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Optimization Study for a Stand-alone Reverse Osmosis (RO) Desalination Plant

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ABSTRACT

Seawater desalination is a vital source of drinking water, especially in coastal and remote areas. However, its sustainability is constrained by the high energy requirement. The need for fresh water supplies continues to rise due to its intensive use in many development sectors, such as agriculture and industry, as well as the continued increase in population. This has led to the idea of using nuclear power in seawater desalination to reduce the stress on the main electrical grid and enhance sustainable. The paper's goal is to optimize a reverse osmosis (RO) desalination plant to produce 100,000 m^3 of fresh water daily. The best membrane is selected by testing 10 FilmTec membranes, with a focus on achieving optimal product quality (TDS) while maintaining an acceptable level of specific energy consumption (SEC). The study aims to address the challenge of delivering potable water by designing and modeling a standalone desalination plant powered by small modular reactors (SMRs). According to ROSA's analysis, the optimal RO desalination unit consists of two stages with a total of 175 membranes. The FilmTec SW30XHR-400 is identified as the best option based on superior water quality. This membrane has a specific energy consumption of 5.17 kWh/m^3 and a low TDS of 141.4 mg/L. The total power consumption of the RO plant is approximately 21.5 MW; therefore, the KAREM-25 MWe reactor has been selected to be coupled with the RO desalination plant.

1. INTRODUCTION

Egypt faces a water scarcity issue due to its rapidly growing population (exceeding 100 million people), the expansion of industry and agriculture, and the development of new towns in desert areas with limited freshwater resources primarily relaying on the Nile River. Egypt's water crisis has worsened since the construction of Ethiopia's EL-Nahda Dam. To meet the increasing demand for water, Egypt has implemented a strategy to diversify its freshwater sources, with seawater desalination emerging as a key solution to address water scarcity and potable water challenges.

Desalination is a process that converts large volume of seawater or brackish water into fresh water by removing salt and minerals. The main desalination methods are thermal distillation and membrane separation, with thermal relying on heat and membrane requiring electricity. The most widely used desalination technology worldwide include reverse osmosis (RO), multi-effect desalination (MED), and multi-stage flash (MSF). Consequently, numerous seawater desalination plants have been constructed over the past several decades.

In recent years, several desalination plants have been installed in Egypt; for example, RO plants have been established along the Red sea and Mediterranean coasts. Additionally, thermal desalination plants are integrated into power stations, such as the Sidi Krir MSF plant [1].

Comparing Conventional Water Treatment with RO Desalination was presented by Jiayuan Han, et al [2]. The study revealed that RO desalination plants outperform conventional water treatment facilities due to reduced carbon emissions, lower maintenance and operation, and fewer hazardous waste discharges.

A review study by Muhammad Qasim,et al [3] explored RO desalination, covering membrane modules, membrane characterization, cleaning, concentration

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polarization, membrane transport theories, and pre-treatment methods. The study also addressed RO process design, integrated energy and economic factors, and the cost of water desalination. It compared ultrafiltration (UF), microfiltration (MF), and coagulation-flocculation technologies with non-conventional methods. It also discussed hybrid RO desalination methods and their challenges included a summary of these methods.

A wide variety of RO element performance variables, in addition to permeability, were considered by Y.Okamoto and J. H. Lienhard [4]. Major components of the RO system, especially the energy recovery devices, were substantially improved. Optimizing for operating conditions is crucial for further energy consumption reduction.

Jungbin Kima, et al [5] proposed solutions to lower the specific energy consumption (SEC) of seawater reverse osmosis (SWRO) plants via analysis. The study examined the increasing number of large-scale SWRO plants, their designs, and the efficiency of isobaric energy recovery devices (ERDs) in reducing SEC using over 70 datasets. The data found that high salinity increases energy demand, and pumps can decrease SEC, they cannot fully account for SEC in the aggregate. Target water amount and quality also impact SEC.

