2021 NMPWRC Pilot Test Plan

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Topic and Problem Statement

The proposal "Pilot-Scale Test of Hollow Fiber Membrane-Based Direct Contact Membrane Distillation Process to Cost-Effectively Treat Produced Water at the Wellsite to Remove Contaminants to Allowable Levels for Aquifer Recharge" is submitted by the Petroleum Recovery Research Center (PRRC) of the New Mexico Institute of Mining and Technology (NMIMT) located in Socorro, New Mexico, in conjunction with Process Equipment & Service Company (PESCO), a leading manufacturer of oil and gas process equipment located in Farmington, New Mexico, and Hilcorp Energy Company, an oil and gas producer with over 12,000 operated wells located in Aztec, New Mexico. The project will be entirely privately-funded. The proposal addresses the Consortium's first priority Area of Interest (AOI-1).

Produced water (PW) is the most significant byproduct associated with the production of oil and gas. In the San Juan Basin in 2009, the oil and gas industry generated 36.7 million barrels of PW, the majority of which was injected downhole into salt water disposal wells (SWDs) [1]. Further, much of the PW in the San Juan Basin is relatively clean, with total dissolved solids (TDS) ranges from Medium TDS (40,000 – 100,000 mg/L) to Low TDS (<40,000 mg/L). None of the wells involved in this project will have any hydraulic fracturing chemicals as they were drilled in the years 1994 and 2013, respectively; thus, all of the PW constituents to be treated are naturally-occurring minerals from the geologic strata.

The technology proposed for this project is direct contact membrane distillation (DCMD). DCMD is a thermal-driven technology to remediate PW by using novel polyvinylidene fluoride (PVDF) hollow fiber membranes that was developed at the Petroleum Recovery Research Center at the New Mexico Institute of Mining and Technology. The relatively low TDS water in the San Juan Basin would allow this DCMD technology to demonstrate high water recovery and low-energy consumption, making the DCMD process cost-effective and energy-efficient for commercial-scale application in the petroleum industry. Re-filtration of concentrated waste water will allow demonstration of the system on water that approaches High TDS saturation (150,000 to 250,000 TDS) at the same site. The hollow fibers are bundled in a series of membrane modules which are installed in the filtration treatment unit.

PESCO has designed mobile membrane distillation units (MD Units) that would house the DCMD technology and treat PW on-site for fit-for-purpose applications within or outside the oil and gas sector. The MD Units are scalable, but the present design is focused on smaller units. At this size, the MD Units will treat 10,000 gallons per day of PW that contains up to 200,000 mg/L TDS. The MD Units are mobile, skid-mounted, and enclosed in a weatherproof container measuring approximately 8' wide x 20' long x 8' tall. The skid is easily transportable so that it can be readily moved from well site to well site to treat PW at two existing oil and gas well sites operated by Hilcorp in the San Juan Basin, designated for this project. During the project test, all treated water and residuals will be returned to the PW tank at the well site for storage and disposal in accordance with current PW requirements; the project has been designed and will be managed to ensure that there is no planned or accidental discharge or release of produced water outside of a permitted Oil Conservation Commission (OCD) facility.

This project seeks to test the treatment technology with the ultimate goals of (1) treating the PW to the water quality standards that would permit the treated PW to be discharged to surface or groundwater and (2) commercialize the treatment technology to reduce the volume of produced water disposed of in SWDs and increase water resources for fit-for-purpose applications. This proposed nine-month project will be led by principal investigator, Dr. Robert Balch from the NMIMT with an estimated completion date of June 30, 2022.

Keywords: Remediation, Reuse, Membrane Distillation, Waste Reduction, Beneficial Uses

Problem and Objectives

New Mexico is one of the top oil and gas producing states in the county, which means that it is also one of the top PW producers in the county. In 2019, New Mexico produced 1.246 billion barrels of PW [2]. With current technologies, the majority of this PW is hauled to the nearest SWD and disposed of downhole. This is a tremendous volume of water to be disposed of as a waste product in an arid state that receives less than 15 inches of rainfall each year. Further, rainfall is projected to be increasingly scarce in coming years.

