

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof. Reference herein to any social initiative (including but not limited to Diversity, Equity, and Inclusion (DEI); Community Benefits Plans (CBP); Justice 40; etc.) is made by the Author independent of any current requirement by the United States Government and does not constitute or imply endorsement, recommendation, or support by the United States Government or any agency thereof.

FINDINGS ON SUBTASK 3.3 – APPLICABILITY OF AUTOMATED BRINE CHEMISTRY DETERMINATIONS FOR TREATMENT AND RECOVERY PROCESSES THROUGH FACILITY AUTOMATION/MODULARIZATION: ENGINEERING DESIGN STUDY

Topical Report

(for the period of August 1, 2024, through May 31, 2025)

Prepared for:

AAD Document Control

National Energy Technology Laboratory
U.S. Department of Energy
626 Cochran's Mill Road
PO Box 10940, MS 921-107
Pittsburgh, PA 15236-0940

Cooperative Agreement No.: DE-FE0024233
DOE Technical Monitor: Robert Noll

Prepared by:

Marc D. Kurz
Christopher L. Martin
John A. Hamling

Energy & Environmental Research Center
University of North Dakota
15 North 23rd Street, Stop 9018
Grand Forks, ND 58202-9018

EERC DISCLAIMER

LEGAL NOTICE: This research report was prepared by the Energy & Environmental Research Center of the University of North Dakota (UND EERC) as an account of work sponsored by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) (SPONSOR). To the best of UND EERC's knowledge and belief, this report is true, complete, and accurate; however, because of the research nature of the work performed, neither UND EERC, nor any of their directors, officers, or employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the use of any information, apparatus, product, method, process, or similar item disclosed or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement or recommendation by UND EERC. SPONSOR understands and accepts that this research report and any associated deliverables are intended for a specific project. Any reuse, extensions, or modifications of the report or any associated deliverables by SPONSOR or others will be at such party's sole risk and without liability or legal exposure to UND EERC or to their directors, officers, and employees.

ACKNOWLEDGMENT

This material is based upon work supported by DOE NETL under Award No. DE-FE-0024233.

DOE DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

TABLE OF CONTENTS

LIST OF FIGURES	ii
LIST OF TABLES	iii
EXECUTIVE SUMMARY	iv
INTRODUCTION	1
BACKGROUND	1
OBJECTIVES	3
REVIEW OF TREATMENT-TESTING CAPABILITIES	3
PRODUCED WATER TEST PARAMETER REVIEW	4
Automated Brine Chemistry Determination	8
Producing Formation Composition Adjustment	10
High-Value Mineral Recovery	12
BTTF CURRENT CONFIGURATION	13
Description of Demonstration Facility	13
Current Status of Capabilities and Infrastructure	18
PRELIMINARY FACILITY DESIGN	19
Treatment Train Configuration	19
PW Blending.....	19
Pretreatment	20
Primary Treatment	21
Secondary Treatment	23
PW Chemistry Determination	23
System Automation and Data Acquisition	25
Preliminary Retrofit Project Cost Estimate	26
CONCLUSIONS.....	28
MILESTONES.....	29
REFERENCES	29
BEST DEMONSTRATION TEST SITE OVERVIEW	Appendix A
BTTF IMPROVEMENT REPORT	Appendix B

LIST OF FIGURES

1	Conceptual spectrum of PW treatment.....	5
2	High-level treatment train stages for the proposed BTTF retrofit	8
3	Stiff diagram comparison of average Permian and Bakken water compositions, and a calculated composition for Bakken water diluted to match the Permian's dissolved solids	11
4	Comparison of lithium concentration and the Mg:Li ratio for a sample of Permian PW and a sample from the BTTF E-1 extraction well	12
5	Brine treatment demonstration facility.....	14
6	Layout and electrical rating of test bed treatment facility.....	15
7	Various photos and angles of the treatment facility	16
8	SCADA system control area with multiple computer displays.....	17
9	Images of previous demonstration activities in the facility.....	18

LIST OF TABLES

1	Key Water Quality Contaminants for PW Treatment System Testing	6
2	Reviewed PW Treatment Technologies	7
3	Proposed Water Quality Categories for Expanded BTTF Testing.....	8
4	Review of Available Online PW Instrumentation.....	9
5	Comparison of Average PW Compositions	10
6	Reviewed Lithium Recovery Methods Applicable to PW	13
7	Proposed Schedule of Inline PW Instrumentation	24
8	Review of PW Grab Sample Analyses.....	25
9	Estimated Construction Costs for the BTTF Retrofit.....	27
10	Milestones	29

