UPGRADED TECHNOLOGIES FOR BOILER FEED WATER

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CERTIFICATE

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DEDICATION

This FYP Thesis is dedicated to, foremost, our parents, who supported us and had our back throughout our life and our friends and teachers here at SCME, who have always mentored us.

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Firstly, we would like to thank Allah, the Generous and Almighty, for His blessing and numerous rewards, granting us the skill and ability to complete this thesis.

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Authors

ABSTRACT

Boiler Feed Water needs to meet specific standards according to the ASME Standards for Boiler Feed Water, to produce steam that is utilized at different locations in the Attock Oil Refinery Limited (ARL). The project aims to replace the cation exchange system for boiler feed water, at an oil refinery, with upgraded technologies such as UF (Ultrafiltration) and RO (Reverse Osmosis) systems in series, to increase the boiler cycles, boiler efficiency, life of the boilers and for the overall conservation of water. Material and Energy balances, equipment design and economic analysis were done for both the systems in order to compare the effluent quality for both the Cation Exchange and RO (Reverse Osmosis) Technologies [1].

As a result of the proposed methodology, the Boiler Feed Water (BFW) quality increases significantly in terms of the TDS concentration reduced due to which the boiler efficiency and boiler-cycles increase [2]. Although it was seen that the installation and production cost of the proposed RO system was higher, in terms of the boiler maintenance and blow down treatment cost, over all the proposed system becomes more cost efficient as well. Proposed technology is more sustainable in terms of green process engineering where the use of hazardous chemicals such as H2SO4 and NaCl is eliminated. The project follows the SDGs 6, 9, 12 and 14 which are mainly related to the clean water and sanitation, sustainability, and Industry and Innovation [3].

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CHAPTER 01

INTRODUCTION AND BACKGROUND

1.1 Introduction:

Attock Oil Refinery has constantly sought to excel in its industrial processes, putting a significant emphasis on efficiency, sustainability, and cost-effectiveness. The boiler system needs a dependable and high-quality source of feed water to maintain optimal performance and save downtime. It is a crucial part of the refinery's infrastructure. Given this, researching cutting-edge technology for water treatment and purification is essential. Reverse osmosis (RO) membrane devices have been proposed to the Attock Oil Refinery as an updated technology for boiler feed water. This literature review will focus on the unique difficulties, advantages, and uses of this novel strategy. This study aims to shed light on the potential benefits and considerations by combining existing knowledge and research findings [4].

1.2 Background:

In order to meet the ASME standards for Boiler Feed water it is necessary to employ technologies that improve the water quality that is entering the boilers. Also, industries are now redirect their current goals and objective to meet the Sustainable Development Goals (SDGs) and other sustainability and environmental-friendly perspectives to their design and methodologies in order to make their systems more sustainable and environmental-friendly [3].

Keeping this in mind ARL [5] is looking to replace its current 100 years old cation exchange system, for its boiler feed water treatment, with latest technologies that not only improve the water quality but also pose less environmental burden by eliminating the use of hazardous chemicals such as NaCl and H2 SO4 (For Resin regeneration and Blow down treatment), hence increasing the Boiler Cycles , Boiler efficiency and making the process more cost and energy efficient in terms of the boilers.

Also, a low quality of water meaning hard water or water with high TSS (Total Suspended Solids), TDS (Total Dissolved Solids) or dissolved metals ions will cause scaling in the boilers leading to a high maintenance cost and lower quality of steam being produced as boilers become highly inefficient. Scaling is the accumulation or build-up of TSS or TDS on the boiler walls or heat exchange surface.

Boiler scale occurs when impurities in the water are deposited on heat transfer surfaces or settle on the metal and become hard and difficult to remove. When these impurities are concentrated, they can interfere with heat transfer and cause hot spots in the boiler [6].

Figure 1.2.1: Scaling in Boilers [7]

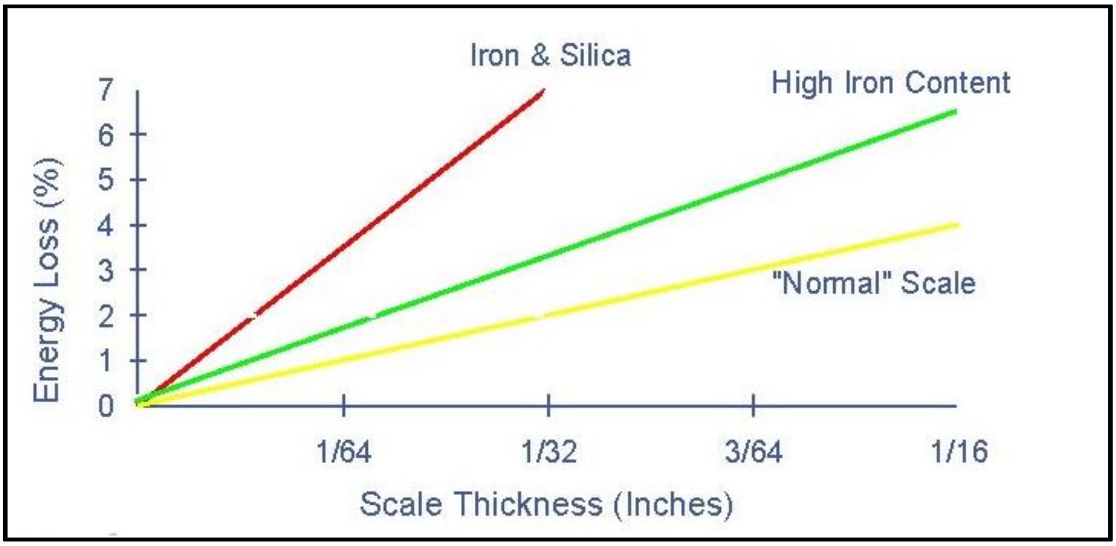


Figure 1.2.2: Above Figure shows the graph of scale thickness vs Energy Loss % [8]

1.3 Cation Exchange Technology

One of the most efficient methods of purifying water from harmful substances is through ion exchange. This process involves replacing certain contaminants in the water with a safer ionic substance. For this process to be successful, both the exchanged substance and the contaminant must have the same electrical charge and must be water-soluble.

Though Cation Exchange has some disadvantages; Long-term costs are high when it comes to operating ion exchange equipment; unable to effectively remove bacteria from water; while, ion exchange beds can be regenerated, salt water is sent directly into the environment during this process [9].

1.3.1 Ion Exchange Process

For the ion exchange process to take place, the equipment must have a micro-porous exchange resin that is filled with a weakly held solution. If the process is intended for water softening, sulfonated polystyrene beds are included in the unit. These beds are filled with a sodium solution that covers the bed's surface. As water flows through the resin bed, the ions will adhere to the beads and release the solution into the sample water. As time progresses, the beds will accumulate contaminants, and the exchange resin will require recharging or regeneration. To complete the regeneration procedure, it is essential to use a salt brine solution to flush the exchange resin. The sodium ions in the salt brine solution take the place of the contaminants that are on the resin bed, and then both the contaminants and wastewater are removed. Due to the way the ion exchange process operates, it's possible to employ it both for water softening in areas with high magnesium and calcium levels, and for water treatment purposes [10].

1.3.2 Ion Exchange Resins

Ion exchange resins can be either artificially manufactured or produced industrially and they're composed of small, micro-porous beads that are insoluble in organic solvents and water. Polyacrylate and polystyrene are the primary materials used to create these resins. Generally, the beads will have a diameter between 0.3-1.3 millimeters and contain 50% water, giving them a gel-like texture. Water flows through the beads, allowing easy movement in and out of them. The resin beads contain either positively or negatively charged ions. If the water has positively charged contaminants, they will be attracted to the negatively charged anions in the beads. Similarly, if the water has negatively charged contaminants, they will interact with the positively charged cations on the resin beads. The process can also be reversed. The resin beads are used in water treatment to trap water impurities. Regardless of whether you are attempting to eliminate pollutants and impurities in acidic water or soften hard water, the ion exchange process can be advantageous [11].

1.4 Ultrafiltration Technology

Ultrafiltration (UF) is a technique that involves using a semi-permeable membrane and hydrostatic pressure to purify water. This process is like Reverse Osmosis. The ultrafiltration membrane has tiny pores that range in size from 103 to 106 Daltons. These pores act as a barrier to various impurities such as suspended solids, bacteria, viruses, endotoxins, and other pathogens, resulting in the production of high-quality water with low silt density. Ultrafiltration (UF) is a type of membrane filtration where pressure is used to push liquid against a semi-permeable membrane. This process separates high molecular weight solids and solutes, while allowing low molecular weight solutes and water to pass through the membrane. Although UF is like other filtration methods like reverse osmosis, microfiltration, and nanofiltration, the main difference is the size of the molecules that are retained **[12]**.

1.5 Reverse Osmosis Technology

Reverse osmosis is a method of purifying water by using a synthetic membrane that acts as a filter to remove undesirable particles and substances such as salt, chlorine, and dirt. The process involves applying pressure to the water to force it through the membrane, which separates the water from contaminants by moving it from areas of high concentration to areas of low concentration. This enables the water to be purified and made safe for various applications [13]. As a result of pressure being applied in the reverse direction, contaminated water in being pressurized or pushed to the clean water(effluent) side, but it is hindered by a filter that captures the pollutants, allowing only the clean water to pass through [14].

1.5.1 Single Pass Reverse Osmosis

A single pass RO system is when only one independent RO system is used and the permeate of that one RO system is the final permeate of the system [15].

1.5.2 Double Pass Reverse Osmosis

A Double Pass Reverse Osmosis (DPRO) System is when the permeate water from first RO system is fed into a second RO unit to produce more pure water. A two or double stage RO is when the concentrate or reject stream is fed into a second RO system to recover water, respectively. A reverse osmosis system is designed to purify water by rejecting around 99% of total dissolved solids from the feed water. Single Pass RO Systems produce product water (permeate) and reject water (concentrate) at the same time [16].

CHAPTER 02

LITERATURE REVIEW

2.1 Objective

The primary objective of this project is to investigate the application of reverse osmosis (RO) membrane technology as an upgraded solution for boiler feed water at Attock Oil Refinery. The project aims to assess the potential benefits, challenges, and feasibility of implementing RO membranes in the refinery's boiler system.

By conducting a comprehensive literature review, the project intends to gather and analyze relevant research findings, case studies, and industry best practices regarding the use of RO membranes for water treatment in similar industrial settings. The objective is to evaluate the effectiveness of RO membrane technology in improving the quality of feed water, reducing the concentration of contaminants, and enhancing the overall efficiency and reliability of the boiler system at Attock Oil Refinery.

Additionally, the project seeks to identify any specific considerations or limitations that may arise when implementing RO membranes in the context of the refinery's operational requirements and environmental factors. The ultimate goal is to provide valuable insights and recommendations for the refinery to make informed decisions regarding the potential adoption of RO membrane technology for their boiler feed water treatment [17].

2.2 Scope and Limitations

The scope of this project is to compare and evaluate the performance and efficiency of two water treatment systems: one comprising a cation exchanger and the other employing a reverse osmosis (RO) system. The project aims to analyze and assess the capabilities, limitations, and suitability of these two technologies in treating water for a specific application or industry [1].

The project will focus on conducting a comprehensive literature review to gather information on the principles, design considerations, and operational aspects of both cation exchange and reverse osmosis systems. The scope includes examining relevant research papers, case studies, and industry practices to compare the effectiveness of these technologies in removing contaminants, improving water quality, and meeting the desired treatment objectives.

However, it is important to acknowledge certain limitations. Firstly, the project will be limited to the comparison between cation exchanger and reverse osmosis systems. Other water treatment technologies or alternative approaches may not be extensively covered within the scope of this project.

Additionally, the project will rely on existing literature and research to draw comparisons between the two systems. The availability and accessibility of research papers and industry information may impact the comprehensiveness of the review.

Furthermore, the project will not involve any experimental work or data collection specific to a particular application or industry. The findings and conclusions will be based on the analysis of existing information and may not capture site-specific conditions or variations in performance that could arise in real-world applications.

Despite these limitations, this project will strive to provide valuable insights and recommendations to facilitate decision-making and contribute to the understanding of the two water treatment technologies in question.

2.3 Islamabad ground water composition

To assess the suitability of reverse osmosis (RO) membrane technology for upgrading the boiler feed water at Attock Oil Refinery, a comprehensive understanding of the groundwater composition is essential [5]. To obtain this crucial information, statistics by Pakistan Standards and Quality Control Authority was consulted. The statistics conducted a detailed analysis of groundwater samples collected from various monitoring wells in the vicinity of the refinery. It provides valuable insights into the levels of different contaminants, such as dissolved solids, organic compounds, and heavy metals, which are critical factors to consider when evaluating the effectiveness of RO membrane systems [18].

By utilizing the data and findings presented in this reference, a thorough evaluation can be conducted to determine the feasibility and potential challenges associated with implementing RO membrane technology for enhancing the quality of boiler feed water at Attock Oil Refinery.

Parameters	Min-max	Range	Mean ± SE	Variance	Skewness	Kurtosis
pH	6.76–8.10	1.34	7.22 ± 0.02	0.05	1.31	2.34
EC (μS/cm)	346.00–13230.00	12884.00	1043.01 ± 107.22	1379404.79	9.28	92.90
TDS (mg/L)	207.60–7938.00	7730.40	626.69 ± 64.36	497008.05	9.26	92.69
Phosphates (mg/L)	0.01–1.17	1.16	0.13 ± 0.015	0.026	3.53	15.52
Arsenic (μg/L)	0.00–14.70	14.70	0.70 ± 0.13	1.94	8.49	81.94
Copper (mg/L)	0.00–0.11	0.11	0.006 ± 0.002	0.00	4.13	16.84
Fluoride (mg/L)	0.11–2.24	2.13	0.49 ± 0.026	0.08	2.82	11.57
Iron (mg/L)	0.02–1.15	1.13	0.094 ± 0.015	0.023	4.61	25.27
Manganese (mg/L)	0.00–0.145	0.145	0.003 ± 0.002	0.00	7.62	59.22
Lead (μg/L)	0.00–692.20	692.20	13.36 ± 6.157	4586.91	8.87	82.36
Zinc (mg/L)	0.00–1.56	1.56	0.10 ± 0.034	0.08	3.73	14.23
δC13 (per mil)	-18.90-- --1.04	17.86	-7.67 ± 0.37	9.62	-0.59	1.37

Figure 2.3; Above table shows the groundwater composition for Islamabad *[18]*.

2.4 ASME standards

After implementing the reverse osmosis (RO) system for water treatment, the composition of the treated water was analyzed to assess its compliance with the American Society of Mechanical Engineers (ASME) standards. The results obtained indicate that the water composition meets the specified guidelines set forth by ASME [19].

The RO system effectively removes a wide range of contaminants, including dissolved solids, organic compounds, and trace elements. Through the process of reverse osmosis, the system applies pressure to the feed water, forcing it through a semipermeable membrane that selectively retains impurities while allowing pure water to pass through. This thorough purification process ensures that the treated water meets the stringent requirements outlined in the ASME standards [19].