The average water hauling and disposal costs in the San Juan Basin are between $3 and $4 per barrel, resulting in significant cost, particularly on the marginal gas wells found in the San Juan Basin. These costs result in a higher threshold of oil and gas production where the well becomes uneconomic leading to the premature plugging of the well, wasting of the remaining reserves. Given this problem, this project seeks to find an alternate way to manage PW that would create water resources and recharge aquifers, as well as significantly reduce water hauling and underground disposal.

In the San Juan Basin, large quantities of PW are produced from individual well sites that often very remote and are not interconnected with a PW pipeline system; because there are no major centralized PW treatment sites in the San Juan Basin, treatment is only cost-effective if the treatment unit can be moved from well site to well site depending on need. A modular approach allows for fitting the system to the needs of particular, often remote, sites.

This project will address AOI-1 by demonstrating a cost-effective, mobile treatment technology applicable to low-, medium-, and high-salinity PW and associated constituents. The objective performance goals of the project tests will be, first, to demonstrate the ability to cost-effectively achieve NMOCD and NMED water quality standards for surface and groundwater discharge of the treated PW. Second, the project seeks to minimize the ratio of post-treatment concentrated brine water to treated PW, thereby minimizing costs of transportation of the concentrated brine to off-site disposal. Third, this project will test the mobility and flexibility of the skid-mounted MD Unit by moving from the first test well site to the second test well site to determine costs and time required.

While this project is focused on well sites in the San Juan Basin that have low- and medium-TDS levels, generally representative of the relatively low TDS levels found throughout the San Juan Basin's PW, the project will simulate the higher TDS levels found in the Permian Basin by further treating the concentrated brine streams produced in this project. This additional treatment step will demonstrate how this project could be expanded in a future "Phase Two" project to test high-TDS water in the Permian Basin.

Methods

Membrane distillation offers the capability to treat high salinity PW with theoretically 100% of salt rejection. In a typical direct contact membrane distillation (DCMD) process, the hot feed and cold permeate solution are separated through a hydrophobic microporous membrane, which prevents the salt permeation but allows water vapor transport through the membrane pores, as shown in **Fig. 1**. The vapor transport is driven by the temperature-induced vapor pressure difference across the two sides of the hydrophobic membrane.

As the DCMD process is not purely thermally driven, membrane distillation can be operated at a much lower temperature than the other conventional thermal distillation processes, leading to lower specific energy consumption. Aside from the energy advantage, DCMD shows a considerably lower fouling potential than the pressure-driven based membrane process, such as reverse osmosis and nanofiltration. Because there is no trans-membrane pressure applied on the membrane surface, the accumulation of foulants on the membrane surface are significantly eliminated. Membranes can also be backflushed periodically using water purified by the system to maintain optimal filtration rates. It shows in **Fig. 1** that DCMD is a simultaneous process that involves both heat transfer and mass transfer. High mass transfer and low heat transfer rates are preferred to enhance the water permeation flux and maintain constant driving force arising from the temperature difference. Unfortunately, both mass and heat transfer resistance increase with the increased thickness of the conventional hydrophobic membranes, which challenges the design and development of suitable membranes for the DCMD application. Typically, water vapor molecules transfer from the hot feed side to the cold condensation side through the hydrophobic membrane pores, while the heat mainly conducts through the polymeric membrane matrix because the heat transfer coefficient of polymers is much higher than that of air. It will be preferable to reduce the vapor transport distance without decreasing the membrane thickness in DCMD. In recent years, New Mexico Tech has successfully developed a novel Janus hollow fiber membrane that comprises a thick porous and superhydrophilic polyvinylidene difluoride (PVDF) and polyethylene glycol (PEG) inner layer and a thin superhydrophobic crosslinked PVDF outer layer. The PVDF outer layer functions as an anti-wetting barrier to avoid the direct water contact between the feed and permeate sides; and the presence of a thick and highly-porous PVDF/PEG inner layer facilitates the vapor transfer with a relatively minor effect on the conductive heat loss. It has been proven from bench-scale experiments that the Janus hollow fiber membrane exhibits simultaneously enhanced water flux and energy efficiency compared to the other conventional PVDF membranes.

