Innovative Venturi-Based Gas Stripping and Destruction for Produced Water Treatment

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KEYWORDS: Produced Water, Wind River Basin, VOC Stripping, Regenerative Thermal Oxidizer, Bioremediation, Pilot Plant, Energy, BTEX, Methanol, TPH

ABSTRACT

Pilot results are presented from an innovative pretreatment for produced water with a Venturi-based volatile organic carbon (VOC) air stripper, and regenerative thermal oxidizer. The system achieved >98% total petroleum hydrocarbon (TPH) removal, and self-sustaining thermal oxidation without supplemental fuel. In addition, dissolved iron was reduced by more than 80% to less than 0.3 mg/L after oxidation and filtration. The modular design supports downstream desalination and reuse, validating a scalable, low-OPEX, no chemical platform for compliant, cost-effective produced water management and meeting regulatory discharge standards.

INTRODUCTION

The Wind River Basin in Wyoming is a site of major oil and gas development that generates significant volumes of produced water requiring treatment prior to reuse or surface discharge. The produced water contains elevated levels of salts, iron, residual hydrocarbons (including volatile organic compounds like BTEX), dissolved organics such as methanol (used in upstream processes), and high biological activity. Discharge permits (Wyoming Pollutant Discharge Elimination System, WYPDES) set stringent limits on contaminants such as oil & grease, total petroleum hydrocarbons (TPH), benzene and other volatile organic compounds (VOCs), total suspended solids (TSS), and require the water to be of high clarity and low toxicity. Conventional produced water treatment often involves combinations of physical separations, chemical additions, and polishing units. In this context, an Energy Company ("Company"), in collaboration with Hyperion Water Technologies (HWT), piloted an integrated treatment approach emphasizing air-based VOC stripping, advanced oxidation, biological treatment, and minimal chemical usage to meet the discharge criteria.

The pilot program progressed in phases. The **2018 Pilot** was a 3-4 week field demonstration of a pretreatment platform that combined stripping of volatile organic and iron oxidation (via a Venturi air stripper), ozone/UV for biological control, clarification for solids/oil separation, and ultrafiltration (UF) membranes. This pilot focused on achieving key effluent quality targets with continuous, chemical-free operation. Next, the **2023 Pilot** revisited the treatment scheme with scaled-up or modified processes, including a patented de-solving unit (DSU) air stripper for VOC removal, a pilot-scale regenerative thermal oxidizer (RTO) for off-gas destruction, and a biological regenerative adsorption (BRAT) unit for methanol removal. Finally, a dedicated **2023 VOC Stripper Emissions Test** was conducted by an independent vendor to measure VOC concentrations in the stripper off-gas and confirm RTO destruction efficiency and fuel independence. Together, these studies provide a comprehensive evaluation of the treatment train's performance and operational considerations.

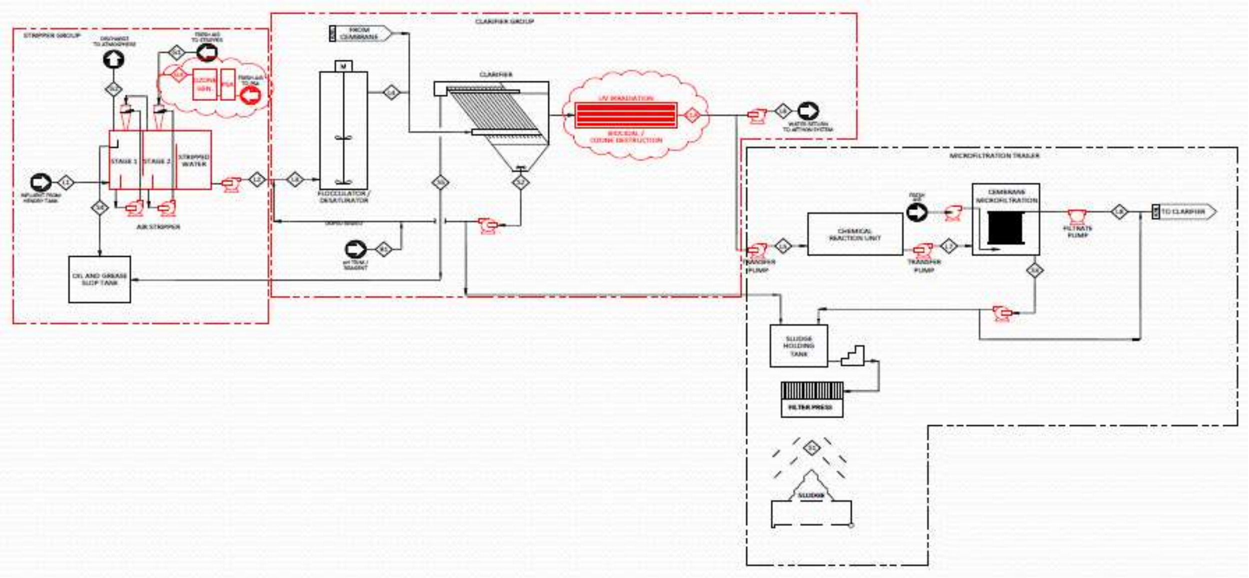
This paper summarizes and compares the pilot results, interprets the performance considering existing literature, and discusses the implications for designing a full-scale produced water treatment system (the planned facility upgrade). By integrating the findings, pilot testing validates the proposed treatment technologies and identifies best practices to ensure reliability, regulatory compliance, and cost-effectiveness in full-scale operation.