Table 2.4; Table below shows the compositions different components according to the ASME standards for boiler feed water [19]

Component	**TDS**	**Magnesium**	**Calcium**	**H2S**	**Bicarbonates**
Composition (ppm)	20-100	-	<0.3	-	-
Component	**Nitrates**	**COD**	**BOD**	**Silica**	**Trace Metals**
Composition (ppm)	50-100	<0.007	<0.007	<150	<0.3

By conforming to the ASME standards, the RO system guarantees that the treated water is of the desired quality for its intended application, such as boiler feed water. This compliance ensures that the water does not pose a risk to the boiler system's components and operations. The removal of impurities, such as dissolved solids and trace elements, reduces the likelihood of scale formation, corrosion, and fouling, which can lead to decreased efficiency, equipment damage, and operational issues.

Overall, the adherence to ASME standards underscores the effectiveness and reliability of the RO system as a robust water treatment solution. The successful implementation of the system provides confidence in its ability to consistently produce high-quality water that meets the necessary criteria for its specific use, promoting efficient and trouble-free operations in line with industry standards.

2.5 Challenges

By reducing power usage and preventing downtime for repairs, proper maintenance of boilers and hot water systems can aid in lowering operating expenses [17]. A reverse osmosis system can greatly reduce expenditures resulting from inadequate boiler system maintenance. Systems using reverse osmosis lessen the dissolved solids that cause scaling. The boiler's efficiency and ability to operate at maximum capacity are both increased by eliminating these contaminants. The best designs for RO systems will make use of ASME pressure vessels, filter tanks, and premium equipment like conductivity and pH meters. The efficiency of a boiler is significantly influenced by the pH of the water.

2.6 Available technologies in order to treat the boiler feed water

Improving the quality of boiler feed water at the Attock Oil Refinery can be achieved through the implementation of various technologies. Given the importance of water quality in maintaining efficient and reliable boiler operations, the refinery can consider the following technologies:

1. Chemical Treatment: Employing appropriate chemical treatment methods is crucial for maintaining water quality within desired parameters. The refinery can use oxygen scavengers, corrosion inhibitors, pH adjusters, and antiscalants to control corrosion, scale formation, and microbial growth. These chemicals, when dosed properly, can help prevent fouling, reduce corrosion rates, and maintain the desired water chemistry [20].

2. Blowdown Control: Implementing an effective blowdown system is important to remove impurities and prevent excessive concentrations in the boiler. Proper control of blowdown helps maintain water quality by reducing the build-up of dissolved solids. The refinery should establish blowdown procedures based on water analysis results to ensure optimal water quality is maintained [21].

3. Activated Carbon Adsorption: Activated carbon is a highly porous material with a large surface area, making it effective for adsorbing a wide range of organic compounds, taste and odor-causing substances, and certain inorganic contaminants. Water treatment facilities often use activated carbon filters to remove pesticides, industrial chemicals, and volatile organic compounds (VOCs) from drinking water sources [22].

4. Chemical Adsorption: Certain chemicals, such as zeolites, clays, and activated alumina, have properties that allow them to selectively adsorb specific contaminants. Zeolites, for example, are used to remove ammonia from water, while activated alumina is effective in removing fluoride. These materials provide a surface for the target contaminants to adhere to, resulting in their removal from the water [23].

5. Polymeric Adsorbents: Polymeric adsorbents are synthetic materials specifically designed for adsorption applications. These materials are highly porous and can be engineered to have specific affinities for certain contaminants. Polymeric adsorbents are commonly used in water treatment for the removal of heavy metals, pesticides, pharmaceuticals, and other organic compounds.

6. Bio adsorption: Bio adsorption utilizes biological materials, such as certain types of algae, fungi, or bacteria, to adsorb and remove contaminants from water. These microorganisms can accumulate pollutants through their natural metabolic processes or by binding to their cellular structures. Bio adsorption can be an effective method for removing heavy metals, dyes, and organic compounds from wastewater [24].

7. Reverse Osmosis (RO): Installing a reverse osmosis system can effectively remove dissolved salts, minerals, and impurities from the feed water. RO uses a semipermeable membrane to separate contaminants, producing high-quality water with low total dissolved solids (TDS) levels. This technology would significantly reduce the risk of scale formation and minimize the potential for corrosion within the boiler system [25].

8. Ion exchange: Ion Exchange is a process where ions in the water are exchanged with ions on a solid resin material. Cation exchange resins attract and remove positively charged ions (such as calcium, magnesium, and heavy metals), while anion exchange resins target negatively charged ions (such as nitrate, sulfate, and arsenic). Ion exchange is commonly used for water softening, deionization, and the removal of specific contaminants [10].

2.7 Drawbacks of the above-mentioned technologies

One common drawback of technologies like activated carbon adsorption and ion exchange is their limited capacity for contaminant removal. Over time, the adsorption or exchange sites of these materials can become saturated, requiring regeneration or replacement. This ongoing maintenance can result in higher operational costs and downtime [9]. Additionally, these technologies may not be suitable for removing certain types of contaminants, such as dissolved inorganic salts or heavy metals, which may require specific treatment methods. Another limitation is the potential for chemical byproduct formation. Some treatment methods, such as chemical adsorption using zeolites or activated alumina, may generate secondary byproducts that need to be managed appropriately. Furthermore, some technologies may have a slower treatment rate or require a larger footprint compared to RO systems. For instance, bio adsorption methods utilizing microorganisms often have slower kinetics and may require larger reactors or contact times. These factors should be carefully evaluated to determine the most suitable technology for boiler feed water treatment, considering the specific contaminants present and the operational requirements of the refinery.

2.8 Conclusion:

In conclusion, reverse osmosis (RO) stands out as the best technology for boiler feed water treatment at the Attock Oil Refinery (ARL), surpassing other options in terms of cost-effectiveness, efficiency, and the potential for increased boiler cycles. RO offers numerous advantages that make it an ideal choice for enhancing water quality in boiler systems [17]. Firstly, its ability to remove dissolved salts, minerals, and impurities ensures a substantial reduction in scale formation and corrosion risks, thereby prolonging the lifespan of the boiler and reducing maintenance costs [4]. Additionally, the high efficiency of RO membranes enables the production of high-quality water with low total dissolved solids (TDS) levels, ensuring optimal boiler performance. This results in improved heat transfer and fuel efficiency, ultimately leading to energy savings for the refinery. Moreover, by providing purified water, RO enhances the overall boiler cycles by minimizing fouling and reducing blowdown requirements, resulting in cost savings through reduced water consumption and chemical usage. Considering the cost-effectiveness, efficiency, and potential for increased boiler cycles, reverse osmosis emerges as the most favorable technology for boiler feed water treatment at ARL, ensuring reliable and efficient boiler operation while optimizing operational costs.

CHAPTER 03

PROCESS DESCRIPTION AND PFDS

3.1 Old system at ARL with Cation Softener

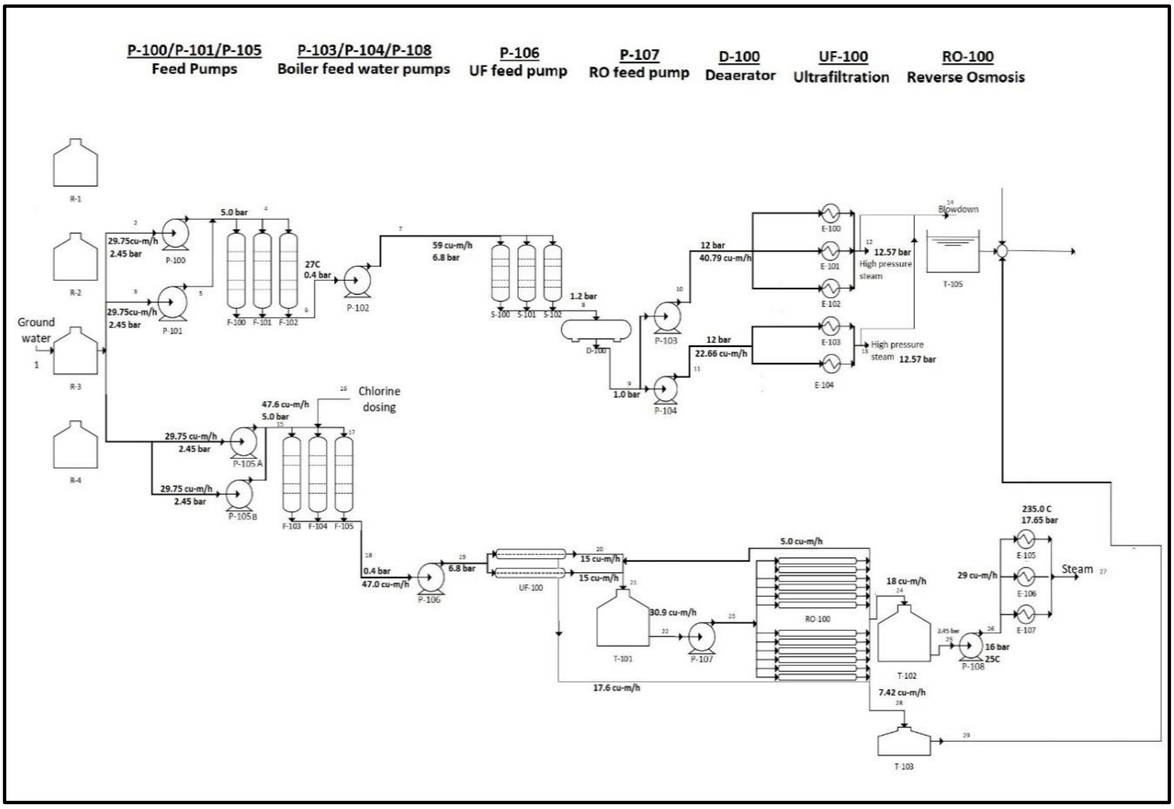


Figure 3.1 Above figure shows PFD for cation softener at ARL

The above process flow diagram shows the cation softener system and the reverse osmosis water treatment currently installed at the ARL site. The upper part of the PFD is the cation softener that is the 100-year-old water treatment system currently installed for boiler feedwater treatment. The lower part of the PFD is a reverse osmosis water treatment system that was recently installed with the new boilers.

The process starts with the multimedia water treatment system that will remove suspended solids from the feed. The multimedia filter has layers of anthracite, sand, and gravel respectively that traps the suspended solids from the feed.

After this separation the feed is pumped into the cation softener that will remove the hardness of the feed water. Hardness of water mainly stems from the presence of calcium and magnesium ions, which can cause scaling and reduce the efficiency of the boiler systems. The water softening process involves passing the feed from the bed of ion exchange resin. The resin bed is made of tiny beads that are chemically charged with sodium ions, that are exchanged with calcium and magnesium ions as the feed passes through the bed.

The cation softener system has three separate identical vessels, and one is used at a time. The cation softener is used for an 8-hour shift, and then the sodium ions are regenerated by flushing the vessel with the brine solution during the next shift. The sodium ions in the brine solution will get replaced with magnesium and calcium ions and the resin bed is recharged. One softener is available as backup.

Next step and last step in the process is the Deaerator, which will remove the COD and BOD. These dissolved gases can cause corrosion inside the boiler and cause damage to the boiler and its performance. After that the de-aerated water is stored in a tank from where it is pumped into the boilers as required.

Coming to reverse osmosis part of the PFD. The R.O plant works independently for the other 3 boilers. The treatment process starts at the multimedia filter, where the suspended solids are separated from the feed. This is crucial for pretreatment of water, otherwise water will damage the R.O membranes. So, the first step is always the multimedia filter.

After that the feed enters the ultrafiltration process. Which will remove components like silicates from the water. The ultrafiltration process also uses membrane technology for separation like the reverse osmosis process. It is installed mainly to protect the R.O membranes. As these silicates can cause fouling in the membranes.

The final step is removal of the hardness of water using reverse osmosis. The reverse osmosis separation occurs at a higher pressure than cation softener. The pressurized water is passed through the RO membranes. This membrane acts as a barrier and only lets water molecules pass through and the dissolved solids are rejected with the concentrate/reject stream. This reject stream passes through another pass of RO membranes and more separation is done. All the softened water is collected in a tank and is fed to boilers as required.

3.2 Proposed system with RO treatment plants

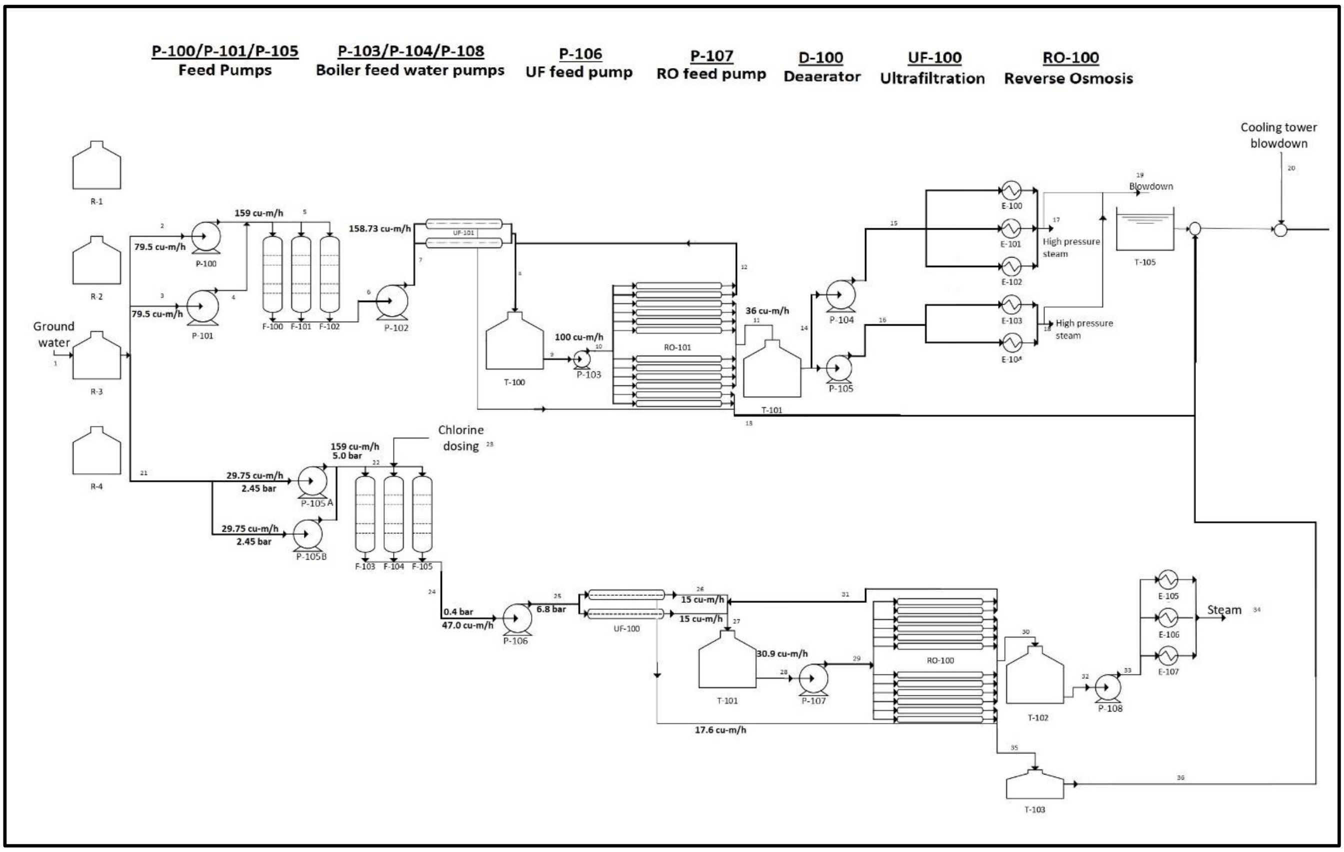


Figure 3.2 shows PFD for the proposed system consisting of RO

This PFD represents the proposed solution with RO system replacing the previous cation softener system. The upper part of the PFD is the replaced RO and the lower part remains unchanged.