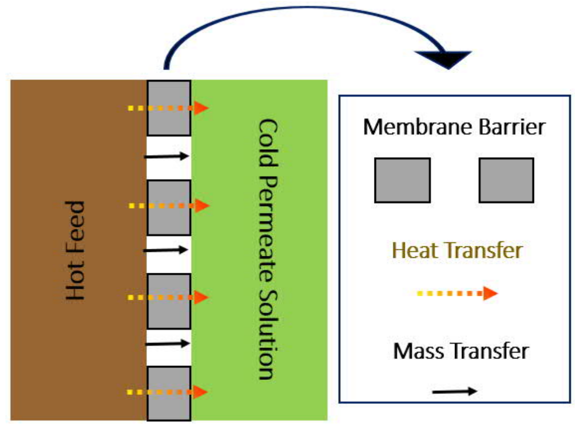


Fig. 1 Schematic of basic principle of DCMD processes.

In this project, a pilot-scale Janus hollow fiber membrane-based DCMD system will be constructed for testing with actual oilfield produced water in the San Juan Basin. The initial test units will be designed to treat 10,000 gallons per day of water that contains up to 200,000 mg/L of total dissolved solids. These membrane distillation units (MD Units) are designed by PESCO as skid-mounted units which are easily transported from well site to well site.

The MD Unit test is designed to demonstrate the viability of the Unit to treat PW at a Hilcorp wellsite to pave the way for allowing the legal discharge of a majority of the PW on site, greatly reducing the volume of contaminated water that must be hauled off from the wellsite to a water disposal facility. The total volume of untreated PW will be compared to the resulting volume of treated water and the residual concentrate. The salinity of each stream will be monitored by real time data sampling from conductivity meters, as well as periodic sampling for laboratory analysis. Operating parameters will be continuously monitored and recorded, including flows, pressures, and water temperatures at various points on the water loops. This data will be used to monitor the Unit to ensure it is operating as planned and to evaluate unit performance at the conclusion of field testing. Daily observations will be taken by field personnel noting any problems or points of interest. Moreover, O&M costs will be tracked to facilitate economic evaluation including fuel usage, filter module replacements, repair work, and other O&M costs.

Anticipated Benefits and Impact

The PW treating process will generate two resulting product streams. One will be a stream of treated water. It is expected that the resulting data from the project will demonstrate that the contaminants from the source PW that remain in the treated water stream will be reduced below NMOCD and NMED water quality standards limits. Thus, in theory, the treated PW could qualify for a discharge permit for discharge to the surface or discharged to groundwater for aquifer recharge. The other waste stream will be a smaller volume of concentrated brine to be disposed of downhole at SWDs used by the operator.

The expected ratio of treated water to concentrated brine will depend on the salinity of the source PW, but it is expected that this ratio will be in the range of 5:1 to 20:1 (treated water to concentrated brine), thereby greatly reducing the volume of water to be hauled to an off-site disposal well. This reduction of the overall PW waste stream that requires SWD disposal is a key component for calculating the money saved versus current practice. If the results show a significant cost savings, then it will pave the way for Hilcorp to work with the Consortium and the State of New Mexico regulatory agencies to pursue a discharge permit for on-site discharge of PW, eliminating most of the current PW hauling and disposal. Once proven to be a cost-effective treatment, this treatment technology could be applied across the San Juan Basin and beyond, reducing operating costs, extending the economic lives of wells, significantly reducing the volume of water truck traffic on lease roads and highways, and resulting in a substantial influx of clean water across the State of New Mexico.

If the project is successful, New Mexico Tech and PESCO are prepared to finance the fabrication of a total of six MD Units, and Hilcorp would seek permits from NMED and NMOCD to the utilize this technology. Subsequent development of the MD Unit manufacturing will be done through a joint venture between New Mexico Tech and PESCO, with additional financing to be provided through that entity.