PILOT SYSTEM DESCRIPTIONS

2018 PILOT PLANT PROCESS OVERVIEW - The **2018 Pilot** was a field-scale pilot unit that treated produced water from Company E's Wind River Basin operations for about one month. **Figure 1** illustrates the pilot process flow, which included sequential unit operations: (1) a two-stage Venturi air stripping system for VOC and acid gas removal and iron oxidation, (2) an ozone-assisted ultraviolet (UV) irradiation reactor for biological control and oxidation of residual organics, (3) a clarifier with flocculation for bulk solids, oil, and paraffin removal, and (4) a ceramic ultrafiltration membrane for final polishing. No coagulant or oxidant chemicals were dosed into the water stream. Instead the process relied on air and ozone/UV to achieve treatment objectives (hence described as chemical-free continuous operation). The air stripper was designed to strip volatile hydrocarbons (e.g. BTEX and light gasoline-range organics) and dissolved CO_2 from the water by contacting it with air in a venturi aeration chamber. Stripping also raised the water pH by CO_2 removal and oxidized ferrous iron (Fe^{2+}) to ferric (Fe^{3+}), causing iron to precipitate as insoluble hydroxides. Precipitated iron and other suspended solids were then removed downstream in the clarifier and UF. An ozone generator and UV reactor provided advanced oxidation and disinfection – effectively inactivating bacteria and preventing biological fouling in downstream membranes. The clarified and filtered effluent was of sufficient quality (low turbidity, low iron and organics) to feed a downstream desalination unit (not piloted but anticipated as electrodialysis reversal, EDR, for removing salinity).

Figure 1:

2018 Pilot Process Flow Diagram



Key design features of the **2018 Pilot** included an air blower supplying a venturi stripper, an off-gas outlet (which in a full-scale design would be connected to a thermal oxidizer or flare), an ozonation system with oxygen feed (Pressure swing adsorption to supply O_2 for ozone generation) feeding into a contact chamber with UV, and a cross-flow ceramic UF module. The pilot treated approximately 10–20 gallons per minute of produced water. Instrumentation monitored parameters like pH (which was observed to rise in stripping), turbidity, and flows, and samples were taken to measure contaminants through the treatment train.

2023 PILOT UPDATED STRIPPER AND METHANOL BIOREACTOR - The **2023 Pilot** built upon the **2018 Pilot** conceptual design, with emphasis on validating VOC removal, handling of off-gas via thermal oxidation, and addressing a newly recognized constituent of concern, methanol. The pilot setup consisted of two main skids:

> <u>DSU Air Stripper & Oxidation Unit</u> A DSU venturi air stripper was used to strip VOCs and CO_2 and partially oxidize dissolved iron, similar in concept to the **2018 Pilot** stripper but with a few design enhancements. The stripper operated at ~20 gpm water flow and used atmospheric air injection (approximately 137 actual cubic feet per minute

in the pilot) to volatilize hydrocarbons. Stripped gas from the unit was piped to an RTO for destruction. The RTO was a natural gas-fired oxidizer with ceramic heat recovery beds, capable of self-sustaining (fuel-free) operation when the inlet VOC concentration was above a certain threshold. A propane-calibrated Flame Ionization Detector (FID) was used to continuously monitor hydrocarbon concentrations in the stripper off-gas and the RTO exhaust during pilot runs. The pilot did not include a full clarifier or membrane step. Instead, the water exiting the stripper was collected for analysis and for feeding the methanol bioreactor test. However, a small settling tank was used at times to observe separation of oils/paraffins. Based on pilot observations, the design of a full-scale clarifier (with an integrated oil-water separator and sludge collection) was planned to handle the heavier hydrocarbons and solids that the stripper does not remove.

BRAT Methanol Removal Bioreactor To remove dissolved methanol, which can have a high chemical oxygen demand (COD) and oxygen depletion effect if discharged, we deployed a bench-scale Biologically Regenerative Adsorptive Treatment (BRAT) unit. This process uses a fixed-film bioreactor concept wherein a culture of denitrifying bacteria is supported on an adsorptive media. The microbes consume methanol as a carbon source while reducing nitrate to nitrogen gas. In essence, methanol is biologically oxidized (via anoxic respiration) to harmless end products. The pilot BRAT was inoculated with biomass from a municipal wastewater plant (Riverton, WY) acclimated for denitrification, and nitrate was dosed into the reactor feed to ensure an electron acceptor was available. By supplying excess nitrate, the process intended to make methanol the limiting nutrient so that it would be fully consumed. The BRAT was fed with stripper-treated water. However, as discussed later, environmental conditions (cold temperatures) and competition from other organics in the feed posed challenges during the pilot run.

