ADVANCED INTEGRATED WATER TREATMENT SYSTEM FOR ULTRA-PURE WATER PRODUCTION IN REFINERIES

Authors: Irina Zaslavschi, Ph.D.[1], Amit Rainer[2]

[1]*IDE Technologies, SW Process Manager, Israel, irenaz@ide-tech.com*
[2]*IDE Technologies, Process Team Leader, Israel, amitr@ide-tech.com*

Presenter: Irina Zaslavschi, Ph.D.

ABSTRACT

The PEMEX Dos Bocas Pre-treatment Project marks a significant milestone in water treatment in the petrochemical industry. The facility is designed to supply treated water and produce ultra-pure water (UPW) for Dos Bocas refinery project, which is in the Gulf Coast state of Tabasco and considered one of Mexico's largest refineries. This paper presents a case study of a cutting-edge integrated water treatment system designed to address the critical need for water in refinery operations while maximizing water recovery and minimizing environmental impact. This large-scale brackish water treatment facility was designed and constructed in close collaboration between IDE Technologies and Techint Engineering & Construction, to produce ultra-pure water, using river water with high hardness as a source for the petrochemical industry.

The plant comprises two consecutive facilities to efficiently handle multi-stage treatment processes. The first one is a Pre-treatment Plant (PPA) with a design flow of about 103 MLD and a Demineralized Water Plant (UDA) with a capacity of almost 28 MLD. The treatment processes incorporate advanced desalination techniques, membrane technologies, and customized filtration methods. They work synergistically to effectively remove salts, minerals, and impurities from the river water, ensuring the production of demineralized water that meets the stringent standards required by the refinery. The facilities were successfully commissioned in February 2024, representing a significant achievement in the project's implementation and ensure operational readiness for providing essential water treatment services.

Keywords: pre-treatment, ultra-pure water, BWRO, ultrafiltration, softening

I. INTRODUCTION

The petroleum industry relies heavily on water resources across its operations, from upstream exploration and production to midstream transportation, and downstream refining processes. Water scarcity and stringent quality requirements pose significant challenges for refineries, necessitating innovative and efficient water treatment solutions. The PEMEX Dos Bocas refinery complex is located near the coast in the Tabasco state of Mexico and uses water from the Gonzales River (20 km from the facility) as a source for the petrochemical plant.

River water often contains impurities and minerals that can be detrimental to refining processes. The Dos Bocas Project, backed by the Techint Engineering & Construction company, overcomes these challenges through advanced water treatment technologies, thereby enhancing the quality of water used in various refinery applications. The large-scale brackish water treatment plant, designed by IDE Technologies, is comprised of a Pre-treatment plant (PPA) and a Demineralized Water Plant (UDA) that incorporate customized softening and filtration methods, advanced membranes, and deionization technologies. The key objectives for the plant are to ensure compliance with product quality requirements under a wide range of operating conditions and to provide flexibility to operate the water treatment systems at variable output capacities from 15% to 100%. The facility design and supplied equipment must comply with stringent local design standards and refinery specifications. This case study aims to provide insights into the water management strategies employed for large-scale industrial projects, specifically a major oil refinery complex.

1.1 Main Challenges

Designing a water treatment plant for a petroleum industry presents numerous challenges that demand effective solutions in the design process, especially when utilizing river water as a raw water source. The primary project challenges encountered during the design phase:

- **Variable Water Quality**: River water quality is subject to fluctuation throughout the year, due to factors such as weather patterns, upstream pollution, and seasonal changes. This variability necessitates the implementation of robust treatment processes and special RO system design to allow flexibility in operation.
- **Variable Capacity**: To comply with the client's industrial grade requirements, the facility must be designed to accommodate fluctuations in product needs and to enable turndown capability without compromising the product water quality while assuring 100% availability in process equipment, electrical equipment, instrumentation, and control.
- **Maintenance Accessibility:** Accessibility for maintenance and repairs is crucial to ensure the ongoing operation and persistence of the treatment facility. Design considerations must prioritize ease of access to key components, such as filtration systems, pumps, and chemical treatment units, to facilitate routine maintenance tasks and troubleshooting.
- **Fast and Easy Construction:** Balancing the need for rapid construction with ensuring structural integrity and adherence to regulatory standards poses a significant challenge. The construction process must be streamlined without compromising on quality, requiring meticulous planning and coordination among stakeholders.
- **Parallel execution:**
  A tight project schedule requires thorough planning to coordinate the commissioning process of the two facilities (PPA and UDA plants) alongside active construction sites. This presents logistical challenges that must be carefully managed.