FINDINGS ON SUBTASK 3.3 – APPLICABILITY OF AUTOMATED BRINE CHEMISTRY DETERMINATIONS FOR TREATMENT AND RECOVERY PROCESSES THROUGH FACILITY AUTOMATION/MODULARIZATION: ENGINEERING DESIGN STUDY

EXECUTIVE SUMMARY

Under the Energy & Environmental Research Center's (EERC's) ~\$22 million Phase II Brine Extraction and Storage Test (BEST) Program, a multimillion-dollar brine treatment technology test bed facility was established in western North Dakota to provide a platform for evaluating developing technologies and approaches for brine treatment and volume reduction. The initial facility, and associated research effort, was funded by the U.S. Department of Energy (DOE), with in-kind contributions provided by several industry participants and the state of North Dakota. Since its opening, the Brine Technology Test Facility (BTTF) has supported performance evaluations of desalination technologies capable of treating high-salinity produced water (PW) and enabled data collection for multiple approaches of PW management and critical material recovery. As part of the decommissioning process for the original project, facility ownership and liability were transferred to Select Water, which is providing the EERC with a continuing site access option for state or federal research and/or commercial technology development. This report documents the findings from a design study conducted by the EERC and the engineering firm that was originally contracted to design and construct the facility (Advanced Engineering and Environmental Services, LLC [AE2S]) that evaluated the current status of BTTF and its systems and developed a retrofit design to increase the facility's capabilities through automation and modularization of its PW treatment infrastructure. The proposed retrofit will provide DOE and industry with an expanded range of conditioned PW that can be produced at the facility for evaluating fit-for-purpose water treatment technologies, online instrumentation for brine chemistry determination, and systems that recover critical materials like lithium and magnesium. The current facility consists of an 9600-square-foot facility that includes a 40-foot by 65-foot Class 1, Division 2-rated demonstration area and associated control rooms and lab-ready space capable of sourcing oil and gas PW and wastewater from industrial sources or tailoring brine compositions up to 300,000 mg/L total dissolved solids (TDS) and supplying them at rates up to 25 gpm for extended-duration technology demonstrations. The colocation of the facility with Select Water's water management facilities allows for access and unloading of more than 10,000 bbl/day of trucked water delivered to site and associated access to on-site Class I and Class II brine disposal wells and nearby hazardous waste landfills operated and/or contracted by Select Water to dispose of concentrate and/or effluents associated with the testing.

The proposed BTTF retrofit will allow on-site sources of Bakken PW, industry-sourced wastewater, extracted saline formation water, and freshwater to be automatically blended to suit desired test conditions, including blending surrogates for PW from other unconventional plays, particularly the Permian in West Texas and eastern New Mexico. The retrofit treatment train employs a cascaded design of treatment modules that can be used to meet the requirements of virtually any PW reuse application, including hydraulic fracturing, enhanced oil recovery, nonenergy applications such as chemical production, and potential alternate water supply scenarios like surface water discharge or groundwater recharge. Online measurements of process chemistry

were included at multiple points within the design for parameters with real-time or near-real-time monitoring potential. Process parameters that are not currently amenable to online measurement are proposed to be monitored via grab sample analysis using techniques that could be performed on-site to minimize data turnaround time. The modular design of the proposed treatment train retrofit will be highly reconfigurable by having the ability to individually add or bypass each unit and by having each unit able to discharge to virtually any other point in the entire train. With this design, individual BTTF units can be swapped out and replaced with test systems. Likewise, test instrumentation can be installed at virtually any point of the operating BTTF system for evaluation. Based on feedback from representatives at DOE and the National Energy Technology Laboratory, the planned flow range for the BTTF retrofit will be 1 to 5 gallons per minute, or approximately 40 to 170 bbl/day of conditioned PW for testing.