Site Selection

a. Test Site

Two currently producing well sites owned and operated by Hilcorp have been selected as sites for these tests. These wells are located in the southern half of the San Juan Basin in northwestern New Mexico. Each well site includes a producing natural gas well, surface separation equipment, and a produced water (PW) tank that is used for on-site storage of the PW from the well. The first well location produces from the Fruitland Coal formation at a depth of 2,250 feet. It was spudded in 1994. Lab tests on the untreated PW from this well showed a TDS of 51,020 mg/L, falling in the “medium” range of salinity. The second well location produces from the Mancos Shale formation at a depth of 11,361 feet. It was spudded in 2013. Lab tests on the untreated PW from this well showed low TDS of 19,160 mg/L. Both wells are located on federal surface managed by the Bureau of Land Management. For purposes of this project, the MD Unit will be moved between both well sites to demonstrate the cost-effective mobility of this treatment technology.

b. Manufacturing Site

PESCO’s manufacturing facilities, located in Farmington, New Mexico cover over twenty acres and include 160,000 square feet of manufacturing and office space and can accommodate over 500 personnel. The manufacturing equipment includes a full array of industrial raw material cutting and bending tools, manual and automated welding equipment, up to 15-ton overhead cranes, fully enclosed industrial sandblast and paint facilities and assembly lines for equipment fabrication. PESCO can design and manufacture equipment ranging from a single, small ASME Code compliant vessels to a full process production unit weighing up to 50 tons and 80 feet long.

Site Prep

Prior to the installation of the project test equipment, each wellsite will be prepared by ensuring that all required secondary-containment berms and/or liners are in place as a contingency against accidental leaks from the test equipment or interconnecting piping.

Next, a PW surge tank with a capacity of at least 30 barrels will be placed on the site, followed by the MD Unit and two additional storage tanks of at least 200 barrels each, one for the concentrate water and one for the treated water. The existing well site PW tank will be piped to the PW surge tank, which will be piped to the MD Unit, which will then the piped to the concentrate and treated water tanks. A natural gas-powered air compressor will be set adjacent to the MD Unit to provide motive power to operate valves and pumps. For further leak detection and prevention, the MD Unit will be configured with an on-skid leak catch tray and detection system that will trigger a unit shutdown if a leak is detected.

During cold weather testing, heat tracing will be run on all water lines, and tank heaters will be installed on the inlet surge tank, the concentrate tank, and the treated water tank to prevent freezing. A 500-gallon propane tank will be set and piping for fuel gas will be run from the propane tank to the MD Unit and the air compressor.

Finally, the untreated PW shall be tested per EPA Drinking Water Standards to establish an updated baseline for comparison to treated water test results.

Sampling and Analysis Plan

In order to meet the experimental objectives of the test, the sampling and analysis plan includes real-time monitoring of the following parameters:

- Flow rate of PW into the Unit
- Flow rate of concentrate out of the Unit
- Flow rate of treated water out of the Unit
- Conductivity measurements of the inlet PW, discharged concentrate, and treated water
- Differential pressure reading across inlet filter to detect plugging
- Measurements to monitor for membrane module fouling
- Fuel use for unit heating
- Fuel use for air compressor

These parameters will be reassured electronically and some shall be used as inputs to an on-board programmable logic controller to control the Unit operation. These measurements will be recorded at the on-board system and uploaded via cellular data link to systems at PESCO for remote monitoring by PESCO personnel and for off-site data logging.

Representative samples of the PW from the well site PW tank, the concentrate from the concentrate tank, and treated water from the treated water tank shall be taken at regular intervals (e.g. every 50 bbls of PW flowing into the system) and sent to the designated testing laboratory where it will be tested for the target constituents listed in EPA Drinking Water Standards, though it is important to note that this application is not designed to turn produced water into drinking water except through the potential of surface disposal with percolation to groundwater.