Addressing these challenges requires a comprehensive approach that integrates innovative design solutions, advanced technology, and proactive planning. The general arrangement of the plant proposed by IDE has been developed based on extensive experience with plants of similar capacity and complexity, and optimizes the available distance and spatial relations between various process areas to reduce the cost of piping and cabling runs, while at the same time providing a safe, practical, and pleasant working environment.

II. PRE-TREATMENT PLANT (PPA)

The PPA (Planta de Pretratamiento de Agua) plant serves as a large-scale pre-treatment facility to treat raw water from the Gonzalez River, to produce quality water (***Table 1***). The water produced by the PPA serves as makeup water for the cooling towers and feed water for the Demineralized Water plant (UDA). A robust pre-treatment system is essential for efficient operation of the demineralized water plant – that is mainly based on membrane processes – and for effective cooling tower water management. The plant's purpose is to filter out most of the suspended matter and colloids that naturally occur in river water and reduce Ca and Mg salt content through softening by chemical treatment.

Table 1: Main parameters of the PPA plant

Parameters	Unit	Raw water	PPA product
Design Capacity	m^3/hr		4285
Calcium	mg/L	85	<64
Magnesium	mg/L	24	<9.5
Total Alkalinity	ppm $CaCO_3$	<180	<150
Total Hardness	ppm $CaCO_3$	310	<200
Total Dissolved Solids	mg/L	500	<1000
pH	-	7.6	7 - 8
Turbidity	NTU	<40	<15
Free Chlorine	mg/L	0.2-0.5	0.2-1.5
Total Suspended Solids	mg/L	51	<15

2.1 PROCESS DESCRIPTION

The design of softening and clarification processes for river water depends on factors like initial water quality, treatment goals, chemical selection and dosage, process optimization, environmental considerations, and cost constraints. Given the inherent variability in raw water quality, conducting Jar tests throughout the project is imperative. A series of Jar tests were performed at the design stage to find the optimum conditions for the softening, coagulation, and flocculation, settling processes, in order to select the proper chemical, determine chemical dosages, mixing intensity, and residence time.

Based on Jar test results, the process design is based on the consecutive steps as per the diagram presented in **Figure *1*: PPA main process diagram*Figure 1***. The hardness removal is performed by dosing Caustic Soda (NaOH) in the softening tanks to increase the pH to levels of 9.5-10.5, depending on the silica content in the raw water. The retention time in this process is around 20 minutes, based on full capacity. After the softening process, the water proceeds to the clarification and sedimentation stages that take place in the Lamella clarifiers where heavy solids are settled down on Lamella tubes. The addition of Polymer and $FeCl_3$, with a specified retention time are used to boost the coagulation and flocculation processes. The clarified water from the overflow of the Lamella clarifier is passed on to the effluent tank, where it is pumped through disc filters to the final water tank. The concentrated sludge from the Lamella bottom is transferred to the sludge treatment system for the further clarification and dewatering by centrifuges, according to the local sludge treatment requirements. The sludge is then sent on to landfill for disposal.

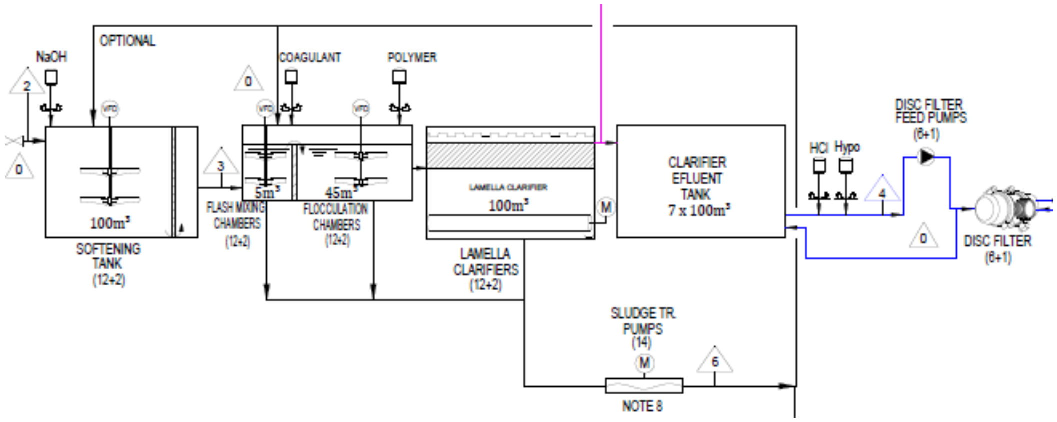


Figure 1: PPA main process diagram

2.2 Modular Design

One of the project objectives is to minimize project costs while reducing onsite civil and installation worksand shortening the project execution timeline, via a modular approach. The PPA plant is constructed as a modular facility containing identical operating units – IDE's custom-designed and prefabricated Lamellas, softening, and clarification systems. In practical terms, the modular concept infers that most of the equipment is prefabricated, wired, and tested at the factory site, and then shipped in 40ft containers to the site, to significantly reduce time-consuming and expensive site works and resources. Removing approximately 60-80% of the plant construction activity from the site location significantly reduces site disruption and vehicular traffic, and improves overall safety and security.