A. Ruiz-García, and I. Nueza [6] evaluated safe operating windows (SOWs) of nine commercial SWMMs in pressure vessels with seven components for a single-stage seawater reverse osmosis (SWRO) system. Utilizing a simulation method, the ideal operating points were found; the largest variation was around 0.2 kWhm^3. According to the study, SWMMs could recover maximal flux at comparable rates for a variety of PV power sources.

C.P. Koutsou, et al [7] investigated the impact of feed-water temperature on specific energy consumption (SEC) in conventional RO units, including energy recovery devices. It found that a minimum SEC of 30°C is necessary for high salinities like seawater, while increasing feed temperature reduces SEC in desalinating low salinity fluids.

The shutdown of a major industrial implementation and negative press had halted the commercialization of PRO technologies. Therefore, developing PRO module designs is crucial due to poor performance and design customization possibilities. Chulmin Lee, et al [8] discussed industry movements, process optimization, module design, and membrane manufacture.

Jangwon Seo,et al [9] proposed a hybrid method combining forward osmosis (FO) and RO to reduce RO energy consumption , comparing it with a standalone RO process using a numerical model. The study found that control parameters for operation are more significant than intrinsic membrane parameters for minimizing RO energy consumption.

Seawater desalination is causing extreme conditions in freshwater production, making seawater reverse osmosis (SWRO) less suitable for treating extremely salty water. Jungbin Kim,et al [10] found that two-stage SWRO with pressure exchangers can achieve a 34% recovery rate, but under severe conditions, permeate quality is comparable. Split partial second pass (SPSP) and internally staged design (ISD) can improve the two-stage SWRO's efficiency by generating high-quality permeate.

Kwanho Jeong et tal [11] evaluated the effectiveness of a full-scale reverse osmosis (RO) system in an industrial water treatment facility by simulating its operations. A numerical model describes mass transport in a pressure vessel, and a global sensitivity analysis assesses critical parameters' impact on model accuracy and SEC. The results show practical fouling development and separation performance characteristics, and regression tree analysis helps in decision-making for RO that uses less energy. The study also revealed that SEC is highly dependent on cleaning frequency within the feed temperature range.

A framework for optimizing reverse osmosis desalination in dry and semi-arid areas was developed by Marcello Di Martino, et al [12]. It considered input energy, saline water sources, and membrane modules. The framework used a superstructure representation to model the process, leading to a mixed-integer nonlinear optimization problem.

Randy Ncube , et al [13] studied the Modeling and improving processes including mass and heat transfer, salt rejection, and membrane permeability which are necessary to build sustainable RO plants. The RO desalination system's efficiency was greatly impacted by the designs and specifications of the membranes. The results revealed that, designing desalination units, membrane design tools and software like ROSA and IMS design help choose membranes with good salt rejection and low energy usage.

Since renewable energy sources might provide a long-term solution for fresh water supply in regions like the Middle East, there is a lot of interest in using them to create drinking water worldwide.

Yoshiki Okamoto, and John H. Lienhard [14] examined how the performance of RO membrane elements impacts the cost of RO operations, particularly the specific energy consumption. RO membrane performance is influenced by water and salt permeability. Redusing membrane surface area and related expenses can be increasing membrane water permeability. Most published materials have the majority in evaluating performance in starting operating conditions.

Joachim M. Schmidt, and Veera Gnaneswar Gude, [15] presented a feasibility analysis of a nuclear energy powered cogeneration facility for Homestead, Florida, which would produce electricity and water. Using the DEEP desalination modeling program, comparisons were made between various energy sources and desalination processes. The study found that the reverse osmosis desalination plant using nuclear energy generated water at the lowest cost, but still costs three times more than Homestead, Florida's current water prices.

The best layout and maintenance plan for a stand-alone hybrid desalination scheme were investigated by Ioannis D. Spyrou, and John S. Anagnostopoulos [16]. A pumped storage unit, solar and wind power, and electricity powered a reverse-osmosis desalination plant. In order to evaluate the investment and model plant operations, computer software was created. The productivity, financial results, and overall plant functionality were displayed in the results, along with the contributions of each subsystem. Even though the system required better usage of renewable energy, it was nevertheless determined to be an economically feasible investment despite large energy losses.