In addition to operating parameter data, cost data shall be gathered throughout the test including:

- Operations and maintenance personnel time
- Operating and maintenance supplies and parts costs including:
  - Filter replacement
  - Lubrication oil
  - Other miscellaneous supplies and repair parts
  - Ancillary equipment rental cost (i.e. natural gas powered air compressor)

At this point when tests have been concluded at the first test site, the mobility of the MD Unit will be tested as it is moved to the second test location wellsite recording time, personnel and equipment needed, and total costs to move. Once moved to the new well site, the well site multi-cycle testing process outlined above will begin.

Performance Goals

Based on prior laboratory and field testing, it is expected the MD Units will have the potential to remove 99% of TDS and other constituents. However, the goal for this test is to show the MD Unit can generate treated water that meets or exceeds New Mexico ground water standards to permit on-site disposal of the treated water. Next, a goal of 50% reduction of the volume of waste water that would be required to be hauled off for disposal; this will be calculated as the percentage of produced concentrate versus the total PW volume treated.

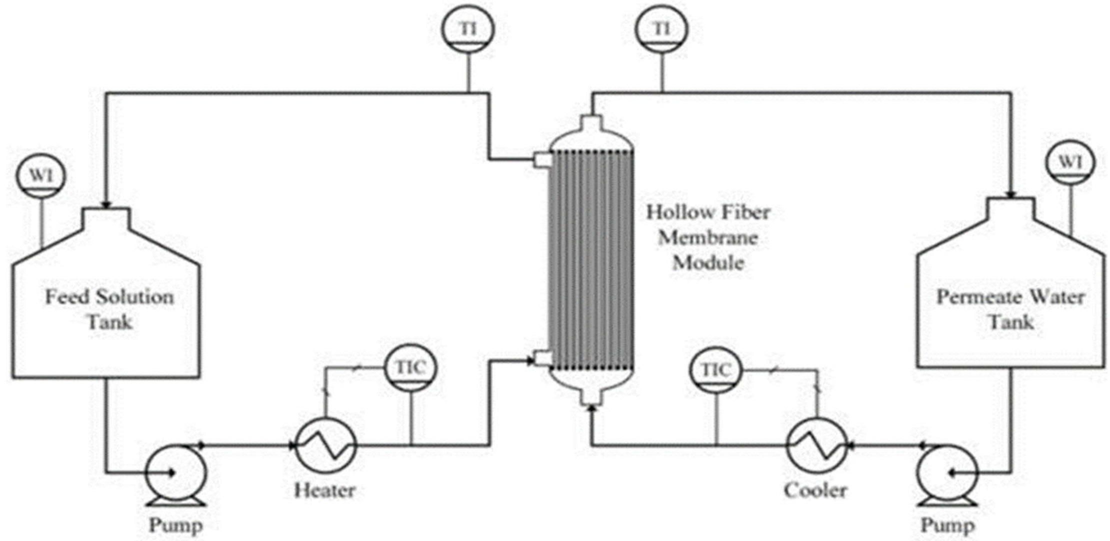
Targeted costs are as follows: Fuel costs to power the MD Unit in this project is targeted to be $0.66 per bbl of treated water using purchased propane as a fuel source with fuel for the air compressor adding an additional $.016 per bbl. Filter replacement costs is targeted to be approximately $0.38 per bbl. Operations and maintenance personnel time is targeted to be $0.42 per bbl.

It is expected that results from the tests will allow for the optimization of the design and operation of future MD Units with significantly lower costs, including the use of wellhead natural gas as a fuel source, longer filter change intervals, and operations and maintenance activities to support normal operations of the Unit rather than experiment test conditions. The above target points are on a per bbl of PW coming into the MD Unit. The portion of clean, treated water will be a function of the initial salinity of the PW.

Process Flow

Since samples from the two test wells indicated there are minimal issues with suspended solids or entrained hydrocarbons that would affect the primary membrane filter media, only a basic level of filtration of the inlet water will be required. If, however, it is determined to be a problem upon testing, additional pre-treatment equipment can be added at that time.

