmh		
		Feed type	RO Permeate

Figure IV.26: Comparison between projection results done using both types of membranes.

IV.6 Diagnosis of the CEDI unit:

IV.6.1 Current Product water characteristics:

The inspection of the daily water analysis provided by GRN shows that the CEDI unit has been practically working as a pipe and doesn't have any positive effect in reducing the conductivity of the feed water. In fact in actually increases the conductivity and TDS by a noticeable margin.

The average TDS for the unit for January 2024 was 49.64 mg/l which is a 10 mg/l increase from the RO2 permeate average values for the same month which is alarming given that the RO2 water is fed directly into the RO2 unit without being stored in the produced water tank for too long.

The same phenomenon can be noticed with the data for April 2024

IV.6.2 General history of the unit:

The unit has been in this current state for a long period of time and rarely managed to produce the required TDS levels during it's whole life time.

It is also noteworthy that the resins inside the unit have never been regenerated and the unit itself has never been subjected to a cleaning protocol since its commissioning.

The CEDI train one first became dysfunctional due to an issue with the ventilation system which lead to the complete reliance on the second train. But given the fact that RO2 unit was producing water that exceeds the maximum allowable values for the CEDI unit (40 $\mu S/cm$ Conductivity equivalent [7] the unit could not give the desired results and was degraded over time until it became completely unusable.

IV.6.3 Design anomalies:

The issues already discussed with RO1 and especially RO2 trickle down to the CEDI unit as the projections for designing the system used the expected results from the RO2 projections without any adjustment for real life operational problems and degradation which in turn were not realistic because the same problem when using the results from RO1 projections.

Figure IV.27 demonstrates the diagram given by the projection software used by the vendor of the unit when first designing it.

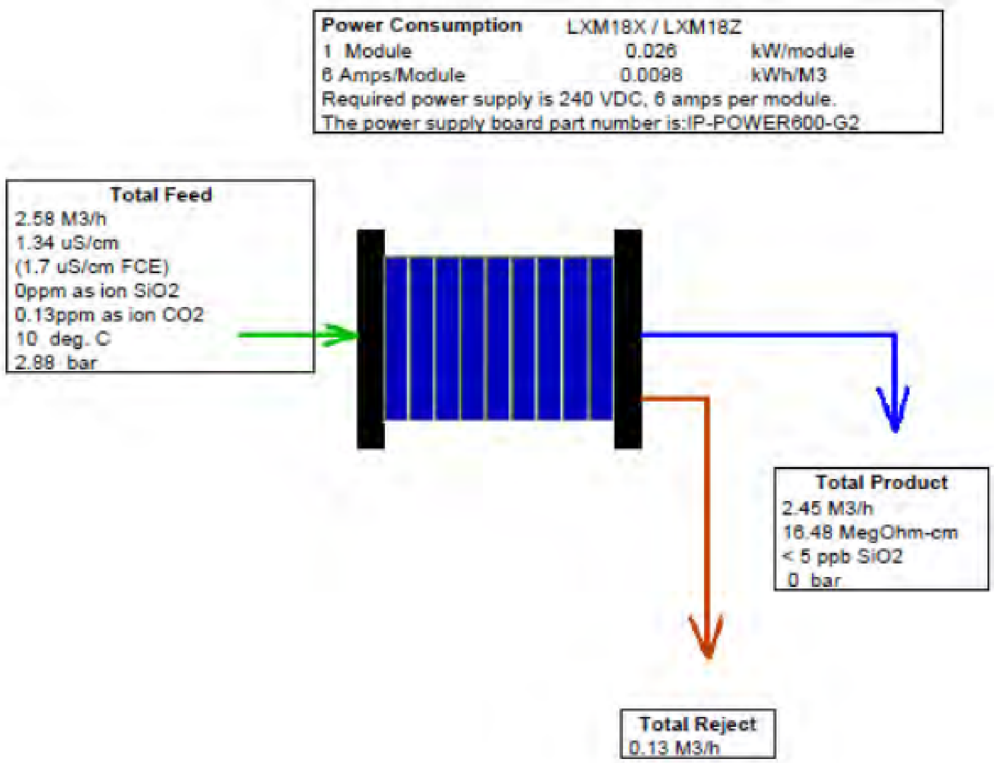


Figure IV.27: CEDI original design projections.

The figure above shows that the feed conductivity used for the simulation was 1.34 $\mu S/cm$ at 10°C (another simulation at 30°C is also available). The effect of this very low conductivity is that the calculated operation current for the unit is also low which in turn means that the unit would not be able to handle a higher feed conductivity (which is the case in reality) and

[7] FCE ($\mu S/cm$) = EC ($\mu S/cm$) + 2.79*CO2(mg/l) + 1.94*SiO2(mg/l)

would never be able to do so without adjusting the current.

Another design anomaly that can be noted is that the CEDI module chosen (IP-LXM18Z-1) is not rated to be able to handle the the feed and product flows required by GRN as demonstrated in Table IV.5.

Table IV.5: CEDI module model numbers and nominal flow rates (IonPure, 2010)

Order Number	Model Number	Nominal Flow	Description
W3T17286	IP-LXM04Z-1	2 gpm [0.44 m^3/hr]	Single LX Type – 4 Cell
W3T17291	IP-LXM10Z-1	5 gpm [1.1 m^3/hr]	Single LX Type – 10 Cell
W3T17297	IP-LXM18Z-1	9 gpm [2.0 m^3/hr]	Single LX Type – 18 Cell
W3T17303	IP-LXM24Z-1	12.5 gpm [2.8 m^3/hr]	Single LX Type – 24 Cell
W3T17312	IP-LXM30Z-1	15 gpm [3.3 m^3/hr]	Single LX Type – 30 Cell
W3T17314	IP-LXM45Z-1	22.5 gpm [5.1 m^3/hr]	Single LX Type – 45 Cell

IV.7 Diagnosis of the DEOX system:

IV.7.1 Product water characteristics:

The DEOX units have been producing water with a dissolved oxygen concentration higher than 100 ppb (it is most likely much higher because 100 ppb is the limit of the measurement method used) with the specifications requiring it to be less than 10 ppb, this means that the product water is 10 times higher than the required value.

IV.7.2 General history of the unit:

The oxygen scavenger membranes membranes were changed in the same time period as the reverse osmosis membrane but no meaningful results were noticed due to the fact that the DEOX unit needs nitrogen gas to function which hasn't been available for a while at GRN due to the fact that the nitrogen utility in the plant hasn't been operational.

There are also some major leaks all around the unit that affect its performance by letting air into the system which in turn increases the dissolved oxygen concentration thus rendering the de-oxygenation process ineffective.

Another issue that can be noted is that even when the nitrogen unit is operational it can only produce gas with a 97 % purity while the DEOX system requires a 99 % purity.

IV.8 Conclusion:

In this chapter, the performance of the water treatment unit of GRN was evaluated at each step of the treatment process with the observed values being compared to the required specifications. The diagnosis of all the parts of the unit was also discussed with the possible issues that affect each one being established so that the rehabilitation of the unit can be conducted so that the unit can return to producing water at the required specifications.

Chapter V

Rehabilitation of GRN's water treatment unit:

V.1 Introduction:

The GRN water treatment unit has demonstrated significant operational challenges, which have been meticulously diagnosed in the previous chapter. This chapter focuses on the comprehensive rehabilitation of the unit to restore and enhance its operational efficiency.

The rehabilitation process will involve a systematic evaluation of each component, identifying necessary upgrades, replacements, and procedural changes. The aim is to not only rectify existing deficiencies but also to future-proof the unit against potential issues and facilitating the troubleshooting process for any potential issues, ensuring sustainable and reliable performance.

V.2 General preventative measures:

The first step to the rehabilitation of the water treatment unit is the implementation of proper preventative measures to ensure the sustainability of the performance of the unit after the changes that will be recommended are implemented. This will also provide valuable information in the case of any future problems as the troubleshooting process will be rendered much simpler and more precise.

V.2.1 Conducting additional chemical analysis:

Certain chemical analysis should be conducted regularly to ensure the effectiveness of pretreatment system as well as the stability of the feed water to each unit. these analysis can be divided into two categories:

V.2.1.1 Analysis to be conducted frequently:

These tests should be conducted on a regular basis due to there importance and immediate effect on the unit:

Turbidity: Turbidity is measure of suspended solids in a liquid, with the membrane manufacturer setting the maximum turbidity value in the feed water going into the RO units as 1 NTU.

Turbidity can be measured by the spectrophotometer already available at GRN's laboratory. the measurements should be conducted on a daily basis. If the turbidity level surpasses the maximum set by the manufacturer increasing the backwash cycle's duration for the sand filters or operating them both simultaneously will solve the issue.

SDI measurements: As discussed in Chapter 3 the silt density index is an important factor in determining the fouling potential of the water to be fed to the RO units.

This test should be conducted on a bi-weekly basis on the feed water to both RO units after passing by the cartridge filters as per the testing standard ASTM D4189-23. The membranes used require the SDI value to be less than 5, therefore any value above 5 indicates that the fouling of the membranes is imminent and that there is an issue in the pretreatment system.

Free chlorine tests: Free chlorine is another parameter that should be tested vigilantly on a daily basis as the RO membranes are very sensitive to oxidants with the manufacturer setting a maximum free chlorine concentration of 0.1 ppm.

This test can give great insight on the effectiveness of the dechlorination system. The free chlorine concentration should be measured at the feed side of both RO units with the ISO 7393-2:2017 being one of the methods that can be used to do so.

LSI measurements: Langelier Saturation Index (LSI), is an essential parameter to observe because it can evaluate the performance of the scale inhibitor.

LSI is measured from the concentrate water coming out of each RO unit once a week, with acceptable values being less than 0.

V.2.1.2 Analysis to be conducted yearly or in case of accidents:

Water composition: Conducting general water analysis to monitor any changes in the feed water quality is an important thing to do as it can give indications on what cleaning protocols to use and whether any additional chemical treatment is necessary for the system. This is conducted on raw water.

Bacterial analysis: Having an idea of the bacteria levels present in the water can help determine the disinfection process to use and optimize current usage.

V.2.2 Data monitoring and interpretation:

As discussed in chapter 4, there is a severe lack of operational data monitoring which in turn makes troubleshooting and diagnosing the systems, especially the RO units much harder. To remedy this problem the following parameters should be be monitored on a daily basis and any deviations from normal levels has to be noted and inspected:

V.2.2.1 RO units:

- Feed flow.
- Permeate flow.
- Reject flow.
- System recovery.
- feed pressure.
- Permeate pressure.
- Reject pressure.
- Feed temperature.
- Feed ORP.
- Membranes pressure drop.
- Cartridge filters pressure drop.

PS: These data are monitored in addition to the parameters that are already followed such as conductivity.

Collecting the data is not enough without a meaningful way of interpreting it. although interpreting and this is where data normalization (Discussed in Chapter 3) comes in. It can provide good insight when used in parallel with troubleshooting charts provided by the manufactures (Table V.1) to diagnose and solve any problems present with the units.

Data normalization can be a laborious task due to the complicated nature of equations and the fact that making a usable program to automate this process would take time. Thankfully, the manufacturer of the membranes used in GRN's unit (As with most other membrane manufacturers) provides a designated Excel program called RODataXL.8.2 that automates this process and provides all the necessary output graphs for all the normalized data therefore using it might be helpful.

Table V.1: RO troubleshooting matrix (DuPont, 2023)

Permeate flow	Salt passage	Differential pressure	Direct cause	Indirect cause	Corrective measure
↑	⇑	→	Oxidation damage	Free chlorine, ozone, $KMnO_4$	Replace element
↑	⇑	→	Membrane leak	Permeate backpressure; abrasion	Replace element, improve cartridge filtration
↑	⇑	→	O-ring leak	Improper installation	Replace O-ring
↑	⇑	→	Leaking product tube	Damaged during element loading	Replace element
⇓	↑	↑	Scaling	Insufficient scale control	Cleaning, scale control
⇓	↑	↑	Colloidal fouling	Insufficient pretreatment	Cleaning, improve pretreatment
↓	→	⇑	Biofouling	Contaminated raw water, insufficient pretreatment	Cleaning, disinfection, improve pretreatment
⇓	→	→	Organic fouling	Oil; cationic polyelectrolytes water hammer	Cleaning, improve pretreatment
⇓	↓	→	Compaction	Water hammer	Replace element or add elements

↑ Increasing ↓ Decreasing → Not changing ⇑ Main symptom

V.2.2.2 CEDI

- Feed flow.
- Permeate flow.
- Reject flow.
- System recovery.
- feed pressure.
- Permeate pressure.
- Reject pressure.
- Feed temperature.
- Pressure drop Across elements.
- Cartridge filters pressure drop.
- Voltage.
- Current.
- Resistance.

The following are the troubleshooting guidelines extracted from the CEDI unit's user manual:

Table V.2: CEDI troubleshooting matrix part 1 (IonPure, 2010)

Nr.	Malfunction	Possible cause	Remedy
1	System does not switch to operate	- start/stop production (XS101) not present	- check start/stop production (XS101) (must be closed contact) - chemical disinfection contact is closed
2	CEDI Feed water pressure too high	- RO plant or feed pump malfunction - Set point feed pressure not correct	- Check RO plant or feed pump - Verify if set point is correct
3	CEDI flow too low	- Low temperature - (Bio)fouling - Resin oxidized (e.g. free chlorine) - Scaling - Differential pressure low - No or not enough flow - Flow instrument defect or wrong settings - Clogged inlet spacers by particles (e.g. piping not flushed after erection) - Flow set point not correct	- Check if feed pressure is enough for low temperature - Clean module - Irreversible damage, contact supplier - Clean module - Feed pressure low and/or backpressure high. - Verify relevant valves adjustments - Verify correct operation and settings flow instrument - Contact supplier for reverse flow procedures - Verify set point

Table V.3: CEDI troubleshooting matrix part 2 (IonPure, 2010)

Nr.	Malfunction	Possible cause	Remedy
4	CEDI product water conductivity instrument	- Loose connections or wrong settings - Measured value higher then range	- Consult supplier manual in digital supplier documentation - Check conductivity value
5	CEDI product water conductivity pre-alarm CEDI product water conductivity alarm	- High feed water FCE - CEDI product flow too high - Scaling - Fouling - Feed water conductivity changed - Reject pressure higher than product pressure - Current too low - One or more module(s) with no or low current	- Check feed water quality - Adjust flow - Clean module - Clean module - Prepare new performance projection, adjust current - Adjust pressure difference to meet required pressure difference - Check DC current manually, adjust current setting - Check module electrical resistance, Voltage may be limited - Check Power board outputs
6	CEDI feed water temperature too high	- High water temperature from pre-treatment - Set point feed temperature not correct - Temperature sensor defect	- Check pre-treatment operation - Verify set point - Check conductivity/temperature electrode
7	CEDI product temperature too high	- High water temperature from pre-treatment - Set point feed temperature not correct - Temperature sensor defect - Continuous recirculation of CEDI product - High current on module(s) with low flow	- Check pre-treatment operation - Verify set point - Check conductivity/temperature electrode - Adjust CEDI feed flow rate - Adjust DC current setting or increase flow
8	Recovery too low (due to high flow concentrate)	- Valve adjustment - Malfunction flow instrument - Flow and or recovery set points not correct	- Adjust flow(s) concentrate - Check flow instrument - Verify set points

Table V.4: CEDI troubleshooting matrix part 3 (IonPure, 2010)

Nr.	Malfunction	Possible cause	Remedy
9	Recovery too high (due to low flow concentrate)	- Valve adjustment - Biological fouling - Flow instrument defect - Flow and or recovery set points not correct	- Adjust flow(s) concentrate - Clean module - Check flow instrument - Verify set points
10	DC power supply failure	- Power board malfunction - Electrical feed contactor to power board not energized - High electrical resistance of module, causes maximum DC voltage output. This result in lower amperage then set point (alarm will beenergized if actual value <75% of set point) -Fuse of powerboard	- Check power board - Verify product and concentrate flow - DC current is limited by the max voltage. Perform a chemical cleaning of the module if applicable. -Replace if broken
11	AC power supply failure	- Wrong phase sequence detected - missing phase(s) detected by phase monitor	- If this happens at first time start-up phase rotation might be different from testing site. Change 2 phases at the phase monitor - Reset or replace electrical feed fuse of transformer. After reset, check amperage and voltage of transformer. - Find the cause of missing phase(s)
12	CEDI pressure sensor defect	- Pressure sensor 2 mA > signal > 22 mA - Loose sensor connection - Malfunctioning sensor	- Check signal current - Check sensor connection - Consult supplier manual
13	Concentrate pressure too high	- Set point concentrate pressure not correct - Feed pressure too high	- Verify set point - See "Feed water pressure too high"
14	Differential (dP) pressure too low	- Valves adjustment -Too high flow through concentrate -Scaling / fouling of reject compartments	- Adjust pressure(s) until dP is within range. Product pressure 0,2 - 0,7 bar higher than reject pressure - Reduce recovery to correct setpoint -Clean module
15	Differential (dP) pressure too high	- Valves adjustment - too high flow through concentrate - scaling/ fouling of reject compartments	- Adjust pressure(s) until dP is within range. Product pressure 0,2 – 0,7 bar higher than reject pressure - Reduce recovery to correct setpoint - Clean module

V.2.2.3 DEOX:

- Nitrogen feed flow.
- Cooling water flow.
- Feed flow.
- Product flow.
- Nitrogen inlet pressure.
- Nitrogen vacuum pressure.
- Product water pressure.
- Cooling water flow.
- Feed water temperature.
- Cooling water temperature.