The second **2023 Pilot** runs took place in summer and early fall of 2023, with test periods focusing on VOC stripping and RTO performance in July, and the methanol bioreactor trial in September. Water samples were collected before and after the DSU stripper (to evaluate VOC/TPH removal and iron oxidation) and before and after the BRAT unit (to evaluate methanol reduction). Off-gas measurements were logged to determine VOC concentrations and oxidation efficiency in the RTO. Operational observations, such as the formation of any deposits, microbial growth, or other issues, were recorded to inform design improvements.

2023 VOC STRIPPER EMISSIONS TEST (JULY 2023) - A dedicated emissions test was performed on July 19–20, 2023 to quantify the VOC content in the stripper off-gas and confirm the RTO's destruction efficiency. In this test, the DSU air stripper was run in conjunction with a pilot RTO, instrumented with a continuous Flame Ionization Detection (FID) analyzer sampling both upstream and downstream of the oxidizer. The stripper operated at 20 gpm during tests, treating produced water drawn from the feed tank. The off-gas from the stripper was directed into the RTO's combustion chamber. The FID (California Analytical Instruments 700 series) measured hydrocarbon concentrations (reported as propane equivalents, C_3 basis) in ppm. The testing followed standard EPA methods for stack testing, including use of heated sample lines (maintained ~400 °F to prevent condensation of heavy hydrocarbons) and calibrated span gases.

During the emissions test, data on off-gas flow rate, VOC concentration, and RTO operating mode (e.g. burner firing or self-sustaining) were recorded. The aim was to simulate the full-scale scenario where stripped VOCs would be sent to a thermal oxidizer sized for the Wind River Basin produce water treatment facility's needs. Key safety and design aspects, such as lower explosive limit (LEL) of the gas and potential buildup of heavy hydrocarbons in ductwork, were also evaluated. This test provided essential data to properly size the full-scale RTO and to ensure it can achieve >98% VOC destruction without supplemental fuel under normal conditions. The results of the FID testing are incorporated in the performance summary below.

RESULTS AND DISCUSSION

WATER TREATMENT PERFORMANCE: VOC AND TPH REMOVAL –

> VOC Stripping Efficiency Both pilots demonstrated that air stripping is highly effective for removing volatile hydrocarbons (BTEX and similar compounds) from the produced water. In the **2018 Pilot** trial, the integrated system consistently met effluent targets of < 5 mg/L total VOCs and < 2 mg/L Oil & Grease in the treated water. This corresponded to an observed >97% reduction in TPH across the stripping and downstream units. During the pilot, quantitative data were collected on specific VOCs. **Table 1** summarizes representative results for key contaminants before and after the DSU air stripper in the **2023 Pilot**. The influent water was high in light hydrocarbons (e.g. gasoline-range organics averaging 50–60 mg/L and BTEX components in the tens of mg/L range). The DSU stripper reduced benzene from ~12.8 mg/L to 0.52 mg/L, toluene from 27.6 to 1.01 mg/L, and total xylenes from ~14.7 to 0.507 mg/L. This equates to 96–98% removal efficiency for these VOCs. Gasoline- range organics (GRO, C6–C10) were lowered by ~94% (from 58.6 to 3.6 mg/L), consistent with the removal of BTEX which dominate that fraction. These results are in line with expectations from literature; air stripping is known to achieve >90% removal of BTEX under favorable conditions when Henry's law constants are high and process conditions are optimized (e.g. warm water, sufficient air-to-water ratio) (Choi 2023) (Abdullahi 2015). The pilots operated near ambient temperature (~20–30 °C) and achieved this high performance without needing elevated temperature. Similar efficiency has been reported in other pilot air strippers operating at 16–28 °C with adequate airflow.

Table 1:

2023 Pilot VOC and TPH Removal by DSU Air Stripper (values in mg/L)

Parameter	Influent (Before Stripper)	Effluent (After Stripper)	Removal Efficiency (%)
Benzene	12.8	0.52	95.9%
Toluene	27.6	1.01	96.3%

Ethylbenzene	1.12	0.03	97.3%
m&p-Xylenes	12.0	0.373	96.9%
o-Xylene	2.69	0.134	95.0%
Gasoline Range Organics (GRO)	58.6	3.58	93.9%
Diesel Range Organics (DRO)	7.47	5.64	24.5%
Total Petroleum Hydrocarbons (TPH, C6–C40)	70.0	15.0	78.6%