The ABV reactor, a floating type nuclear power plant developed for electricity generation, district heating, and sea water desalination in Russia, was designed by Salah Ud-Din Khan et al. [17]. The reactor underwent testing with various thermal loads and examined three modules, ABV-3 (18MWth), ABV-6 (38MWth), and ABV-6M (47MWth). Simulation studies and theoretical calculations were conducted on these modules. Based on the results, the ABV nuclear reactor desalination system's efficiency rises as the water cost ratio drops.

Gang Wang et al, [18] proposed a nuclear-solar complementary power (NSCP) system that uses heavy liquid metal to generate freshwater and energy. The system contains a solar tower receiver and a small nuclear reactor, with an electric power and efficiency of 318.8 MW and 39.3% respectively. The capability of solar electricity is 43.5%, with a daily production of 3891.8 t of freshwater. The study found that high power generating capacity factors can be achieved with a presumptive operation approach, and the desalination block can save $680423.0 annually.

The objective of this work is to optimize the operation of RO desalination plant by testing 10 FilmTec membranes. The ideal membrane is identified by evaluating its ability to produce best product quality (TDS) while maintaining acceptable specific energy consumption (SEC). The energy consumption of the RO plant is calculated based on the specified membrane. The type of SMR is determined according to the total energy required.

2. NUCLEAR POWER

The increasing demand for energy and electricity in Egypt is driven by population growth, urbanization, industrialization, and the desire to improve living conditions. To meet this demand, new sources, particularly for remote areas, needed to be developed due to limited potable water supplies and the scarcity of recognized national primary energy resources. Consequently, nuclear power is considered a viable, cost-effective, and practical energy source. It has the potential to promote technological growth, serve as a catalyst for social and economic development, and complement conventional energy sources [19].

Egypt is actively working on developing nuclear power as an energy source, recognizing it as one of the best effective ways to meet the growing of energy demand. In Sept. 2006, the ruling National Development Party announced a strategic direction to utilize nuclear technology for electricity generation and to increase reliance on renewable energy.

Two of the most promising nuclear technologies for the near future are fast neutron reactors and small modular reactors (SMRs). According to the IAEA, there will be an estimated 96 SMRs globally by 2030. Small modular reactors (SMRs) are nuclear fission reactors capable of produce up to 330 MWe of electrical power [20].

The main advantages of the SMRs include [21]:

1- Built-in safety features that require less space.
2- Enhanced safety and cost-effectiveness.
3- Shorter construction time, which reduce overall costs.

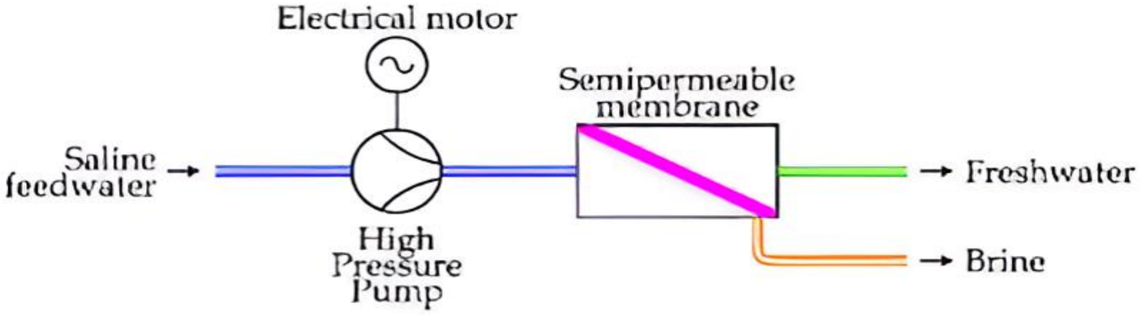


Fig. (1): A simple Diagram of a Reverse Osmosis (RO) Desalination Unit.

Many countries worldwide are now utilizing or constructing SMRs [22–26]. Examples of SMRS plants include the KLT-40 in Russia, IRIS in the United States, CAREM in Argentina, and SMART in Korea. Other notable designs include the Chinese designed HTR-PM, the Korean SMART, the American NuScale, and the IRIS.