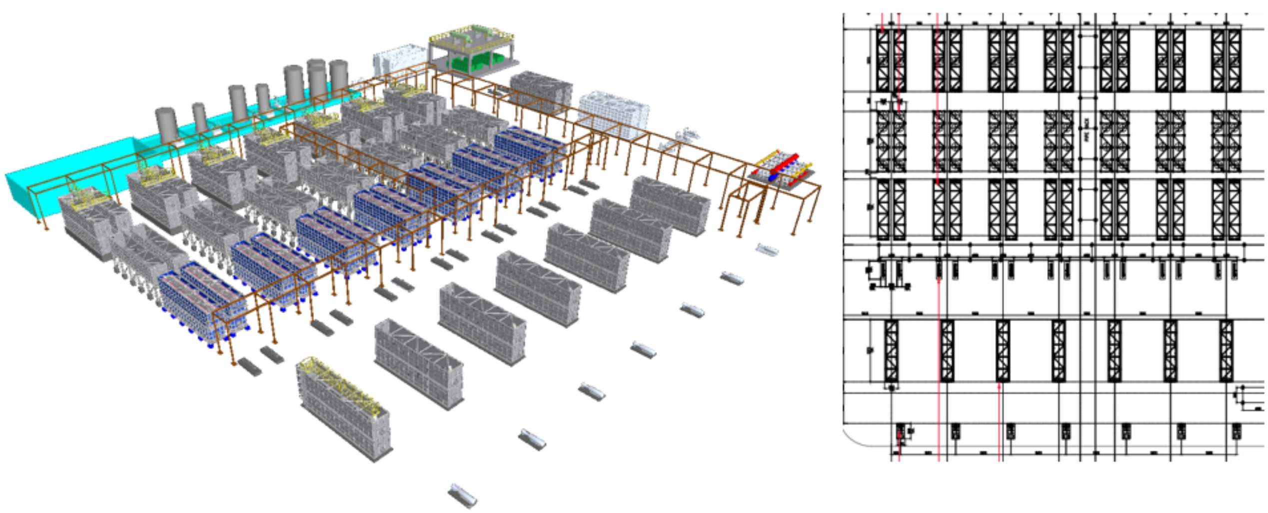


Figure 2: PPA Modular units layout

The softening and clarifying process is divided into fourteen (14) individual streams (***Figure 2***), to provide the highest plant availability and operational flexibility. Each line contains three tanks: A Softening tank, A Coagulation and Flocculation tank that is divided into two chambers: flash mixing chamber and flocculation chamber, and the third tank is the Lamella clarifier. Every two trains' effluent flows to a common Effluent tank.

The Lamella unit, showed in ***Figure 3***, is constructed from two segments, each of which will be shipped in a 40ft container to the site. The upper section will then be placed on top of the bottom section and they will be bolted together.

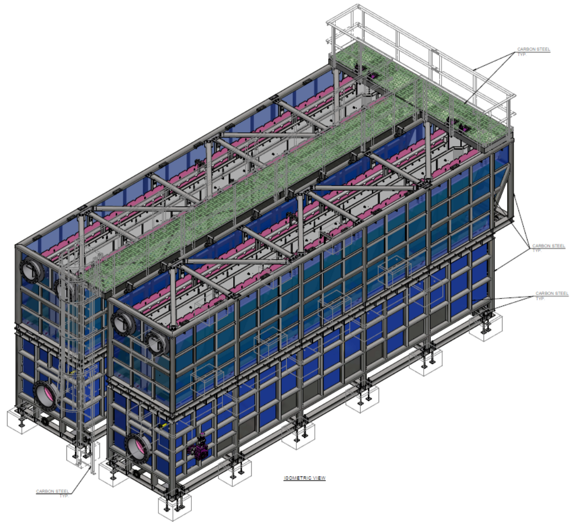


Figure 3: Lamella Clarifier modular unit

2.2 CFD Analysis

The PPA general arrangement is based on gravity flow from section to section in the main treatment area. Computational Fluid Dynamics (CFD) analysis is essential in engineering gravitational flow systems to ensure proper design and hydraulics. CFD analysis, performed in ANSYS Fluent 2024R1, was also utilized for the Lamella clarifier to guarantee optimal flow distribution, mitigate stagnant areas, and ensure effective water evacuation through gravity.

It can be seen from ***Figure 4*** that flow is well distributed. There is a large volume compartment under the tube settler that enables the water to slow down, and the Lamellas' positioning in the opposite direction to the flow enables a uniform distribution of water inside the tube settlers.