As shown in **Table 1**, lighter hydrocarbons (BTEX and GRO) were removed very efficiently by the air stripper, whereas heavier fractions like diesel-range (C10–C28) saw relatively low removal (only ~25% of DRO was stripped) and some heavy oil range (C28–C40) remained essentially unchanged (not shown in table, but C28+ oil was ~0.7 mg/L in both influent and effluent). This outcome is expected: the stripping process is governed by volatility. Compounds with high vapor pressure and Henry's constant (such as BTEX) transfer readily from water to air, while less volatile, long-chain hydrocarbons do not. In fact, the presence of these heavy hydrocarbons often controls the design capacity of an air stripper – if significant TPH includes semi-volatile or non-volatile components, stripping alone cannot meet ultra-low oil & grease limits. The pilots addressed this by incorporating a clarification step to remove the heavy fraction. In the **2018 Pilot**, a clarifier followed by UF brought the final oil & grease in effluent to <2 mg/L consistently. In the **2023 Pilot**, even though a clarifier was not physically run, it was observed that the stripped water often had fine oil droplets and precipitated iron that would need removal. The pilot findings confirmed that this clarification step will serve as the control point for paraffin waxes and any emulsified oils, preventing them from reaching downstream membranes or discharge. Notably, the pilot team observed accumulation of waxy solids in some equipment (e.g. a thin film on hoses and a fan) after one day, underscoring the need to manage these via heated lines or separation equipment.

<u>Iron and water quality</u> Iron is another important parameter. Initial total iron in the produced water was about 1–2 mg/L in pilots. The stripping process oxidized most Fe^{2+} to Fe^{3+}, but the iron was not removed until clarification/filtration. In the **2018 Pilot**, the combination of stripping (oxidation) and subsequent clarification/UF consistently achieved <0.3 mg/L dissolved iron in the UF permeate. The **2023 Pilot** DSU by itself did not reduce dissolved iron to that level (stripper effluent still ~1.17 mg/L Fe), because the iron precipitate remained in suspension without a clarifier. However, the pilot qualitatively confirmed that the oxidized iron would settle given time or with coalescence. Therefore, the full-scale design will integrate the clarifier to achieve the same iron goal of <0.3 mg/L. Turbidity in the **2018 Pilot** effluent was likewise kept <1 NTU through the UF step, ensuring the water was clear and suitable for final desalination. While turbidity data from the **2023 Pilot** are not explicitly reported, visual observation indicated that without filtration the stripper effluent had some haze due to fine solids, reinforcing the need for the UF or other filtration step in the full process.

In summary, the pilots demonstrated that a multi-stage treatment train can reliably produce treated water meeting stringent quality targets without chemical coagulants. The air stripper removes the bulk of VOCs and some COD, the clarifier/filters remove particulate, heavy hydrocarbons and iron flocs, and an optional polishing (such as reverse osmosis or EDR for salts, if needed) can follow. This aligns with industry practices where air stripping is often used as a front-end process for VOC-laden waters, provided the stripped air is managed properly. It is worth noting that alternative VOC removal methods (activated carbon adsorption, advanced oxidation, etc.) were considered, but air stripping proved advantageous for produced water because of its effectiveness and low operating cost (the pilot measured only ~0.086 kW/bbl energy for stripping). Energy efficiency stems from not having to heat the water significantly and leveraging the inherent volatility of contaminants.

OFF-GAS TREATMENT: RTO PERFORMANCE AND FUEL INDEPENDENCE - A critical aspect of the integrated system is controlling air emissions from stripping. The pilots approached this with an RTO to destroy the volatilized hydrocarbons. The concept, validated in both pilots, is that the concentration of VOC in the stripper off-gas can be sufficient to fuel the RTO without the need for auxiliary natural gas or propane, once the unit is up to temperature. This “fuel independence” is highly desirable as it minimizes operating cost and avoids adding greenhouse gas emissions beyond what is inherent in the removed VOCs.

During the **2023 VOC Stripper Emissions Test** , the DSU stripper’s off-gas was found to contain approximately 1,500– 2,100 ppm (as propane) of total hydrocarbons at steady state, with initial peaks up to ~4,000 ppm C_3 observed at startup. These concentrations correspond to roughly 5–8% of the Lower Explosive Limit (LEL) for typical hydrocarbon mixtures. According to the RTO vendor, a concentration of only ~3% of the LEL is generally sufficient for an RTO to self-sustain (i.e. the exothermic oxidation of VOCs provides enough heat to maintain chamber temperature). In the pilot, once the stripper was producing ~1500+ ppm C_3, the RTO was indeed able to go into “self-sustain” mode, where its main burner shut off and the unit operated on the energy content of the inlet VOCs. The RTO maintained its combustion chamber around ~815°C (1500°F), which is a typical operating temperature for high VOC destruction efficiency. Even as the VOC levels fluctuated (e.g. dropping towards 1500 ppm at times when flow conditions changed), the RTO cycled in and out of burner assist, indicating that in a full-scale continuous operation the burner would rarely need to fire except perhaps during low-loading periods or startup/shutdown.