Desalination systems can be integrated with SMRs in cogeneration mode as SMR facilities are designed for industrial applications. Due to their superior nuclear safety, SMR-based nuclear desalination facilities can be located near load centers, reducing transportation costs.

For this study, the SMR model KAREM-25 has been selected for integration with desalination facilities. The KAREM is integral PWR with thermal power of 100 MWth and an electric power of 25 MWe. It uses light water as both moderator and coolant. A distinguishing features of the KAREM design is its capability to couple with desalination system or process heat applications.

The existing SWRO plant in this study is entirely powered by nuclear energy. However, solar energy can serve as an alternative energy source for the SMRs. A power converter can implemented for facilitate the energy flow between the AC and DC buses. Additionally, battery banks (UPS) can provide backup power to the system in case of main supply cut-off.

3. Theoretical Work

The purpose of this research is to design an RO plant to supply water to a new residential area. A simple Ro configuration as shown in Fig. (1) has been selected. In an Ro plant, the membrane is the primary component. FilmTec specializes in manufacturing advanced thin-film composite membranes for water treatment applications. Now part of DuPont Water Solutions, FilmTec Corporation, under DowDuPont, is one of the world's leading membrane producers.

A program called **Reverse Osmosis System Analysis (ROSA)** is used to evaluate the performance of an RO system in both design and real-world scenarios utilizing performance standard for the FILMTEC system components. Developing by the DOW firm in the USA, ROSA design software continues to evolve to meet the stringent requirements of system design. Numerous studies [27-31] have employed ROSA to simulate and design Ro systems.

The reverse osmosis system analysis method ROSA9.2 is used in this research to design an optimal system for softening saline water. As described in detail in [32], ROSA is used to run simulations and input sea water data for system configuration and performance evaluation.

In this study ROSA9.2 is used to select the optimum membrane for the RO plant. Input data is specified on the first page of the ROSA software. The composition of the Mediterranean seawater [33, 34] for a remote region on the north coast is determined and entered in page 2 of the software.

The operational conditions for the ROSA technical input are specified in page 4 as follows:

1- **Product water output:** 2500 m^3/day of freshwater per unit.

2- N**umber of units:** 40 in the RO plant.

3- **Feed water temperature**: Constant at 25 ºC.

4- **Membranes per pressure vessel:** Seven.

5- **Stages**: One, two, or three stages can be selected for operation.

6- **Membrane type:** The same type of membrane is used in every pressure vessel.

7- **Pressure vessels per stage**: the number is selected to ensure operation at peak pressure, recovery, and flow rate.

The ROSA software provides outputs including the total element, pressure, TDS and flow rate for each stage as well as, the overall TDS, and specific energy consumption (SEC). It is critical to check for warning in the results. If a warning appears, the input parameters must be adjusted to match the operating condition of each membrane. The results are considered acceptable only when no warning are presented.

The results obtained for the membranes under each condition are tabulated. A total of 70 runs are reported for 10 membranes across various stages and recovery rates. The best results for each membrane will be presented in the next section.

4. RESULTS AND DISCUSSION

Ten seawater membranes are used in the optimization of the RO desalination plant under different operating conditions. The RO plant is designed to provide a continuous fresh water supply of 100,000 m^3/day. Each membrane operates in one, two, or three stages, with recovery (Y) ranging from 35 to 60%. The optimal number of pressure vessels (N) is determined at each stage.

Each membrane in Rosa undergoes multiple computations based on its unique inputs parameters. The optimal conditions for each membrane are identified by achieving the lowest SCE and the highest permeate quality. **Table (1)** compare the input and output parameters of each membrane to determine the optimal choice. The ideal RO plant configuration consists of two stages. The first stage includes eight pressure vessels, each containing seven membrane elements. The second stage comprises five pressure vessels, each with seven membranes. The feed to the second stage, whith a flow rate of 976 m^3/day and a pressure of 60 bar, is supplied from the brine outlet of the first stage.