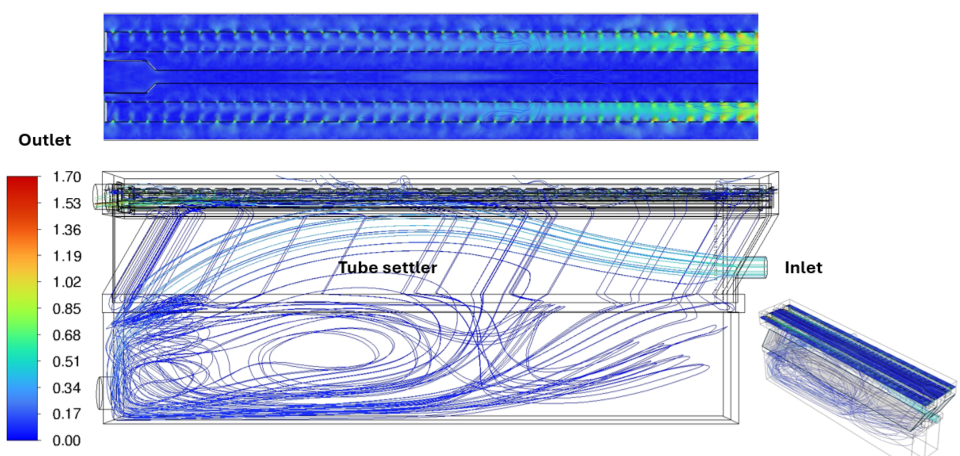


Figure 4: CFD analysis for Lamella Clarifier unit

2.3 COAGULATION OPTIMIZATION WITH PAC

Given the dynamic nature of river water as a challenging water source, the plant design must possess flexibility in adapting the coagulant selection to enhance performance and optimization. During the initial plant startup, the raw water parameters were monitored and some of the values were above the contractual thresholds/limits, so new alternatives for coagulant were proposed. To enhance the settling process, the effectiveness of Polyaluminum Chloride (PAC) was assessed. Its notably high charge density facilitates effective neutralization of charged particles in water, thereby promoting efficient coagulation and precipitation of impurities. Nevertheless, optimizing PAC dosage is crucial to mitigate residual aluminum concentrations in treated water, thereby averting the risk of aluminum species precipitation on RO membranes in the UDA plant.

A series of tests, commencing with jar tests and extending to a comprehensive examination of the entire plant, were conducted to evaluate the impact of PAC dosing on turbidity and TSS removal efficiency. Dosing of PAC at a concentration range of 15-25ppm can improve plant performance (***Figure 5)***. Utilizing PAC in the PPA plant achieves promising results concerning solids settling, TSS, and turbidity removal, meeting contractual specifications of TSS<15 mg/l and turbidity<15 NTU. Aluminum (Al^{3+}) concentrations in PPA and UDA UF product water were found to be below the upper limit specified by the membrane vendor (0.05mg/l) (***Figure 6***). This indicates that continuous use of PAC at the plant is feasible with no significant impact expected on membrane fouling, and almost all aluminum is removed as settled solids in the Lamella.

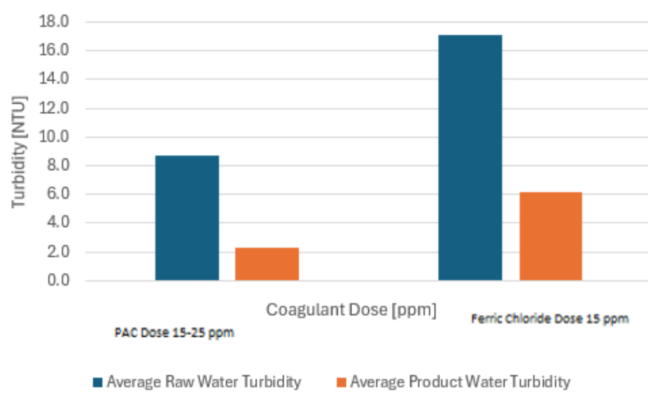
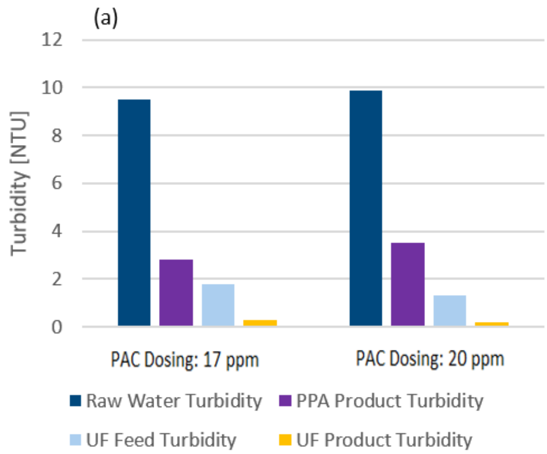