Table V.5: DEOX unit troubleshooting matrix (PureWater, 2015)

Nr.	Malfunction	Possible cause	Remedy
1.	O_2 removal insufficient	- Sweep gas settings incorrect - Degassed water flow rate too high - Degassed water temperature below specification - Vacuum pressure not low enough - Presence of deposit (biology) - Incorrect Oxygen measurement - Insufficient Nitrogen quality - Air (Oxygen) leakage to Nitrogen sweep gas.	- Check sweep gas settings - Check flow rate - Check temperature - Check vacuum pump operation - Check cooling water flow and temperature - Check for leakages at the vacuum piping - Check if vacuum pump need descaling - Check cleaning guidelines info membrane supplier (Membrana) - Calibrate Oxygen sensor or perform maintenance on oxygen sensor - O2 transmitter was not energized for some time: 6 hours of polarization and calibration needed. - Check Nitrogen quality - Check for leakages through flanges and connections
2.	Vacuum pump stopped	- Low cooling water flow - Thermal overload of pump	- Check flow rate is above cooling water flow switch - Check Fuse 100F5 and possible cause of overload: see vacuum pump manual.
3	General Alarm	- Low Nitrogen flow - Low cooling water flow - Thermal overload pump - Instrument alarm Feed water oxygen transmitter - Instrument alarm Degassed water oxygen transmitter	- Check flow rate - Check flow rate - Check Fuse 100F5 and possible cause of overload. - Check cause of transmitter alarm - Check cause of transmitter alarm

V.2.3 Chemical cleaning:

Chemical cleaning is arguably the most important preventative and corrective operation that can be conducted as a response to many issues in all the units of the water treatment plant with each unit having its own cleaning procedure and protocol.

V.2.3.1 RO unit:

Cleaning the RO units can be done periodically (every 6 months) but ideally it should be done following the trend of the normalized data where the following are the cases that indicate the necessity of conducting a cleaning:

- Normalized permeate flow decrease is less than 10%.
- Normalized permeate quality decrease is less than 10%.
- Normalized pressure drop, as measured between the feed and concentrate headers, increase is less than 15%.

The cleaning solution to be used should be selected according to the fouling/the issue at hand and the procedure should be done in accordance with the manufacturer's manual.

V.2.3.2 CEDI unit:

The CEDI unit is not as demanding in terms of cleaning as the RO units when they're properly designed, especially with double pass RO systems such as the one present at GRN as this means cleaning can be conducted once every 2 to 4 years using a chemical solution. But given the state of the system at GRN more frequent cleaning may be required (twice a year) to ensure proper operations.

The following cases indicate the need for cleaning the system:

- Product(dilute) differential pressure increases by 50% without a change in temperature and flow.
- Reject(concentrate) differential pressure increases by 50% without a change in temperature and flow.
- Product quality declines without a change in temperature, flow, or feed conductivity.
- The module's electrical resistance increases by 25% without a change in temperature.

V.2.3.3 DEOX unit:

The DEOX units usually do not need any cleaning due to the high purity of the feed water, but in certain cases the cooling water can carry deposits such as sand and solids which makes regularly cleaning the vacuum pumps necessary.

The unit should also be cleaned in case it is idle for a prolonged period of time.

V.3 Rehabilitation of the pretreatment system:

V.3.1 General recommendations:

The diagnosis of the pretreatment system exposed certain anomalies that subject the entire unit to devastating consequence. Dealing with the issues mentioned in chapter 4 is therefore essential. The following are the recommendation suggested for the Pretreatment system:

- Replacing the damaged parts of the descender found by the wells and getting back to operational status.
- Restarting the weekly biocide injection coupled with daily chlorine injections.
- Cleaning the raw water tank on a yearly basis
- Replacing the stroke of the dosing pumps (dechlorination and scale inhibitor) and ensuring proper dosing based on feed free chlorine concentration for the dechlorination system and LSI values for the scale inhibitor.
- Making sure the pumps automatically work as intended by the manufacturer (one duty and one on standby).

The aforementioned recommendations can be applied without the need of going through a long administrative and technical process and without incurring important costs. But a better more permanent solution that aligns with the current industry standards is the replacing the conventional pretreatment system currently used with micro or ultra-filtration (micro-filtration is more suitable) previously discussed in chapter 2. The technical details for such a change will be explained in chapter 6.

V.3.2 Expected results:

Conducting these operations will have positive results on the the quality of the feed water going into the RO1 unit, keeping the bacteria levels low, therefore protecting the reverse osmosis membranes from biofouling as well as the piping and equipment from corrosion. free chlorine concentration will also be kept at acceptable levels (< 1 ppm) in addition to removing any potential issues with scaling (confirmed with negative LSI in the RO1 and RO2 concentrates). Finally, overdosing issues will be solved and the RO membranes will therefore benefit from an increased operational life.

V.4 Rehabilitation of the service water package(RO1):

The rehabilitation of the RO1 unit is a multi step process that addresses each issue found in the diagnoses part separately:

V.4.1 Adjustment of the specifications:

The first step is to reevaluate the actual specifications of the unit.The specifications set for the service water package found in the original design requirements for the gas treatment plant (Petrofac, 2014a) is 200 mg/l TDS therefore using the following equation:

$$TDS = K \cdot EC \tag{V.1}$$

with:

TDS: Total dissolved solids (mg/l)
K: Conversion coefficient that varies from 0.5 to 0.89.
EC: Electrical conductivity ($\mu S/cm$).

Assuming a conversion factor K of 0.65 we get the following conductivity:

$$EC = \frac{TDS}{K}$$

$$= \frac{200}{0.65}$$

$$= 308\ \mu S/cm$$

Therefore the specifications for the RO1 unit permeate conductivity should be changed from 125 $\mu S/cm$ to 310 $\mu S/cm$ to get a more accurate idea on the state of operations of the unit.

V.4.2 Membrane elements replacement:

As previously noted only one RO1 train is currently operational with the other one being offline for a very long period of time due to both mechanical and membrane issues, therefore replacing the membranes is an important measure that needs to be done.

Although the RO1 unit train 1 is outputting permeate water of a quality consistent with the given specifications, due to the RO2 unit being designed based on very low TDS (around 30 mg/l) it is essential to keep the RO1 unit's quality as high as possible (TDS concentration as low as possible), thus the membranes of this train should also be changed.

The following are some considerations to keep in mind:

- Making sure to purchase the right membrane elements used for the initial design of the unit (Hydranautics ESPA2-LD) illustrated in Figure V.1.
- Ensuring the proper installation of the membranes and considering their delicate nature.

- Respecting proper storage conditions set by the manufacturer in the period prior to the replacement.
- The used membranes should be sent to a credited specialized laboratory to conduct an autopsy and determine the exact sources of fouling/scaling or physical damage.

Figure V.1: ESPA2-LD hydranautics reverse osmosis membranes (Hydranautics, 2024)

It is also recommended to keep a stock of spare membrane elements in case of any future issues.

V.4.3 General recommendations:

The following are some general recommendations to ensure the proper operations of the service water package:

- Repairing the pressure vessels for both trains while ensuring the availability of spare parts for any future issues.
- Adjusting the frequency of the high pressure pumps to be consistent with the design discharge pressure (16.6 bar @ 10°C, 10.7 bar at 30°C).
- Adjusting the feed and reject flows of the unit to get back to the design recovery of the system (75%).
- Ensuring the unit does not operate when water temperatures exceed 45°C and to only operate it at night in the summer time.

V.4.4 Expected results:

Applying these recommendations coupled with the preventative measures stated up above should provide the following results:

- Permeate water conductivity $< 300\ \mu S/cm$ and TDS 200 mg/l (actual projected results at 35°C illustrated in TableV.6).
- Stable permeate quality that degrades at a slower rate.
- Longer membrane operational lifespan.
- Less frequent need for membrane cleaning.
- Lower operating costs due to the less frequent membrane changes, cleanings and operating the unit at night time when energy prices are lowest.

Table V.6: Projected results of the RO1 unit at 35°C. (IMSDesign)

Ion (mg/l)	Raw Water	Feed Water	Permeate Water	Concentrate 1	Concentrate 2
Hardness, as CaCO3	407.21	407.21	0.299	752.8	1625.7
Ca	76.00	76.00	0.056	140.5	303.4
Mg	53.00	53.00	0.039	98.0	211.6
Na	200.00	200.00	7.629	367.0	776.1
K	33.00	33.00	1.426	60.5	127.5
NH4	0.00	0.00	0.000	0.0	0.0
Ba	0.000	0.000	0.000	0.0	0.0
Sr	0.000	0.000	0.000	0.0	0.0
H	0.00	0.00	0.002	0.0	0.0
CO3	0.17	0.17	0.000	0.6	3.4
HCO3	159.00	159.00	5.771	292.7	621.4
SO4	340.00	340.00	1.739	628.0	1352.9
Cl	255.00	255.00	5.181	469.6	1003.1
F	0.00	0.00	0.000	0.0	0.0
NO3	42.00	42.00	6.024	75.4	149.7
PO4	0.25	0.25	0.001	0.5	1.0
OH	0.00	0.00	0.000	0.0	0.0
SiO2	0.00	0.00	0.000	0.0	0.0
B	0.00	0.00	0.000	0.0	0.0
CO2	19.82	19.82	19.82	19.82	19.82
NH3	0.00	0.00	0.00	0.00	0.00
TDS	**1158.42**	**1158.42**	**27.87**	**2132.59**	**4550.17**
pH	**7.00**	**7.00**	**5.62**	**7.25**	**7.55**

V.5 Rehabilitation of the RO2 unit:

The process of rehabilitating the RO2 unit can follow a similar methodology as the RO1 unit:

V.5.1 Adjustment of specifications:

Similarly with the RO1 unit the specifications set for the unit are highly inaccurate due to the fact that they have been confused with the specifications of the entire demineralized water package (RO2 + CEDI + DEOX).

The remedy for this issue is rather simple and consistence of using the maximum input conductivity of the CEDI unit, mentioned in its user manual as the specification for the RO2 unit which is a conductivity equivalent including CO2 of 40 $\mu S/cm$ which can be converted to a regular conductivity using:

$$FCE\ (\mu S/cm) = EC\ (\mu S/cm) + 2.79 \cdot CO2\ (mg/l) + 1.94 \cdot SiO2\ (mg/l) \quad \text{(V.2)}$$

Therefore from Equation V.2 we get:

$$EC\ (\mu S/cm) = FCE\ (\mu S/cm) - 2.79 \cdot CO2\ (mg/l) - 1.94 \cdot SiO2\ (mg/l) \quad \text{(V.3)}$$

And by plugging in the projected results of the permeat quality of the unit we get the following:

$$\begin{aligned} EC\ (\mu S/cm) &= FCE\ (\mu S/cm) - 2.79 \cdot CO2\ (mg/l) - 1.94 \cdot SiO2\ (mg/l) \\ &= 40 - 2.79 \times 0.03 - 1.94 \times 0 \\ &\approx 40 \mu S/cm \end{aligned}$$

This value can be converted using Equation V.1 assuming a K value of 0.65 the equivalent TDS value is 26 mg/l

Meaning the specifications of the RO2 unit should be set at 40 $\mu S/cm$ conductivity and a TDS of 26 mg/l.

V.5.2 Membrane elements replacement:

Changing the RO2 membranes is a very important procedure to be conducted given the fact that the RO2 train 1 is completely offline and train 2 has gone off the required specifications, but more importantly, the membranes that are currently inside the pressure vessels do not match with the ones used for the initial design.

Following the proceeding considerations should help yield satisfactory results:

- Making sure to purchase the right membrane elements used for the initial design of the unit (Hydranautics ESPA2-LD-4040) illustrated in Figure V.1.

- Ensuring the proper installation of the membranes and considering their delicate nature.
- Respecting proper storage conditions set by the manufacturer in the period prior to the replacement.
- The used membranes should be sent to a credited specialized laboratory to conduct an autopsy and determine the exact sources of fouling/scaling or physical damage.
- Verifying that no leaks exist after the replacement process.

Figure V.2: ESPA2-LD-4040 hydranautics reverse osmosis membranes (Hydranautics, 2024)

V.5.3 General recommendations:

As for the general recommendations, the RO2 unit shares some of the same recommendations as the RO1 unit such as:

- Repairing the pressure vessels for both trains while ensuring the availability of spare parts for any future issues.
- Ensuring the unit does not operate when water temperatures exceed 45°C and to only operate it at night in the summer time.

In addition to the previously mentioned recommendation, another thing that should be done is going back to 5 micron cartridge filters instead of the 1 micron filters that are currently installed.

Finally, the initial design philosophy and assumptions such as using the projected results of the RO1 unit to design the RO2 unit without making any adjustments that take account of the gradual degradation of the permeate water quality of the RO1 unit especially with the increased risk due to high feed water temperature could lead to unreliable results regardless of the steps that are taken. Therefore a complete redesign of the RO2 unit will be conducted in the next chapter.

Table V.7: Projected results of the RO1 unit at 35°C (IMSDesign)

Ion (mg/l)	Raw Water	Feed Water	Permeate Water	Concentrate 1	Concentrate 2
Hardness, as CaCO3	0.31	0.31	0.000	0.6	1.4
Ca	0.06	0.06	0.000	0.1	0.3
Mg	0.04	0.04	0.000	0.1	0.2
Na	7.63	7.63	0.601	13.3	31.2
K	1.43	1.43	0.127	2.5	5.8
NH4	0.00	0.00	0.000	0.0	0.0
Ba	0.000	0.000	0.000	0.0	0.0
Sr	0.000	0.000	0.000	0.0	0.0
H	0.00	0.00	0.000	0.0	0.0
CO3	0.09	0.09	0.000	0.3	1.5
HCO3	5.77	5.77	0.302	10.0	23.0
SO4	1.64	1.64	0.012	2.9	7.1
Cl	5.18	5.18	0.152	9.2	22.0
F	0.00	0.00	0.000	0.0	0.0
NO3	6.02	6.02	1.233	10.0	22.1
PO4	0.00	0.00	0.000	0.0	0.0
OH	0.09	0.09	0.005	0.2	0.3
SiO2	0.00	0.00	0.000	0.0	0.0
B	0.00	0.00	0.000	0.0	0.0
CO2	0.03	0.03	0.03	0.03	0.03
NH3	0.00	0.00	0.00	0.00	0.00
TDS	**27.86**	**27.86**	**2.43**	**48.50**	**113.10**
pH	**8.40**	**8.40**	**7.13**	**8.64**	**8.99**

V.5.4 Expected results:

The following are the expected results of applying these recommendations:

- Permeate water conductivity $< 40\ \mu S/cm$ and TDS 25 mg/l (actual projected results at 35°C illustrated in Table V.7).
- Stable permeate quality that degrades at a slower rate.
- Longer membrane operational lifespan.
- Less frequent need for membrane cleaning.
- Less frequent changes for the cartridge filters.
- Lower operating costs due to the less frequent membrane and cartridge filter changes and cleanings and operating the unit at night time when energy prices are lowest.