The process for RO is the same as mentioned before. The feed passes through the multimedia filter first, to remove the suspended solids. Then the water passes through the ultrafiltration to remove the silicates. And the last step is reverse osmosis. The hardness of the water is removed as the water feed passes through the cellulose acetate spiral wound membranes.

CHAPTER 04

4. MATERIAL BALANCE

4.1 Material balance for the current system

The current water treatment system has a cation softener and a reverse osmosis treatment system. The cation softener system has a multimedia filter, cation softener, and a deaerator installed. And the RO system has multimedia filter, ultrafiltration plant and the reverse osmosis plant. Detailed material balance for each equipment is presented.

4.1.1 Multimedia filter

Flow rate IN = 37 cu-m/hr

Flow rate OUT = 36.3 cu-m/hr

Efficiency = 60%

Multimedia filter removes Hydrogen Sulfide and Silica. Multimedia filter consists of three layers, Anthracite, Coal, and Gravel. All calculations are based on efficiency percentages. [26]

Table 4.1.1 Material Balance on Multimedia Filter

Component	**IN(4)**	**OUT(6)**
TDS	1250	1250
Magnesium	35	35
Hydrogen Sulfide	180	72
Calcium	44.4	44.4
Chloride	42	42
Sodium	69.6	69.6
Nitrates	3.8	3.8
COD	132.7	132.7
BOD	42.14	42.14
TSS	44.57	17.83
Bicarbonate	318.6	318.6
Silica	22	8.8
Trace metals	1.53	1.53

4.1.2 Cation Exchange System

Flow rate IN = 36.3 cu-m/hr

Flow rate OUT = 36 cu-m/hr

Efficiency = 57%

Cation exchange system removes ions from the water and reduces Total Suspended Solids as well. All these calculations are done on basis of Efficiency, which is taken as 57% [27].

Table 4.1.2 Material Balance on Cation Exchange System

Component	IN(6)	OUT(7)
TDS	1250	712.5
Magnesium	35	19.95
Hydrogen Sulfide	72	72
Calcium	44.4	25.4
Chloride	42	23.9
Sodium	69.6	105.1
Nitrates	3.8	3.8
COD	132.7	132.7
BOD	42.14	42.14
TSS	17.83	10.16
Bicarbonate	318.6	181.6
Silica	8.8	8.8
Trace metals	1.53	1.53

4.1.3 Deaerator

Flow rate IN = 36 cu-m/hr

Flow rate OUT = 36 cu-m/hr

Deaerator is used here to remove dissolved gases and air from the feedwater. Hence, corrosive gases are removed from the feedwater [28].

Table 4.1.3 shows the Material Balance on Deaerator

Component	**IN(7)**	**OUT(8)**
TDS	712.5	712.5
Magnesium	17.5	17.5
Hydrogen Sulfide	90	90
Calcium	22.2	22.2
Chloride	42	42
Sodium	105.1	105.1
Nitrates	3.8	3.8
COD	132.7	0.007
BOD	42.14	0.007
TSS	10.16	10.16
Bi Carbonate	318.6	318.6
Silica	8.8	8.8
Trace metals	1.53	1.53

4.1.4 Multimedia Filter for RO

Flow rate IN = 47.6 cu-m/hr

Flow rate OUT = 47 cu-m/hr

Efficiency = 80%

Second part of old equipment is the Reverse Osmosis system. Multimedia filter for RO process removes TSS, Hydrogen Sulfide and Silica. This is used to prevent fouling in the system [29].

Table 4.1.4 shows the Material Balance on RO

Component	**IN**	**OUT(30)**
TDS	1250	1250
Magnesium	35	35
Hydrogen Sulfide	180	36
Calcium	44.4	44.4
Chloride	42	42
Sodium	69.6	69.6
Nitrates	3.8	3.8
COD	132.7	132.7
BOD	42.14	42.14
TSS	44.57	8.9
Bi Carbonate	318.6	318.6
Silica	22	4.4
Chlorine	600	-
Trace metals	1.53	-

4.1.5 Ultrafiltration

Feed = 47.6 cu-m/hr

Permeate = 30.92 cu-m/hr

Reject=17.62 cu-m/hr

Efficiency = 80% (for TSS)

Average salt (TDS) rejection

Rate is 20%

Permeate = 63% of the feed

After Multimedia filter, an Ultrafiltration system is installed, which reduces TDS, Calcium, Nitrates, and Silica [30].

Table 4.1.5 shows the Material Balance on Ultrafiltration

Component	IN (30)	OUT (31)
TDS	1250	1000
Magnesium	35	28
Hydrogen Sulfide	36	36
Calcium	44.4	35.52
Chloride	42	42
Sodium	69.6	55.68
Nitrates	3.8	3.8
COD	132.7	132.7
BOD	42.14	42.14
TSS	8.9	1.78
Bi Carbonate	318.6	254.9
Silica	4.4	0.88

4.1.6 Reverse Osmosis System: Current

The RO plant has two passes: A1& A2. So, material balance for each pass is explained below. These values are calculated based on theoretical separation at each pass.

4.1.6.1 Reverse Osmosis System A1

(Vol. of feed) *(Conc. of feed) = (Vol. of reject) *(Conc. Of reject) + (Vol. of permeate) *(Conc. Of permeate)

Permeate = 60% of Feed (For systems A1 and A2)

Average Salt (TDS) Rejection = 95% (For systems A1 and A2)

95% = 1000 – Product

Product = 50ppm

Reject TDS = 1/ (1- % recovery) * Feed TDS

= 1/ (1-0.6)*1000

= 2500ppm

Feed1 Flowrate = 30.92 cu-m/hr

Permeate1 Flowrate = 23.5 cu-m/hr

Reject1 Flowrate = 7.42 cu-m/hr

Reverse Osmosis system A1 purifies feedwater and Permeate of this system is the Feed of System A2 [29].

TABLE 4.1.6.1 Material Balance on Reverse Osmosis System A1

Component	Feed1 (ppm)	Permeate1 (ppm)	Reject1 (ppm)
TDS	1000	65.8	6250
Magnesium	28	1.84	175
Calcium	35.52	2.34	222
Chloride	42	2.8	262.5
Sodium	55.6	3.6	347.5
Bicarbonate	254.9	16.8	1593

4.1.6.2 Reverse Osmosis System A2

Feed2 Flowrate = 23.5 cu-m/hr

Permeate2 Flowrate = 18 cu-m/hr

Reject2 Flowrate = 5.5 cu-m/hr

Permeate of System A1 is now fed into the System A2 to reduce TDS value, which gets reduced to 4.36 ppm [29].

Table 4.1.6.2 Material Balance on RO System A2

Component	Feed2(ppm)	Permeate2(ppm)	Reject2(ppm)
TDS	65.8	4.36	411
Magnesium	1.84	0.11	11.5
Calcium	2.34	0.14	14.6
Sodium	2.80	0.17	17.5
Bicarbonate	3.60	0.21	22.5
Chloride	16.8	1.01	105

4.2 Material balance for proposed Reverse Osmosis systems.

The proposed solution has the cation softener part of the system replaced with a new RO plant. The new water treatment system will produce a better-quality boiler feed water. The proposed system will have a multimedia filter, ultrafiltration plant and RO plant. No changes are made to the RO plant currently installed along the cation softener.

4.2.1 Multimedia Filter

Flow rate IN = 116.0 cu-m/hr

Flow rate OUT = 115.3 cu-m/hr

Efficiency = 92%

Multimedia filter is used to reduce Silica value. Efficiency for old system was 80%, but for new system, it is 92%. Hence, 92% removal of Silica occurs in this process [26].

Table 4.2.1 Material Balance for Multimedia Filter of New RO System

Component	IN	OUT(30)
TDS	1250	1250
Magnesium	35	35
Hydrogen Sulfide	180	14.4
Calcium	44.4	44.4
Chloride	42	42
Sodium	69.6	69.6
Nitrates	3.8	3.8
COD	132.7	132.7
BOD	42.14	42.14
TSS	44.57	3.6
BiCarbonate	318.6	318.6
Silica	22	1.76
Chlorine	600	-
Trace metals	1.53	-

4.2.2 Ultrafiltration

Flow rate IN = 115.3 cu-m/hr

Flow rate OUT = 73.0 cu-m/h

Efficiency = 80% (for TSS)

Average salt (TDS) rejection rate is 20%

In next step, some TDS and most of TSS is removed. Efficiency of this system is 80%, for TSS removal [30].

Table 4.2.2 Material Balance of Ultrafiltration for New RO

Component	IN(30)	OUT(31)
TDS	1250	1000
Magnesium	35	28
Hydrogen Sulfide	14.4	14.4
Calcium	44.4	35.52
Chloride	42	33.6
Sodium	69.6	55.6
Nitrates	3.8	3.8
COD	132.7	132.7
BOD	42.14	42.14
TSS	3.6	0.72
BiCarbonate	318.6	254.4
Silica	1.76	0.352

4.2.3 Reverse Osmosis System B1

Flow Rate of Feed1 = 100.59 cu-m/hr

Flow Rate of Permeate1 = 63.05 cu-m/hr

Flow Rate of Reject1 = 37.53 cu-m/hr

Reverse Osmosis B1 is the proposed system for Reverse Osmosis. Reverse Osmosis uses pressure as a driving force to remove dissolved solids [29].

Table 4.2.3 Material Balance on RO System B1

Component	**Feed1 (ppm)**	**Permeate1 (ppm)**	**Reject1 (ppm)**
TDS	1000	49.64	2679.87
Magnesium	35	1.73	93.8
Calcium	44.4	2.20	118.9
Sodium	20	0.99	53.6
Bicarbonate	318.6	15.81	853.8
Chloride	42	2.08	112.56

4.2.4 Reverse Osmosis System B2

Flow Rate of Feed2 = 63.05 cu-m/hr

Flow Rate of Permeate2 = 36 cu-m/hr

Flow Rate of Reject2 = 27.04 cu-m/hr

In Reverse Osmosis system B2, Permeate of System B1 is introduced in as Feed. Hence, purification of feedwater occurs as TDS value drops to 2.4 ppm, which is acceptable according to ASME Standards.

Table 4.2.4 Material Balance on RO System B2

Component	**Feed2 (ppm)**	**Permeate2 (ppm)**	**Reject2 (ppm)**
TDS	49.64	2.396	115.76
Magnesium	1.4	0.067	3.2
Calcium	1.77	0.0853	4.12
Sodium	0.8	0.038	1.86
Bicarbonate	12.74	0.614	29.61
Chloride	1.68	0.0809	3.91

4.3 Comparison for quality of water and ASME standards

The final quality of the water from the currently installed cation softener system is not suitable to be used as boiler feed water according to the ASME standards for boiler feedwater. As the TDS for cation exchange system is close to 700 ppm that way above the suitable range of 20-100 ppm. So, shifting to the RO system is very important as it can produce higher quality water with less than 10 ppm.

Table 4.3 Comparison for quality of water

Component	ASME Standards for BFW (0-300 psig) (ppm)	OUT (New System) (ppm)	OUT (Old System) (ppm)
TDS	20-100	2.396	712.5
Magnesium	-	0.067	17.5
Hydrogen Sulfide	-	14.4	90
Calcium	<0.3	0.085	22.2
Chloride	-	0.080	42
Sodium	-	0.133	105.1
Nitrates	50-100	3.80	3.8
COD	<0.007	0.006	0.007
BOD	<0.007	0.006	0.007
TSS	-	0.72	10.16
BiCarbonate	-	0.609	318.6
Silica	<150	0.352	8.8
Trace metals	<0.3	-	1.53

4.4 Quantitative Analysis of water quantity for old and new system

The quantities of water used as backwashes and rejected stream for the old cation system and the proposed RO water treatment system are listed in the tables below. Reverse Osmosis rejects a significant amount of water as concentrate, as it has higher selectivity. The ultra-filtration process works very similar to the RO, and it also has a higher reject ratio. Therefore, in terms of water quantity used; cation softener is better. However, considering the final quality of the water of both systems, it is advisable to opt for reverse osmosis water treatment system.

Table 4.4.1 Water quantity used in cation softener.

Equipment	Old System (Cation exchange) Water use (cu-m/hr)
Multimedia filter backwash water	2.22
Softener regeneration brine solution	1.0
Multimedia filter backwash water	2.86
UF1 Reject	17.6
UF1 backwash	2.35
RO1 Reject	7.42
RO1 Backwash	3.09

Table 4.4.2 Water quantity used in Proposed RO

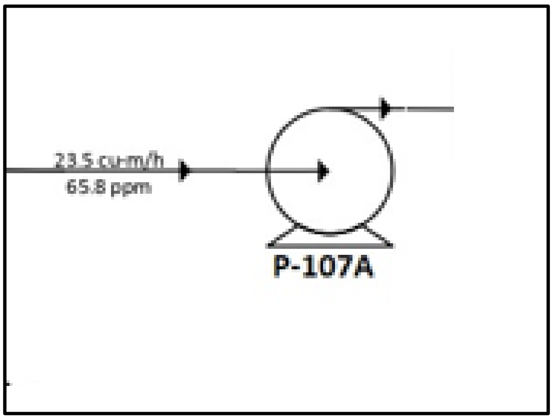
Equipment	New System (Reverse Osmosis) Water use (cu-m/hr)
Multimedia filter backwash water	5.8
UF2A Reject	40.3
UF2A backwash	5.77
RO2A Reject	37.53
RO2A Backwash	10
Multimedia filter backwash water	2.86
UF2B Reject	17.6
UF2B backwash	2.35
RO2B Reject	7.42
RO2B Backwash	3.09

CHAPTER 05

ENERGY BALANCE

Energy balance is mainly done for equipment like pumps and boilers. The energy required for pumps of both systems is calculated according to the required pressure and flowrates. The efficiency is estimated to be 75%. For the boilers, we have calculated the amount of energy that will go into the boiler to produce required steam as utility.

5.1 Energy balance for pumps in old system



Calculations:

H2-H1 = V.(P2-P1)

W = V.(P2-P1) Where V is the volumetric flowrate

For example, pump P-107A

W = 23.5 cu-m/h * (10-7.8) * 100

W = 5.17E+03 kJ/h

Table 5.1; Below table shows the energy requirements for all pumps in old system.