DESTRUCTION EFFICIENCY **-** The pilot RTO achieved measured destruction removal efficiency (DRE) in the range of 92–95% during the test runs. The outlet of the RTO had residual hydrocarbon readings only in the low tens of ppm. The slightly lower DRE observed (compared to typical full-scale units that guarantee 98– 99% DRE) was attributed to the small scale and short retention of the pilot unit and the fact it was not always in steady state “lean VOC” mode. Importantly, the collected data allowed engineers to size a full- scale RTO that will ensure >98% VOC destruction consistently. Modern full-scale RTOs are designed with ~95-97% thermal energy recovery and can routinely achieve 99%+ destruction of VOCs when properly sized and maintained (Anguil 2025). The planned RTO for Wind River Basin produced water will incorporate sufficient heat recovery media and residence time to hit these marks.

One practical insight from the pilot emissions was the handling of transient VOC spikes and heavy organics in the off-gas. Upon cold start, a burst of VOC (~4000 ppm C_3) was noted; while still only ~15% of LEL, it momentarily exceeded the FID's calibration range. The operators recommended installing LEL monitors and an automatic bypass damper on the full-scale RTO inlet to divert flow if a spike approaches flammable limits a standard safety measure per NFPA guidelines. Additionally, the appearance of condensed paraffin wax on the RTO inlet duct and fan after one day suggested that condensation or fouling controls are needed. In the full-scale system, this may be mitigated by using an induced-draft fan configuration (pulling the hot RTO exhaust through the system so that the inlet stays under slight vacuum and hotter) or by pre-heating the inlet duct to keep heavy hydrocarbons from condensing. The design phase is evaluating these options so that long-chain hydrocarbons stripped from the water do not plate out in the oxidizer system. It is notable that such heavy compounds were only a minor component of the Wind River Basin gas (~0.65 mg/L of C28+ oil range in water, **Table 1**), but even a small absolute amount can accumulate over time when air flow rates are large. Technologies like thermal oxidizers are generally robust to VOC variety, but careful engineering is required for streams with condensable organics (Anguil 2025).

Overall, the pilots confirmed that capturing and incinerating stripped VOCs is both feasible and effective. The "zero supplemental fuel" operation of the RTO was achieved, validating a key cost assumption. This finding is consistent with vendor reports that RTOs can maintain self-sustaining combustion at surprisingly low VOC concentrations (on the order of a few grams per cubic meter, or a few thousand ppm). In this case, the produced water's VOC load is sufficient to not only eliminate its own emissions but also to reduce fuel costs for the treatment system. This contrasts with alternative emission controls like activated carbon, which would have ongoing media replacement costs and potentially lower removal efficiency for very volatile compounds. The destruction of VOCs to CO_2 and H_2O in the RTO also minimizes any environmental impact from the stripping process, ensuring compliance with air quality regulations.

METHANOL BIOREMEDIATION: BRAT UNIT PERFORMANCE - Methanol was identified as a significant dissolved organic in Wind River Basin produced water, reportedly due to its use as an anti-freeze agent in gas production and processing. In the **2023 Pilot**, influent methanol concentrations varied but were on the order of 50–150 mg/L in the water. The **2018 Pilot** did not specifically target methanol (and any present was likely handled incidentally by the biological/UV process or simply passed through). By 2023, however, Company needed to ensure methanol would not be released at levels that could exert high biochemical oxygen demand (BOD) in the receiving waters. Methanol is a fully miscible, low-volatility compound (Henry's constant is very low), so air stripping only partially removes it. Indeed, the **2023 Pilot** showed the DSU stripper incidentally stripped some methanol (e.g. ~59% removal, from 46 mg/L down to 19 mg/L in one test), but the remainder required a different approach.

> <u>BRAT Process Concept</u> The Biological Regenerative Adsorptive Treatment (BRAT) system was tested to biologically destroy methanol. In wastewater engineering, methanol is well-known as a readily biodegradable carbon source, commonly added to

treatment plants to drive denitrification reactions. Here, we inverted that practice: adding nitrate so that indigenous or seeded microbes consume the methanol. The BRAT unit is essentially a biofilter or bioreactor where microbes grow on media and continuously convert nitrate to nitrogen gas using methanol as the electron donor. The "regenerative adsorptive" aspect refers to the media adsorbing some organics and retaining biomass, while regeneration occurs as the biomass consumes those organics. In theory, if nitrate is abundant and competing substrates are minimal, the bacteria will consume virtually all methanol to depletion, achieving effluent concentrations below detection (<0.5 mg/L). Methanol's biodegradability is extremely high – it yields low residual biomass and is often the preferred substrate for heterotrophs if no other carbon sources are present.