Figure 5: Coagulation with Ferric Chloride versus PAC



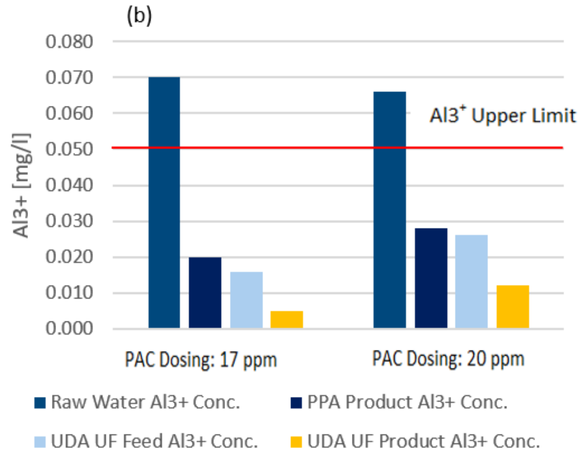


Figure 6: Turbidity (a) and Al^{3+} (b) measurement along PPA and UDA processes

III. ULTRA-PURE WATER PLANT – UDA

The complementary facility, the UDA (Unidad Demineralizadora de Agua) Demineralized Water Plant, is the heart of ultra-pure water production, deploying cutting-edge technologies and IDE's engineering expertise to thoroughly remove minerals and impurities. The UDA plant is fed with pre-treated water from the PPA plant, and is designed to produce a capacity of 1126 m^3/hr of demineralized water with conductivity of less than 0.1 µS/cm. The water produced by the UDA is used in the cogeneration plant, as boiler feedwater and as an evaporative cooling water, and must therefore comply with strict quality requirements. The project objectives are to comply with product quality requirements (***Table 2***) under a wide range of operating conditions and provide flexibility in operating the system with a variable output capacity (33%-100% of design flow).

The design consists of five (5) main stages that produce water according to the project requirements:

- Ultra-filtration (UF)
- Micronic filtration
- First Pass RO – RO1
- Hardening - Evaporative cooling stream
- Second Pass RO – RO2
- Continuous Electrodeionization (CEDI)

Evaporative cooling water is used as a replenishment for evaporated circulation water and must comply with the required quality at 6 COC (concentration cycles). The design use side stream of first pass RO rear permeate. The permeate is diverted to remineralization process where $CaCl_2$ and $NaHCO_3$ is used to achieve the required quality as per ***Table 2*** and required values of stability indices, such as LSI and Ryznar.

Table 2: Main parameters of UDA plant

Parameters	**Unit**	**UDA Feed Maximum**	**Demineralized water**	**Evaporative cooling water quality**
Design Capacity	m^3/hr		1126	150

Parameters	Unit	UDA Feed Maximum	Demineralized water	Evaporative cooling water quality
Conductivity	µS/cm	<1600	<0.1	>50
Total Hardness	ppm $CaCO_3$	<160	<0.01	>15
Total Alkalinity	ppm $CaCO_3$	<70	-	>15
Total Dissolved Solids	mg/L	<1000	<0.05	>30
Total Organic Carbon	mg/L	<1	<0.1	-
Total Suspended Solids	mg/L	<7	-	<30
pH	N/A	7-8	6 - 8	7-8.5

Incorporating CEDI as an advanced technology for ultrapure water production typically requires the quality of feed water to be RO permeate. The maximum TDS level in the RO permeate should ideally be less than 10 ppm to ensure high-quality feed water for CEDI system. This low TDS level is crucial because CEDI systems are designed to achieve very high purity levels, often greater than 99.9% removal of dissolved ionic impurities. Higher TDS levels can lead to increased fouling of the CEDI membranes and reduce system efficiency and lifespan. To achieve the low TDS levels required for feed water in CEDI systems, the design of a two-pass RO system is needed.

3.1 PROCESS DESCRIPTION

The UDA plant was designed to operate at overall plant recovery above 70%. This enables to minimize the brine disposal along with capital expenses and operational costs. ***Figure 7*** demonstrates the detailed process flow diagram of the plant including all main areas and equipment. The UF, RO trains, and CEDI modules are skid-mounted, fully pre-assembled, pre-wired, and equipped with all necessary equipment, piping, valves, and instrumentation as per ***Figure 8***.

UF is used as a first stage in the water treatment process to remove particles, colloids, and macromolecules from the raw water, ensuring that the water entering the RO system is of the required quality. The UF is comprised of five (5) skids with a net operational flux of about 50 lmh, enabling operation with an N-2 configuration during backwash/CEB/CIP and maintenance activities, if required.