V.6 Rehabilitation of the CEDI unit:

V.6.1 Adjusting the current of the unit:

As previously noted, the current set for the unit at the design level is not consistent with the feed water characteristics, therefore an electrical current adjustment is necessary and it should be calculated using the following formula provided by the manufacturer (IonPure, 2010):

$$I = \frac{1.31 \cdot Q \cdot FCE}{Dilute\ cells \cdot CE} \tag{V.4}$$

With:

I: Electrical current (Amp)

Q: Product flow (l/min).

FCE: Conductivity equivalent including CO2 ($\mu S/cm$).

Dilute cells: number of product(dilute) compartment cells(LX4 has 4 product compartment cells and LX10 has 10 product compartment cells ... LX45 has 45 product compartment cells) .

CE: Current efficiency in % (generally between 10 and 20).

Using the previous equation we can calculate the required current to operate the unit and get satisfactory results with feed water having the maximum allowable characteristics (40 $\mu S/cm$ FCE):

$$I = \frac{1.31 \cdot Q \cdot FCE}{Dilute\ cells \cdot CE}$$

$$= \frac{1.31 \times 40.83 \times 40}{18 \times 20}$$

$$= 5.94 \approx 6\ Amps$$

Therefore the unit should be set at 6 Amps in the next startup and adjusted after getting a better idea about the feed water quality going into the unit.

Although it is noteworthy to add that changing the CEDI module at use could be beneficial giving the fact that the current module model is not rated to handle the current feed flow rate, therefore the current calculations should be adjusted accordingly.

V.6.2 General recommendations:

- Replacing the CEDI modules due to the older ones being exposed to feed water with characteristics exceeding its maximum designated values.
- Verifying the proper installation of the new modules.
- Investigating the possibility of changing the module models to IP-LXM24Z-1 instead of IP-LXM18Z-1 with the manufacturer to better match operation conditions.

- Ensuring that the quality of the feed water (RO2 permeate) is within the acceptable range set by the manufacturer before staring up the unit.
- Adjusting the current of the unit regularly depending on the feed water conductivity.
- Replacing the cartridge filters diligently as soon as the differential pressure across them exceeds acceptable norms.

V.6.3 Expected results:

The following figures represent the projection summery of the CEDI unit performance with adjusted feed water characteristics based on RO2 permeate water projected characteristics at 35°C multiplied by a security factor assumed to be 6.5 (the projection was done using the projection software provided by IONPURE in their website) :

Table V.8: CEDI performance projection details.

Product Flow Rate	2.45 m^3/h
Module Type	LXM18-Z
Number of Modules	1
Flow per Module	2.4 m^3/h
Feedwater Conductivity @ 25°C	22.9 µS/cm
Feedwater Conductivity Equivalent	23.44 µS/cm
Total Exchangeable Anions (TEA)	10.9 ppm as $CaCO_3$
Maximum System Recovery	95 %
Product Water Resistivity	14.5 MΩ-cm
Product Water Conductivity	0.069 µS/cm
Salt Rejection	99.7 %
Dilute Pressure Drop	2.69 bar
Total Hardness (ppm as $CaCO_3$)	0

The table up above demonstrates that by adjusting the start up current of the unit it can achieve the desired dilute water specifications ($< 0.1\ \mu S/cm$) even in the most unfavourable conditions.

Applying the other recommendations will ensure the sustainability of the results achieved by the CEDI unit as well as lowering operational costs.

V.7 Rehabilitation of the DEOX unit:

V.7.1 General recommendations:

The rehabilitation of the de-oxygenation system is the most straight-forward in the whole water treatment unit as the issues are apparent and mostly related to the feed water, therefore by fixing the issues present in the previous steps of the treatment process good results should be observed at the DEOX level.

The follow recommendations should also be taken in consideration:

- Fixing all the leaks present in both DEOX trains.
- Replacing any faulty equipment.
- Replacing the DEOX contactors due to them being exposed to bad quality water for a long period of time.
- Ensuring the unit only functions within the specified range in terms of feed water quality.

V.7.2 Expected results:

By fixing all the aforementioned issues the unit is expected to go back into perfect operational conditions, producing product with a dissolved oxygen concentration < 10 ppb in a stable manner.

It will also decrease the operational cost of the unit especially in terms of chemical usage as well as decreasing the frequency of changing the degassing contactors and other parts.

V.8 Conclusion:

The rehabilitation of the water treatment unit at the gas treatment plant is essential for restoring functionality, improving efficiency, and ensuring regulatory compliance. This chapter outlined a thorough strategy involving assessment, prioritization of issues, and implementation of corrective measures, preventive maintenance, and technological upgrades.

Key areas of concern, such as membrane fouling and chemical imbalances, were identified and prioritized. The rehabilitation plan includes a structured implementation with clear timelines and responsibilities, supported by continuous monitoring and evaluation to ensure effectiveness.

In summary, the proposed rehabilitation strategy offers a comprehensive approach to address current challenges and ensure long-term operational excellence, contributing to the overall efficiency and sustainability of the gas treatment plant.

Chapter VI

Design of the improved water treatment unit:

VI.1 Introduction:

This chapter can be considered as drastic rehabilitation recommendation that will detail the design process of a new and improved water treatment unit of GRN, making sure to provide product water that respects the specifications set by GRN, therefore improving the overall operations of the gas treatment plant.

The overall process and individual steps of the water treatment unit will be retained with each sub-unit being redesigned to optimize their operations.

The first step in redesigning each unit is evaluating the new design considerations and philosophy as it will be a fundamental change in contrast with the current system.

VI.2 Design considerations:

Designing the new and improved water treatment unit will be undergone following certain design philosophies that are intended to be an adaption to the harsh conditions found in Reggane as well as the strict product water specifications to ensure no damage is done to the gas treatment facilities.

VI.2.1 Design considerations for the pretreatment system:

As opposed to the current unit that uses a conventional pretreatment system, the new system will utilise ultra-filtration witch is currently considered the optimal pretreatment choice for brackish water reverse osmosis system (Im et al., 2022). This choice will serve to decreace the need for chemical injections (biocide and chlore) by the wells to kill bacteria as ultra-filtration is more then capable of physically eliminating them due to the small pore size.

Designing the ultra-filtration system will be based on the following assumptions due to the lack of a comprehensive feed water analysis:

- Feed water turbidity > 1 NTU.
- Feed water TOC[1] > 2 ppm.
- Minimum feed water temperature of 10°C
- Maximum feed temperature of 35°C

VI.2.2 Design considerations for the first reverse osmosis system (RO1):

The design of the first reverse osmosis unit will not differ too much from the existing unit except for two major considerations:

- The use of WAVE reverse osmosis design software instead of IMSDesign which will in turn imply changing the membrane manufacturer.
- The focus of the unit will be to provide the highest quality water possible regardless of the energy consumption due to the abundance of energy resources at GRN and the critical need for a highly purified water.

VI.2.3 Design considerations for the second reverse osmosis system (RO2):

As for RO2 unit, it will also be subjected to the same design philosophies mentioned for RO1 with the main difference being that the unit will also be over-dimensioned to compensate for the the higher chance for faster degradation of the quality of the RO1 unit due to the harsh site conditions (mainly high feed temperatures).

VI.2.4 Design considerations for the CEDI and DEOX units:

Finally, as with the previously discussed units the CEDI will be designed following the worst case scenario which implies a feed equivalent conductivity including CO2 of 40 $\mu S/cm$ as opposed to directly using the permeate water conductivity extracted from the projection software.

As for the software that will be used for the CEDI unit, IONPURE IP PRO performance projection software made by EVOQUA is the choice. As for the DEOX unit, due to it not having any major design problems the original design will be retained.

[1] Total organic carbon

VI.3 WAVE projection software:

The water value application engine (WAVE) is a projection software developed by DuPont water solutions that integrates three of the leading technologies (ultrafiltration, reverse osmosis and ion exchange resin) into one comprehensive platform. The WAVE software is used to design and simulate the operation of water treatment systems using the UF, RO, and IER component technologies.

VI.3.1 Design process:

Upon opening the program, the user is first greeted with the screen illustrated in Figure VI.1 where the user can choose the technologies he would like his system to be comprised of as well as the feed and product flows in addition to the feed water type.

Project specific information (Currency, energy costs,pumps) can all be modified in the "User settings" tab.

Figure VI.1: WAVE software introduction screen

The second step in the design process entails entering the chemical characteristics of the feed water, with the most important ones being the anions and cations in addition to the PH in addition to the temperature settings as they are the minimum requirements to design the system, Although it is preferable to fill out all the information (Turbidity, SDI...) as this can lead to a more accurate design.

The program also provides to option to balance the chemical charge of the chemicals and provides different options to do so. It also provides the option to have multiple streams in case the feed water is comprised from a mix of different sources.

The following figure illustrates the feed water analysis entry screen:

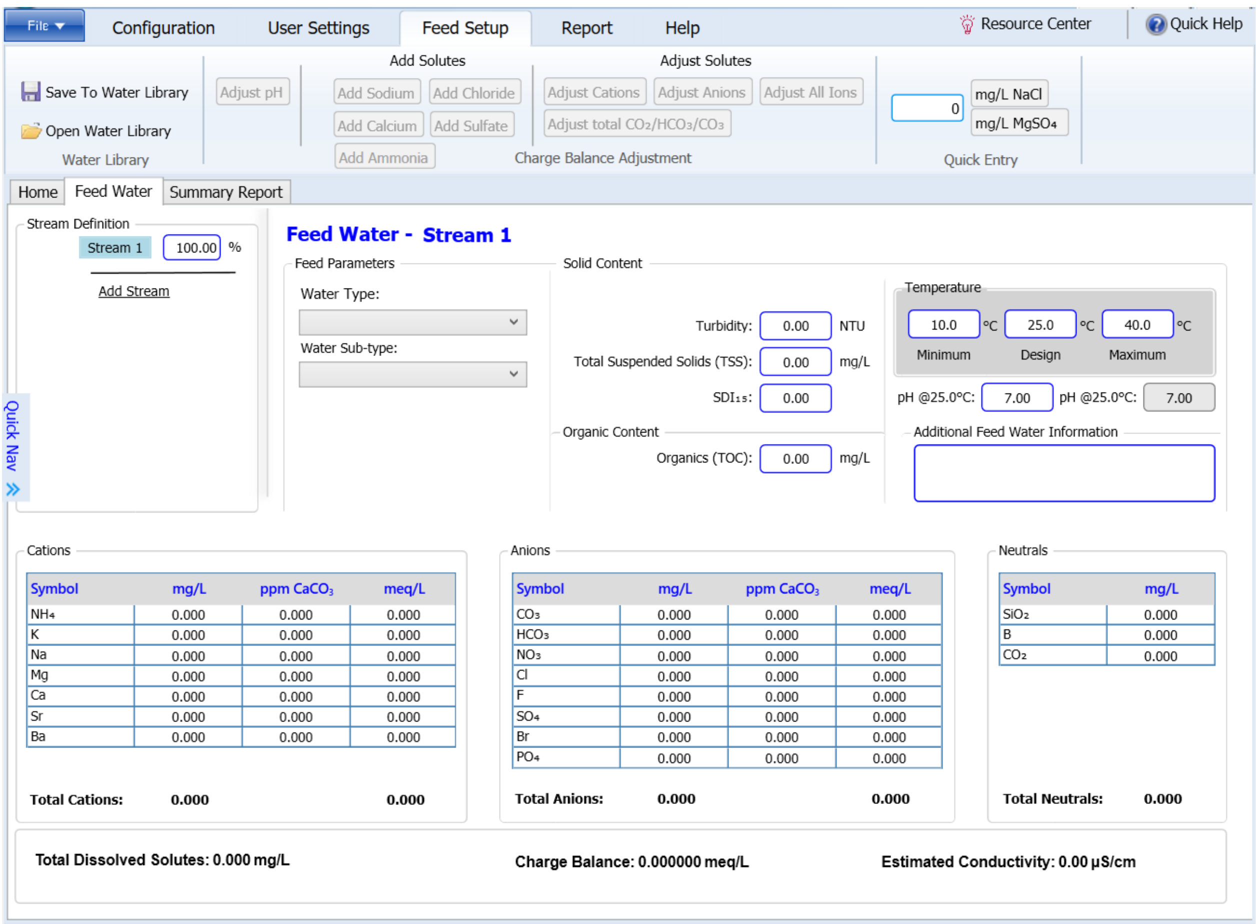


Figure VI.2: Feed water analysis entry screen.

The following steps depend on the chosen water treatment processes with each one having its own specific design screen that provides all of the specialised tools it needs.

Figure VI.3 illustrates an example of one of the design screens which is used for reverse osmosis systems.

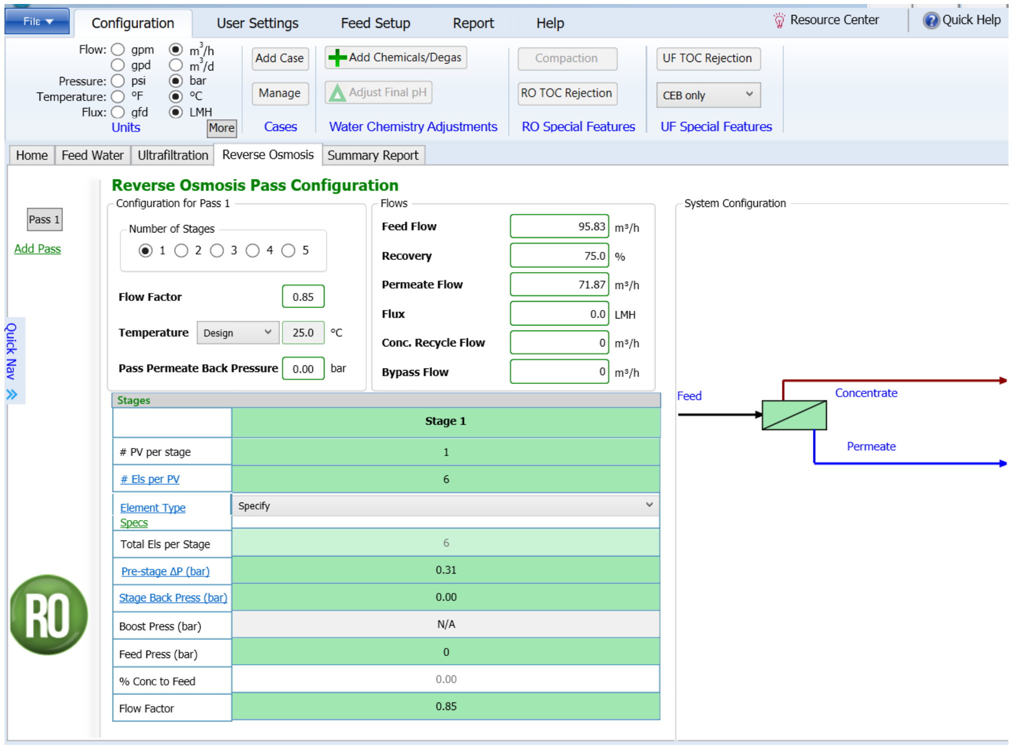


Figure VI.3: WAVE reverse osmosis system design screen

In this section the user can choose RO specific details such as the number of passes, stages, recovery of the system, number of elements per pressure vessel, as well as the RO membrane that will be used.