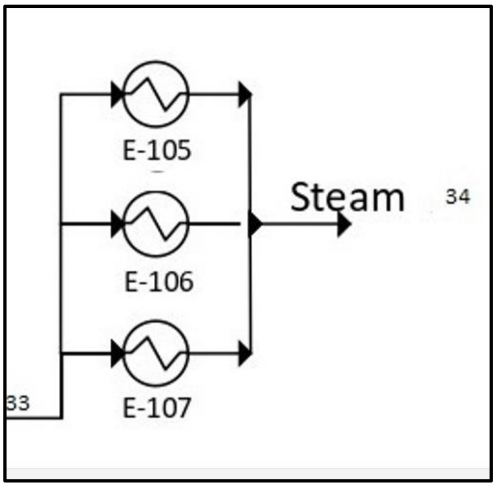
Equipment (existing plant)	Q in kJ/h at 100% eff	Q in kJ/h at 75% eff
P-100	4.72E+03	6.29E+03
P-101	4.72E+03	6.29E+03
P-102 @ Softener inlet	2.32E+04	3.09E+04
P-103 for top 3 boilers	4.49E+04	5.99E+04
P-104 for bottom 2 boilers	2.49E+04	3.32E+04
P-105	6.07E+03	8.09E+03
P-106	5.99E+03	7.99E+03
P-107	2.81E+04	3.75E+04
P-108	2.43E+04	3.24E+04
P-109	5.17E+03	6.89E+03
P-110	3.99E+04	5.32E+04
Total	**2.12E+05**	**2.83E+05**

5.2 Energy balance for pumps in new system

Table 5.2; Table below shows the list of all the pumps and their corresponding energy requirements.

Equipment (new plant)	Q in kJ/h at 100% eff	Q in kJ/h at 75% eff
P-200	1.48E+04	1.97E+04
P-201	2.03E+04	2.71E+04
P-202 @ UF inlet	1.11E+05	1.48E+05
P-203 @ RO inlet	7.60E+04	1.01E+05
P-204 RO mid pump	3.78E+04	5.04E+04
P-205A 3boilers	4.49E+04	5.99E+04
P-205B 2boilers	2.49E+04	3.32E+04
P-206	6.07E+03	8.09E+03
P-207	5.99E+03	7.99E+03
P-208	2.81E+04	3.75E+04
P-209	2.43E+04	3.24E+04
P-210	5.17E+03	6.89E+03
P-211 A/B/C	3.99E+04	5.32E+04
Total	**4.39E+05**	**5.86E+05**

5.3 Energy balance for boilers in old system.



Calculations:

Q = m.cp.(T2-T1)

Q = m.Lv

For boilers E-100/E-101/E-102

Q = 12000 * 4.461 * (192-25) + 12000 * 2260

Q = 3.61E+07 kJ/h

Table 5.3; Table below shows the energy balance on boilers for the old system.

Equipment (old system)	Q in kJ/h at 100% eff	Q in kJ/h at 75% eff
E-100/E-101/E-102	3.61E+07	3.61E+07
E-103/E-104	3.80E+07	3.80E+07
E-105/E-106/E-107	3.19E+07	3.19E+07
Total	**1.06E+08**	**1.06E+08**

5.4 Energy balance for boilers in new system

Calculations are same as shown in the section 5.3.

Table 5.4: Table below shows the energy balance on boilers for new system

Equipment (new system)	Q in kJ/h at 100% efficiency	Q in kJ/h at 75% efficiency
E-200/E-201/E-202	3.90E+07	3.90E+07
E-203/E-204	3.25E+07	3.25E+07
E-205/E-206/E-207	3.61E+07	3.61E+07
Total	**1.08E+08**	**1.08E+08**

CHAPTER 06

DESIGN AND CALCULATIONS

6.1 Design of Multimedia Filter

Table 6.1: Table below shows the specifications of the Multimedia Filter

Design specifications of Multimedia Filter	
Material of construction	Fiber reinforced polymer
Tank size D” x H”	24” x 72”
Multimedia quantity	10 ft^3
Material used	Sand, gravel, and Anthracite

Design of the Multimedia Filter is relatively simple as compared to the other equipment; where the Multimedia filter quantity is dependent on the amount of flow rate in, and the Vessel diameter and depth is consequently dependent on the multimedia quantity [31].

6.2 Design of Cation Exchanger

We will first need the compositions of the in and out water streams for the cation exchanger from previous Material Balance calculations already done.

Table 6.2: Table below shows the composition of water entering and leaving the Cation Exchanger

Components	In(ppm)	Out(ppm)
TDS	1250	712.5
Magnesium	35.0	19.45
Calcium Ions	44.40	25.40
Sodium Ions	69.60	105.1
TSS	17.83	10.16
Carbonate Ions	318.6	181.6
Trace Metals	1.53	1.53

The methodology used for the design of the cation exchanger is that first a small-scale experiment is performed on a similar cation exchange resin model. The experimental values are than used to find the constants in the equations below derived from the Fick's Law of Mass Transfer.

6.2.1 Experimental Data

The experimental data is taken from a research paper [32].

Table 6.2.1; Table below shows the experimental data used in the design.

Experimental Data	
Inside Dia. of column	1.30 cm
Length of Column	45.7 cm
Mass of Resin	41.50 g
% Moisture in Resin	44%
Bulk Density of Resin	716.5 kg/m^3
Liquid Flow Rate	1.0428 L/d

6.2.2 Actual Data

The actual data used in the design is according to the daily water processing capacity of the cation exchange currently used at ARL.

Table 6.2.2; Table below shows the actual data used in the design.

Actual Data	
Inside Dia. of column	TBD
Length of Column	TBD
Liquid Flow Rate	435,600L/day
TDS (ppm)	1250 ppm
TDS (mg/L)	523.7 mg/L

6.2.3 Calculations

The actual data and the experimental data sets are now used combined to find the constants, k1(rate constant) and q_o (Maximum solid phase concentration).

The Equations used are derived from Fick's Law of Mass Transfer, since the process taking place is the adsorption of metal ions on the resin beads, and adsorption is one of the examples of mass transfer.

ASSUMPTIONS AND EQUATIONS:

Assumptions [32]:

- C_a = 57% C_a; where C is the combined conc. Of Mg and Ca ions.
- Resin Depth = 2 x Column Diameter
- Resin Material: Polystyrene Gel type

Equations:

Fick's Law for Mass Transfer (Adsorption of ions on resin beads) equation is converted into the equation below;

$$\frac{C}{Co} = \frac{1}{1 + e^{\frac{k1}{Q}(qo\ X\ M)-(Co\ X\ V)}}$$

Above equation is now converted into equation of straight line as shown below.

$$\ln\left(\frac{Co}{C} - 1\right) = \frac{k1\ X\ qo\ X\ M}{Q} - \frac{k1\ X\ Co\ X\ V}{Q}$$

Above is now an equation of straight line, plotting it will give us the following.

$y = bx + c$; **where y=ln(** $\frac{Co}{C} - 1$**), x=V, m(gradient) = -** $\frac{k1\ X\ Co}{Q}$**,**

$$\textbf{b(y-intercept)} = \frac{k1\ X\ qo\ X\ M}{Q}$$

where, C = effluent solute conc., C_0 = influent solute conc., k1 = rate constant, q_o = max. solid phase conc., M = mass of absorbent, V = Volume treated, Q = Flow rate.

$$\ln\left(\frac{Co}{C} - 1\right) = \frac{k1\ X\ qo\ X\ M}{Q} - \frac{k1\ X\ Co\ X\ V}{Q}$$

Use the above-mentioned equation to plot a straight line and fine values of constants k1 and qo, by equating them with the y-intercept and the gradient of the straight line.

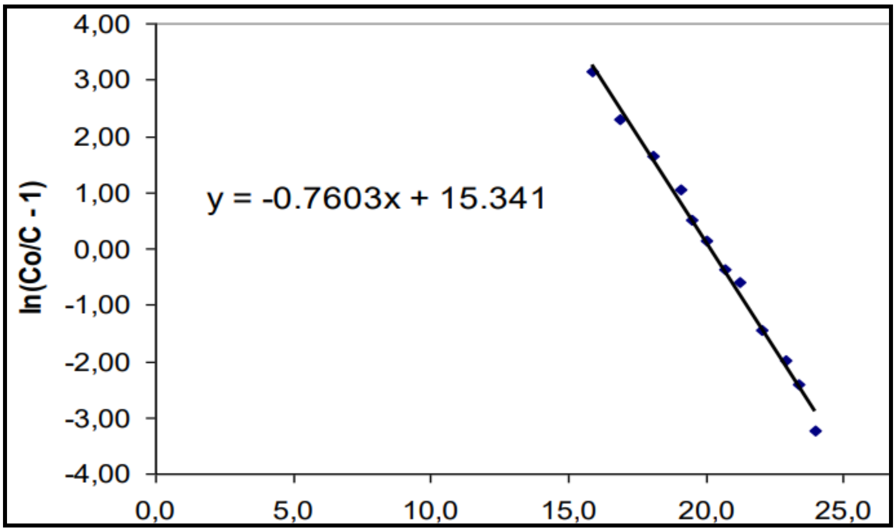


Figure 6.2.3; Above is a figure showing the graph of the straight line plotted from the equation shown above.

M = - 0.7603 (gradient)

b = 15.431 (y-intercept)

$$-0.7603 = -\frac{k1\ X\ Co}{Q}$$

k1 = 236 L/d.eq

$$15.431 = \frac{k1\ X\ qo\ X\ M}{Q}$$

qo = 2.92 eq.

Mass of resin:

$$\ln\left(\frac{Co}{C} - 1\right) = \frac{k1\ X\ qo\ X\ M}{Q} - \frac{k1\ X\ Co\ X\ V}{Q}$$

$$\ln\left(\frac{Co}{0.57Co} - 1\right) = \frac{236\ X\ 292\ X\ M}{435600} - \frac{236\ X\ 4.76\ X\ (7\ x\ 10^{-3})\ X\ 435600}{435600}$$

$$M = \frac{-0.28+7.86}{(1.58\ x\ 10^{-3})}$$

M = 4797.468 kg

Depth and diameter of the column:

$$Resin\ Volume = Mass\ of\ Resin\ x\ \frac{Dry\ Weight}{Wet\ Weight}\ \text{x}\ \varrho(resin)$$

$$Resin\ Volume = 4797.468\ x\ \frac{41.5}{23.24}\ \text{x}\ \frac{1}{716.5}$$

V (resin) = 11.96 m^3

$$Vol. = \left(\frac{\pi D^2}{4}\right) x\ 2D$$

Diameter = 1.967 m

Depth = 2 x 1.95 = 3.93 m

6.3 Ultrafiltration Design

First, we will use the data calculations done in the material balance section and use it to carry out the first step, which is the calculation of area of membrane used in Ultrafiltration **[33].**

Table 6.3: Table below shows the concentrations and flowrates of Feed, Permeate and Reject for UF

	Feed	**Permeate**	**Reject**
Concentration of TDS (ppm)	1250	1000	250
Flowrate (m^3/h)	47.6	30.92	17.62

Step 1 – Calculating Area of Membrane

Spiral Wound Membrane

Made of Poly-sulfone

Flowrate = 47 m^3

Membrane Water Flux = 0.25 L m^-2 h^-1

Area = Flow rate / Membrane Water Flux =47/0.25

Area = 190 m^2

Step 2 – Calculating Length of Vessel per Module

Pore size = 0.01-0.1 microns

No. of modules = 12

Diameter = 0.2 meter

Length of vessel = Total Area / (No. of modules x Membrane Area per Module)

Length of one vessel = 0.9895 meters

Step 3 – Calculating Total Length of Vessel

Total Length = Length x No. of modules =0.9895 x 12

Total Length = 11.874 meters

6.4 Equipment Design for Reverse Osmosis

The design of a Reverse Osmosis (RO) system involves a series of crucial steps to ensure its effective implementation. Firstly, flows and concentrations within the RO system are carefully tabulated, considering the feed water flow rate, product water flow rate, and concentrate flow rate, as well as the concentrations of various components in the feed water and desired product water. This step helps in determining the overall system performance and the removal efficiency of contaminants. In the project the following tabulated data was obtained [34].

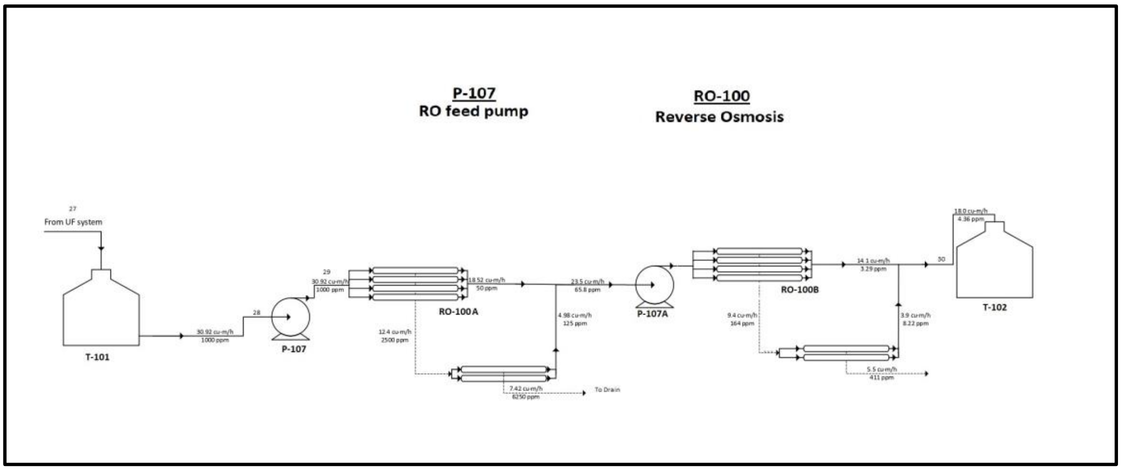


Figure 6.4.1 Above is a PFD of system B1 (Existing RO system)

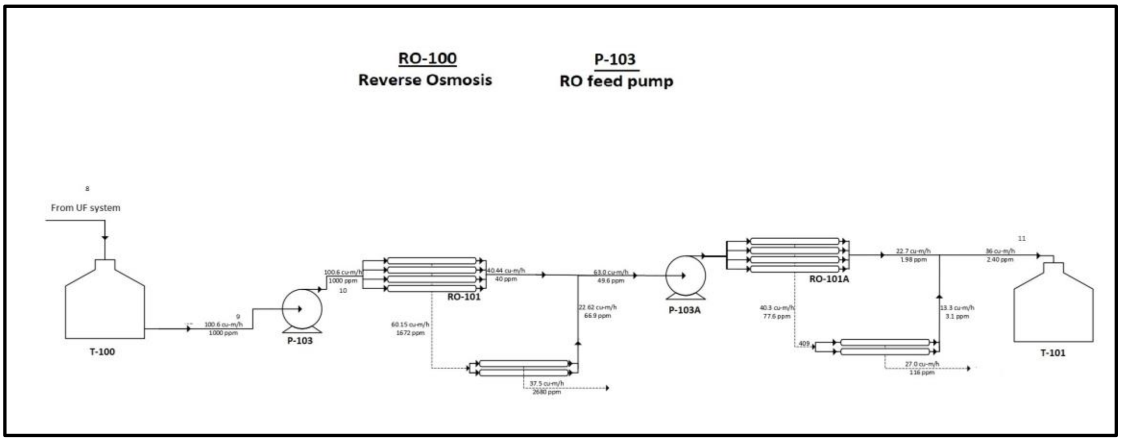


Figure 6.4.2 Above is a PFD of system B1 (Existing RO system)

Table 6.4; Table below shows the flowrates and concentrations of feed, permeate and reject for system B1 and B2.