The process flow of the MD Unit begins with the inflow of the contaminated water source (feed solution) through pre-treatment filters into an internal surge tank. After the PW enters the internal surge tank, it is circulated by a pump through a feed solution cycle loop where it flows through the filter modules, coming in direct contact with the hollow fiber membranes. Vapor from the hot feed solution side migrates, via the DCMD process, across the highly-porous and hydrophobic membrane barriers over to a permeate water circulation loop. As permeate water builds in the treated water surge tank, it is routed to a treated water storage tank and then on for testing to verify it met treatment objectives. During the DCMD process, the concentration of TDS in the feed solution loop will build as that water is cycled back through the system; when it reaches a pre-determined set point of max concentration for the system, the concentrate will be moved to a concentrate holding tank. At this point, the cycle starts again. The TDS concentration of the contaminated water source directly affects the ratio of treated water to concentrate produced by the MD Unit. Below is a simplified process flow diagram of this process:



SOP

Once the test equipment is in place, an onsite process safety review will be conducted with Hilcorp and PESCO personnel. A Process and Hazard Review will be conducted to identify all personal and public safety and environmental hazards. Each hazard will be evaluated to determine the associated risk, evaluated as the consequence of the event weighted by the probability of the event occurring. The disposal plan for the concentrated brine will include on-site storage with secondary containment and leak detection. At the conclusion of the tests, the concentrated brine will be returned to the PW tank along with the treated water and disposed of per Hilcorp's standard operating procedure.

To begin the test, the air compressor will be started and pressures verified to the MD Unit. The Unit will then be charged with approximately 100 gallons of potable water to fill all internal piping, tankage, and filter modules. Flow circulation tests will be carried out to verify proper control system operation, pump operation, flow control, and shutdown trips, and to verify that the heater is on and operational. Upon a successful startup, the PW can start to be fed into the system. Once the startup of the MD Unit is complete, the PW tank drain valve will be opened to allow PW to flow from the PW tank to the PW inlet surge tank. After a minimum of 20 bbls of reserve PW is in the surge tank, the inlet valve from the surge tank to the MD Unit can be opened.

During the tests, flowrates shall be varied through the filter modules to test treated water flux through the membrane as a function of flowrate and PW salinity. Once the Unit has treated 200 bbls of PW, the Unit will be powered down and all valves isolating the Unit and the respective tanks will be closed. Final representative samples of the PW from the well site PW tank, the concentrate from the concentrate tank, and treated water from the treated water tank shall be taken and analyzed for the target constituents. At the conclusion of each 200-bbl test, the water from the three test tanks can be recombined and returned to the on-site PW tank where PW will be hauled away under Hilcorp's normal PW disposal process. It is the goal of the project to perform 15 such 200-bbl cycles of the test performed with breaks in between or through continuous operation, depending on available PW and the performance of the MD Unit.

At the conclusion of these cycles, the MD Unit will be shut down, purged of PW and concentrate, and prepared for transport. The flow lines will be drained of water in preparation for disassembly and transport to the next test well site. At this point, the mobility of the MD Unit will be tested as it is moved to the second project location, recording time, personnel, and equipment needed, as well as total costs to move. Once moved to the new well site, the well site multi-cycle testing process outlined above will begin.

In addition to multiple in-person visits to the project site by Hilcorp and/or PESCO personnel each week, the MD Unit will be monitored by real-time telemetry to verify proper Unit operation and to detect upset conditions or MD Unit shutdown. The MD Unit will have on-board leak detection and auto-shutdown sensors and trips as follows:

- Conductivity meter detects high TDS downstream of filters
- Loss of flow into the MD Unit
- High pressure
- Leak detected on skid
- High temperature shutdown
- Loss of fuel gas
- Monitoring for fouling
- On-skid tank high liquid level

Cost and Schedule

The cost of the testing shall be entirely born by the participating parties: New Mexico Tech, PESCO, and Hilcorp. It is anticipated that the tests will run for approximately nine months starting in September of this year through June of 2022. With the ability to recombine the treated water and concentrate back into the PW tank, the total volume of treating can far exceed the PW production rate of the individual wells, which are expected to range from 10 to 30 bbls per day. The goal of the test is to treat approximately 13,000 bbls of PW over the total duration of the testing program, with total expenses expected to exceed $200,000. These costs will cover:

- personnel costs for administration ($38,000)
- O&M personnel ($5,600)
- supplies ($16,000)
- equipment ($35,400)
- contract services including site construction and lab services ($92,000)
- fuel (propane) for heating and air compressor operation ($10,000)

At the approximate midpoint of the test program, it is planned to move the MD Unit to the second test well location and resume the same testing regime.