Adapting the BTTF to accommodate evolving PW treatment testing needs is believed to be more cost-effective than establishing a new facility with equivalent capabilities elsewhere given the existing permitted infrastructure that is in place. During the site assessment, the BTTF building and fixed infrastructure were determined to be in good condition, including exterior and interior brine-holding tanks and related piping. A Class 3-level (i.e., -20% to +30%) construction budgetary estimate for the as-described BTTF retrofit is approximately \$5,000,000, which includes conservative assumptions to account for potential price increases prior to starting a retrofit project. The estimate also includes the prerequisite detailed design effort and associated labor needed to finalize design requirements, and that will include full equipment specifications, bill of materials, and price quotations for the to-be-configured equipment and/or systems, as well as EERC project management and oversight and system shakedown testing upon completion. The EERC management will include oversight of design and construction activities with the engineering subcontractor and interfacing with DOE project/program management and site owner, Select Water, to ensure system modifications are completed in an efficient and timely manner.

This project was funded through the EERC–DOE Joint Program on Research and Development for Fossil Energy-Related Resources Cooperative Agreement No. DE-FE0024233.

FINDINGS ON SUBTASK 3.3 – APPLICABILITY OF AUTOMATED BRINE CHEMISTRY DETERMINATIONS FOR TREATMENT AND RECOVERY PROCESSES THROUGH FACILITY AUTOMATION/MODULARIZATION: ENGINEERING DESIGN STUDY

INTRODUCTION

Under the Energy & Environmental Research Center's (EERC's) ~\$22 million Phase II Brine Extraction and Storage Test (BEST) Program, a multimillion dollar brine treatment technology test bed facility was established in western North Dakota to provide a platform for evaluating developing technologies and approaches for brine treatment and volume reduction. The brine technology development and test facility was built through the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) BEST Program, is managed by the EERC, and is located at a Select Water-operated saltwater disposal (SWD) host site where it is integrated with commercial wastewater-handling offload, management, and disposal infrastructure. Since its opening, the Brine Technology Test Facility (BTTF) has supported performance evaluations of desalination technologies capable of treating high-salinity produced water (PW) and enabled data collection for multiple approaches to PW management and critical material recovery. As part of the decommissioning process for the original project, facility ownership and liability were transferred to Select Water, which is providing the EERC with a continuing site access option for state or federal research and/or commercial technology development. The current facility consists of a 9600-square-foot facility that includes a 40-foot by 65-foot Class 1, Division 2-rated demonstration area and associated control rooms and lab-ready space capable of sourcing oil and gas produced water and wastewater from industrial sources or tailoring brine compositions up to 300,000 mg/L total dissolved solids (TDS) and supplying them at rates up to 25 gpm for extended-duration technology demonstrations. The colocation of the facility with Select Water's water management facilities allows for access and unloading of more than 10,000 bbl/day of trucked water delivered to site and associated access to on-site Class I and Class II brine disposal wells and nearby hazardous waste landfills operated and/or contracted by Select Water to dispose of concentrate and/or effluents associated with the testing.

This project comprised three activities: Activity 1, project management and reporting; Activity 2, idling of the treatment facility; and Activity 3, a design study to retrofit BTTF for automated modular control. Activities 1 and 2 were executed according to plan as reported in prior progress reports. This report documents the findings from Activity 3, which evaluated the current status of BTTF and developed an enhanced retrofit design. The study includes recommended replacement systems to keep the facility functioning along with options to enhance its capabilities based on automation, modularization, and online chemistry determination to support future testing of cascaded treatment systems and high-value product and critical mineral recovery.

BACKGROUND

The United States is the world's largest producer of crude oil and natural gas, with more than 60% of its crude oil and natural gas coming from unconventional, low-permeability

formations (U.S. Energy Information Administration, 2025a, b). Furthermore, projections show that these unconventional resources will continue to be the dominant source of U.S. production for the foreseeable future (U.S. Energy Information Administration, 2025c). Given the importance of these resources, improved methods of PW management are being sought to ensure that unconventional oil and gas can continue to be produced in an economical and environmentally responsible manner.

Compared to conventional oil production, unconventional production presents different challenges with respect to PW management, primarily due to the fact that the water cannot typically be reinjected into the producing formation. Instead, unconventional PW must be managed differently, through disposal or reuse (Scanlon et al., 2020a). The most common method for PW management has been disposal using deep well injection into a permeable, nonproducing formation. This practice is generally cost-effective; however, in some of the most prolific unconventional plays, e.g., the Permian, Bakken, and Woodford, among others, subsurface injection has led to other management issues including the pressurization of overlying formations and induced seismicity (Energy & Environmental Research Center, 2024; Hennings and Smye, 2024; Walsh and Zoback, 2015). PW treatment is one management alternative that could lead to reductions in subsurface injection by increasing the proportion of PW diverted for reuse.