	Feed	**Permeate**	**Reject**
Concentration of TDS for B1 (ppm)	1000	49.64	2680
Flowrate for B1 (m^3/h)	100.6	63.05	37.53
Concentration of TDS for B2 (mg/L)	49.64	2.396	115.8
Flowrate for B2 (m^3/h)	63.05	36.00	27.04

The next step is to define the type, size, material, and design flux of the membrane elements to be used in the RO system. Factors such as membrane selectivity, fouling resistance, and compatibility with the feed water composition are considered. The selection of suitable membrane elements is critical to achieving the desired water quality and system efficiency. The membrane type selected was AG 8040F Cellulose Acetate Membrane with a design flux of 34 $L/h.m^2$.

Following the selection of membrane elements, the number of elements required for the RO system is calculated. This calculation takes into consideration factors such as the desired product water flow rate, the design flux and active area of the membrane. By determining the appropriate number of membrane elements, the system can be designed to achieve the desired water production capacity while maintaining the required level of water quality.

$$N_E = \frac{Qp}{f A_E}$$

Where;

Q_p = permeate flow

f = design flow

A_E = Active area

The active area for AG 8040F 400 membrane is 46 m^2.

$$N_E = \frac{63.05*10^3}{46*34} =$$

40 membrane elements in the first system, B1

$$N_E = \frac{36*10^3}{46*34} =$$

23 membrane elements in the second system, B2

In addition to calculating the number of membrane elements, the design of the RO system also involves determining the number of pressure vessels required. This calculation considers factors such as the pressure vessel size and the number of membrane elements that can be accommodated within each pressure vessel. By optimizing the number of pressure vessels, the RO system can be efficiently designed to ensure proper hydraulic performance and minimize energy consumption.

By following these design steps, including tabulating flows and concentrations, selecting suitable membrane elements, calculating the number of elements, and determining the number of pressure vessels, an efficient and reliable reverse osmosis system can be designed to meet the desired water treatment goals.

$$\textbf{Number of vessels} = \frac{\textbf{Total number of elements}}{\textbf{Number of elements per vessel}}$$

For the system B1:

$$\textbf{Number of vessels} = \frac{40}{4}$$

10 vessels

For the system B2:

$$\textbf{Number of vessels} = \frac{23}{4}$$

6 vessels

CHAPTER 07

COST ESTIMATION AND ECONOMIC ANALYSIS

7.1 Purchase cost of equipment

Purchase cost of equipment is estimated by keeping the equipment size, specification, and the material of construction in consideration. One by one, the purchase cost of all major equipment is estimated and added.

7.1.1 Cation exchanger

Table 7.1.1; Table below shows the equipment specifications for Cation Exchanger.

Resin Type	**Polystyrene Gel type**
Resin Mass	4797.468 Kg
Vessel Diameter	2.0 m
Vessel Depth	4.0 m

Vessel Cost:

Using the figure below and the equipment specifications in the table, we can find the PCE of the Cation Exchanger.

To convert the pounds to dollars the cost is multiplied by a factor of 1.26.

To apply the time correction factor, we use cost index (1.82 as per the CEPCI Index) [35] as well.

Vessel cost = $ 22702.68

Resin Cost:

Resin Type: Polystyrene Gel Type Strong Acid Cation Exchange Resin

Cost of resin: US $ 0.68/kg

Mass of resin = 4797.46 kg

Cost of Resin = Mass of Resin x Cost/kg of Resin

Cost of Resin = $ 3262.27

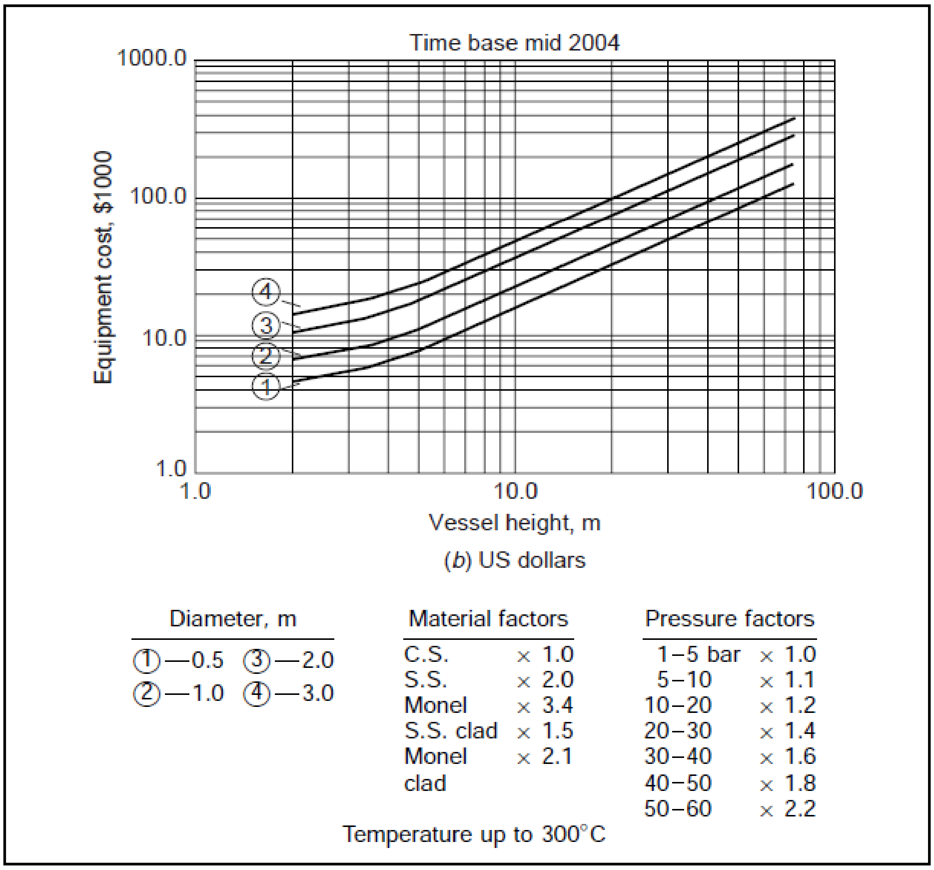


Figure 7.1.1; Above is a Figure showing a graph for the costing of Vessels [36]..

Total Cost = Resin Cost + Vessel Cost

Total Cost of 1 vessel = $25964

Total Cost of all 3 Vessels = **$ 77892**

7.1.2 Reverse Osmosis

Surface Area of one module = (pi x D x L)/4

Cost per cm2 = Price per module/ Surface Area

Total cost of one module = Surface Area x Cost per cm2

Total cost of 12 modules = Cost of one module x No. of modules

The dimensions of the membrane are 8'' by 40''.

The cost of AG8040 F RO membrane is $750 per membrane module.

Total number of membrane modules used = 60

Total purchase cost of equipment (PCE) for the RO system installed is calculated as follows:

PCE = number of membrane module * cost of one module

PCE = 60 * 750

PCE for membrane modules = $45,000.

Cost of pressure vessel = $400

Total cost on pressure vessels = 1000 * 15 = $15,000

Total PCE for the entire system = $15,000 + $45,000 = $60,000

Table 7.1.2; Below is a table of different specs and cost of membrane modules.

Diameter	8 in (20.3 cm)
Area per module	1607.75 cm^2
Cost per cm^2	$0.25/$cm^2$
Total cost of one module	$7658.18
Total cost of 12 modules	$91,898.16

7.1.3 Pumps of the old system

Each pump is individually sized, and the cost is calculated using the graph attached below.

Table 7.1.3; Below is a table showing different pumps, their sizes and their corresponding costs.

Equipment	Size (kW)	Cost ($)
P-100	131.6	17100
P-101	131.6	17100
P-102	136.8	17500
P-103	148.5	17800
P-104	148.5	17800
P-105A	45.8	8700
P-105B	45.8	8700
P-106	204	20400
P-107	182	21900
P-108	283.8	24100
Total cost (2001)		171100
Total cost (2023)		345700

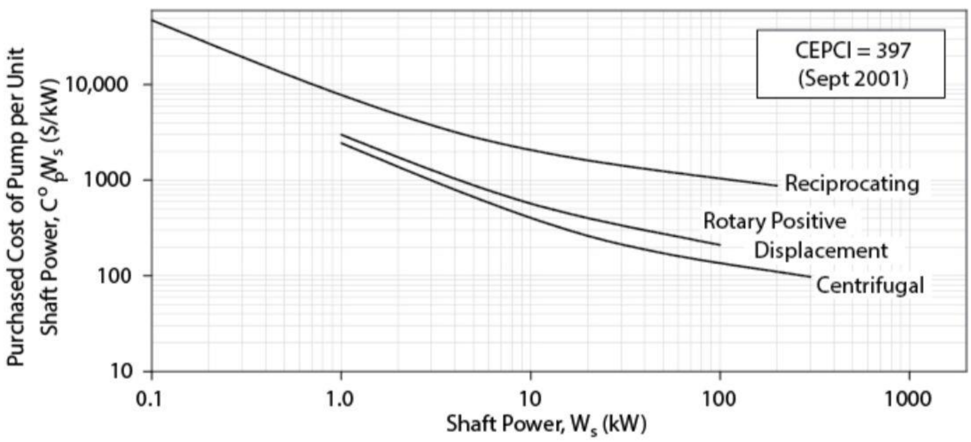


Figure 7.1.3; The above graph shows a graph of shaft power vs purchase cost of different types of pumps.

7.1.4 Sizes and costs for Pumps of the new system

Table 7.1.4.1; Below is a table showing different pumps, their sizes and their corresponding costs.

Equipment	Size (kW)	Cost ($)
P-100	100	13000
P-101	100	13000
P-102	382(2)	64540
P-103	141(4)	67600
P-104	337	28600
P-mid	170	19550
P-105	187	20600
P-105A	45.8	8700
P-105B	45.8	8700
P-106	204	20400
P-107	182	21900
P-108	283.8	24100
Total cost (2001)		310690
Total cost (2023)		631500

7.1.4.2 CEPCI Index [35]

CEPCI Index Value	
Year	Value
2001	397
2023	806

7.1.5 Summary of the Purchase Cost of Equipment

Table 7.1.5.1: Below table shows the summary of purchase cost of all equipment in the old system

Equipment (Old System)	Cost
Pumps	$ 345.7K
Multimedia filter	$ 18.9K
Cation Exchanger	$77.8K
Deaerator	$ 6.8
Ultrafiltration	$ 96.9K
Multimedia filter 2	$ 18.9K
R.O. system	$ 150.7K

Table 7.1.5.2: Below table shows the summary of purchase cost of all equipment in the new system.

Equipment (New System)	Cost
Pumps	$ 631.5K
Multimedia filter	$ 18.9K
Ultrafiltration	$ 96.9K
Proposed R.O. system	$ 301.5K
Multimedia filter 2	$ 18.9K
Ultrafiltration	$ 96.9K
Old R.O. system	$ 150.7K

7.2 Physical Plant cost (PPC)

Table 6.1. Typical factors for estimation of project fixed capital cost

Item	Process type		
	Fluids	Fluids–solids	Solids
1. Major equipment, total purchase cost	PCE	PCE	PCE
f_1 Equipment erection	0.4	0.45	0.50
f_2 Piping	0.70	0.45	0.20
f_3 Instrumentation	0.20	0.15	0.10
f_4 Electrical	0.10	0.10	0.10
f_5 Buildings, process	0.15	0.10	0.05
* f_6 Utilities	0.50	0.45	0.25
* f_7 Storages	0.15	0.20	0.25
* f_8 Site development	0.05	0.05	0.05
* f_9 Ancillary buildings	0.15	0.20	0.30
2. Total physical plant cost (PPC) $PPC = PCE\ (1 + f_1 + \cdots + f_9)$ $= PCE \times$	3.40	3.15	2.80
f_{10} Design and Engineering	0.30	0.25	0.20
f_{11} Contractor's fee	0.05	0.05	0.05
f_{12} Contingency	0.10	0.10	0.10
Fixed capital $= PPC\ (1 + f_{10} + f_{11} + f_{12})$ $= PPC \times$	1.45	1.40	1.35

*Omitted for minor extensions or additions to existing sites.

Figure 7.2; Physical Plant cost is estimated by using the above table and the PCE [36].

Tables 7.2 (1)/ (2); Tables below show summary of PPC and PCE for the old and the new systems.

PCE (Old system)	$716K
PPC	$2.86M

PCE (New system)	$1.31M
PPC	$4.45M

7.3 Total Investment required

The total investment required is calculated by adding fixed capital cost and the working capital cost.

2. Total physical plant cost (PPC)			
PPC = PCE $(1 + f_1 + \cdots + f_9)$			
= PCE ×	3.40	3.15	2.80
f_{10} Design and Engineering	0.30	0.25	0.20
f_{11} Contractor's fee	0.05	0.05	0.05
f_{12} Contingency	0.10	0.10	0.10
Fixed capital = PPC $(1 + f_{10} + f_{11} + f_{12})$			
= PPC ×	1.45	1.40	1.35

Old System	
Fixed capital cost	PPC * 1.45
	$ 2.86M * 1.45
	$ 4.15M
Working capital	5% of Fixed capital
	$ 207.8K
Total investment required	$4.36M

Table 7.3.1: Below table shows the total investment required calculations for the Old System

New System	
Fixed capital cost	PPC * 1.45
	$ 4.45M * 1.45
	$ 6.45M
Working capital	5% of Fixed capital
	$ 323K
Total investment required	$ 6.77M

Table 7.3.2: Below table shows the total investment required calculations for the New System

7.4 Annual Production Cost

Annual production cost is estimated by calculating cost of utilities and cost of raw materials. Direct and indirect costs are estimated and added to calculate the total production cost.

Table 7.4.1; Below table shows the cost of utilities in pounds and dollar [36].

Table 6.5. Cost of utilities, typical figures mid-2004

Utility	UK	USA
Mains water (process water)	60 p/t	50 c/t
Natural gas	0.4 p/MJ	0.7 c/MJ
Electricity	1.0 p/MJ	1.5 c/MJ
Fuel oil	65 £/t	100 $/t
Cooling water (cooling towers)	1.5 p/t	1 c/t
Chilled water	5 p/t	8 c/t
Demineralised water	90 p/t	90 c/t
Steam (from direct fired boilers)	7 £/t	12 $/t
Compressed air (9 bar)	0.4 p/m^3 (Stp)	0.6 c/m^3
Instrument air (9 bar) (dry)	0.6 p/m^3 (Stp)	1 c/m^3
Refrigeration	1.0 p/MJ	1.5 c/MJ
Nitrogen	6 p/m^3 (Stp)	8 c/m^3

Note: £1 = 100p, 1$ = 100c, 1 t = 1000 kg = 2200 ib, stp = 1 atm, 0°C

Table 7.4.2; Below table shows the cost of utilities in old system

Old System	
Yearly electricity consumption	654 MW
Cost of electricity	$ 35325
Yearly water consumption	801575 tonnes
Cost of water	$8015
Variable Production cost	$43335

Table 7.4.3; Below table shows the cost of utilities in new system

New System	
Yearly electricity consumption	1354 MW
Cost of electricity	$ 73150
Yearly water consumption	1610057 tonnes
Cost of water	$16100
Variable Production cost	$89250

Table 6.6. Summary of production costs

Variable costs	*Typical values*
1. Raw materials	from flow-sheets
2. Miscellaneous materials	10 per cent of item (5)
3. Utilities	from flow-sheet
4. Shipping and packaging	usually negligible
Sub-total A	. . . .
Fixed costs	
5. Maintenance	5–10 per cent of fixed capital
6. Operating labour	from manning estimates
7. Laboratory costs	20–23 per cent of 6
8. Supervision	20 per cent of item (6)
9. Plant overheads	50 per cent of item (6)
10. Capital charges	10 per cent of the fixed capital
11. Insurance	1 per cent of the fixed capital
12. Local taxes	2 per cent of the fixed capital
13. Royalties	1 per cent of the fixed capital
Sub-total B	. . . .
Direct production costs A + B	. . . .
13. Sales expense	20–30 per cent of the direct production cost
14. General overheads	
15. Research and development	
Sub-total C	. . . .
Annual production cost = A + B + C =	. . . .

$$\text{Production cost £/kg} = \frac{\text{Annual production cost}}{\text{Annual production rate}}$$

Figure 7.4; Above figure shows the steps for the production cost calculation.