Two passes of the RO system with a front permeate split are designed to produce a low conductivity product of less than 10 µS/cm, needed for efficient CEDI operation. The RO section of the plant is comprised of four (4) independent RO membrane trains of 1st pass and three (3) of 2nd pass, based on IDE's in-house design and engineering. The 1st pass and 2nd pass RO systems are designed to operate at high recoveries of 80% and 90%, respectively. This special RO system design is capable of adapting to varying water compositions and enables flexibility in operation. Use of a high-pressure pump bypass ensures proper operation at low feed conductivities.

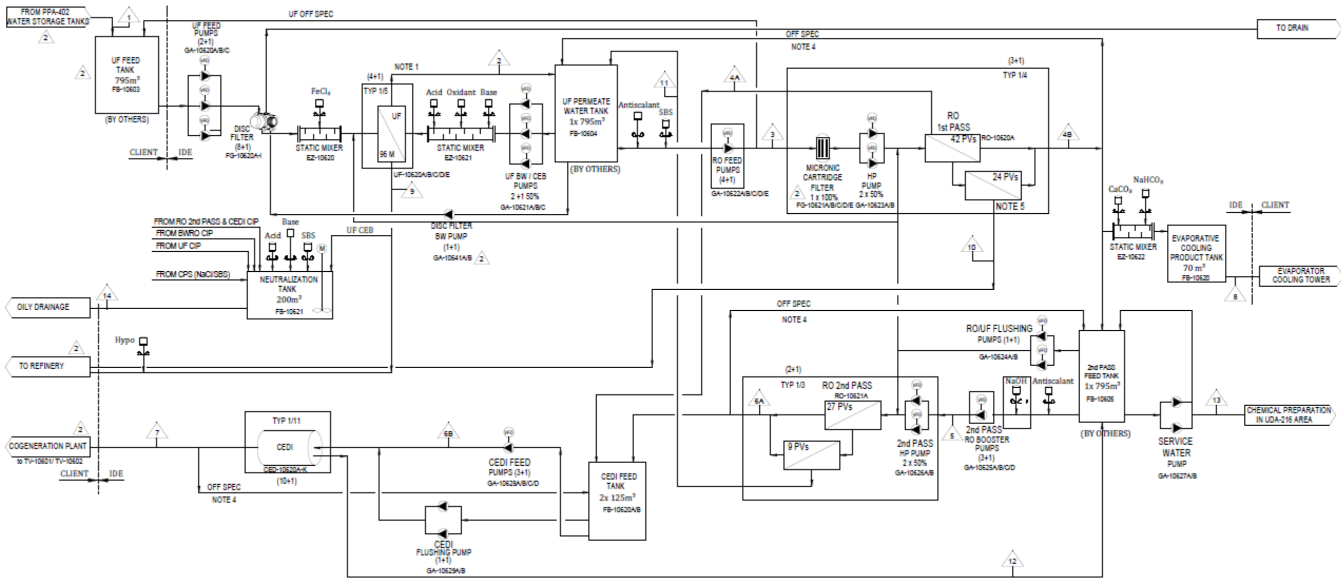


Figure 7: UDA plant process flow diagram

The final polishing stage incorporates a large-scale CEDI system with ten (11) high-capacity modules to provide a total capacity of 1252 m^3/hr ultra-pure water with guaranteed conductivity levels lower than 0.1 µS/cm. The systems use electricity, resins, and ion exchange membranes, to separate dissolved impurities and ions from the water, including reactive silica. Continuous EDI means that the electric current continuously regenerates the required resin mass through the water splitting reaction. Due to this combination of internal elements, CEDI is also capable of reducing reactive silica content in the water through a specific mechanism involving the polishing zone.