An additional driver for PW treatment is to extract value from its resource potential. PW resources are considered to be a potential domestic source of critical energy materials (CEMs), particularly lithium and magnesium (Smith et al., 2024). The potential economic value of recovered salable materials from PW, like CEMs, could be a complementary incentive for PW disposal reduction since it may offset some of the increased costs that are expected for treatment-based PW management versus a disposal-only model (Able et al., 2025).

A wide variety of reuse options for PW have been proposed that will require the development and validation of adaptable PW treatment technologies to meet reuse-specific requirements (Scanlon et al., 2020b). Potential PW reuse opportunities include recycling the water for hydraulic fracturing, using it as a feedstock (e.g., for CEM recovery or other chemical production), and purifying it to the point that it could be used for irrigation, discharged into surface waters, or injected for groundwater recharge (Scanlon et al., 2020b). Each reuse application will set the required level of PW treatment, from basic solids and oil separation to altering its dissolved solids composition using advanced ion exchange or membrane processes. Given the complexity of most PW compositions, multiple treatment steps, likely in the form of cascaded treatment trains, will be required for all but the most basic levels of primary treatment (Nath et al., 2023; Conrad et al., 2020). The division of treatment into interoperable modules has been proposed for PW treatment as a way to build customized treatment trains that are tailored to the specific PW composition and the reuse treatment objectives (Conrad et al., 2020).

Another factor in developing PW treatment technology is the distributed and dynamic nature of water production and its impact on treatment system deployment. U.S. unconventional PW originates at over 200,000 oil and gas wells that are spaced across thousands of square miles within each shale play (Ground Water Protection Council, 2023). Therefore, it is expected that the PW treatment systems themselves could be distributed at well pads or at local aggregation sites and be sized accordingly, thereby limiting the economy of scale that these systems can leverage and

placing a premium on low-cost operation (Cole et al., 2022). Furthermore, the flow of PW from an unconventional well is dynamic and changes over the course of its producing lifetime. The PW production rate of an individual unconventional well is characterized by a steep decline relative to its initial production rate, and this decline is accompanied by a change in composition as fracturing flowback constituents are flushed out and the proportion of natural formation water increases.

Treatment system automation is considered an important feature for addressing frequent process changes at distributed sites where operator supervision is limited. For example, some of today's commercial offerings for transporting and blending PW into hydraulic fracturing fluids already highlight the value of automation in reducing cost (Tetra Automation and Monitoring, 2025; Select Water AquaView, 2025). These examples appear to be based on currently available online instrumentation such as oil-in-water and conductivity sensors, among others. However, as PW reuse expands to other applications, treatment requirements may become more sophisticated, which may necessitate the parallel development of advanced PW instrumentation and control systems alongside the treatment technologies themselves.

OBJECTIVES

The goal of this subtask was to evaluate the potential for the automation/modularization and online chemistry determinations to adapt BTTF in Watford City, North Dakota, to explore innovative approaches to brine treatment technology cascading and the incorporation of high-value product and mineral recovery. Specific objectives included the following:

- Assess current capabilities, and design a conceptual retrofitting process to convert the facility infrastructure to include automated process and salinity outlet control and automated pretreatment and technology cascade capability.
- Assess pretreatment capabilities, and provide an enhanced design through recommending replacement of aging components and/or addition of brine-conditioning stages.
- Assess multiple technologies for possible inclusion in the modular treatment system, and consider an anticipated cascade approach, such as ion exchange resins, nanofiltration (NF), reverse osmosis (RO), membrane distillation, and various other applicable technologies.
- Assess add-on technology options for recovery of high-value minerals and products from concentrated brine streams.