Table 7.4.4 Table below shows the calculations for the direct production cost of the old and the new system

Fixed cost =24% of FCI
Direct Production cost = Fixed cost + Variable cost
Old system Fixed cost= $1.04M **Direct production cost = $1.083M**
New system Fixed cost = $1.62M **Direct production cost = $1.714M**

Table 7.4.5 Table below shows the calculations for the direct production cost of the old and the new system

Indirect Production cost= 25% of Direct production cost
Production cost = (Direct + Indirect) Production cost
Old system Indirect production cost= $270.8K **Annual production cost = $1.31M**
New system Indirect production cost = $428K **Annual production cost = $2.14M**

7.5 Production cost/m^3 of water produced.

Annual production and the rate of production are used to estimate the cost/ cu-m.

Table 7.5; Below table shows the Yearly production rate of old and new system.

Yearly production = 449388 tone	
Cost/cu-m (Old)	$2.91
Cost/cu-m (New)	$4.76

7.6 Summary of economic analysis

Below tables shows the summary of the purchased cost of the equipment, physical plant cost, working capital, fixed capital, total investment required and the annual production cost for the old and new system.

Table 7.6.1; The table below shows the summary of economic analysis for the old system.

Old System	
Purchased Equipment Cost (PCE)	$ 716k
Physical Plant Cost (PPC)	$ 2.86M
Working Capital	$ 207.6K
Fix Capital	$ 4.15M
Total investment required	**$ 4.36M**
Fix Operating Cost	$ 1.04M
Annual production Cost	$ 1.31M
Annual production	449 kilo tonne/Y
Cost/cu-m	**$ 2.91/cu-m**

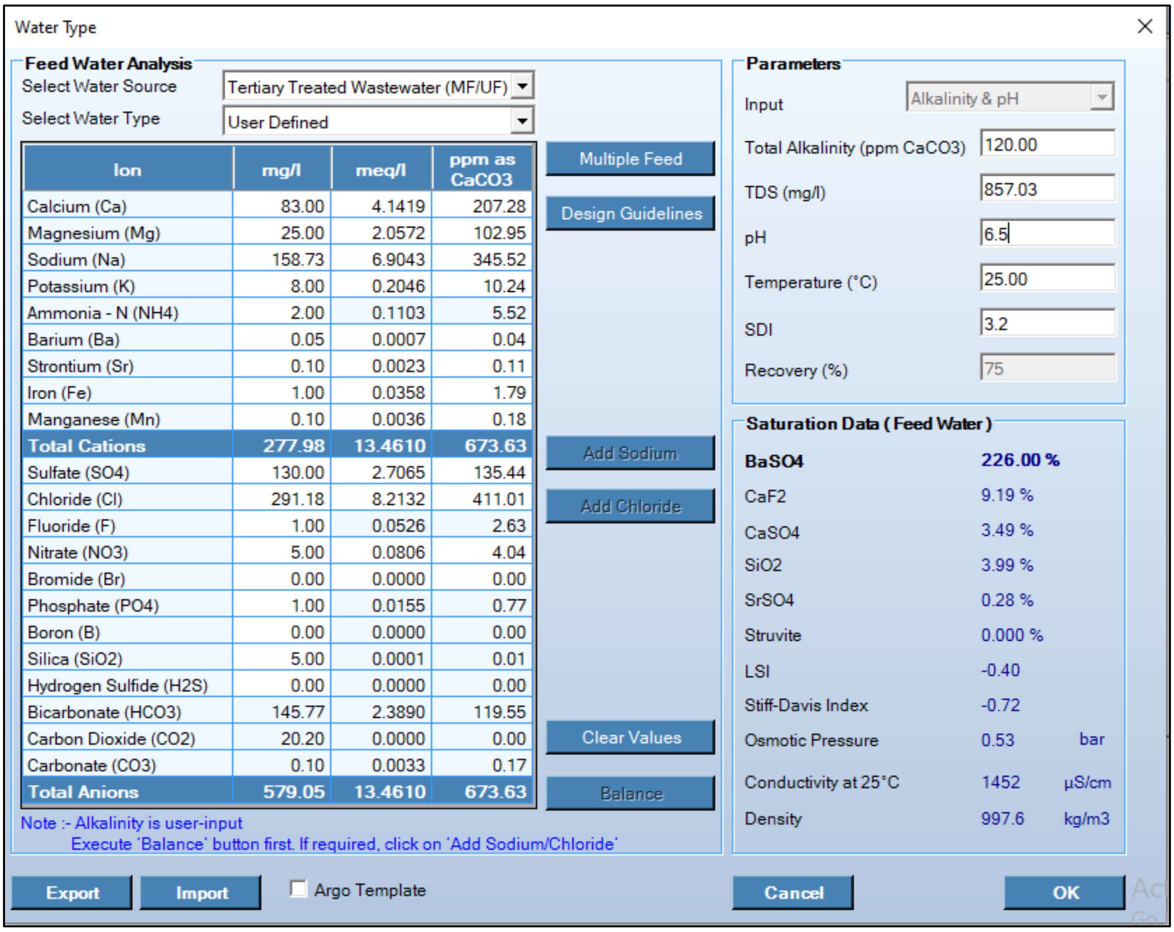
Table 7.6.1; The table below shows the summary of economic analysis for the new system.

New System	
Purchased Equipment Cost (PCE)	$ 1.31M
Physical Plant Cost (PPC)	$ 3.157M
Working Capital	$ 323K
Fix Capital	$ 6.45M
Total investment required	**$ 6.67M**
Fix Operating Cost	$ 1.11M
Annual Operating Cost	$ 2.14M
Annual production	449 kilo tonne/Y
Cost/cu-m	**$ 4.67/cu-m**

CHAPTER 08

SIMULATION

The simulation of the process was carried out on three different software – **Aspen HYSYS** for pump simulation, **Win-flows** for RO system design and simulation and **IMS design software** for design and simulation of Ultrafiltration system. The flowsheets and results of design are attached.



Ion	mg/l	meq/l	ppm as CaCO3
Calcium (Ca)	83.00	4.1419	207.28
Magnesium (Mg)	25.00	2.0572	102.95
Sodium (Na)	158.73	6.9043	345.52
Potassium (K)	8.00	0.2046	10.24
Ammonia - N (NH4)	2.00	0.1103	5.52
Barium (Ba)	0.05	0.0007	0.04
Strontium (Sr)	0.10	0.0023	0.11
Iron (Fe)	1.00	0.0358	1.79
Manganese (Mn)	0.10	0.0036	0.18
Total Cations	277.98	13.4610	673.63
Sulfate (SO4)	130.00	2.7065	135.44
Chloride (Cl)	291.18	8.2132	411.01
Fluoride (F)	1.00	0.0526	2.63
Nitrate (NO3)	5.00	0.0806	4.04
Bromide (Br)	0.00	0.0000	0.00
Phosphate (PO4)	1.00	0.0155	0.77
Boron (B)	0.00	0.0000	0.00
Silica (SiO2)	5.00	0.0001	0.01
Hydrogen Sulfide (H2S)	0.00	0.0000	0.00
Bicarbonate (HCO3)	145.77	2.3890	119.55
Carbon Dioxide (CO2)	20.20	0.0000	0.00
Carbonate (CO3)	0.10	0.0033	0.17
Total Anions	579.05	13.4610	673.63

Figure 8.1; Above figure shows the feed water composition of RO system B1.

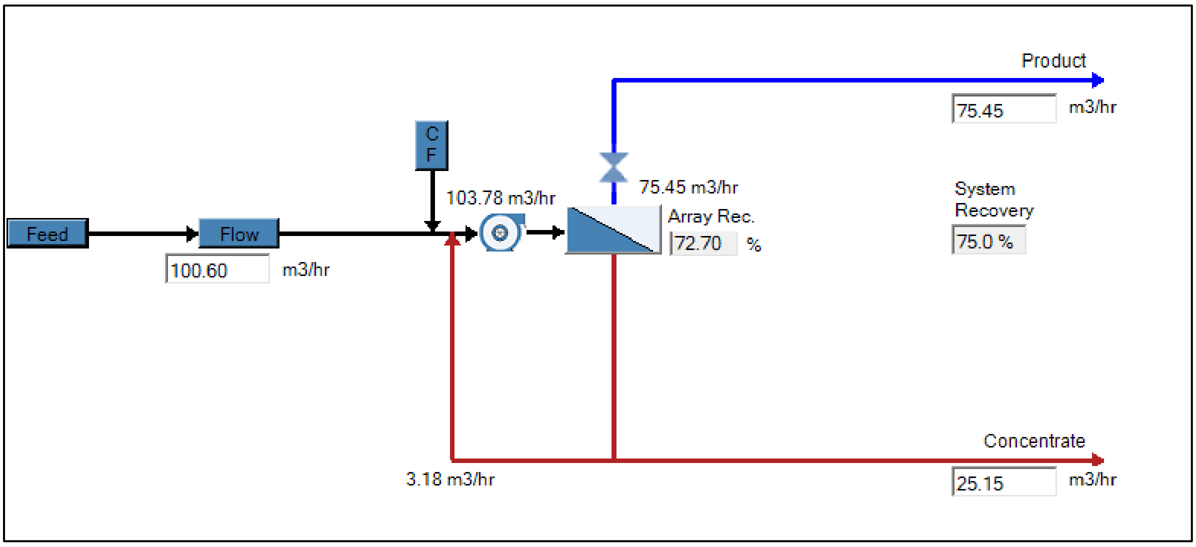


Figure 8.2; Above figure shows the simulation flowsheet for the RO system B1.

Results Summary

Flow Data	m3/hr	Analytical Data	mg/L
Raw Feed	100.60	Raw Feed TDS	857.03
Product	75.45	Product TDS	8.17
Concentrate	25.15	Concentrate TDS	3401.39

System Data			Single Pass Design
Temperature: °C	RO-1: 25	System Rec.	75%

Average Flux (m/hr), Pass and Stage

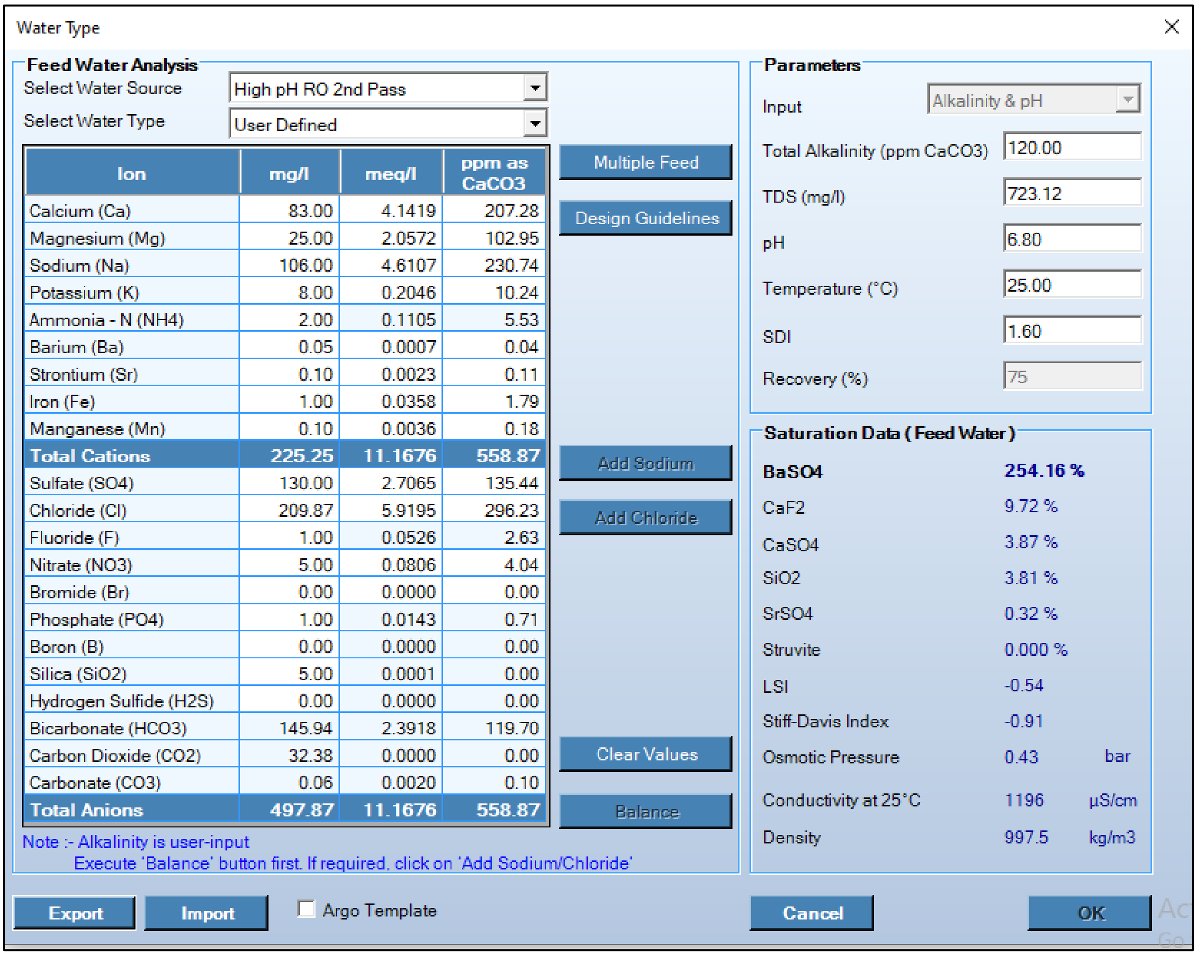
Pass	Average	Stage 1	Stage 2	Stage 3
Pass 1	0.05	5.65E-02	4.84E-02	3.97E-02

Array Data — Pass 1

Recovery %: 72.7 Conc. TDS mg/L: 3401.39 Conc. Flow m3/hr: 28.33

	Total			Flow m3/hr		Pressure bar		Perm TDS
Stage	Housing	Element	Element Type	Feed	Perm	Feed	DP	mg/L
1	5	20	AG8040F 400	103.78	42.02	20.75	1.99	5.18
2	3	12	AG8040F 400	61.76	21.61	18.69	2.06	9.37
3	2	8	AG8040F 400	40.15	11.81	16.56	2.08	16.83
Total	10	40						

Figure 8.3; Above figure shows the results for RO system B1.