Chemical dosing can also be added in this section in case it is needed for the system to function properly.

VI.3.2 Simulation results and analysis:

WAVE offer three types of reports and analysis options for users with each one offering various functionalities:

VI.3.2.1 Standard summery report:

The standard summery report is generated as soon as all the information is inputted in the previously mentioned steps. Each treatment process has its own separate summery report that shows information specific to it. in general, the reports show the following data:

- System flow diagram.
- Projected treatment results.
- Projected ion concentrations.

- Operating data at different points of the system (feed, permeate/filtrate, reject).
- Design warnings when certain parameters surpass maximum limits.
- Special comments and recommendations.

VI.3.2.2 Detailed summery report:

The detailed summery reports differs from the standard one in several aspects, but mainly the fact that it adds operating costs of each unit and the eventual cost per m^3 of produced water.

VI.3.2.3 Batch simulation:

This is the most interesting aspect about WAVE as this functionality does not exist within other projection programs, and for this reason WAVE was chosen to design the new water treatment unit.

This option, demonstrated in Figure VI.4, allows the user to simulate the operation of the unit while changing certain variables which are the feed temperature, flow factor[2], and compaction. The availability of this option will make designing the RO2 unit at the worst case scenario easier.

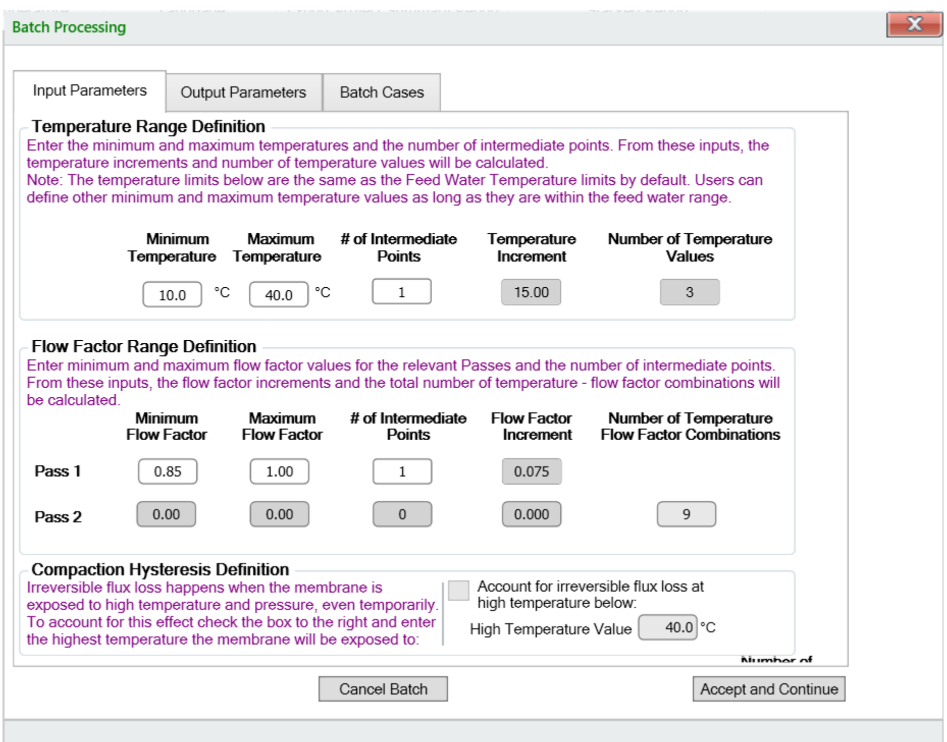


Figure VI.4: WAVE batch simulation input screen

[2]The Flow Factor is used in WAVE to account for flow loss due to fouling.

VI.4 Design of the ultrafiltration pretreatment system:

VI.4.1 Design parameters:

The first step in designing the ultrafiltration pretreatment system as discussed previously is inputting the feed water analysis as well as the temperature variations. The analysis illustrated in (CHAPTER 4) will be used (This step will carry over to the RO system design).

After inputting the feed water analysis the program estimates the following values:

- **TDS:** 1154 mg/l
- **Estimated electrical conductivity:** 1916.24 $\mu S/cm$

A product flow of 15.8 m^3 was also specified for the ultrafiltration system so that the appropriate volume of water is provided for the subsequent RO units, while the feed flow will be subsequently calculated based on the calculated recovery of the system.

VI.4.2 Membrane selection and specifications:

The membranes chosen for the pretreatment unit belong to the Integraflux family of ultrafiltration membranes which are the newest and most advanced ultrafiltration range made by DuPont water technologies. The choice was based on the following properties:

- The modules provide Up to 35 % higher permeability than previous generation modules helping to improve operating efficiencies and productivity.
- 0.03 μm nominal pore diameter for removal of bacteria, viruses, and particulates including colloids to protect downstream processes such as RO.
- The construction material provides high mechanical and chemical resistance therefore increasing the membrane's operational life.
- Does not need any form of pretreatment.

The following table provides the technical information about the membranes available in this range:

Table VI.1: Typical Properties of Integraflux ultrafiltration membranes (DuPont, 2019)

		Membrane Area		Volume		Weight (empty/water filled)	
Product	**Type**	**m^2**	**ft^2**	**liters**	**gallons**	**kg/lbs**	**kg/lbs**
SFP-2860XP	Industrial	51	549	35	9.3	48/83	106/183
SFD-2860XP	NSF/ANSI 61 and 419	51	549	35	9.3	48/83	106/183
SFP-2880XP	Industrial	77	829	39	10.3	61/100	135/220
SFD-2880XP	NSF/ANSI 61 and 419	77	829	39	10.3	61/100	135/220

Given the information provided in Table VI.1 the **SFD-2860XP** modules were chosen to them having the highest membrane surface area, therefore providing the highest operating flux, in addition to them being approved for drinking water purposes.

Table VI.2 provides the suggested operating conditions for the membranes:

Table VI.2: Suggested Operating Conditions (DuPont, 2019)

	SI Units	US Units
Filtrate Flux (25ºC)	40 – 110 l/m^{2}hr	24 – 65 gfd
Flow Range Per Module[1]	2.0 – 8.5 m^3/hr	8.8 – 37.4 gpm
Temperature	1 – 40ºC	34 – 104ºF
Maximum Inlet Module Pressure (20ºC)	6.25 bar	90.65 psi
Maximum Inlet Module Pressure (40ºC)	4.75 bar	68.89 psi
Maximum Operating TMP	2.1 bar	30.5 psi
Maximum Operating Air Scour Flow	12 Nm^3/hr	7.1 scfm
Maximum Backwash Pressure	2.5 bar	36 psi
Operating pH	2 – 11	
Maximum NaOCl	2,000 mg/L	
Maximum Particle Size	300 µm	
Flow Configuration	Outside in, dead end flow	
Expected Filtrate Turbidity	≤ 0.1 NTU	
Expected Filtrate SDI	≤ 2.5	

[1] Flow range represents DUPONT™ Ultrafiltration SFP-2860XP, SFD-2860XP, SFP-2880XP, and SFP-2880XP Modules for filtrate flux range shown

VI.4.3 System configuration:

The following are the system configuration parameters chosen for the unit:

- The system is designed to provide constant product flow and variable operating flux, therefore only backwash tank is needed as opposed to both a backwash and filtrate tanks.
- Strainer pore size of 150 μm with the limit of the modules being 300 μm.
- Filtration duration of 60 minutes before every backwash cycle.

After inputting the parameters up above the program suggests the following configurations:

Table VI.3: Recommended system configuration.

Option	Online Trains	Standby Trains	Total Trains	Max Offline BW/CEB	Modules/ Skid	Skids/ Train	Modules/ Train	Online Modules	Total Modules
1	1	1	2	1	-	-	6	6	12
2	2	1	3	1	-	-	4	8	12

VI.4.3.1 Option 1:

The following are the design results of the first suggested configuration:

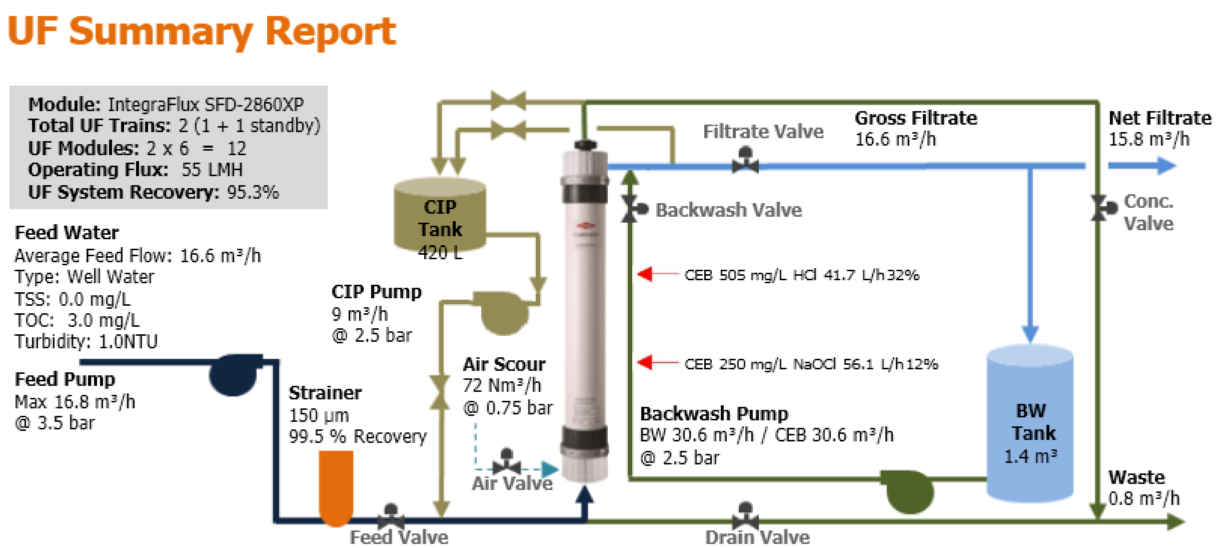


Figure VI.5: Option 1 summery overview

VI.4.3.2 Option 2:

The following figure illustrates the summery overview of the second suggested system configuration:

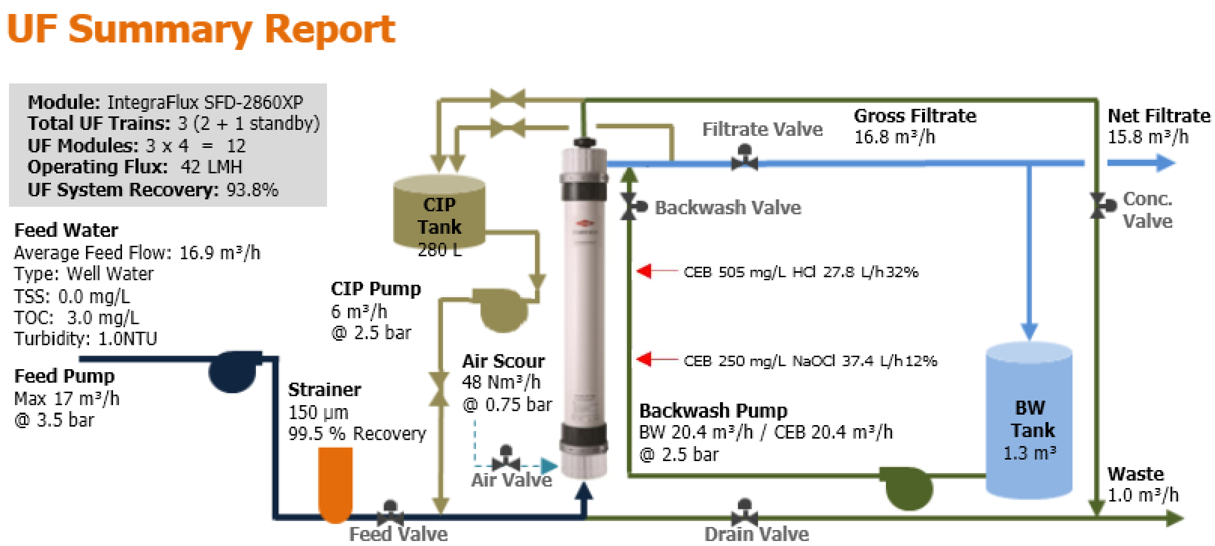


Figure VI.6: Option 2 summery overview

VI.4.4 Choosing a system configuration option:

The first option is the chosen system configuration for the pretreatment unit for the following reasons:

- Option one provides higher operating flux.
- Option one has higher system recovery therefore requiring less feed water and being more economical.
- The first option also has less operational trains therefore making maintenance and changing the membranes easier.
- The waste generated by option 1 is also lower than the second option.

VI.4.5 Final design results:

After choosing the system configuration and confirming all the previous parameters the following figures demonstrate various system results.

The first one being the system diagram containing the various flows and pressure at each set point in addition to the chemical injection points and the different doses.

Table VI.4: Ultrafiltration system overview

UF System Overview

Module Type		IntegraFlux SFD-2860XP		
# Trains		Online = 1		Standby = 1
				Redundant = 0
# Modules		Per Train = 6		Total = 12
System Flow Rate	(m^3/h)	Gross Feed = 16.6		Net Product = 15.8
Train Flow Rate	(m^3/h)	Gross Feed = 16.6		Net Product = 15.8
UF System Recovery	(%)	95.26		
TMP	(bar)	0.34 @ 10.0 °C		0.19 @ 35.0 °C
Utility Water		Forward Flush:	UF filtrate water	Backwash: UF filtrate water

Table VI.5: Ultrafiltration system operating conditions:

UF Operating Conditions

	Duration	Interval	Flux/Flow
Filtration:	60.0 min	62.7 min	-
Instantaneous			
1 Online Trains			55 LMH
2 Total Trains			27 LMH
Average			27 LMH
Net			26 LMH
Backwash	2.7 min	62.7 min	100 LMH
Acid CEB	14.6 min	36 h	100 LMH
Alkali CEB	14.6 min	12 h	100 LMH
CIP	308.4 min	90 d	1.50 m^3/h
Membrane Integrity Testing	12.0 min	24 h	-

It should be noted that the calculated flux of each operation was calculated by the program and fixed to be within the recommended range for the chosen membranes with:

CEB: Chemically enhanced cleaning.

CIP: Cleaning in place.

Table VI.6: Ultrafiltration system projected water quality results at 35°C

UF Water Quality

Stream Name		Stream 1	
Water Type		Well Water (10.0 - 40.0 °C)	
		Feed	**Expected UF Product Water Quality**
Temperature	(°C)	35.0	35.0
Turbidity	(NTU)	1.0	≤ 0.1
Organics (TOC)	(mg/L TOC)	3.0	2.7
TDS	(mg/L)	1160	1160
pH		7.6	7.6

VI.5 Design of the first reverse osmosis unit (RO1):

VI.5.1 Design parameters:

As previously discussed the the design parameters inputted for the ultrafiltration system carry over to the RO unit so there is no need to repeat the first step.

The following are the additional information that need to be set to design the unit:

- **Permeate flow:** 11.82 m^3/h
- **Recovery:** 75 %
- **Permeate back pressure[3]:** 1.5 bar calculated based on the service water tank height (15 m).
- **Flow factor:** 0.85.
- **Temperature range:** min: 10°C, design: 35°C, max: 40°C.

[3]Necessary when sending the permeate to a storage tank

VI.5.2 Membrane selection and specifications:

The membrane elements chosen for the design of the unit is the **ECO PRO-400** Spiral-wound element with polyamide thin-film composite reverse osmosis membrane made by DuPont.