REVIEW OF TREATMENT-TESTING CAPABILITIES

Proposed retrofits to BTTF are intended to make it more adaptable to testing and validating the performance of a wide range of PW treatment modules and/or process chemistry instrumentation within a cascaded PW treatment system. The original BTTF design included key features such as PW blending and pretreatment unit operations that could produce a stabilized

brine with a selectable TDS concentration for treatment technology testing. However, there were limited options to insert test systems into the existing PW-conditioning system, and virtually no capability to generate conditioned water for test systems that required a higher level of pretreatment. As part of this study, several test capabilities have been identified as being useful for increasing the adaptability of BTTF to address the development and validation needs of advanced PW treatment systems.

- Expand BTTF's PW-conditioning options so that water can be generated to meet the requirements of virtually any PW reuse application. Include advanced process chemistry instrumentation where feasible to generate added information from testing.
- Include a greater number of treatment subdivisions in BTTF's treatment train to allow testing with PW after varying levels of pretreatment. In this more adaptable configuration, individual stages within the cascaded treatment train could then be swapped out and replaced with test systems. For instrumentation tests, test devices could be incorporated at virtually any point within BTTF's treatment system for evaluation.
- Enhance BTTF's PW-blending system to generate PW surrogates for key unconventional plays, particularly the Permian. The Bakken PW available at BTTF is generally more concentrated with dissolved solids than most other unconventional plays in the country, and when diluted, it can be a close approximation of the bulk composition of PW found elsewhere. This similarity can be further enhanced with injection of key species that are important to the evaluation and could include CEM content or target contaminants. BTTF will retain the ability to test with PW transported from other plays via bulk containers or tanker truck.
- Automate the treatment train to allow control system testing, e.g., evaluate feedback control using novel PW chemistry instrumentation, and to allow the evaluation of non-steady-state conditions, e.g., simulate the impact of PW composition change or an upstream module failure. Such tests can be used to improve the operation of treatment systems to further their commercial readiness.

PRODUCED WATER TEST PARAMETER REVIEW

A generalized spectrum of PW treatment is shown in Figure 1; it begins with raw PW at the bottom and extends to clean, desalinated water at the top. The figure is not intended to represent any specific treatment configuration; instead, it is intended to illustrate the many intermediate stages of water quality that may be suitable for certain reuse applications, some of which are noted in the figure. The original BTTF provided essentially a single level of PW conditioning for testing; it roughly corresponded to the "stabilized" category in Figure 1. However, advanced PW treatment systems may target contaminants across the broader spectrum of treatment shown in Figure 1. As such, the BTTF design study looked at expanding test capabilities to emulate a cascaded treatment system by providing multiple levels of PW conditioning.