Ion	mg/l	meq/l	ppm as CaCO3
Calcium (Ca)	83.00	4.1419	207.28
Magnesium (Mg)	25.00	2.0572	102.95
Sodium (Na)	106.00	4.6107	230.74
Potassium (K)	8.00	0.2046	10.24
Ammonia - N (NH4)	2.00	0.1105	5.53
Barium (Ba)	0.05	0.0007	0.04
Strontium (Sr)	0.10	0.0023	0.11
Iron (Fe)	1.00	0.0358	1.79
Manganese (Mn)	0.10	0.0036	0.18
Total Cations	225.25	11.1676	558.87
Sulfate (SO4)	130.00	2.7065	135.44
Chloride (Cl)	209.87	5.9195	296.23
Fluoride (F)	1.00	0.0526	2.63
Nitrate (NO3)	5.00	0.0806	4.04
Bromide (Br)	0.00	0.0000	0.00
Phosphate (PO4)	1.00	0.0143	0.71
Boron (B)	0.00	0.0000	0.00
Silica (SiO2)	5.00	0.0001	0.00
Hydrogen Sulfide (H2S)	0.00	0.0000	0.00
Bicarbonate (HCO3)	145.94	2.3918	119.70
Carbon Dioxide (CO2)	32.38	0.0000	0.00
Carbonate (CO3)	0.06	0.0020	0.10
Total Anions	497.87	11.1676	558.87

Figure 8.4; Above figure shows feedwater composition for RO system B2.

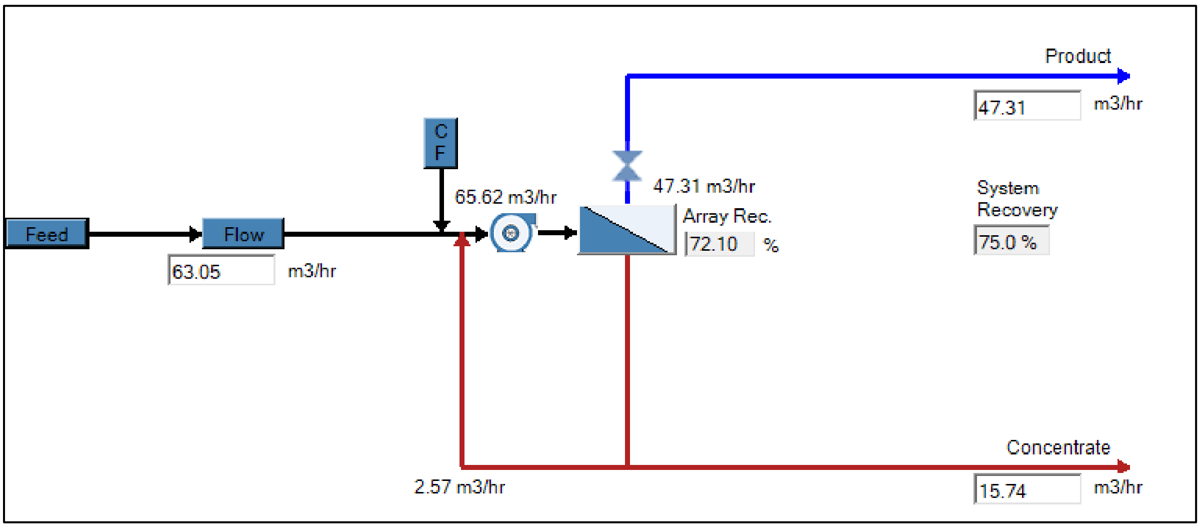


Figure 8.5; Above figure shows the simulation flowsheet for RO system B2.

Results Summary

Flow Data	m3/hr	Analytical Data	mg/L
Raw Feed	63.05	Raw Feed TDS	723.12
Product	47.31	Product TDS	5.98
Concentrate	15.74	Concentrate TDS	2878.91

System Data — **Single Pass Design**

Temperature: °C RO-1: 25 System Rec. 75.04%

Average Flux (m/hr), Pass and Stage

Pass	Average	Stage 1	Stage 2
Pass 1	0.06	6.67E-02	5.92E-02

Array Data — **Pass 1**

Recovery %: 72.1 Conc. TDS mg/L: 2878.91 Conc. Flow m3/hr: 18.30

Stage	Total Housing	Total Element	Element Type	Flow m3/hr Feed	Flow m3/hr Perm	Pressure bar Feed	Pressure bar DP	Perm TDS mg/L
1	3	12	AG8040F 400	65.62	29.72	23.81	2.06	4.36
2	2	8	AG8040F 400	35.89	17.59	21.05	1.46	8.77
Total	5	20						

Figure 8.6; Above figure shows the result summary for RO system B2.

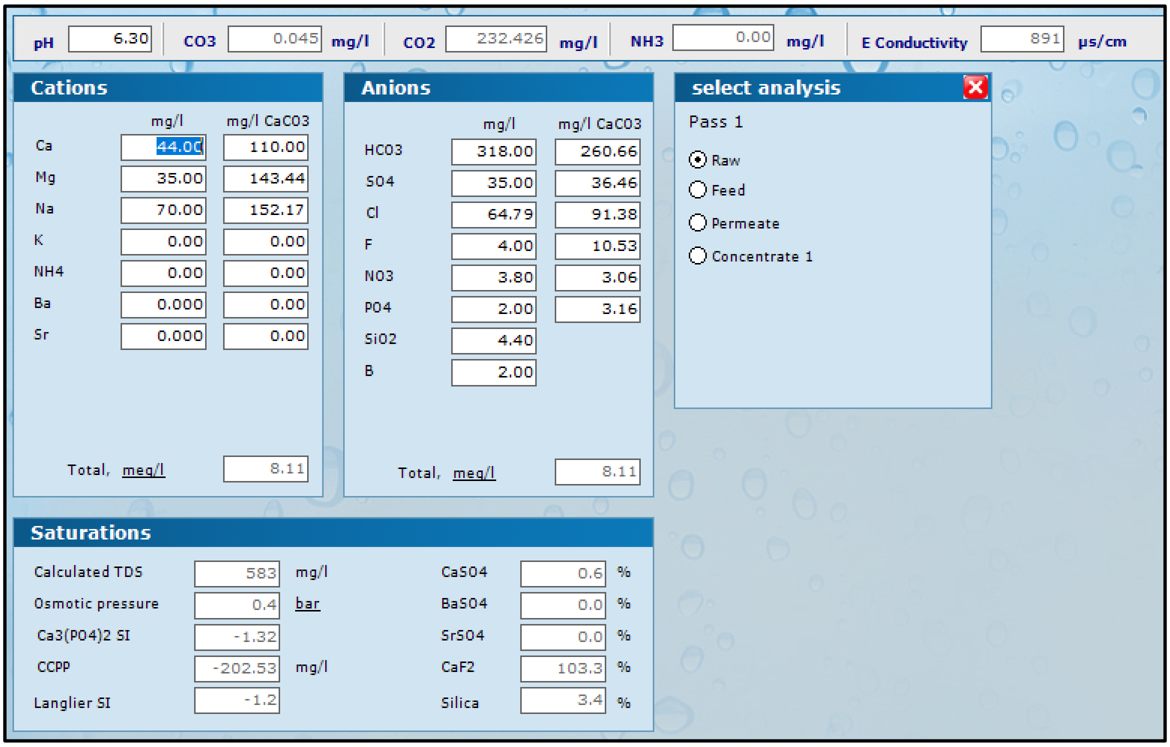


Figure 8.7; Above figure shows feed properties for ultrafiltration system.

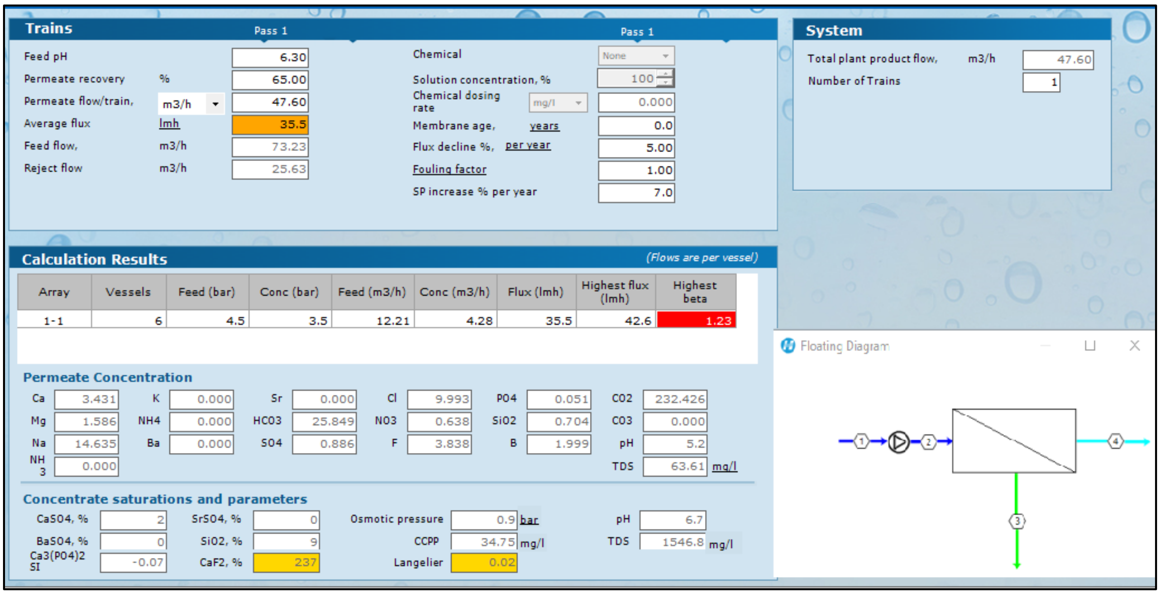


Figure 8.8; Above figure shows simulation and calculations for ultrafiltration system.

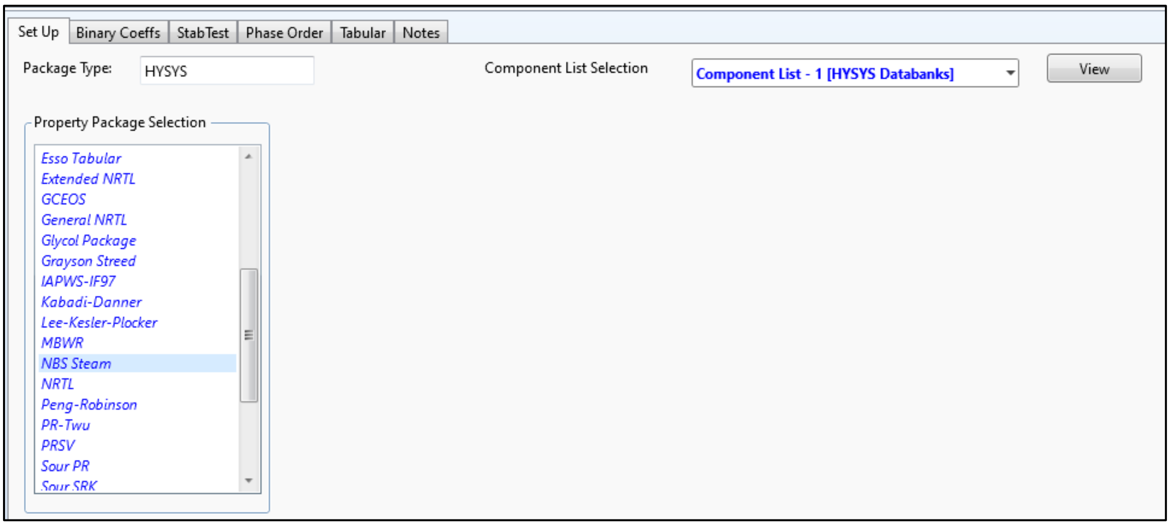
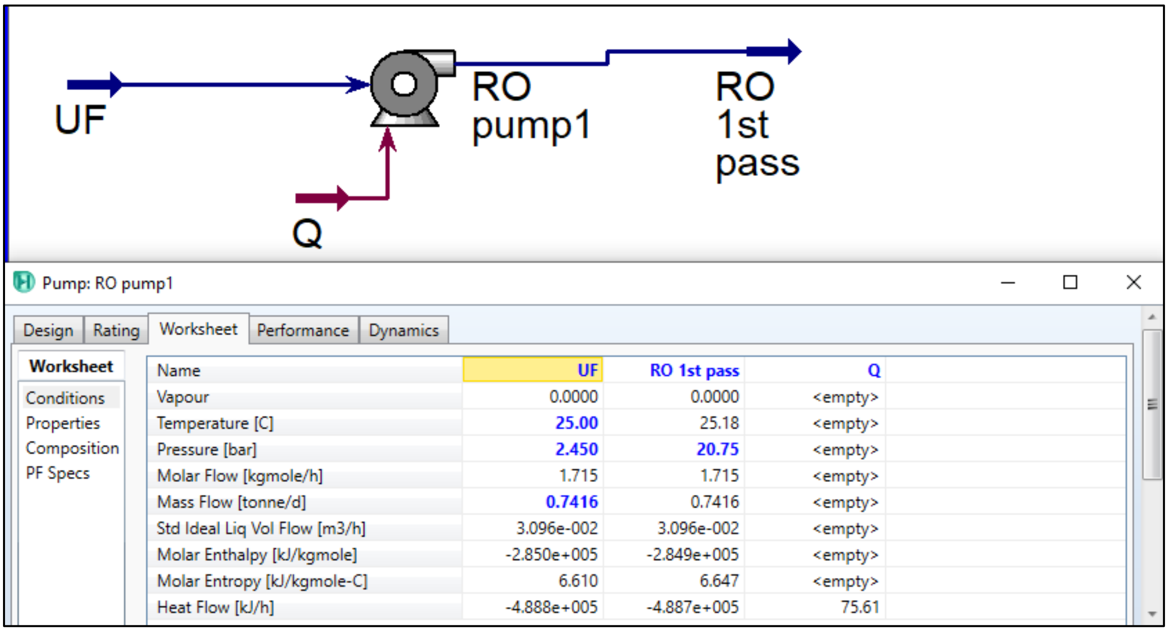
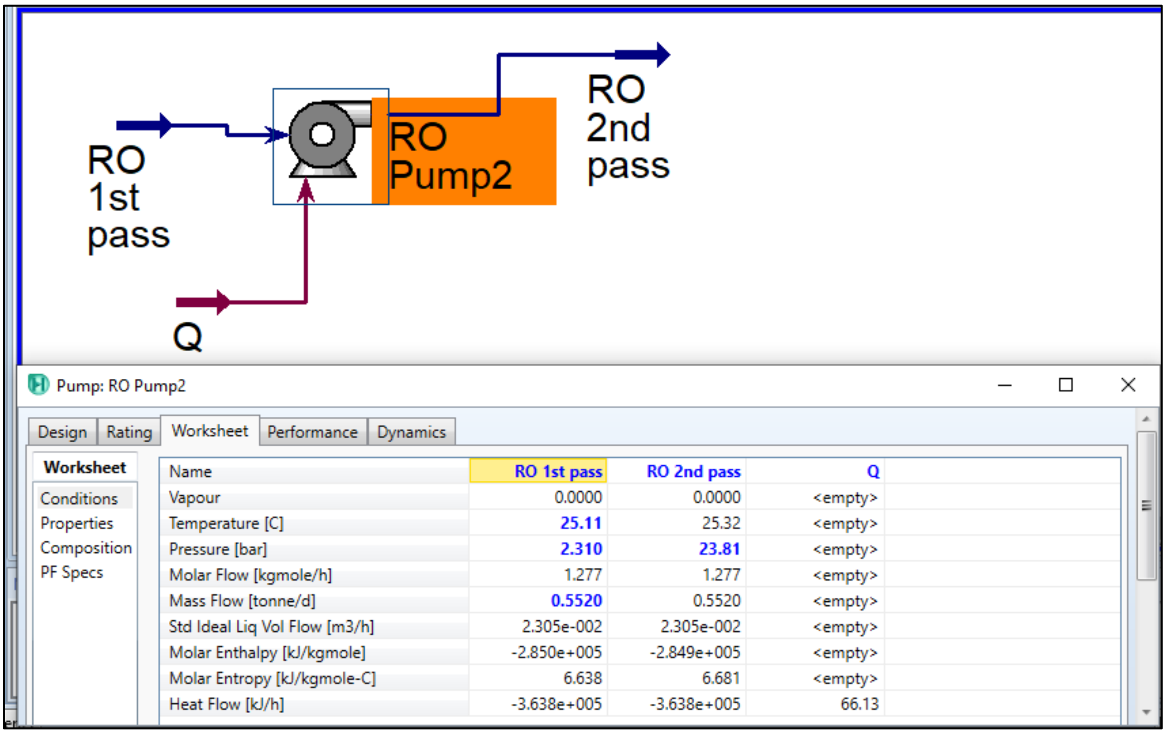


Figure 8.9; Above figure shows the fluid package.