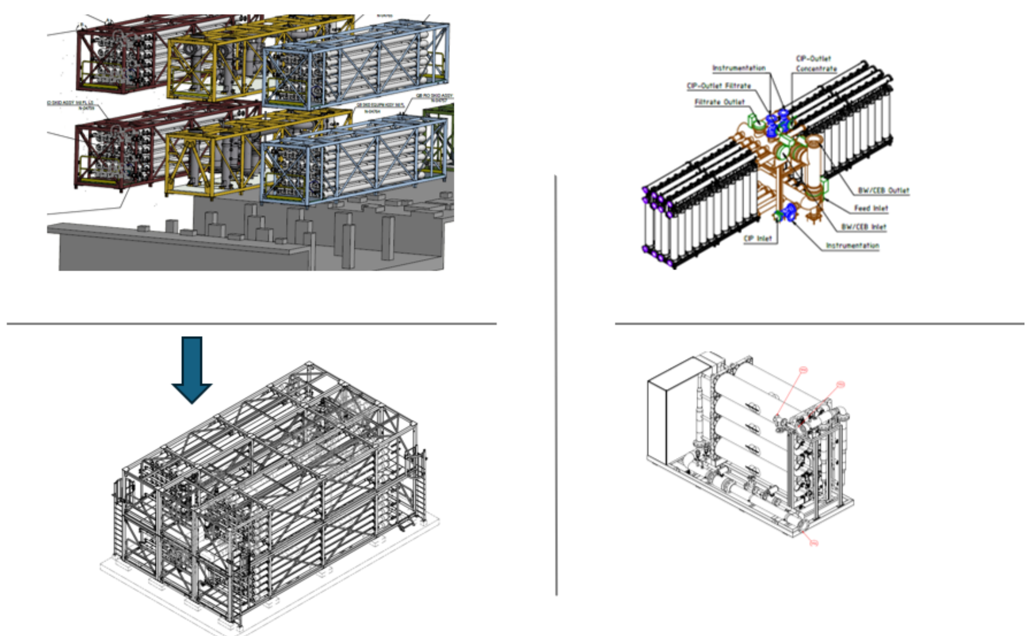


Figure 8: Skid mounted units of UF, CEDI and modular design of RO train

IV. PLANT PERFORMANCE

The close collaboration between the IDE, Techint, and Pemex teams, contributed to a successful accomplishment of a performance test during February 2024. The test was carried out in the presence of the Pemex Operations Chief, Techint Commissioning Chief, IDE Commissioning Manager, and the engineering teams. The primary objective of the performance test was to ensure that the plant meets the contractually guaranteed performance specifications. This test aimed to validate the plant's ability to achieve the promised operational parameters and demonstrate reliable, trouble-free operation over an extended period. All the units were tested, including operation at different production flow set points, as well as during the startup and shutdown of all plant equipment. Chemical dosages were adjusted according to raw water quality, to achieve the specified final product quality. The river water quality exceeded the contractual limits, but the facility successfully resolved the issue, nonetheless.

Table 3 presents the performance of the PPA plant during the performance test.

Table 3: Measured parameters of PPA plant

Parameters	Unit	Raw water	PPA Product requirements	PPA Average tested Product
Design Capacity	m^3/hr		4285	3300
Total Alkalinity	ppm $CaCO_3$	<180	<150	85
Total Hardness	ppm $CaCO_3$	310	<200	94
Total Dissolved Solids	mg/L	500	<1000	280
pH	-	7.6	7 - 8	7.5
Turbidity	NTU	<40	<15	12
Ferric	mg/L	0.3	<1.75	2.3
Free Chlorine	mg/L	0.2-0.5	0.2-1.5	1
Total Suspended Solids	mg/L	51	<15	14

The high Ferric content of 2.3 mg/L in the PPA effluent is due to use of high dosages of $FeCl_3$ coagulant to improve sedimentation in the Lamella clarifier. As described in Section 2.3, the coagulation process was improved by using PAC. ***Table 4*** summarizes the plant performance during the period of PAC testing.

Table 4: Plant performance with PAC dosage

Parameter	Unit	Raw Water	Water Pretreat	Feed Water UF (UDA)	Permeate UF (UDA)
Turbidity	NTU	9.93	3.46	1.3	0.190
TSS	mg/L	6	4	1	0
pH	-	8.15	7.80	7.83	7.9
TDS	mg/L	410	395	380	384
Hardness	ppm $CaCO_3$	178	178	180	176
Al^{3+}	mg/L	0.066	0.028	0.026	0.012

The average parameters measured during the performance test in the UDA plant are summarized in **.**

***Table* 5**. These measurements indicate that each stage in the treatment process operates according to the design specifications and consistently meets the quality standards required by the contract. This successful test highlights the efficiency and reliability of the UDA plant.

Table 5: Average Parameters During Performance Test – UDA plant

Stream	Parameter	Units	Average Measured	Design
Feed from PPA	TDS	mg/L	200	<1000
	Turbidity	NTU	7	<15
UF	Recovery	%	95%	91.7%
	Production	m^3/hr	1478	
	Product Turbidity	NTU	0.2	<1
1st Pass RO	Recovery	%	80%	80%
	Product Front Cond.	µS/cm	6.5	<18
	Product Rear Cond.	µS/cm	14	<54
2nd Pass RO	Recovery	%	90%	90%
	Product Cond.	µS/cm	3.7	<6
CEDI	Product Flow rate	m^3/hr	1128	
	Recovery	%	93.5%	90%
	Product Cond.	µS/cm	0.1	<0.1
Overall Plant	Recovery	%	76%	70%

Figure 9 shows the HMI (Human-Machine Interface) screen of the CEDI system. The display indicates that the ten (10) modules of CEDI are in normal operation and have reached the design product flow of 1140 m^3/hr with 0.05 µS/cm conductivity at recovery rate of 95.6% that higher than the design ratio of 90%. Both quality and quantity targets specified in the design are met, demonstrating the system's effectiveness. The plant design offers flexible modes of operation, which allows for optimization and increased recovery rates at each stage. This flexibility not only ensures compliance with quality standards but also contributes to cost savings by enhancing operational efficiency.