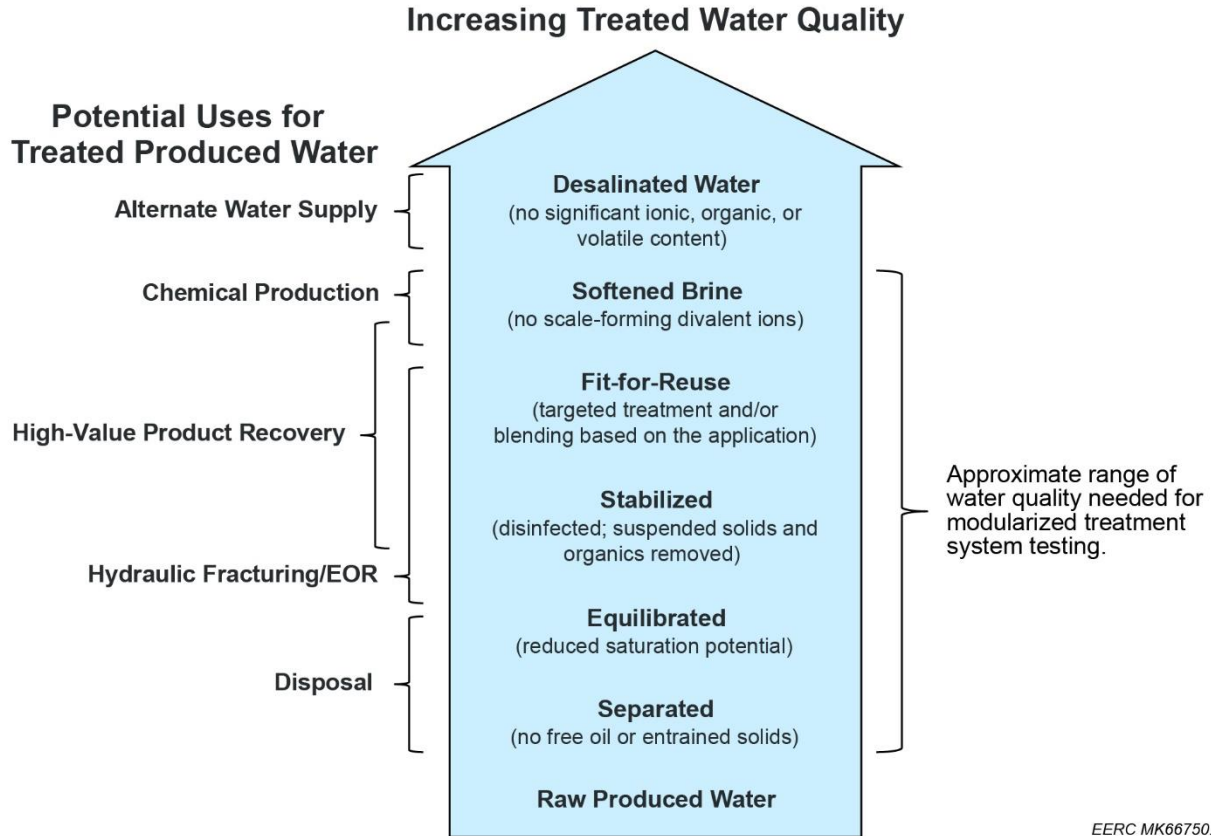


Figure 1. Conceptual spectrum of PW treatment.

Several review articles regarding PW treatment technologies (Nath et al., 2023; Conrad et al., 2020; Abdelhamid, et al., 2025; Amakiri et al., 2022; Ghafoori et al., 2022; Khatoon et al., 2023) were consulted as a way to survey the PW-conditioning capabilities that would be useful for BTTF to incorporate. While the actual composition of PW is complex, for this evaluation the contaminant categories targeted by treatment systems were reduced to the ten shown in Table 1. Reviewed technologies are summarized in Table 2, which shows the contaminants they target and the key sensitivities of each. These sensitivities provide an indication of where the technology might fit within a cascaded treatment train. For example, surface fouling is a common sensitivity, meaning that the active surfaces of these technologies are likely to be plugged or blocked by oil or solids and rendered ineffective. Such technologies would then best be applied to, or tested with, PW that has been conditioned to remove these foulants. Another common sensitivity is from inorganic scale formation, which is a frequent concern when PW is concentrated as in desalination or when the water equilibrates with atmospheric carbon dioxide that can react with divalent cations to form scale. Those technologies identified as having “minimal” sensitivity are

Table 1. Key Water Quality Contaminants for PW Treatment System Testing

Contaminant	Description
Emulsified Oil	Droplets of free oil that remain suspended in the aqueous phase.
Unstable Precipitates	Dissolved species that become supersaturated after the water is produced, due to temperature or pressure changes, exposure to atmospheric oxygen, etc. Examples include compounds of iron, manganese, carbonate, and sulfate.
Suspended Solids	Solids native to the PW or those that form during the precipitation of unstable compounds. By definition, they are captured by a 2- μ m filter.
Colloidal Solids	Suspended solids that pass through a 2- μ m filter for this classification. Can be native materials or precipitates that form during stabilization or during some treatments like desalination.
Microbes	Microscopic organisms that can proliferate in PW. Bacteria are the most consequential constituent since they have the ability to oxidize (e.g., Fe and Mn) or reduce (e.g., SO ₄) dissolved solids that can lead to fouling, corrosion, and other issues.
Dispersed Organics	Organic compounds associated with the aqueous phase but not limited to those that are water-soluble. This classification includes regulated organics like benzene, toluene, ethylbenzene, and xylene (BTEX) and polycyclic aromatic hydrocarbons (PAHs) and may also include residual hydraulic fracturing chemicals.
Volatiles	Nonwater species that can volatilize from PW under heating and/or vacuum. Typically includes some portion of dissolved organics and possibly ammonia. Particularly a concern for evaporation-based water treatment.
Heavy Metals	Dissolved ions, mostly metals, characterized by their negative impact on PW disposal or reuse. This classification includes the Resource Conservation and Recovery Act (RCRA) metals and radioactive elements and some nonmetals such as boron that impair specific reuse options.
Divalent Cations	Dissolved Ca, Mg, Sr, and Ba that could lead to scale formation if the PW composition is altered during treatment, e.g., by mixing with a carbonate-rich water or from the formation of hydroxide ions during electrolytic treatment.
Chloride Salts	Monovalent chloride salts that are highly soluble and have limited scale-forming potential. Typically a major component of the dissolved solids in PW.