The selection was made based on the following considerations:

- Membrane active area per element.
- Salt rejection in relation to energy consumption.
- Fouling resistance and chemical tolerance.
- Brackish water specific elements.

Table VI.7 demonstrates the typical properties of the membrane elements:

Table VI.7: Typical properties of the ECO PRO-400 membrane elements (DuPont, 2023)

Typical Properties

FilmTec™ Element	Active Area (ft^2)	Active Area (m^2)	Feed Spacer Thickness (mil)	Permeate Flow Rate (GPD)	Permeate Flow Rate (m^3/d)	Typical Stabilized Salt Rejection (%)	Minimum Salt Rejection (%)
Eco Pro-400	400	37	34-LDP	11,500	43.5	99.7	99.4

While Table provides the operating limits of the aforementioned elements:

Table VI.8: Operating and cleaning limits of the ECO PRO-400 membrane elements (DuPont, 2023)

Maximum Operating Temperature [a]	113°F (45°C)
Maximum Operating Pressure	600 psig (41 bar)
Maximum Element Pressure Drop	15 psig (1.0 bar)
pH Range	
Continuous Operation [a]	2 – 11
Short-Term Cleaning (30 min.) [b]	1 – 13
Maximum Feed Silt Density Index (SDI)	SDI 5
Free Chlorine Tolerance [c]	< 0.1 ppm

VI.5.3 System configuration:

As opposed to the ultrafiltration unit, the system configuration for the RO units needs to be calculated manually, and this is done by following these steps:

VI.5.3.1 Water flux:

Selecting the appropriate water flux range for the specific water type found in site is essential for a well made design that respects set norms. The water flux range suggested by DuPont in their membrane system design guidelines for 8" FilmTec™ elements is **27-34 LMH**. It should also be noted that designing for the lowest possible water flux is recommended to minimize the effect of concentration polarization and preserve the membranes.

VI.5.3.2 Number of elements:

The required number of elements is calculated using the following equation:

$$J_w = Q_p \, \frac{1}{m_a \cdot n_e} \tag{VI.1}$$

With:

J_w: selected water flux (29 LMH for our purposes).
Q_p: Permeate flow rate (m^3/h).
m_a: Membrane active surface area (m^2).
n_e Number of elements.

Therefore :

$$J_w = Q_p \, \frac{1}{m_a \cdot n_e}$$

$$0.029 = 11.82 \cdot \frac{1}{37 \cdot n_e}$$

$$n_e = 11.82 \cdot \frac{1}{37 \cdot 0.029}$$

$$= 11.01 \; elements$$

Therefore the calculated total number of elements for the system is 11 elements but to get more logical results the number of elements will be rounded up to **12 elements**.

VI.5.3.3 Number of pressure vessels:

The number of pressure vessels present in the system relies mainly on the number of pressure elements present in each pressure vessel which ranges between 1 and 8, with the most common being **6 elements per pressure vessel** which will be the one used in this system. the number of pressure vessels is calculated as follows:

$$n_V = \frac{n_e}{n_{epv}} \tag{VI.2}$$

With:

n_v: Number of pressure vessels in the system.
n_{epv}: Number of elements per pressure vessel.

Which implies:

$$n_V = \frac{n_e}{n_{epv}}$$

$$= \frac{12}{6}$$

$$= 2\ Pressure\ vessels$$

VI.5.3.4 Final array choice:

The system array configuration is chosen based on the desired recovery, the number of pressure vessels present in the system, and the number of elements per pressure vessels.

Given our selected system recovery of 75 %, and the number of pressure vessels, a **1:1 system** is the most common array configuration that is used to achieve the desired recovery, therefore it will be used for GRN's unit.

VI.5.4 Final design results:

In contrast with the ultrafiltration system, the simulations for the RO units have to be done at the minimum and maximum feed water temperatures to account of differences in the water viscosity and therefore permeate quality and high pressure pumps configurations.

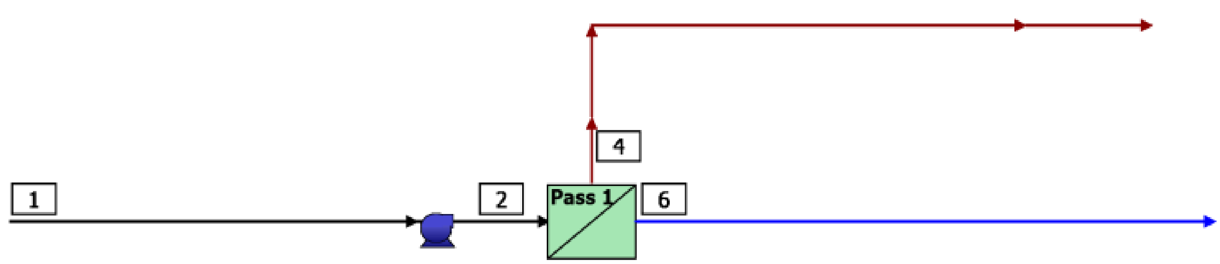


Figure VI.7: Reverse osmosis system diagram

VI.5.4.1 Results at 10°C:

Table VI.9: Revers osmosis system overview at 10°C

Pass		**Pass 1**
Stream Name		Stream 1
Water Type		Well With DuPont UF, SDI < 2.5
Number of Elements		12
Total Active Area	(m^2)	446
Feed Flow per Pass	(m^3/h)	15.8
Feed TDS[a]	(mg/L)	1,155
Feed Pressure	(bar)	14.4
Flow Factor Per Stage		0.85, 0.85
Permeate Flow per Pass	(m^3/h)	11.8
Pass Average flux	(LMH)	26.5
Permeate TDS[a]	(mg/L)	9.93
Pass Recovery		74.7 %
Average NDP	(bar)	9.8
Specific Energy	(kWh/m^3)	0.67
Temperature	(°C)	10.0
pH		7.7
Chemical Dose		-
RO System Recovery		75.0 %
Net RO System Recovery		75.0%

Several notes can be extracted from Table VI.9:

- The required maximum feed pressure for the system is 14.4 bar.
- The permeate quality is of an extremly high quality (10 mg/l TDS) which is compliant with the required specifications.
- The average flux of the system is within the recommended range.

Table VI.10: Reverse osmosis system solutes results at 10°C

Concentrations (mg/L as ion)						
		Concentrate		Permeate		
	Feed	Stage1	Stage2	Stage1	Stage2	Total
NH_4^+	0.00	0.00	0.00	0.00	0.00	0.00
K^+	32.85	55.76	129.7	0.36	0.88	0.59
Na^+	189.1	321.5	749.5	1.46	3.66	2.45
Mg^{+2}	52.76	89.94	211.0	0.02	0.06	0.04
Ca^{+2}	79.63	135.8	318.4	0.05	0.12	0.08
Sr^{+2}	0.00	0.00	0.00	0.00	0.00	0.00
Ba^{+2}	0.00	0.00	0.00	0.00	0.00	0.00
CO_3^{-2}	0.71	2.02	9.30	0.00	0.00	0.00
HCO_3^-	159.4	268.6	613.8	2.10	5.15	3.47
NO_3^-	42.19	71.47	165.5	0.67	1.67	1.12
F^-	0.00	0.00	0.00	0.00	0.00	0.00
Cl^-	261.2	444.7	1,040	0.99	2.47	1.65
Br^{-1}	0.00	0.00	0.00	0.00	0.00	0.00
SO_4^{-2}	321.5	548.0	1,285	0.23	0.59	0.39
PO_4^{-3}	0.20	0.34	0.80	0.00	0.00	0.00
SiO_2	14.57	24.78	57.90	0.08	0.20	0.13
Boron	0.00	0.00	0.00	0.00	0.00	0.00
CO_2	4.35	4.83	6.82	4.57	6.00	5.22
TDS[a]	1,154	1,963	4,582	5.96	14.80	9.93
Cond. µS/cm	1,916	3,145	6,827	9	22	15
pH	7.7	7.9	8.0	6.0	6.3	6.2

It is important to not that these results show that the PH at the permeate level drop bellow the recommended range for another RO pass which means a PH adjustment is necessary.

Table VI.11: Reverse osmosis chemical adjustment results at 10°C

	Pass 1 Feed	RO 1st Pass Conc
pH	7.7	8.0
Langelier Saturation Index	-0.11	1.32
Stiff & Davis Stability Index	0.23	1.14
TDS[a] (mg/l)	1,154	4,582
Ionic Strength (molal)	0.02	0.10
HCO_3^- (mg/L)	159.4	613.8
CO_2 (mg/l)	4.35	6.82
CO_3^{-2} (mg/L)	0.71	9.30
$CaSO_4$ (% saturation)	4.7	37.1
$BaSO_4$ (% saturation)	0.00	0.00
$SrSO_4$ (% saturation)	0.00	0.00
CaF_2 (% saturation)	0.00	0.00
SiO_2 (% saturation)	15.3	55.3
$Mg(OH)_2$ (% saturation)	0.00	0.02

Finally Table VI.11 illustrate the concentrations of notable scaling chemicals in the concentrate of the system. Given the LSI and SDSI results which are positive in the concentrate, an antiscalant is required to avoid any issues.

VI.5.4.2 Results at 40°C:

The following tables demonstrate the results of the worst case scenario of the RO1 unit, which occurs at a feed temperature of 40°C.

The information provided with Table VI.12 illustrates that the maximum TDS result achieved at the worst case scenario is 58.94 mg/l which is still significantly below the set specifications of 200 mg/l, even while factoring in the salt rejection loss due to cleaning and other site conditions the RO1 unit is guaranteed to always produce water that complies with the client's demands.

Table VI.12: Revers osmosis system overview at 40°C

Pass		**Pass 1**
Stream Name		Stream 1
Water Type		Well With DuPont UF, SDI < 2.5
Number of Elements		12
Total Active Area	(m^2)	446
Feed Flow per Pass	(m^3/h)	15.8
Feed TDS[a]	(mg/L)	1,154
Feed Pressure	(bar)	7.1
Flow Factor Per Stage		0.85, 0.85
Permeate Flow per Pass	(m^3/h)	11.8
Pass Average flux	(LMH)	26.5
Permeate TDS[a]	(mg/L)	58.94
Pass Recovery		74.7 %
Average NDP	(bar)	2.9
Specific Energy	(kWh/m^3)	0.33
Temperature	(°C)	40.0
pH		7.6
Chemical Dose		-
RO System Recovery		75.0 %
Net RO System Recovery		75.0%

Another note that can be added is that the system operates at lower feed pressure at the higher temperatures which is reflected by the lower pump specific energy (0.33 KWh/m^3 compared to 0.67 KWh/m^3). Therefore given the fact that the system would operate at higher temperatures more often than not, the operational costs (calculated subsequently) will be based on this specific energy.

Table VI.13: Reverse osmosis system solutes results at 40°C

Concentrations (mg/L as ion)						
		Concentrate		Permeate		
	Feed	Stage1	Stage2	Stage1	Stage2	Total
NH_4^+	0.00	0.00	0.00	0.00	0.00	0.00
K^+	32.85	60.56	121.3	1.92	5.84	3.37
Na^+	189.1	351.2	712.2	8.24	25.99	14.81
Mg^{+2}	52.76	99.89	210.3	0.14	0.47	0.26
Ca^{+2}	79.63	150.7	317.0	0.28	0.95	0.53
Sr^{+2}	0.00	0.00	0.00	0.00	0.00	0.00
Ba^{+2}	0.00	0.00	0.00	0.00	0.00	0.00
CO_3^{-2}	0.86	2.78	9.30	0.00	0.02	0.01
HCO_3^-	158.9	288.8	564.5	11.22	33.84	19.59
NO_3^-	42.19	76.78	150.3	3.58	10.59	6.18
F^-	0.00	0.00	0.00	0.00	0.00	0.00
Cl^-	261.2	490.0	1,013	5.77	19.21	10.74
Br^{-1}	0.00	0.00	0.00	0.00	0.00	0.00
SO_4^{-2}	321.5	608.2	1,278	1.39	4.69	2.61
PO_4^{-3}	0.20	0.38	0.78	0.00	0.01	0.01
SiO_2	14.57	27.21	55.79	0.45	1.47	0.83
Boron	0.00	0.00	0.00	0.00	0.00	0.00
CO_2	4.57	5.41	7.80	4.70	5.71	5.07
TDS[a]	1,154	2,157	4,433	32.99	103.1	58.94
Cond. µS/cm	1,916	3,438	6,654	49	154	88
pH	7.6	7.7	7.8	6.5	6.9	6.7

The table up above demonstrates that all solute concentrations rise with the temperature increase while always staying below the recommended levels.

Finally, the LSI and SDSI both slightly increase which does not have an effect on the previous conclusion which is the need for using an antiscalant to prevent any potential scaling issues.

VI.5.5 Batch simulation:

Running a batch simulation helps follow the performance of the RO unit as different factors change.

The following graph represents the change in permeate TDS in function of both temperature and flow factor:

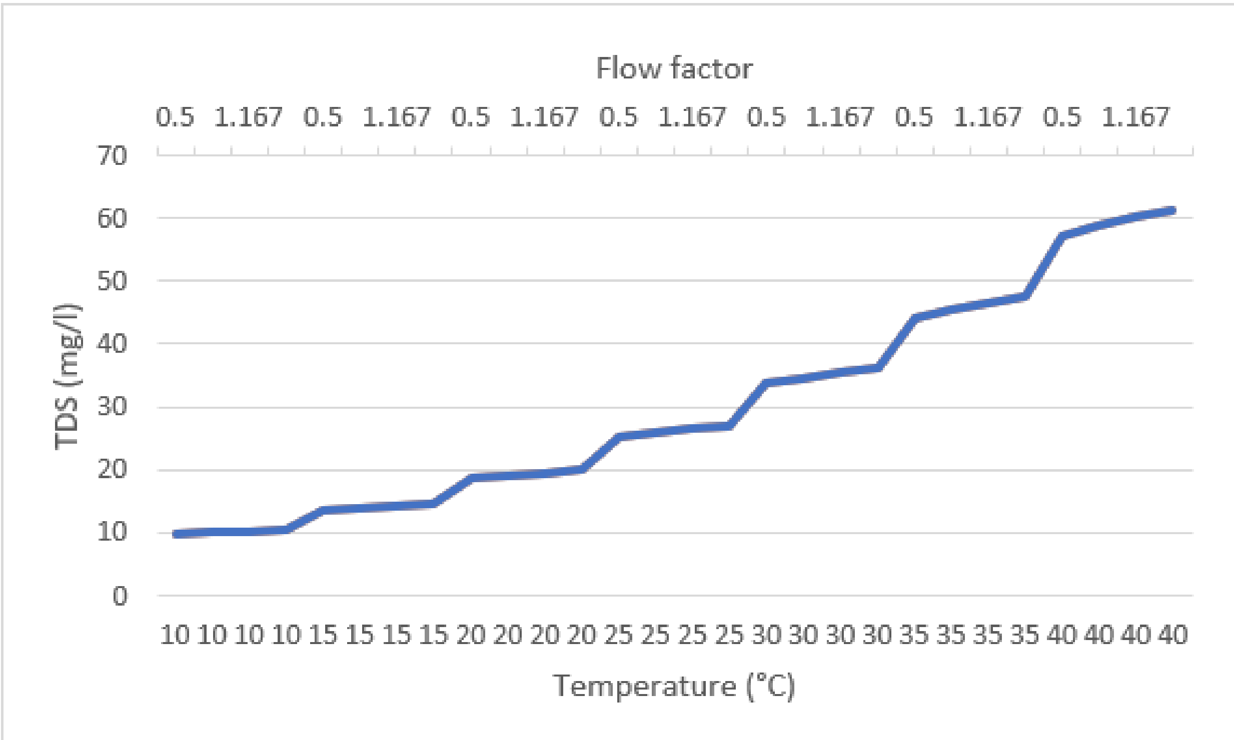


Figure VI.8: Evolution of permeate TDS in function of temperature and flow factor

The graph up above demonstrates that temperature and flow factor both have a negative impact on permeate quality with the the most significant impact being noticed from the increased temperature. The final maximum TDS obtained is 61 mg/l which will subsequently be used to design the RO2 unit.