Data Management Plan

All operating parameters on the Unit will be logged and uploaded to a central database. This data will be analyzed and compiled in an appropriate format to show the status of the Unit and the productivity of the Unit to treat the PW. The laboratory tests of all water samples shall be assembled and correlated to conductivity readings from the Unit to verify field reading accuracy, and to provide detailed constituent breakdown of all three flow streams from the testing over time. Field notes from O&M personnel shall also be compiled and correlated to Unit operating data to show any changes in performance over time, and in response to upset or changing conditions. Finally, all cost data will be gathered through New Mexico Tech, PESCO, and Hilcorp accounting systems, compiled and then analyzed to present O&M costs data on an average daily, monthly, and per bbl of PW treated.

Residual and Environmental Risk Plan

All water that is hauled away for offsite disposal shall be handled under the standard operating procedures for PW handling. No water is to be disposed of on site. All water will be contained in on-site storage tanks and recombined prior to hauling. Additional air pollutant generation will come from the combustion of propane gases for the HD Unit heater and the natural gas-fired air compressor. Hilcorp personnel will be responsible for obtaining the appropriate permitting for such emissions.

3rd Party Review Coordination

New Mexico Tech, PESCO and Hilcorp administrative personnel will be available for contact by 3rd party reviewers. A specific testing project – 3rd Party liaison shall be appointed to provide needed information at the request of 3rd Party reviewers.

Summary of Operational Data

a. Current Status of Technology

The treatment technology used for this project is direct contact membrane distillation (DCMD). DCMD is a thermal-driven technology by using a porous hydrophobic membrane to remediate PW that was developed by the Petroleum Recovery Research Center at the New Mexico Institute of Mining and Technology (NMIMT). Hollow fiber membrane (HFM) offers a compact, cost-effective solution for filtering large volumes of impaired water utilizing minimal space and energy. NMIMT has successfully fabricated different types of HFMs for oilfield produced water management [3-7]. Recently, a novel crosslinked PVDF based hydrophilic-hydrophobic dual-layer Janus hollow fiber membrane (Janus-HFM) was fabricated for particular use in desalination of high-salinity oilfield produced water (PW)[6]. The morphology of the Janus-HFM is shown in **Fig. 2.** The diameter of the Janus-HFM is around 800μm. Compared to the neat PVDF HFM, the water contact angle of the Janus-HFM increased from 82° to 151°, indicating a significantly enhanced hydrophobicity of the crosslinked PVDF membrane. The bulk porosity, effective surface porosity, mean pore size, and bubble point pore size are 80.6%, 6471.3 m^{-1}, 0.27 μm and, 0.40 μm, respectively. The Janus-HFM shows all the desirable membrane properties for the particular use in DCMD [7].

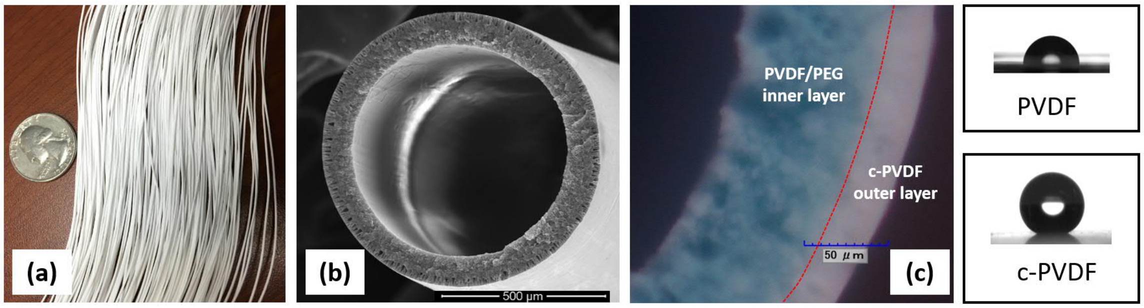


Fig. 2 Image of the fabricated Janus-HFMs; (b, c) Cross-sectional SEM images of the membrane; and water contactor angle of the neat PVDF and crosslinked PVDF (c-PVDF) membrane.