generally pretreatment systems that are sufficiently robust to process raw PW. Generally, the listing in Table 2 assumes that the sensitivity for any particular technology includes all or most of the sensitivities listed above it. For example, reverse osmosis (RO) membranes are particularly sensitive to inorganic scaling since they are used for desalination; however, they are also sensitive to surface fouling from oil, solids, organic compounds, and biofilms.

Based on the high-level review in Table 2, four discrete levels of PW conditioning were identified based on common foulants and sensitivities among the reviewed technologies. These four levels are described in Table 3, which refers to the high-level treatment cascade diagrammed in Figure 2. The treatment train in Figure 2 is not intended to be prescriptive; instead, it shows the minimum proposed level of system segregation that allows for testing the widest range of modular treatment technologies.

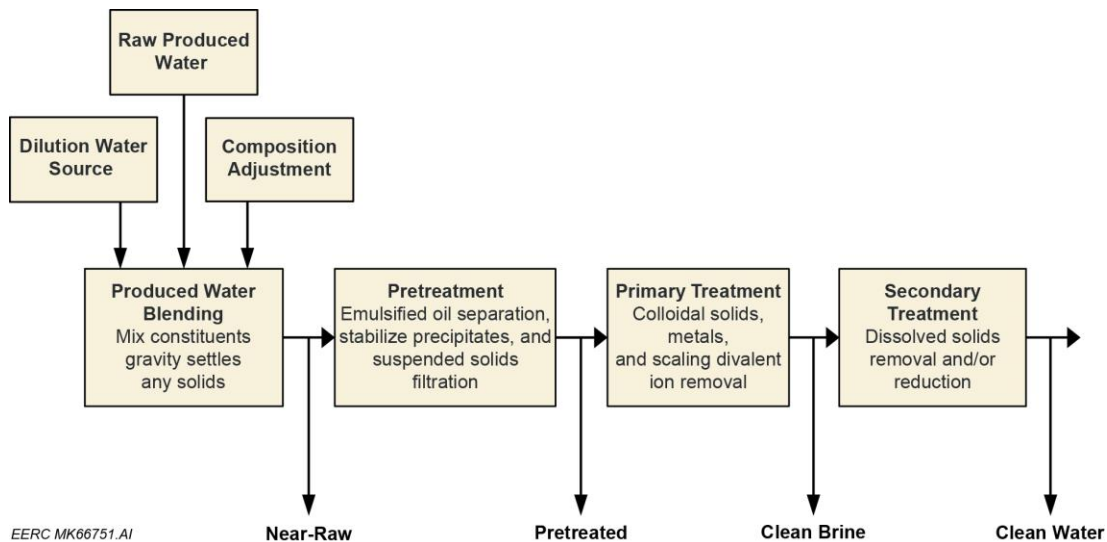
Table 2. Reviewed* PW Treatment Technologies

Technology	Targeted Contaminant(s)	Key Operational Sensitivities
Media Filtration	Suspended solids	Minimal
Hydrocyclone	Suspended solids Emulsified oil	Minimal
Coagulation/Flocculation	Suspended solids Colloidal solids Emulsified oil	Minimal
Phase Separators	Suspended solids Emulsified oil	Minimal
Flotation	Suspended solids Colloidal solids Emulsified oil Volatiles	Minimal
Freeze–Thaw	Chloride salts (TDS general)	Minimal
Chemical Oxidation	Dispersed organics Heavy metals Microbes	Minimal
Chemical Precipitation	Divalent cations Heavy metals	Minimal
Biological Treatment	Dispersed organics Volatiles	Residual oxidants and biocides
Liquid Coalescer	Emulsified oil	Solids fouling
Adsorption, e.g., granular activated carbon (GAC), zeolite	Dispersed organics Heavy metals	Surface fouling
Electrochemical Advanced Oxidation	Microbes Dispersed organics	Surface fouling
Microfiltration	Microbes Suspended solids Emulsified oil	Surface fouling
Ultrafiltration	Colloidal solids	Surface fouling
NF	Dispersed organics Divalent cations	Surface fouling
Catalytic Advanced Oxidation Processes	Dispersed organics Microbes	Surface fouling
Electrocoagulation	Emulsified oil Heavy metals Microbes	Surface fouling
Engineered Nanomaterials	Dispersed organics Microbes	Surface fouling
Solvent Extraction	Dispersed organics Heavy metals	High TDS selectivity
Ion Exchange	Heavy metals Divalent cations	Organic fouling
Thermal Distillation/Evaporation	Chloride salts (TDS general)	Inorganic scaling
Electrodialysis	Chloride salts	Inorganic scaling
Capacitive Deionization	Chloride salts	Inorganic scaling
Electrodeionization	Chloride salts	Inorganic scaling
Reverse Osmosis	Chloride salts (TDS general)	Inorganic scaling