VI.6 Design of the second reverse osmosis unit (RO2):

VI.6.1 Design parameters:

The design of the second reverse osmosis unit starts with inputting the feed water characteristics for which the The RO1 solute results at 40°C illustrated in Table VI.13 will be used. The following are additional system parameters:

- **Permeate flow:** 2.79 m^3/h
- **Recovery:** 77 % (To comply with maximum flow rate specifications.

- **Permeate back pressure[4]:** 1.5 bar.
- **Flow factor:** 0.85.
- **Temperature range:** min: 10°C, design: 35°C, max: 40°C.

VI.6.2 Membrane selection and specifications:

Based on the same previously mentioned considerations the membrane elements selected for the RO2 unit is **BW30PRO-4040** made by DuPont.

The selected membrane elements have the following specifications:

Table VI.14: Typical properties of the BW30PRO-4040 membrane elements (DuPont, 2023)

Product	Part Number	Active Area ft^2 (m^2)	Permeate Flow Rate gpd (m^3/d)	Stabilized Salt Rejection %
BW30 PRO-4040	12080524	85 (7.9)	2,600 (9.8) ±15%	99.7
BW30 PRO-2540	12081023	28 (2.6)	1,000 (3.8) ±20%	99.7

Table VI.15: Operating and cleaning limits of the ECO PRO-400 membrane elements (DuPont, 2023)

Membrane Type	Polyamide Thin-Film Composite
Maximum Operating Temperature[a]	113°F (45°C)
Maximum Operating Pressure	600 psi (41 bar)
Maximum Feed Flow Rate	
4040 Elements	16 gpm (3.6 m^3/h)
2540 Elements	6 gpm (1.4 m^3/h)
Maximum Pressure Drop	15 psig (1.0 bar)
pH Range	
Continuous Operation[a]	2 - 11
Short-Term Cleaning (30 min.)[b]	1 - 13
Maximum Feed Silt Density Index (SDI)	SDI 5
Free Chlorine Tolerance[c]	< 0.1 ppm

VI.6.3 System configuration:

VI.6.3.1 Water flux:

As per Membrane System Design Guidelines for Mid size FilmTec™ Elements, the appropriate flux rang for such a system that utilises RO permeate as feed water is **36-43 LMH**, and for our calculation we will use **37 LMH** for the same previously discussed reasons.

[4]Necessary when sending the permeate to a storage tank

VI.6.3.2 Number of elements:

Using Equations VI.1 it found that:

$$J_w = Q_p \, \frac{1}{m_a \cdot n_e}$$

$$0.037 = 2.79 \cdot \frac{1}{7.9 \cdot n_e}$$

$$n_e = 2.79 \cdot \frac{1}{7.9 \cdot 0.037}$$

$$= 9.54 \; elements$$

The number of elements is rounded down to **8 elements** for the same previously discussed reasons.

VI.6.3.3 Number of pressure vessels:

The RO2 unit will use **4 elements per pressure vessel** to achieve the desired results. Using Equation VI.2 It is calculated that:

$$n_V = \frac{n_e}{n_{epv}}$$

$$= \frac{8}{4}$$

$$= 2 \; Pressure \; vessels$$

VI.6.3.4 Final array choice:

Due to the aforementioned results coupled with the 77 % recovery of the system, the most appropriate system array is a **1:1 system**.

VI.6.4 Final results:

The system will has the same diagram as the first RO unit shown in Figure VI.7. The results for this unit will also be shown at the minimum and maximum design temperatures.

VI.6.4.1 Results at 10°C:

Table VI.16: Second revers osmosis system overview at 10°C

Pass		**Pass 1**
Stream Name		Stream 1
Water Type		RO/NF Permeate (SDI < 1)
Number of Elements		8
Total Active Area	(m^2)	69.9
Feed Flow per Pass	(m^3/h)	3.62
Feed TDS[a]	(mg/L)	59.01
Feed Pressure	(bar)	25.5
Flow Factor Per Stage		0.85, 0.85
Permeate Flow per Pass	(m^3/h)	2.79
Pass Average flux	(LMH)	39.9
Permeate TDS[a]	(mg/L)	0.58
Pass Recovery		77.1 %
Average NDP	(bar)	23.2
Specific Energy	(kWh/m^3)	1.15
Temperature	(°C)	10.0
pH		6.9
Chemical Dose		-
RO System Recovery		77.0 %
Net RO System Recovery		77.0%

The following information can be concluded from the table above:

- The required maximum discharge pressure of the high pressure pumps is 25.5 bar.
- The permeate water is of an extremely pure nature and but is still far from reaching the final desired quality of 0.1 $\mu S/cm$ which means the CEDI unit is still needed.
- The average flux of system is within the required limits.

Table VI.17: Second reverse osmosis system solutes results at 10°C

Concentrations (mg/L as ion)						
		Concentrate		Permeate		
	Feed	Stage1	Stage2	Stage1	Stage2	Total
NH_4^+	0.00	0.00	0.00	0.00	0.00	0.00
K^+	3.37	5.58	14.63	0.01	0.01	0.01
Na^+	14.81	24.52	64.26	0.04	0.08	0.06
Mg^{+2}	0.26	0.43	1.13	0.00	0.00	0.00
Ca^{+2}	0.53	0.88	2.31	0.00	0.00	0.00
Sr^{+2}	0.00	0.00	0.00	0.00	0.00	0.00
Ba^{+2}	0.00	0.00	0.00	0.00	0.00	0.00
CO_3^{-2}	0.01	0.02	0.12	0.00	0.00	0.00
HCO_3^-	19.60	32.42	84.80	0.40	0.43	0.41
NO_3^-	6.18	10.21	26.68	0.04	0.09	0.06
F^-	0.00	0.00	0.00	0.00	0.00	0.00
Cl^-	10.74	17.79	46.66	0.01	0.03	0.02
Br^{-1}	0.00	0.00	0.00	0.00	0.00	0.00
SO_4^{-2}	2.61	4.32	11.35	0.00	0.00	0.00
PO_4^{-3}	0.01	0.02	0.04	0.00	0.00	0.00
SiO_2	0.83	1.37	3.61	0.00	0.00	0.00
Boron	0.00	0.00	0.00	0.00	0.00	0.00
CO_2	5.44	5.45	5.51	5.19	5.22	5.20
TDS[a]	58.94	97.56	255.6	0.51	0.65	0.58
Cond. µS/cm	88	145	374	3	3	3
pH	6.9	7.1	7.5	5.2	5.3	5.3

VI.6.4.2 Results at 40°C:

Table VI.18: Second revers osmosis system overview at 40°C

Pass		Pass 1
Stream Name		Stream 1
Water Type		RO/NF Permeate (SDI < 1)
Number of Elements		8
Total Active Area	(m^2)	69.9
Feed Flow per Pass	(m^3/h)	3.62
Feed TDS[a]	(mg/L)	58.96
Feed Pressure	(bar)	7.6
Flow Factor Per Stage		0.85, 0.85
Permeate Flow per Pass	(m^3/h)	2.79
Pass Average flux	(LMH)	39.9
Permeate TDS[a]	(mg/L)	1.75
Pass Recovery		77.1 %
Average NDP	(bar)	5.9
Specific Energy	(kWh/m^3)	0.34
Temperature	(°C)	40.0
pH		6.7
Chemical Dose		-
RO System Recovery		77.0 %
Net RO System Recovery		77.0%

The following notes can be concluded from the table above:

- The required discharge pressure of the high pressure pumps drops to 7.6 bar meaning it will rarely operate at the previously mentioned max pressure.
- The permeate water is still of an extremely pure nature.
- The average flux of system is within the required limits.

Table VI.19: Second reverse osmosis system solutes results at 40°C

Concentrations (mg/L as ion)						
		Concentrate		Permeate		
	Feed	Stage1	Stage2	Stage1	Stage2	Total
NH_4^+	0.00	0.00	0.00	0.00	0.00	0.00
K^+	3.37	5.78	14.41	0.05	0.10	0.07
Na^+	14.81	25.38	63.17	0.24	0.53	0.37
Mg^{+2}	0.26	0.45	1.13	0.00	0.00	0.00
Ca^{+2}	0.53	0.91	2.30	0.00	0.00	0.00
Sr^{+2}	0.00	0.00	0.00	0.00	0.00	0.00
Ba^{+2}	0.00	0.00	0.00	0.00	0.00	0.00
CO_3^{-2}	0.01	0.02	0.15	0.00	0.00	0.00
HCO_3^-	19.59	33.56	83.40	0.62	0.88	0.73
NO_3^-	6.18	10.47	25.50	0.27	0.58	0.41
F^-	0.00	0.00	0.00	0.00	0.00	0.00
Cl^-	10.74	18.46	46.23	0.09	0.20	0.14
Br^{-1}	0.00	0.00	0.00	0.00	0.00	0.00
SO_4^{-2}	2.61	4.50	11.31	0.01	0.02	0.01
PO_4^{-3}	0.01	0.02	0.04	0.00	0.00	0.00
SiO_2	0.83	1.43	3.59	0.00	0.01	0.01
Boron	0.00	0.00	0.00	0.00	0.00	0.00
CO_2	5.44	5.46	5.53	5.20	5.29	5.25
TDS[a]	58.94	101.0	251.2	1.28	2.33	1.75
Cond. µS/cm	88	150	369	4	5	4
pH	6.7	6.9	7.3	5.3	5.4	5.3

Based on the info of the table above and on Table VI.17 the PH levels at the outlet of the RO2 unit are low which brings forward the need to adjust the PH back to acceptable levels after exiting the unit.

VI.6.5 Batch simulation:

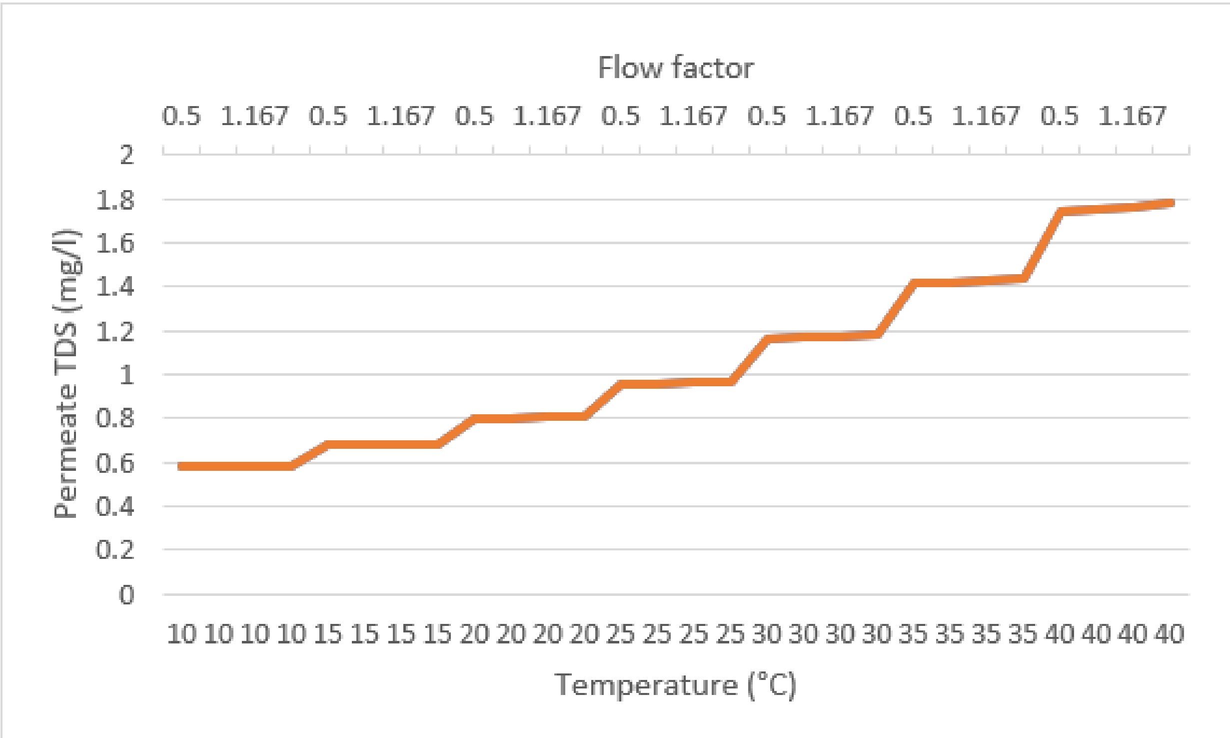


Figure VI.9: Evolution of permeate TDS in function of temperature and flow factor for RO2

The line graph illustrated above demonstrates the evolution of permeate TDS as a function of fouling and Temperature variations. It shows that the RO2 unit can produce permeate quality (TDS) that ranges from 0.6 mg/l to around 1.8 mg/l in the worst case scenario. This data sets the starting point for designing the CEDI unit.

VI.7 Design of the CEDI unit:

The design of the continuous electrodionization unit will be done using the IONPURE IP-PRO projection software made by EVOAQUA. The following steps will be followed:

VI.7.1 Design parameters:

The first step in designing the CEDI unit is to input the feed water analysis, which in this case will be the RO2 permeate solute concentrations at 40°C illustrated in Figure VI.19 to comply with the the worst conditions.

The following figure represents the feed water characteristics calculated by the program:

FEEDWATER SUMMARY

Conductivity @ 25 °C	2.32 µS/cm
Feedwater Conductivity Equivalent	25.8 µS/cm
Total Exchangable Anions (TEA)	17.9 ppm $CaCO_3$
Total Hardness CaCO3	0 ppm $CaCO_3$
Temperature	40 °C

Figure VI.10: IP-PRO feed water quality calculations

VI.7.2 Module selection:

The second step in designing the CEDI unit is selecting the appropriate CEDI module required for the applications at hand.

The program offers the choice of three families of modules to choose from, MX for low flow applications, LX for medium flow, and VNX for high flow applications. For the purposes of GRN's unit the most appropriate choice is the **LX family**.

Within the LX CEDI family there exists four additional sub-types:

- **LX-Z modules:** Have PVC spacers, they are ideal when no FDA[5] approval is needed but high quality water is still required.
- **LX-X modules:** Have no PVC parts so design for more critical applications.
- **LX-HI modules:** Can be sanitized with hot water, a perfect solution for high end applications in Pharmaceutical, Biotechnology and Food and Beverage industries.
- **LX-MK modules:** Can be used to retrofit E-cell-MK EDI units.

The most appropriate choice for GRN's unit is LX-Z modules. Finally Table IV.5 demonstrates the different modules available in the range, and based on that table and on the fact that the required product flow is 2.65 m^3/h, the selected CEDI module is **IP-LXM24-Z**.