The Janus-HFM based DCMD process has been evaluated for the desalination of actual oilfield PW in the PI's previous work [7]. The total dissolved solid (TDS) and non-purgeable organic carbon (NPOC) are 154,220 mg/L and 57.6 mg/l, respectively. During the DCMD experiment, the temperatures of the PW and permeate water were 60°C and 20°C, respectively. The flow velocities of the two streams were 0.4 m/s. The membrane was flushed at 2.0 m/s every 12 hours using DI water for membrane regeneration. The membrane exhibited stable desalination performance in 6 cycles of the DCMD operation (see **Fig. 3**). The permeate water flux at each cycle is around 17.5 $kg \cdot m^{-2} \cdot h^{-1}$. The salt rejection of the Janus HFM was higher than 99.9%. A preliminary cost analysis was performed based on the laboratory results. The proposed Janus-HFM based DCMD system can reduce the PW desalination cost to $0.10 per barrel with the use of the waste natural gas generated as a byproduct with the production of oil and produced water.

b. Other Research Support

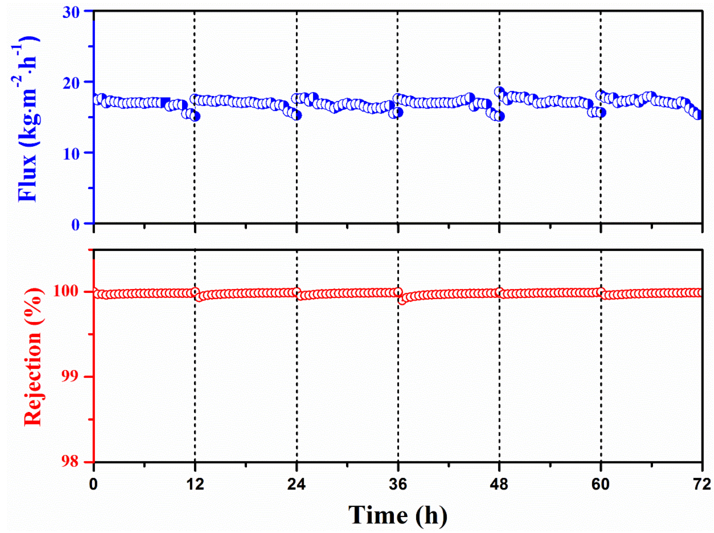


Fig. 3 Desalination performance of the Janus-HFM in desalination of actual oilfield produced water.

The research on the novel hollow fiber membranes has been financially supported by the Department of Energy (DOE) through the Research Partnership to Secure Energy for America (RPSEA) (award number 12123-16). The Janus-HFM used in this proposed DCMD process was also supported for a laboratory-scale study from the Bureau of Reclamation (BOR) (agreement number R17AC00143). Most recently, two new projects are selected by the BOR for both laboratory-scale and pilot-scale demonstrations of innovative hollow fiber membranes-based DCMD process for high-salinity produced water treatment. The details of the new research supports are listed as follows:

1. “Pilot-scale validation of a novel Janus hollow fiber membrane based DCMD process for high salinity produced water desalination by using waste heat”, $299,752.00, (6/2021 to 12/2022), just selected for fund by the Bureau of Reclamation.
2. “Hydrophilic-omniphobic HF membrane-based DCMD and crystallization for zero liquid discharge of oilfield produced water (R20AC00054), $500,000.00 (1/2021 to 12/2022), funded by the Bureau of Reclamation.

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