The SEC is a critical parameter for comparing membranes performance, as it represents the cost associated with energy consumption. **Fig. (2)** shows the SEC for the 10 membranes under identical operating conditions. The results indicate that membrane 10 (SW30ULE-400i) has the lowest SEC, while the membrane 2 (SW30XHR-400) has the highest.

The total dissolved solids (TDS) of the product water is the another key factor in selecting the best membrane. For drinking water, the TDS must be less than 500 mg/L. **Fig. (3)** illustrates the TDS value of the 10 FilmTec membranes. The results reveal that membrane 2 (SW30XHR-400) produces the lowest TDS, while the membrane 10 (SW30ULE-400i) has the highest.

To determine the optimal membrane for the RO plant, **Fig (4)** presents both the SEC and TDS of each membrane. While membrane 10 (SW30ULE-400i) is the most energy-efficient, membrane 2 (SW30XHR-400) delivers the best product quality with the lowest TDS. Given that product quality (TDS) is a crucial factor for remote regions, membrane 2 (SW30XHR-400) is selected as the best option under the given operating conditions.

The findings from ROSA confirm that membrane 2 **(SW30XHR-400)** is the most suitable choice for this RO plant, as it ensures optimal water quality, which is critical for drinking water applications in remote areas.

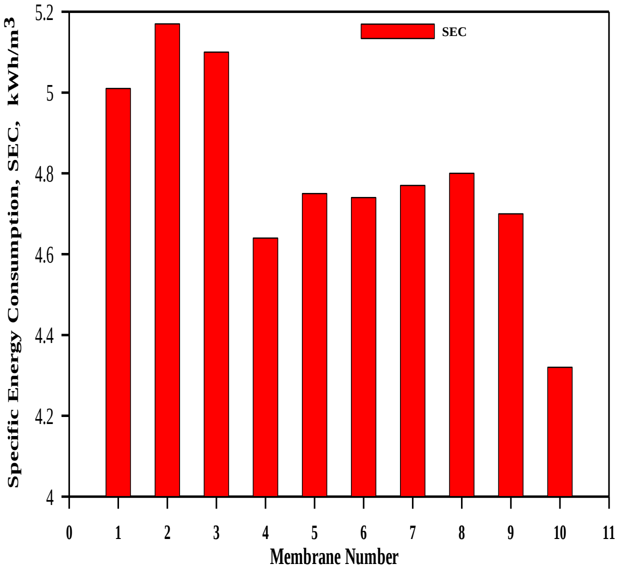


Fig. (2): SEC for Each Membrane.

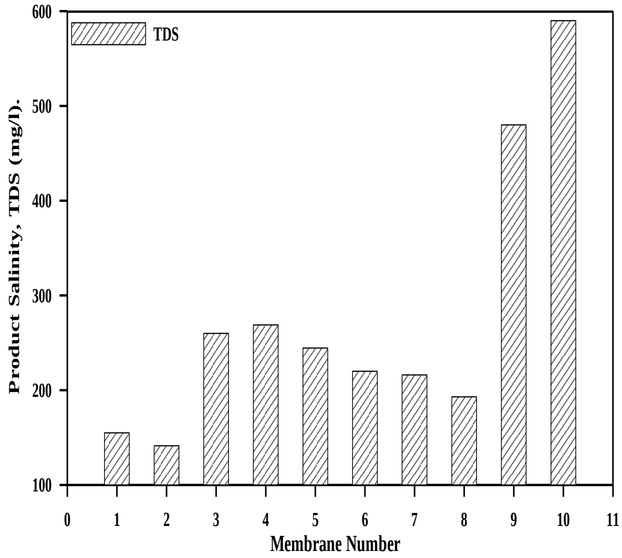


Fig. (3): TDS for Each Membrane.

The selected FilmTec membrane **(SW30XHR-400)** is a Seawater membrane that provides the best water quality. This reverse osmosis membrane element feature unique characteristics detailed in data sheet [35]. The **(SW30XHR-400)** is used for seawater desalination applications in industrial and municipal facilities and is ideal for medium-and high-salinity feed water. For the optimal Internally Staged Designs (ISD), this membrane can be combined with other FilmTec TM seawater membranes.