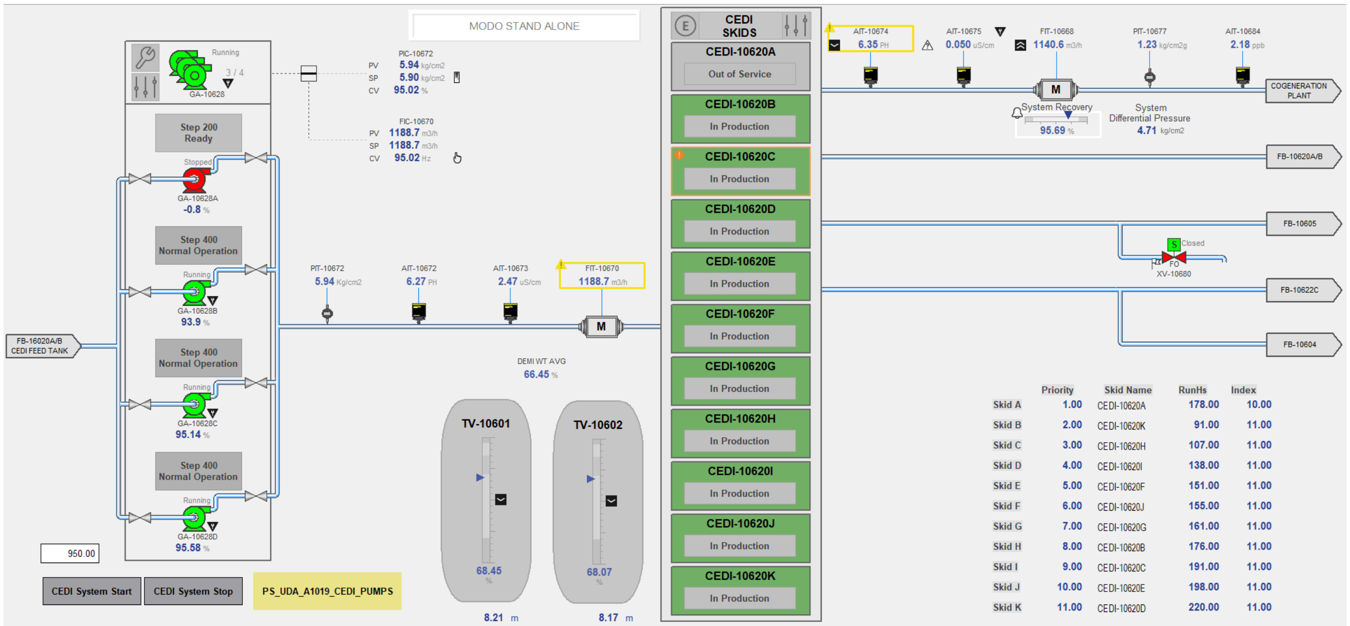


Figure 9: CEDI system HMI screen

Since the UDA plant is the major energy consumer between the two plants, the compliance for energy consumption was evaluated based solely on this plant. The UDA plant was designed to consume 2.1 kWh/m³, with 50% of power allocated to two passes of RO and 30% to CEDI. Actual measurements show a consumption of 1.88 kWh/m³, indicating compliance and superior efficiency compared to the design specification. This indicates an efficient operation of the UDA plant with regards to energy consumption.

V. CONCLUDING REMARKS

The PEMEX Dos Bocas Pre-treatment Project represents a significant milestone in water treatment for the petrochemical industry. The integrated water treatment system showcases cutting-edge technologies and innovative solutions to address the critical need for ultra-pure water production in refineries. The plant successfully overcame all challenges, completing its commissioning and now produces water for the refinery use. It meets both production capacity and quality requirements, marking it as the first large-scale BWRO (Brackish Water Reverse Osmosis) and UPW (Ultra-Pure Water) facility, designed by IDE Technologies in collaboration with Techint Engineering & Construction. This milestone achievement is attributed to the close and professional collaboration between the IDE, Techint, and Pemex companies.

Overall, the PEMEX Dos Bocas Pre-treatment Project exemplifies the integration of innovative technologies, robust design solutions, and proactive planning to address the water management challenges faced by the petrochemical industry, setting a benchmark for future projects in the sector.