[5]United states food and drugs administration

VI.7.3 Design results:

The following are various projection results:

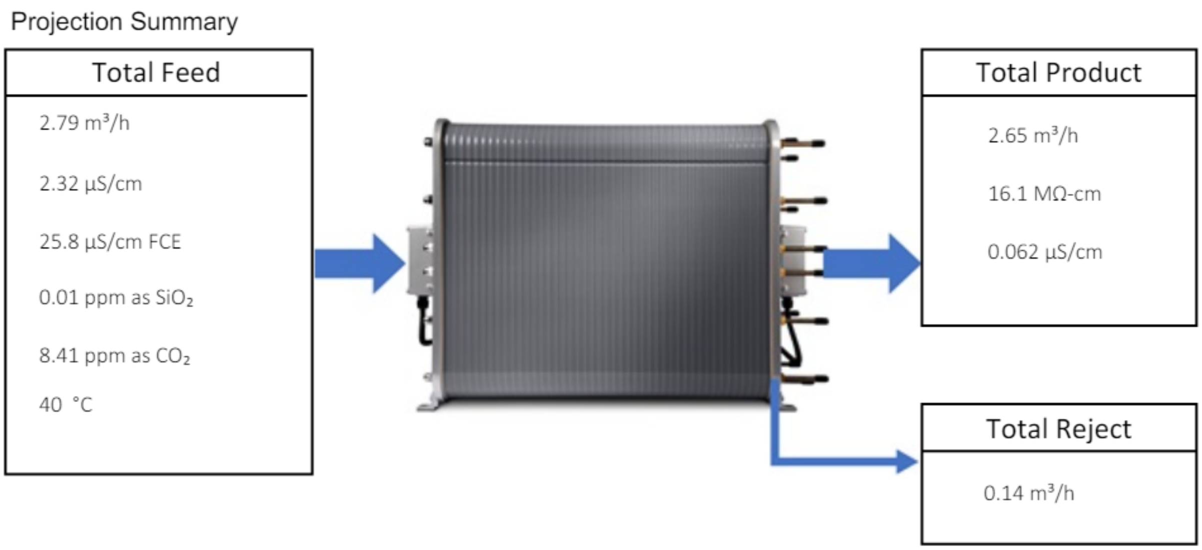


Figure VI.11: CEDI unit summery diagram

The results above show that even at the wort case scenario the CEDI unit can still produce ultra-pure demineralized water that complies with the client's specifications of a conductivity below 0.1 $\mu S/cm$.

It should also be added that the minimal reject that is produced by the unit is also of a relatively high quality, therefore it could be recycled into the service water tank (RO2 feed) to avoid any additional waste disposal charges.

Finally the table below demonstrates the power requirements to run the CEDI unit:

Table VI.20: CEDI unit summery overview

Product Flow Rate	2.65 m^3/h
Module Type	LXM24-Z
Number of Modules	1
Flow per Module	2.6 m^3/h
Feedwater Conductivity @ 25°C	2.32 µS/cm
Feedwater Conductivity Equivalent	25.8 µS/cm
Total Exchangeable Anions (TEA)	17.9 ppm as $CaCO_3$
Maximum System Recovery	95 %
Product Water Resistivity	16.1 MΩ-cm
Product Water Conductivity	0.062 µS/cm
Salt Rejection	99.8 %
Dilute Pressure Drop	2.07 bar
Total Hardness (ppm as $CaCO_3$)	0

Table VI.21: CEDI unit estimated power requirements

Estimated Power Requirements	
AC Power Consumption	0.16 kW/module
Total AC Power Consumption	3.85 kWh/day (24/7 operation)
DC Energy Consumption	0.21 kWh/kgal
DC Energy Consumption	0.06 kWh/m^3
DC Voltage	48 V
Start-up DC Current	3.1 A
* Assumes 93% efficiency of AC to DC power controller	

VI.8 Power consumption calculations:

Power consumption is a big part of operational costs in water treatment units therefore calculating is an important step. Thankfully, the programs previously used for projections also do those calculations.

One important remark should be made is that the following calculations are based on a feed temperature of 35°C which is the closest to reality in site. The energy cost per KW/h is assumed to be 0.022 $.

VI.8.1 Ultrafiltration power consumption:

Table VI.22: Ultrafiltration system power consumption

Pump	Peak Flowrate (m^3/h)	Average Pressure (bar)	Mechanical Power (kW)	Electrical Power (kW)	Energy (kWh/d)	Cost ($/d)
Feed	16.77	1.19	0.55	0.75	17.88	0.39
Backwash	30.60	0.84	0.72	0.97	0.39	0.01
CEB	30.60	0.84	0.72	0.97	0.05	0.00
HCl (32%) Metering Pump	0.04		0.00	0.00		
NaOCl(12%) Metering Pump	0.06		0.00	0.00		
CIP	9.00	2.50	0.62	0.85	0.02	0.00
HCl (32%) Metering Pump	0.01		0.00	0.00		
Citric Acid(100%) Metering Pump	0.11		0.01	0.02		
NaOH (50%) Metering Pump	0.02		0.00	0.00		
NaOCl(12%) Metering Pump	0.13		0.01	0.01		
CIP Solution Heating				0.00	0.00	0.00
Air Compressor	72.00	0.75	1.23	2.67	0.59	0.01
Electrical Valves				0.00	0.00	0.00
PLC and Instrumentation				0.20	4.80	0.11
Total Electrical Cost					23.73	0.52

Using the official conversion rate of USD to DZD the total electrical cost of the ultrafiltration unit assuming 24/7 operations is 70 DA per day.

Factoring in the fact that GRN produces its own electricity via the residual energy of the gas treatment process, the cost is rendered almost negligible.

VI.8.2 RO1 power consumption:

Table VI.23: Power consumption of the RO1 unit

Peak Power	(kW)	5.2
Energy	(kWh/d)	125.6
Electricity Unit Cost	($/kWh)	0.0220
Electricity Cost	($/d)	2.8
Specific Energy	(kWh/m³)	0.44

Pump	Flow Rate (m³/h)	Power (kW)	Energy (kWh/d)	Cost ($/d)
Pass 1				
Feed	15.75	5.23	125.59	2.76
Pass 1 Total		5.23	125.59	2.76
System Total		5.23	125.59	2.76

Going through the same conversion process we get a daily energy cost of 377.41 DA per day. It should be noted that the overall price of one cubic meter of product water factors in several other charges such as chemical costs and service utilities so it should be calculated just based on the electrical cost.

VI.8.3 RO2 power consumption:

Table VI.24: Power consumption of the RO2 unit

Peak Power	(kW)	1.1
Energy	(kWh/d)	27.2
Electricity Unit Cost	($/kWh)	0.0220
Electricity Cost	($/d)	0.6
Specific Energy	(kWh/m³)	0.41

Pump	Flow Rate (m³/h)	Power (kW)	Energy (kWh/d)	Cost ($/d)
Pass 1				
Feed	3.62	1.13	27.17	0.60
Pass 1 Total		1.13	27.17	0.60
System Total		1.13	27.17	0.60

Finally the RO2 unit has a power consumption of 80.87 DA.

VI.8.4 CEDI power consumption:

Based on the estimated power consumption of the CEDI unit illustrated in Table VI.21 and the average KWh price in Algeria of 0.022 $ the estimated cost of running the unit is 0.085 $ which is equivalent to 11.46 DA.

VI.9 Conclusion:

The improved water treatment unit's design incorporates advanced technologies such as ultrafiltration, reverse osmosis, and continuous electrodionization to ensure efficient and high-quality water treatment. The ultrafiltration unit effectively removes larger particulates and contaminants, while the reverse osmosis units (RO1 and RO2) significantly reduce total dissolved solids (TDS), ensuring that the water meets stringent quality standards. The continuous electrodionization unit achieves the final water quality target of conductivity below 0.1 µS/cm. The use of WAVE projection software facilitated precise simulation and analysis, leading to optimal design choices that account for varying conditions and energy efficiency.

Overall, the comprehensive design process ensures the delivery of high-purity water reliably and efficiently, with manageable operational costs. The system's adaptability and energy efficiency make it a sustainable solution for modern water treatment challenges. This design serves as a model for future projects, highlighting a robust approach to meeting stringent water quality standards while optimizing operational costs and energy use.

Chapter VII

Environmental and security considerations:

VII.1 Introduction:

As with any water treatment installation water demineralization systems have a considerable environmental impact due to the various chemicals that are used in addition to energy consumption and the production of waste water. This implies the necessity of carefully evaluating these factors so no negative effects are brought to nature.

In addition to the environmental considerations, the safe operation of such units is also essential for the safety of the operators and other collaborators, and this is done by following a set of guidelines the govern these types of activities.

All of the this will be covered in detail in the present chapter.

VII.2 Energy consumption:

Energy consumption is big factor affecting the environmental impact of water demineralization units as they tend to have high energy demands especially when it comes to electricity.

VII.2.1 Factors Affecting Energy Consumption:

The energy demand of water demineralization systems varies based on several factors:

VII.2.1.1 Feedwater quality:

The main factor influencing energy demands in water demineralization systems is the feed water quality, for instance reverse osmosis energy demands vary depending on the osmostic pressure of the feed water as the more it increases, the more energy is needed to overcome it and initiate the reverse osmosis process. Similarly with RO, electrically driven processes such electrodialysis also base their energy consumption on the concentrations of ions in the feed water as the higher solute concentrations the more energy is needed to drive the separation.

Temperature is also a big factor when it comes to energy consumption as demonstrated in the previous chapter. The lower the feed temperature the higher the required feed pressure which in turn translates to higher electricity demand. The increase in required feed pressure is due to the lower viscosity.

VII.2.1.2 System effeciency:

Another influencing factor that needs mentioning is the system effeciency. This can be tied with several parameters, mainly the recovery of each unit as a higher recovery implies that the unit needs to separate more solutes from the feed water thus increasing energy consumption. The individual efficiencies of the pumps and motors of the entire system also contribute to this but to a lesser degree.

VII.2.1.3 System design and configurations:

System design and configuration play a crucial role in optimizing the energy efficiency of water demineralization systems.

The selection of high-efficiency membranes with lower fouling rates and higher permeability can significantly reduce energy consumption by decreasing the required pressure and flow rates. Advanced pressure vessels and optimized pumping systems further enhance energy efficiency by minimizing energy losses and ensuring uniform flow distribution. Incorporating energy recovery devices, such as pressure exchangers, can capture and reuse energy from the concentrate stream, significantly lowering overall energy usage. Additionally, innovative module designs that reduce pressure drops and improve flow dynamics contribute to more efficient and cost-effective demineralization processes.

VII.2.2 Energy recovery techniques:

Energy recovery devices (ERD) are a way of lowering energy costs that can take up to 70 % of the operating costs in seawater RO systems where the osmostic pressure is extremely high.

The principle they use is recovering the excess pressure with which the reject stream usually comes out. This excess pressure is not needed in the reject stream therefore recovering it and using it to drive a booster pump after the HP pump lowers their operating pressure, therefore lowering energy costs.

Their are two main ERDs types currently used in desalination, the first being classic centrifugal turbines (including Pelton turbine, Francis turbine, and hydraulic turbochargers) while the second ones are pressure and work (isobaric) exchangers.

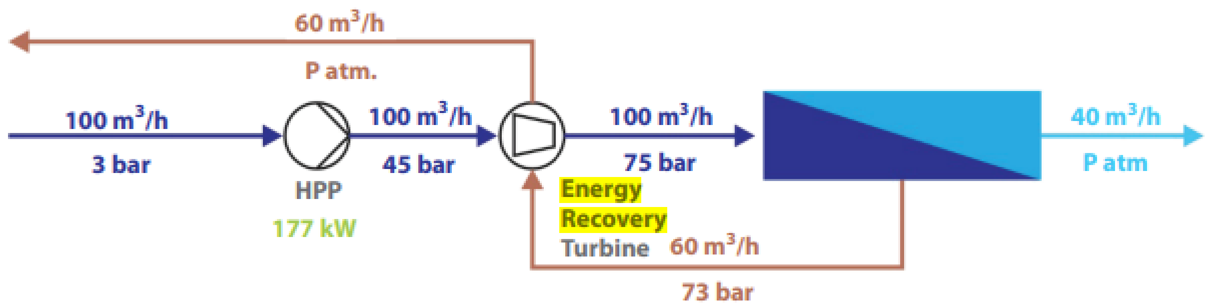


Figure VII.1: 0 Energy recovery turbine for a single-stage seawater system at 35,000 ppm TDS (Kucera, 2023)

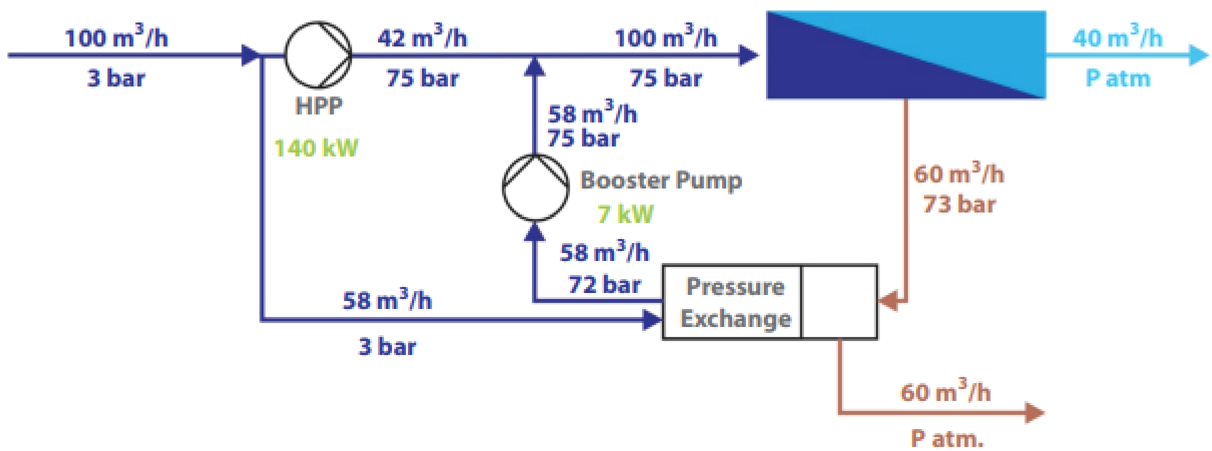


Figure VII.2: Energy recovery pressure exchanger for a single-stage seawater system at 35,000 ppm TDS (Kucera, 2023)

The diagrams above demonstrate identical single stage systems where both ERD types are used. These figure demonstrate the fact that pressure exchangers are more energy saving as the total energy consumption for the system that uses them is 147 kw while it is 177 kw for the system that uses a turbine.

VII.2.3 Integration of renewable energies:

Integrating renewable energy sources into water demineralization systems offers a promising approach to reduce energy consumption and enhance sustainability. Solar power, in particular, can be harnessed in various forms, such as photovoltaic (PV) panels for electricity generation or solar thermal collectors for heat-driven processes. Solar-powered reverse osmosis systems can operate during peak sunlight hours, leveraging the abundant energy supply to drive the high-pressure pumps necessary for the RO process. Additionally, concentrated solar power (CSP) plants can generate both electricity and heat, making them suitable for combined thermal and membrane-based desalination processes.

Wind energy provides another viable renewable source, particularly in coastal and offshore areas where wind speeds are consistently high. Wind turbines can generate the electricity needed to power demineralization systems, either directly or by feeding into the grid. The intermittent nature of wind energy can be mitigated by integrating energy storage solutions, such as batteries or pumped hydro storage, ensuring a stable and continuous power supply.

Incorporating renewable energy into water demineralization systems represents a significant step towards sustainable water management. It ensures a resilient supply of clean water while addressing energy consumption challenges and contributing to broader environmental goals. As technology advances and the cost of renewable energy continues to decrease, the integration of these sources will become increasingly viable and economically attractive for a wide range of demineralization applications.

VII.3 Waste management:

Waste management is another important cost driving measure that is necessary and vital in water demoralization as disposing of concentrates produced by the various processes previously discussed can pose both an economical and a environmental problem.

This issue is less pronounced in brackish water demineralization due to the lower TDS levels but is still present especially in single pass RO systems. As for second pass and polishing technologies such as CEDI, the waste management task becomes much easier due to the fact that the concentrate has TDS levels that are usually less than even the feed water to the first pass RO system. A practical example of this is seen in the previous chapter.

VII.3.1 Waste management techniques:

There are many waste management techniques and choosing the correct one for the system at hand is essential to minimize both the environmental footprint and the operational costs.

The first method is simply discharging the concentrate. Whether it is into surface waters such as lakes and rivers (which is the less costly yet more environmentally dangerous option) or directly into the public sewer system which is often used for brackish water RO systems with a lower capacity to not overload the wastewater purification plants.