Pilot Findings In the **2023 Pilot** BRAT trial, there were challenges that prevented achieving the hoped-for non-detect effluent. The test was conducted outdoors in late September; ambient temperatures were low (near 5–10°C at night), and despite insulation, the bioreactor temperature dropped below optimal range for the denitrifying bacteria (who prefer >20°C). Additionally, because the full pretreatment train was not in operation, the water fed to the BRAT still contained other soluble organics (residual hydrocarbons, possibly some organic acids, etc.) contributing to COD. The DSU stripper removed a "considerable amount" of VOCs and some organics, but not all; hence the BRAT influent had competing carbon sources beyond methanol. The unintended result was that the bacteria in BRAT consumed not just methanol but also other organics, and they ran out of nitrate before all methanol could be degraded – i.e. methanol was not truly rate-limiting under those conditions. Consequently, after a period of operation, methanol dropped only partially. The pilot data showed a decrease from ~159 mg/L to 114 mg/L methanol in the BRAT effluent in one trial run. This ~28% reduction was well short of the target, but it was attributed to the above factors (cold temperatures slowing microbial activity, and excess COD from non-methanol sources consuming the nitrate).

Despite the limited quantitative success in the field trial, the pilot provided valuable lessons to refine the approach.

Biological Methanol Removal Pilot testing confirmed biological culture was viable and did begin to consume methanol (evidence of nitrate uptake and nitrogen gas production was observed). There was no accumulation of nitrite, indicating the denitrification pathway was proceeding as expected when resources allowed. This validates the fundamental science that methanol can be bioremediated in produced water given suitable conditions, echoing the widespread use of methanol in engineered denitrification where it is nearly completely consumed by microbes.

Feed Conditioning Pilot testing also highlighted the importance of feed conditioning for the BRAT. The full-scale design will feed the BRAT unit with a treated water that has already had the bulk of other organics removed – notably, the plan is to take the permeate of a reverse osmosis (RO) or similar polishing step as the influent to BRAT. In full operation, upstream processes (stripping, clarification, possibly an RO targeting salts) would remove most hydrocarbons and higher-chain organics, leaving methanol as the primary remaining carbon. This ensures that in the BRAT, methanol will indeed be the limiting substrate and will be fully consumed (any residual trace organics would be insufficient to outcompete methanol for the added nitrate). The pilot's mistake was feeding BRAT with DSU effluent directly, which still had appreciable COD from other sources (measured COD was ~900 mg/L after DSU, only slightly down from ~970 mg/L before).

<u>Process Controls</u> Temperature control is critical. The BRAT reactor needs to be in a controlled environment (heated enclosure or tank heating) to maintain microbial efficiency. During the cold outdoor pilot, the bacteria's metabolism likely slowed dramatically, which alone could account for much lower removal. Studies published on denitrification show that each 10°C drop can reduce the reaction rate by roughly half or more, depending on the microbial community (Metcalf & Eddy 2014). Thus, what might achieve complete methanol removal in 4–6 hours at 25°C could require several days at <10°C – far beyond the pilot contact time. The full-scale system will mitigate this by insulation and possibly maintaining a warm internal environment for the bioreactor year-round.

<u>Biological Startup</u> Proper seeding and acclimation time must be allowed. The pilot used biomass from a municipal plant, which was a good starting point, but the culture may need adaptation to high salinity conditions of produced water and to methanol-rich feed. Given more run time, the microbial community could acclimate to preferentially consume methanol. In fact, the vendor anticipates that a full-scale BRAT with an appropriate culture will have faster kinetics favoring methanol over any residual organics. The pilot's truncated schedule (with weather interference) did not allow optimization of the culture. Future pilot trials will aim to demonstrate the BRAT performance conclusively.

From a literature standpoint, methanol is one of the easiest organic compounds to biodegrade. Numerous wastewater facilities intentionally dose methanol and achieve > 95% removal in their anoxic filters or reactors, often yielding effluent methanol below detection (< 0.1 mg/L) (Methanol 2020) . The key is ensuring the process is electron-acceptor limited rather than carbon-limited (exactly as the BRAT concept does by adding excess nitrate). Given that over 200 treatment plants successfully use methanol-fed denitrification in the U.S., there is high confidence that a properly engineered BRAT unit can reduce methanol in produced water to environmentally benign levels. The pilot's result of only partial removal is viewed not as a failure of the concept but as a lesson in proper integration and controls. The forthcoming full-scale system will incorporate these lessons by placing BRAT downstream of RO (to minimize competing COD) and by controlling temperature and retention time.

OPERATIONAL OUTCOMES AND FULL-SCALE IMPLEMENTATION CONSIDERATIONS

Each pilot study provided insights that are influencing the full-scale Wind River Basin produced water treatment design. Key operational outcomes and decisions include:

VALIDATED VOC/TPH REMOVAL STRATEGY - The pilots confirmed that a two-stage air stripping process can achieve the necessary reduction in volatile hydrocarbons without chemical additions. The first stage significantly knocks down VOC levels and oxidizes iron; additional stages (as planned in full- scale) will further ensure minimal VOC carryover. The full-scale design is considering two venturi stages in series to maximize removal (the **2018 Pilot** already used staged stripping). This is bolstered by literature suggesting multi-stage (counter-current) stripping can approach > 99% BTEX removal. The outcome is that the Company will proceed with air stripping as the core pretreatment for organics, instead of alternatives like advanced oxidation or carbon adsorption, due to its efficiency and cost-effectiveness demonstrated (operating cost projected ~$0.006 per barrel for stripping in **2018 Pilot**).