The primary advantages of the **SW30XHR-400** membrane include optimized energy use and enhanced system productivity, delivering water at a low overall cost. The **SW30XHR-400** membrane is made of Polyamide Thin-Film Composite, with specific operating conditions recommended for optimal performance. 45°C and 83 bar are the maximum working temperatures and pressures, respectively. While the maximum pressure drop per element and per pressure vessel (minimum 4 elements) are 1.0 bar and 3.5 bar, respectively. The pH range for continuous operation is (2–11). Finally, the maximum feed silt density index (SDI) is 5.

The properties and dimension of the **SW30XHR-400** membrane are presented in **Table (2) and Figure (5),** with further details provided in the membrane worksheet [35].

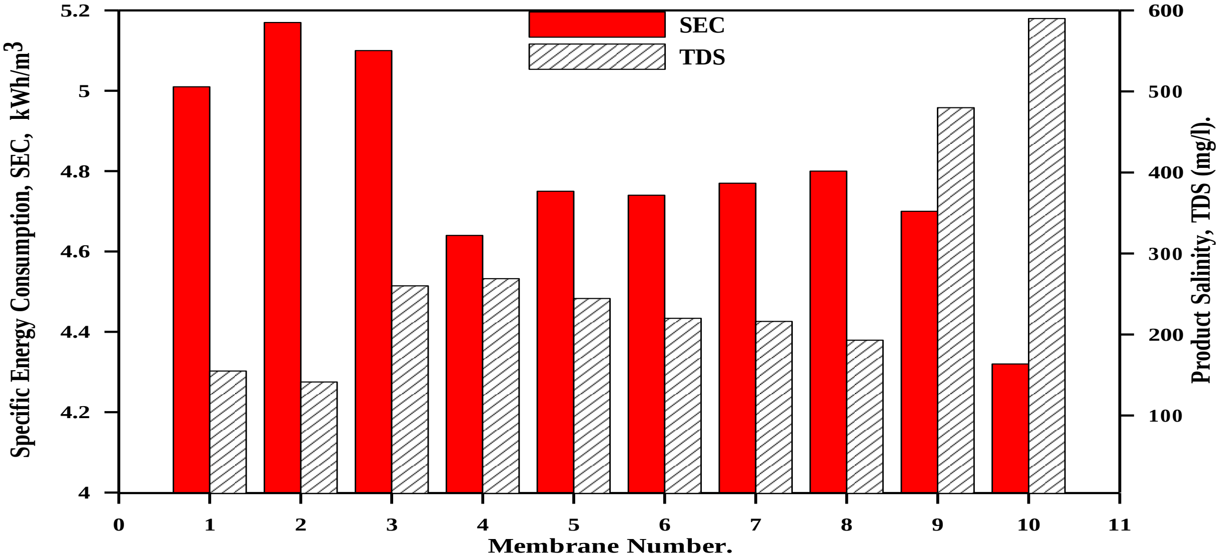


Fig. (4): **The Specific Energy Consumption (SEC) and the Product Salinity (TDS) for Each Membrane.**

Table (1): The Results of 10 Membranes Under Various Operating Circumstances.

	Membrane Type	Y%	N1	P1	Q1	C1	N2	P2	Q2	C2	Nt	SEC,	Ct
1	**SW30XHR-440i**	50	15	71.78	5000	102.3	10	68.95	2938.69	407.5	175	5.01	155
2	**SW30XHR-400**	50	15	74.1	5000	94.1	10	70.96	2897	344.1	175	5.17	**141.4**
3	**SW30HR-380**	45	18	65.72	5556	177.4	12	62.57	3539.9	605.8	210	5.1	260
4	**SW30XLE-440i**	45	18	59.8	5556	182.5	10	57.3	3310.7	1031	196	4.64	268.9
5	**SW30XLE-400i**	45	18	61.2	5556	167.3	10	58.4	3335	859.8	196	4.75	244.5
6	**SW30HRLE-400i**	50	16	67.94	5000	135.5	12	65.13	2897	669.7	196	4.74	220
7	**SW30HRLE-440i**	50	15	68.3	5000	138.4	10	65.5	2860.9	678.6	175	4.77	216.1
8	**SW30HRLE-370/34i**	50	18	62.7	5000	134.4	10	67.01	3858	545.3	196	4.8	193
9	**SW30ULE-440i**	40	18	53.8	6250	312.9	12	50.77	4038.2	1766	210	4.7	480
10	**SW30ULE-400i**	45	20	55.64	5556	335.45	18	53.21	3364.6	2396	266	**4.32**	590