Name	UF	RO 1st pass	Q
Vapour	0.0000	0.0000	<empty>
Temperature [C]	25.00	25.18	<empty>
Pressure [bar]	2.450	20.75	<empty>
Molar Flow [kgmole/h]	1.715	1.715	<empty>
Mass Flow [tonne/d]	0.7416	0.7416	<empty>
Std Ideal Liq Vol Flow [m3/h]	3.096e-002	3.096e-002	<empty>
Molar Enthalpy [kJ/kgmole]	-2.850e+005	-2.849e+005	<empty>
Molar Entropy [kJ/kgmole-C]	6.610	6.647	<empty>
Heat Flow [kJ/h]	-4.888e+005	-4.887e+005	75.61

Figure 8.10; Above figure shows the simulation of pump for RO system B1.



Name	RO 1st pass	RO 2nd pass	Q
Vapour	0.0000	0.0000	<empty>
Temperature [C]	25.11	25.32	<empty>
Pressure [bar]	2.310	23.81	<empty>
Molar Flow [kgmole/h]	1.277	1.277	<empty>
Mass Flow [tonne/d]	0.5520	0.5520	<empty>
Std Ideal Liq Vol Flow [m3/h]	2.305e-002	2.305e-002	<empty>
Molar Enthalpy [kJ/kgmole]	-2.850e+005	-2.849e+005	<empty>
Molar Entropy [kJ/kgmole-C]	6.638	6.681	<empty>
Heat Flow [kJ/h]	-3.638e+005	-3.638e+005	66.13

Figure 8.11; Above figure shows the simulation of pump for RO system B2.

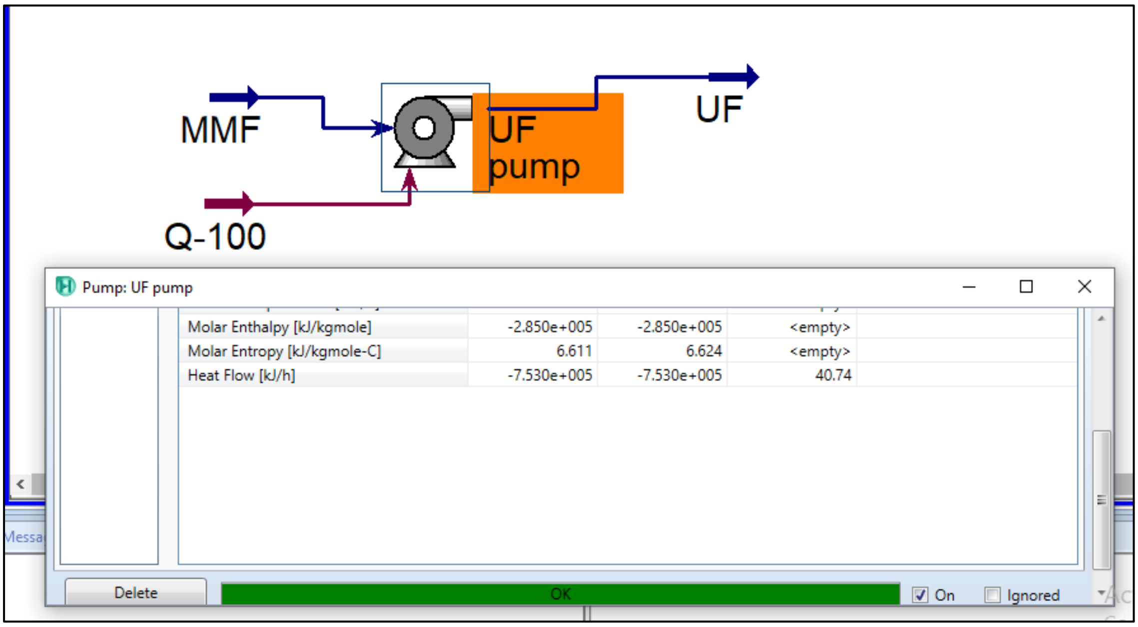


Figure 8.12; Above figure shows simulation of pump for ultrafiltration.

CHAPTER 09

HAZOP ANALYSIS

Hazard and Operability study (HAZOP) is a procedure that systematically and critically examines the operability of a process. Its application to an operating plant gives indication of potential hazards that arises because of deviation from intended design. At the flow-sheet stage, it can be used for preliminary examination of the design and for a detailed study at a later stage. An Operability study examines the design line by line, and vessel by vessel and uses guidewords to produce thought about the way deviances from planned design can lead to hazardous situations.

9.1 Keywords

The following are some of the keywords that are used to carry out HAZOP studies.

Table 9.1; Table below shows the Keywords for the HAZOP Study.

No	Keyword	Explanation
1	**Intentions**	It defines how a specific part of the process was planned to operate.
2	**Deviations**	These are the aberrations from designer's intention. and are detected using guide words.
3	**Causes**	These are the reasons that triggered deviations. A deviation is treated as meaningful only if it has a realisticcause.
4	**Consequences**	Following resultsfrom occurrence of meaningful deviances.
5	**Hazards**	Consequences that can bring about damage or injury.
6	**Guide words**	These are the words that qualities or quantifies the intention to guide and bring about the thought process so that deviation can be discovered.

9.2 Guide Words

The following are some of the guide words that are used most often in HAZOP analysis.

TABLE 9.2 HAZOP Guide Words

S. No.	Keyword	Explanation
1	No	Negation of the design intent
2	Less	Quantitative decrease
3	More	Quantitative increase
4	Part of	As well as
5	As well as	Logical opposite of the intent
6	Reverse	Reverse
7	Other than	Complete substitution

Guide words application covers both general (react, transfer) and specific (pressure, temperature) parameters. When dealing with a design intention involving a complex set of interrelated plant parameters (e.g., temperatures, reaction rates, composition, or pressure), it may be better to apply the whole sequence of guide words to each parameter individually than to apply each guide word across all the parameters as a group.

9.3 Procedure

HAZOP study is usually conducted by a team of experienced professionals, who have complementary skills and comprehensive understanding of the technique and led by an experienced leader.

The team carries out comprehensive study of the process vessel by vessel, and line by line, and then use guide words to detect any hazards. Extent of information depends upon the information required for study.

9.4 Sequence of HAZOP

Following are the steps used to conduct HAZOP study:

1. Selection of the vessel
2. Explanation of intention of vessel and its line
3. Selection of a line
4. Application of guide word
5. Development of meaningful cause
6. Examination of possible causes
7. Examination of possible consequences1
8. Detection of hazards
9. Making of suitable records

9.5 Cation Exchange System

An Operability study examines the design line by line, and vessel by vessel and uses guidewords to produce thought about the way deviances from planned design can lead to hazardous situations.

TABLE 9.3; Table below shows the HAZOP of Cation Exchange System

Process Parameter	GUIDE Words	Possible Causes	Possible Consequences	Actions Required
Flow Rate	More	Equipment failure	Excessive pressure	Inspect equipment
	Less	Human error	Insufficient treatment	Implement safeguards
Temperature	More	Control failure	Chemical degradation	Improve monitoring
	Less	Cooling failure	Inefficient treatment	Enhance cooling system
Pressure	More	Pump malfunction	Pipe rupture	Conduct maintenance
	Less	Valve leakage	Insufficient flow	Repair or replace
Concentration	More	Feed contamination	Oversaturation	Improve filtration
	Less	Inadequate dosage	Incomplete treatment	Adjust dosage
pH	More	Acidic feed	Corrosion	Adjust chemical dosing
	Less	Alkaline feed	Scale formation	Adjust chemical dosing
Resin Regeneration	None	None	Loss of treatment efficiency	Schedule regular regeneration

9.6 RO Membrane

HAZOP study of Reverse Osmosis Membrane is as follows.

TABLE 9.5; Table below shows the HAZOP of Membrane

Process Parameter	Guide Word	Possible Causes	Possible Consequences	Actions Required
FLOW	NO / LESS	Feed lines/valves blocked. Particulate film on membrane Aging of membrane.	No separation. Less efficiency of separation. Condensate on membrane Added pressure on membrane	Maintenance of valves Check of valves & lines Clean the membrane. Substitute the membrane
	MORE	Membrane failure Feed flow rate increase Temperature increase Valve on retentate side partially closed	No separation Purity loss, overpressure Recovery increase, purity loss	Membrane substitution Split feed on parallel modules Fit a high T alarm. Maintenance of valve
TEMPERATURE	LESS	Low ambient temperature Heat loss through insulation	Reduced permeate flowrate.	Membrane cleaning Fit a low T alarm.

		Scaling or fouling	Elevated energy consumption Increased pressure requirements	Maintenance of instrumentation
	MORE	High ambient temperature Inadequate thermal regulation Failure in pump	Membrane damage Less efficiency Scaling and fouling Increased energy consumption	Install temperature sensors. Install heat insulation. Flow control Process optimization

9.7 Multimedia Filter

Table 9.5; Table below shows the HAZOP for Multimedia Filter

Process Parameter	Guide Word	Possible Causes	Possible Consequences	Actions Required
FLOW	NO / LESS	Feed lines/valves blocked. Filtering media is choked	No separation. Less efficiency of separation.	Maintenance of valves Clean the filtering media. Substitute the filter.
	MORE	Filter media failure Feed flow rate increase Valve on retentate side partially closed	No separation Purity loss, overpressure Recovery increase, purity loss	Filter media substitution Split feed on parallel modules Maintenance of valve

9.8 Pumps

Table 9.6; Table below shows the HAZOP for Pumps for Flow

Parameter	Guide Word	Causes	Consequences	Actions Required
FLOW	NO	1.Closed Outlet Valve 2.Blocked pipelines 3.Pump failure	1.Lines over pressure 2.Pumps overheating	1.Proper monitoring of pumps 2.Installation of alarms on valve
	MORE	1.Too high shaft power 2.Blockage in valve outlet 3.Fail open valve.	1.Overheating of the pump 2. Can cause damage to the pump by cavitation	1.Check and decrease the speed of shaft rotation 2.Fail close the valve at the time of delivery
	LESS	1.Failure at the outlet valve/pump 2.Low rotational speed of shaft 3.Improper suction at the inlet 4.Partial opening of downstream valve	1.Pressure buildup in pipelines 2.Pump overheating	1.Check and increase speed of shaft rotation 2.Install control system to change valve opening according to flow
	REVERSE	1.Valves not closed when needed	1.Due to gravity, the fluid can flow from higher level vessel into lower-level vessel.	1.Install Check valves 2.Operational procedures to open and closed valve before and after the product transfer

Table 9.7; Table below shows the HAZOP of Pumps for Temperature

Parameter	Deviation	Possible Causes	Possible Consequences	Actions Required
TEMPERATURE	MORE	1.Cooling system failure 2.Leakage in cooling system 3.Rubbing of rotating components with fixed component 4.Shaft connected incorrectly 5.Increased pressure in the pump	1.Risk of explosion in pump 2.Bearings can be damaged 3.Cavitation as vaporizing liquid increases 4.Destruction of the internal pump (wheels)	1.Cool different parts of the pump with water 2.check the level of required liquid 3.check pressure in the pump 4.check cooling system 5.Open and clean the pump
	LESS	1.Failure in cooling system 2.Low flow rates 3.Operating fault	1.Rubbing of rotating components with fixed part may cause damage to bearings	1.Check the cooling system, 2. Check the flow rates

Table 9.8; Table below shows the HAZOP of Pumps for Pressure

Process Parameter	Deviation	Possible Causes	Possible Consequences	Actions Required
PRESSURE	NO	1.Suction valve closed 2.Pump failure 3.Power outage 4.Shaft failure 5.Faulty pressure sensor	1.Production is stopped.	1.Check the type of liquids that can be used, 2.Make sure that NPSHA > NPSHR, 3.Check for loss in filters
	MORE	1.Blockage in valve outlet. 2.Operating fault. 3.Faulty pressure sensor 4.Vaporizing liquid	1.Explosion 2.production is stopped 3.deterioration of bearings 4.increased leakage	1.Check and drain the pipes and system 2.Replace the gasket and check the damage
	LESS	1.Suction valve is closed 2.Air leakage in suction line 3.operating fault 4.faulty pressure sensor	1.Cavitation 2.Vibration causes destruction of the internal pump (wheel bearing)	1.Make sure that NPSHA > NPSHR 2.Check for loss in filters 3.Check and drain the pipe and system

CONCLUSION

In conclusion, the replacement of the cation exchange system with the Reverse Osmosis (RO) system has proven to be a highly efficient and effective solution for the boiler feed water treatment process. The RO system's remarkable efficiency has resulted in a higher number of boiler cycles, optimizing the steam generation process, hence making the proposed system more energy efficient in terms of the boilers. Due to reduced TDS amount, scaling is also reduced allowing more efficient heat transfer and allowing a better-quality High-Pressure steam to be produced.

Although one drawback of RO system is that its fixed investment cost and production cost is higher than the current cation exchange system, but increased number of boiler cycles allows for prolonged operations without the need for frequent system shutdowns and maintenance, thereby enhancing overall refinery productivity and reducing the maintenance cost of the boilers. Also, due to the better quality of water now the cost for the treatment of boiler blowdown is also reduced/eliminated. These 2 factors allow the overall cost for the RO system to be compensated for in terms of the reduced costs in the boiler section.

From the calculations above it was seen that the effluent of RO system contained TDS composition of 2.4 ppm which is well within the ASME (American Standard for Mechanical Engineering) limits (20-100 ppm), while the effluent of the old cation system was found to be almost 700 ppm which exceeds the limits by a large value. This exceptional water quality significantly reduces the risk of equipment corrosion and scaling, thereby extending the lifespan of the boilers and hence the steam generation system.

In terms of sustainability and the proposed system being environmentally friendly, from the green process engineering perspective the proposed system eliminates the use of hazardous and toxic chemicals such as NaCl and H_2SO_4.

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