RTO SIZING AND INTEGRATION **-** The RTO will be included in the full-scale system to manage air emissions. Thanks to the FID test, engineers now have concrete data on flow (~100–150 SCFM per 20 gpm of water) and VOC content (~0.2–0.3 lb VOC per 1000 gal, estimated from ppm readings) of the stripper off-gas. This allows accurate sizing of burners, heat recovery media, and chamber volume to guarantee >98% destruction. Operationally, the RTO will be equipped with safety controls (LEL monitors, automatic dampers) to handle any sudden surges. The pilot's demonstration of self-sustain mode means the full-scale RTO will likely consume negligible auxiliary fuel during normal operation, using the VOC load as its fuel. This dramatically lowers operational carbon footprint and cost. Economic analysis shows essentially only a pilot flame cost for RTO during steady state, contributing mere ~$0.001 per barrel to treatment cost. By comparison, if the VOC were low and supplemental fuel needed, costs would rise and reliability could suffer. Thus, the ability to run fuel-free is a significant win. Additionally, the RTO provides a level of future- proofing: if regulations tighten or if other VOCs (like hydrogen sulfide, which was low in Wind River Basin water) become concerns, the RTO can destroy them as well. The only operational caveat is maintenance of the heat exchanger media if any fouling occurs; the design might include an online bake-out or easy media replacement, informed by the minor paraffin fouling noted in pilot.

SOLIDS AND FOULING MANAGEMENT **-** The importance of robust solids removal and biological control was evident. The **2018 Pilot** experienced rapid biological growth (biofilm) in the system due to warm water with organics, requiring periodic cleaning of the UF and use of UV/O_3 to keep microbes in check. In scaling up, the team plans to incorporate a side-stream or recycle of treated water with residual ozone or chloride (from EDR) to suppress biological growth in the front-end – essentially maintaining a low-biological-activity condition throughout pretreatment. Ozone/UV will likely be installed after the stripper in full-scale as an added barrier for any bacteria and to oxidize any residual dissolved organics that could cause biofouling downstream. The pilots confirmed that ozone/UV provided >99% microbial kill in the water, so this step will be retained to ensure the UF or RO membranes do not bio-foul and that discharge water meets bacterial limits. In terms of oil/ solids, the clarifier in full-scale is being designed with an integrated oil skimmer and sludge withdrawal. The pilot results (especially the need to remove paraffins and the observation that clarifier underflow would contain the majority of solids/oil) guides the sizing of that clarifier and the expected sludge production. Company estimates from pilot mass balances that sludge will be < 0.05% of treated volume, and handling as either non-hazardous oilfield waste or potentially fuel source (if it has significant BTU content) will be decided. The Utopia cost analysis assumed a worst-case of treating sludge as hazardous waste at $150/ton, which contributed ~$0.024/bbl; efforts will be made to minimize such costs by dewatering and characterizing sludge properly.

INTEGRATION WITH DESALINATION **-** Both pilots were ultimately aimed at enabling downstream desalination (RO/EDR) to function better and produce discharge-quality water. By removing organic contaminants and reducing turbidity/iron, the pilots showed that the RO membranes will have a much lower fouling tendency. The **2018 Pilot**'s UF filtrate consistently met the RO feed criteria (turbidity <1 NTU, TSS <1 mg/L). Furthermore, stripping out CO_2 raised the pH from ~7.2 to ~8.4, which in turn reduces the dosing of acid needed for scaling control in RO and lowers corrosivity. The pilots thus suggest that the full-scale system can likely operate the RO at higher recovery or with less chemical adjustment, thanks to the upstream VOC stripping and degassing. The presence of methanol and its removal is also relevant to discharge permits (methanol itself might not be explicitly regulated, but its oxygen demand is). Ensuring methanol is non-detect will help in meeting effluent BOD limits and preventing any toxicity to aquatic life (though methanol is not particularly toxic, high concentrations could affect dissolved oxygen in the creek). With the planned BRAT unit treating RO permeate, the final effluent is expected to have BOD5 and COD near background levels, essentially addressing any concern of oxygen depletion in the receiving environment.

ECONOMIC AND ENVIRONMENTAL IMPACT **-** The integrated pilot results allowed a refined cost model for full-scale. The projected operating cost for the pretreatment + desalination system is on the order of $0.18 per barrel of water (including power, chemicals for membrane cleaning, labor, and sludge disposal). This cost is competitive when compared to alternatives like deep well injection or extensive chemical treatment, and it delivers the benefit of surface discharge (augmenting local water resources). The fact that the system runs largely on "free" reagents (air for stripping, biologically supplied treatment for methanol, self-fueled RTO) means the incremental cost per barrel is low and mostly electricity. From an environmental standpoint, destroying the VOCs in an RTO converts them to CO_2; given that much of these VOCs (like light hydrocarbons) would likely volatilize eventually even if water were stored or handled, controlling them via thermal oxidation is a net positive for air quality (albeit with CO_2 emissions). The pilots also showed no use of hazardous chemicals except small amounts for membrane cleaning, aligning with a sustainability goal of chemical minimization. By proving out the "chemical-free" approach (air/ozone/UV/biological), the project avoids issues of handling large volumes of chemical additives on site.