Where:

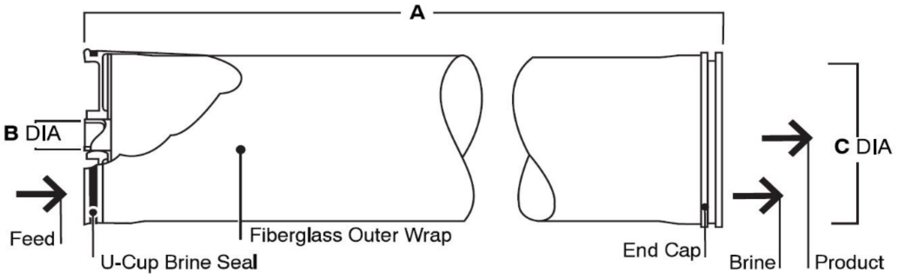
- **Y%**: The recovery percentage
- **N1**: The number of pressure vessels in Stage 1
- **C1**: The permeate TDS in Stage 1 (mg/L)
- **N2**: The number of pressure vessels in Stage 2
- **C2**: The permeate TDS in Stage 2 (mg/L)
- **Nt**: The total number of membranes in the plant

- **P1**: The feed pressure in Stage 1 (bar)
- **Q1**: The feed flow rate in Stage 1 (m^3/day)
- **P2**: The feed pressure in Stage 2 (bar)
- **Q2**: The feed flow rate in Stage 2 (m^3/day)
- **SEC**: The specific energy consumption (kWh/m^3)
- **Ct**: The total permeate TDS (mg/L)

Table (2): Typical Properties of (SW30XHR-400)

FilmTec™ Element	Active Area		Feed Spacer Thickness (mil)	Permeate Flow Rate		Stabilized Boron Rejection (%)	Minimum Salt (Rejection (%)R
	(ft2)	(m2)		(gpd)	(m3/d)		
SW30XHR-400	400	37	28	6,000	23	93	99.7

- The benchmark numbers mentioned above are predicated on the following test parameters: 77°F (25°C), pH 8, 8% recovery, 800 psi (5.5 MPa), and 32,000 ppm NaCl.
- Permeate flows for individual elements may vary ± 15%.



FilmTec™ SW30XHR-400 Dimensions – inches (mm)		
A	40.0	(1,016)
B	1.125 ID	(29) ID
C	7.9	(201)
ID	Inner Diameter	

Fig. (5): The SW30XHR-400 Element Dimensions.

6. CONCLUSION

This study aimed to optimize a reverse osmosis (RO) desalination plant by testing 10 FilmTec membranes. The analysis identified the membrane with acceptable specific energy consumption (SEC) and the best water product quality. A stand-alone RO desalination plant was designed to meet the potable water requirements of a remote area, producing approximatly 100,000 m^3/d. The RO plant requires about 21.5 MW of electrical energy, which can be supplied by **SMRs (KAREM-25)**. Each unit of the RO desalination plant consists of two stages with 175 membranes, determined using ROSA's analysis. The RO plant comprises 40 units, with each unit producing 2500 m^3/d. Based on the specified operating conditions, the **FilmTec SW30XHR-400** membrane was identified as the best choice. The **SW30XHR-400** membrane achieved a specific energy consumption **(**SEC) of 5.71 kWh/m^3 and lowest total dissolved solids (TDS) of 141 mg/L These results demonstrate that the SW30XHR-400 membrane provides the best water quality and energy efficiency for the RO plant under the given conditions.

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