The second more expensive yet less impactful technique is reusing the concentrate in one of various applications:

VII.3.1.1 Irrigation:

The most obvious field in which the reuse of concentrate water may be useful is irrigation which is also a relatively inexpensive option. It is on the other hand quite limited as it can only be used for high salinity resistant crops. In addition to the fact that there is a risk of contaminating the soil and ground water sources.

VII.3.1.2 Evaporation ponds:

This solution is best suited for brackish water systems in arid areas (which is the case for the Reggane development project). There are limited tho in terms of the need for large areas especially with higher capacity systems, in addition to running the risk of ground water contamination if the ponds are not well maintained and preserved.

VII.3.1.3 Direct reuse:

RO concentrate can also be directly used in industrial settings for various applications such is cooling tower make-up and to wash equipment. It should be noted tho that this application is highly contingent on the salinity of the concentrate as waters with high TDS counts can be corrosive to metals.

VII.4 Chemical use:

As the previous chapters have demonstrated, water demineralization is a process that uses a multitude of chemicals that have different purposes and aim at bettering the permeate water quality and keep it in compliance with the guidelines set by the client. But a consequence of this use is the fact that they can have a negative impact on the environment in addition to being a potential hazard for workers.

VII.4.1 Chemical discharge:

The end point of all of most of the injected chemicals such as biocides and antiscalants is often the concentrate, which increases the importance of the proper discharge of the latter as the previously mentioned chemicals can have adverse effects on the environment especially marine life in the case of seawater desalination.

This also highlights the importance of proper dosing and making sure chemicals are used in a controlled manner.

VII.4.2 Chemical handling:

Proper chemical handling and storage are crucial to mitigating environmental risks associated with demineralization systems. Improper handling and storage can lead to spills and leaks, which in turn can contaminate soil and groundwater, posing significant risks to local ecosystems and human health. To prevent such incidents, stringent safety protocols must be implemented. This includes using appropriate containers that are resistant to corrosion and degradation, correctly labeling all chemicals to avoid mix-ups, and ensuring that storage areas are well-ventilated and secure from unauthorized access or environmental hazards.

Personnel involved in the handling and storage of chemicals must be adequately trained. Training should cover the safe handling, storage, and disposal of chemicals, emphasizing the importance of following established procedures. Regular training programs and drills are essential to keep staff updated on the latest safety practices and to prepare them to respond effectively in the event of a spill or leak. These drills can simulate real-life scenarios, allowing personnel to practice their response and improve their readiness.

Chemicals should be stored under conditions that prevent their degradation and reduce the risk of hazardous reactions. This involves maintaining appropriate temperature and humidity levels and ensuring that storage areas are free from sources of ignition or contamination. Incompatible chemicals must be stored separately to avoid dangerous reactions that could lead to fires, explosions, or the release of toxic gases. Proper segregation and labeling of chemicals are critical to maintaining a safe storage environment.

Finally, adherence to local, national, and international regulations regarding chemical storage and handling is essential to ensure the implementation of best practices and reduce environmental risks. Regulatory compliance not only protects the environment but also safeguards the health and safety of workers and the community. Regulations typically provide guidelines on proper storage conditions, labeling requirements, training standards, and emergency response procedures. By complying with these regulations, facilities can minimize the risk of chemical spills, leaks, and subsequent environmental contamination.

VII.5 Water resources depletion:

It is readily apparent that water demineralization in general and RO specifically is very resource intensive and requires large volumes of feedwater especially in industrial settings which raises various environmental concerns especially in arid areas where water is a rare resource.

VII.5.1 Aquifers and groundwater depletion:

Aquifers and groundwater sources are critical for providing fresh water for drinking, agriculture, and industry. RO systems that draw heavily on these sources can lead to a significant drop in groundwater levels, known as the lowering of the water table. This requires deeper wells, which increases the cost and energy needed to extract water. Additionally, over-extraction can reduce the base flow to rivers and lakes, further diminishing surface water availability.

Another serious consequence of groundwater depletion is land subsidence. As water is extracted, the support provided by the groundwater is removed, causing the ground to sink. This subsidence can damage buildings, roads, and other infrastructure, leading to expensive repairs and posing safety risks.

In coastal regions, excessive extraction of groundwater can cause saltwater intrusion. This occurs when seawater infiltrates freshwater aquifers, increasing the salinity of groundwater. The resultant saline water is unsuitable for most uses without extensive treatment, exacerbating water scarcity and increasing treatment costs.

VII.5.2 Mitigation strategies:

Addressing the issue of water source depletion requires a multifaceted approach. Sustainable water management practices are essential to balance the water needs of RO systems with environmental and societal requirements. This includes monitoring water extraction rates, enforcing regulations to prevent over-extraction, and encouraging the use of alternative water sources.

Integrating water recycling and reuse within RO systems can significantly reduce the overall demand for fresh water. Treated wastewater can be reused for agricultural irrigation, industrial processes, or even replenishing aquifers. This approach not only conserves water but also reduces the environmental impact of wastewater discharge.

Developing and deploying more efficient RO technologies can also help mitigate water source depletion. Innovations such as low-energy membranes, concentrate recovery systems, and hybrid desalination processes can improve the efficiency of RO systems, reducing the amount of source water needed and the volume of brine produced.

Public awareness and education are crucial for promoting water conservation. Raising awareness about the impacts of water source depletion and encouraging sustainable water use practices can help reduce pressure on natural water sources. Educating communities and industries about responsible water consumption can foster more sustainable behaviors and support the implementation of water-saving technologies and practices.

Overall, addressing water source depletion requires collaboration between governments, industries, communities, and researchers to develop and implement effective strategies that ensure the long-term sustainability of water resources.

VII.6 General safety precautions:

Safety is the number one priority in an industrial setting and GRN as a company is no different as its goal is to have zero work place incidents. in this section will focus on some general safety guidelines that should be followed when handling the water treatment unit to ensure the safety of all collaborators.

The first step is to train all personnel on proper operating protocols and conduct a hazard review of all operational steps. Another important measure is equipping all the personal with proper protective clothing such as gloves and protective eye-wear. The following are some general safety precautions:

- Follow all standard safety precautions, operating instructions, and environmental regulations.
- Maintain good housekeeping by keeping the floors clean and dry and storing excess materials properly.
- Ensure fire safety by keeping all fire exists accessible and clear, maintaining safety equipment like fire extinguishers and hoses in good working order, and preparing and practice an evacuation plan.
- Regularly check safety interlocks, pressure relief devices, and shield all rotating equipment such as pumps.
- Follow ergonomic guidelines and avoid manual lifting of heavy materials.
- Maintain and test eyewash stations and safety showers.
- Use floor markings to identify safety areas and potential hazards.
- Implement routine training programs for all personnel on operations, maintenance, environmental, and safety requirements.

VII.7 High pressure systems handling and operations:

Demineralization plants heavily rely in high pressure driven systems such as reverse osmosis, and this opens up the door of various safety issues, these issues can be avoided by doing the following:

- Do not over-pressurize equipment, operate at too high a temperature, or modify a pressure vessel without the expressed written approval of the manufacturer. Label equipment with the appropriate operational limitations.
- All pressure vessels must be suitably anchored and restrained. Where possible, avoid standing in front of pressurized equipment.
- Use maximum care in handling, installing, dismantling, and maintaining pressure vessels. It is very important to be sure devices are depressurized before conducting maintenance work.
- Install proper relief and shutdown protection devices. Regularly inspect these devices and vessels for equipment integrity.
- Minimize equipment and piping vibrations, and avoid water hammer.
- Routinely inspect equipment for defects, corrosion, and other signs of abnormal wear.

VII.8 Conclusion:

Water demineralization systems require careful management of energy use, chemical handling, and waste disposal to minimize environmental impact and ensure safety. Utilizing advanced technologies and renewable energy sources can reduce energy consumption. Proper handling and disposal of chemicals are crucial to prevent environmental damage and protect workers. Effective waste management, such as reusing wastewater and using evaporation ponds, can further reduce environmental impact. By integrating advanced technology, strict safety protocols, and sustainable practices, water treatment needs can be balanced with environmental preservation.

General conclusion:

In this thesis, the comprehensive diagnosis and rehabilitation of the GRN water treatment unit, with a particular focus on the RO1 and RO2 units, have been successfully carried out to address critical operational challenges and restore optimal functionality. The initial diagnosis identified key issues such as high dissolved oxygen levels, high TDS levels, equipment inefficiencies, and system leaks, which significantly impaired the performance of the treatment unit.

The diagnostic process revealed that both the RO1 and RO2 units were facing several operational challenges. The RO1 unit's high-pressure pumps and membranes were found to be operating below optimal conditions due to equipment wear and system inefficiencies. Specifically, the cartridge filters, manufactured by AQUA PURIFICATION, needed replacement to prevent suspended solids from damaging the membranes. The high-pressure pumps made by GRUNDFOS required upgrading to maintain the necessary driving pressure for the membranes. Additionally, the RO2 unit exhibited anomalies that affected its ability to produce high-quality permeate, which is essential for the subsequent demineralization process.

Rehabilitation efforts for the RO1 unit included replacing outdated components such as the cartridge filters, high-pressure pumps, and HYDRANAUTICS ESPA2-LD membranes. The cartridge filters, with a pore size of 5 microns, were essential for maintaining membrane integrity under high operating pressures. Similarly, the high-pressure pumps were upgraded to ensure a flow rate of 15.76 m^3/h and a pressure of 16.6 bar at 10°C, which are critical for efficient RO1 operation. For the RO2 unit, the focus was on replacing membranes and optimizing cleaning protocols to address fouling issues, thereby enhancing its efficiency and reliability.

In addition to component replacements, the rehabilitation included the implementation of a robust preventative maintenance program. This program encompassed regular data monitoring and analysis, calibration of instrumentation, and routine mechanical inspections to sustain the improvements and prevent future operational issues. The DEOX unit also received significant attention, with repairs to air leaks and ensuring a consistent supply of high-purity nitrogen to achieve the desired deoxygenation levels, thereby complementing the overall treatment process.

The systematic approach to diagnosis and rehabilitation can not only restore the GRN water treatment unit's capability to produce water meeting the required specifications but also enhance its operational efficiency and reliability. The comprehensive strategy, supported by continuous monitoring and evaluation, provides a solid foundation for sustaining the unit's performance and adapting to future challenges.

In conclusion, this project highlights the importance of detailed diagnosis and proactive rehabilitation in maintaining and enhancing critical water treatment infrastructure. By addressing both immediate and long-term concerns, the GRN water treatment unit, particularly the RO1 and RO2 units, can operate more efficiently and reliably. These efforts ensure that the unit can meet current demands while being resilient to future operational challenges, thereby contributing significantly to the overall sustainability and effectiveness of the water treatment processes within the Reggane North Development Project. The successful rehabilitation will demonstrate substantial improvements in water quality, system efficiency, and operational resilience, providing a robust foundation for continued and reliable operation.

Bibliography

ANRH. (2014). *Resultats d'analyse d'eau* (tech. rep.). Adrar.

ASTM. (2013). *Standard practice for standardizing reverse osmosis performance data* [ASTM D4516-13]. ASTM International.

A.W.W. Association. (1995). *Electrodialysis and electrodialysis reversal: M38*. American Water Works Association. https://books.google.dz/books?id=chnPBgAAQBAJ

A.W.W. Association. (2005). *Microfiltration and ultrafiltration membranes for drinking water*. American Water Works Association. https://books.google.dz/books?id=xQxSAAAAMAAJ

A.W.W. Association. (2011). *Reverse osmosis and nanofiltration, (m46)*. American Water Works Association. https://books.google.dz/books?id=GwATsvphRLEC

Baruth, E., of Civil Engineers, A. S., & Association, A. W. W. (2005). *Water treatment plant design*. Mcgraw-hill. https://books.google.dz/books?id=R4tUAAAAMAAJ

DuPont. (2019). *Filmtec™ integraflux™ ultrafiltration modules*.

DuPont. (2023). *Filmtec™ reverse osmosis membranes technical manual*.

EMCO engineering LTD. (2014). *Service water package and demineralized and deoxigination package* (Z) [Installation, operating and maintenance manual]. GRN.

Essa, F. A., Elasyed Abd Elaziz, M., Shanmugan, S., & Elsheikh, A. H. (2022). Chapter seven - artificial neural network and desalination systems. In A. H. Elsheikh & M. E. Abd Elaziz (Eds.), *Artificial neural networks for renewable energy systems and real-world applications* (pp. 159–187). Academic Press. https://doi.org/https://doi.org/10.1016/B978-0-12-820793-2.00010-0

Grundfos. (2024). *Crn multi-stage pumps*. https://product-selection.grundfos.com/products/cr-cre-cri-crie-crn-crne-crt-crte/crn?tab=models

Hydranautics. (2024). *Hydranautics reverse osmosis membranes*. https://membranes.com/solutions/products/ro/

Hydrocarbons technology. (2018). *Reggane north development project, sahara desert*. https://www.hydrocarbons-technology.com/projects/reggane-north-development-project-sahara-desert/

Im, S., Kim, M., Jeong, G., Choi, H., Shin, J., & Jang, A. (2022). Possibility assessment of ultrafiltration membrane pre-treatment efficiency for brackish water reverse osmosis-based wastewater reuse: Lab and demonstration. *Chemosphere*, *303*, 134897. https://doi.org/https://doi.org/10.1016/j.chemosphere.2022.134897

IonPure. (2010). *Lx-z cedi modules operations and maintenance manual*. GRN.

Ismail, A. F., Khulbe, K. C., & Matsuura, T. (2019). Chapter 8 - ro membrane fouling. In A. F. Ismail, K. C. Khulbe, & T. Matsuura (Eds.), *Reverse osmosis* (pp. 189–220). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-12-811468-1.00008-6

Kucera, J. (2023). *Reverse osmosis 3rd edition*. John Wiley; Sons, Ltd. https://doi.org/https://doi.org/10.1002/9781119725183.ch1

Ma biologie. (2018). *Osmosis and reverse osmosis*. https://www.mabiologie.com/2016/11/loi-dosmose.html

MI SWACO. (2022). *Recommendations to reduce bacteria activity* (tech. rep.). GRN.

Office national de la météorologie. (2006). *Adrar meteorological station* (tech. rep.).

Ouali, S., & Khellaf, A. (2006). Etude géothermique du sud de l'algérie, 299.

Petrofac. (2014a). *Eps basis of design*. GRN.

Petrofac. (2014b). *Reggane site conditions and meteorological data* (tech. rep.).

PureWater. (2015). *Deoxigynation systems installation, operation and maintenance manual*. GRN.

Reynolds, L. B. (1933). History of chemical precipitation. *Sewage Works Journal*, 595–599.

Ruiz-García, A., Melián-Martel, N., & Nuez, I. (2017). Short review on predicting fouling in ro desalination. *Membranes*, *7*, 62. https://doi.org/10.3390/membranes7040062

Rusydi, A. F. (2018). Correlation between conductivity and total dissolved solid in various type of water: A review. *IOP Conference Series: Earth and Environmental Science*, *118*(1), 012019. https://doi.org/10.1088/1755-1315/118/1/012019

Saadat, A. H. M., Islam, M. S., Fahmida, P., & Sultana, A. (2018). Desalination technologies for developing countries: A review. *Journal of Scientific Research*, *10*, 77–97.

Yousef, M. S., & Hassan, H. (2023). Chapter 9 - solar desalination with energy storage. In V. G. Gude (Ed.), *Energy storage for multigeneration* (pp. 221–249). Academic Press. https://doi.org/https://doi.org/10.1016/B978-0-12-821920-1.00006-6

Zaidi, J., & Saleem, H. (2022, January). *Reverse osmosis system troubleshooting*. https://doi.org/10.1016/B978-0-12-823965-0.00011-0

ZooFari. (n.d.). *Diagram showing the differences between a compound, a precipitate, a supernate, and a suspension*. https://commons.wikimedia.org/wiki/File:Chemical_precipitation_diagram.svg