In comparing the pilot efforts, it is clear that each addressed a crucial piece of the puzzle. The **2018 Pilot** provided confidence in water quality attainment and baseline design parameters, the **2023 Pilot** confirmed the VOC removal and off-gas treatment viability at field scale, and the FID test gave precise data to finalize RTO specs. Taken together, they de-risk the scale-up.

CONCLUSIONS

The series of pilot studies carried out for an energy Company's produced water treatment project have successfully validated a robust treatment scheme that can meet stringent discharge requirements. Key findings and conclusions include:

HIGH VOC AND BTEX REMOVAL - The venturi air stripping process consistently removed >95–98% of volatile hydrocarbons (BTEX/GRO) from the produced water, reducing VOC concentrations to only a few mg/L or less. This level of performance was achieved without chemical addition and is supported by literature benchmarks for air-stripping efficiency. The approach will effectively protect downstream units from organic fouling and ensure the effluent meets low hydrocarbon limits.

TPH MANAGEMENT - While the stripper removes some heavier hydrocarbons, it alone is insufficient for the highest molecular weight fraction. The pilots underscore the need for a clarification step to capture oils and waxes that are stripped out or remain suspended. The planned clarifier/OWS will serve this purpose, as indicated by pilot observations, and should be capable of delivering effluent oil & grease well below 5 mg/L, especially when followed by ultrafiltration as in the **2018 Pilot**.

IRON AND SOLIDS CONTROL - The integrated process of air oxidation and solid-liquid separation proved effective for iron removal to <0.3 mg/L and for producing low-turbidity water. This is critical for the success of the downstream desalination (EDR/RO). Pilot lessons on managing biological growth (via ozone/UV) will be applied to keep the system running smoothly with minimal membrane fouling.

RTO FUEL INDEPENDENCE AND VOC DESTRUCTION - The pilots demonstrated that the stripped VOCs can be destroyed in a regenerative thermal oxidizer without the need for continuous auxiliary fuel firing. The VOC energy content (on the order of 5–8% of LEL) is sufficient for auto-thermal RTO operation, which is corroborated by RTO industry data (self-sustain possible at ~3% LEL). Measured destruction efficiencies of 92–95% in the pilot indicate that a properly sized full-scale RTO will achieve >98% DRE, essentially eliminating organic emissions and odors. Operational considerations like LEL monitoring and mitigating any paraffin condensation will be incorporated into the design to ensure safety and reliability.

METHANOL BIOREMEDIATION FEASIBILITY - Although the BRAT denitrification unit did not reach non- detect levels in the short pilot run, it did achieve substantial methanol reduction and provided a proof-of-concept for biological removal of methanol. With adjustments (feeding post-RO permeate, maintaining optimum temperature, and ensuring nitrate is not exhausted), the BRAT process is expected to drive methanol to <0.5 mg/L, effectively eliminating this potential environmental pollutant. The use of methanol as a bacterial substrate is well-founded in wastewater treatment practice, and the pilot helps tailor that knowledge to produced water conditions. Additional testing in a controlled environment was recommended to fine-tune the kinetics, but no insurmountable obstacle was identified.

SCALABILITY AND DESIGN INTEGRATION - Data from the pilots have been translated into design criteria for the full-scale facility upgrade. Flows, concentrations, and removal rates observed will guide equipment sizing (e.g., air stripper dimensions, blower capacity, RTO volume, clarifier area, BRAT reactor volume). Importantly, the pilot program-built confidence among stakeholders (Company and regulators) that the proposed technology train can meet or exceed permit requirements. The pilots also provided training opportunities for operations staff and identified practical issues (like cold-weather operations and system controls) early in the project. By addressing these in design (for instance, heat tracing on critical lines, inclusion of backup systems, etc.), the full-scale implementation will be more robust.

In conclusion, the collaborative pilot testing program has validated the treatment technologies for Wind River Basin produced water and informed a comprehensive design that emphasizes sustainability (chemical-free operation, energy recovery), compliance (high removal efficiencies), and cost-effectiveness (low OPEX per barrel). The integrated removal of VOCs, TPH, iron, and methanol positions the Company to responsibly manage its produced water by converting a waste stream into water that can be safely discharged or reused. The knowledge gained extends beyond this project, contributing to the body of practice for treating complex oilfield wastewaters. Ongoing efforts will focus on minor optimizations and scaling up construction, with the confidence that the core processes are sound. Future work may include continuous monitoring of full-scale performance and possibly extending the biological treatment concept to other organics. The success of these pilots serves as a case study for the industry, demonstrating how a combination of air stripping, thermal oxidation, and biologically enhanced polishing can achieve environmental compliance in a challenging water matrix.

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