* Nath et al., 2023; Conrad et al., 2020; Abdelhamid et al., 2025; Amakiri et al., 2022; Ghafoori et al., 2022; Khattoon et al., 2023.

Table 3. Proposed Water Quality Categories for Expanded BTTF Testing

PW Stage	Water Characteristics	Testing Uses
Blended PW	Bakken PW with or without adjustments made to represent other formation waters. Likely not a complete substitute for other formation waters given the site-dependent nature of oil and suspended solid contaminants.	Pretreatment technologies and multifunction systems with minimal operational sensitivities that are intended to treat raw PW.
Pretreatment	Saturation-stabilized PW with emulsified oil and larger solids (greater than ~2 μm) removed. Potentially devolatilized.	Technologies sensitive to surface fouling from oil and suspended solids. Oxidation technologies targeting dissolved organics and/or microbes. Certain levels of membrane filtration.
Primary Treatment	Clean brine with colloidal solids, heavy metal contaminants, and scale-forming divalent ions removed.	Technologies that are sensitive to colloidal particle fouling or inorganic scale formation. Examples may include ion exchange resins and electrochemical and electric field-based technologies for desalination.
Secondary Treatment	Clean water with the majority of TDS constituents removed.	Treatability studies for reuse applications such as discharge to the environment or nonedible crop irrigation.

**Figure 2. High-level treatment train stages for the proposed BTTF retrofit.**

Automated Brine Chemistry Determination

Automation and control of PW treatment systems will rely on various forms of instrumentation to provide process feedback. Advanced Engineering and Environmental Services, LLC (AE2S) performed a review (Table 4) of available real-time or near-real-time PW instrumentation since the BTTF retrofit will be an opportunity to incorporate and evaluate the latest instrumentation offerings. While evaluating instruments under development is an anticipated use of BTTF, this review included only vendor-supported instruments that are available for integration into BTTF's treatment train design.

Table 4. Review of Available Online PW Instrumentation

Parameter	Description
Turbidity	Turbidity is the measure of suspended solids in the water and is generally caused by clay, silt, and organic and inorganic matter. The technology to measure suspended solids is through the detection of the amount of light scattered by the particle. Methods for the analysis of turbidity include U.S. Environmental Protection Agency (EPA) 180.1 and Standard Methods 2130 B. Both bench top and inline turbidimeters/probes are available, with several manufacturers to choose from.
Total Suspended Solids (TSS)	TSS in water refers to the undissolved portion of solids that do not settle. Like turbidity, these particles can be caused by clay, silt, and organic and inorganic matter. TSS reduces water clarity and makes the water look cloudy or murky. Generally, TSS has been measured by gravimetric analysis, but more recently, insertable probes have been developed that absorb and scatter light. The difference between the measurement of turbidity and TSS is that turbidity measures light scattering, while TSS measures the mass of suspended solids per unit volume of water. Inline TSS probes are available, with multiple manufacturers to choose from.
pH	pH is one of the most important and frequently used tests in the treatment of water. Nearly every process in water or wastewater treatment is dependent on pH. Methods for the analysis of pH include EPA 150.3 and Standard Methods 4500-H ⁺ B. Bench top and inline pH meters are available, with multiple manufacturers to choose from.
Electrical Conductivity (EC)	Conductivity is commonly used as a surrogate for the TDS of highly saline brines like PW. Conductivity is the measure of the ability of a solution to carry an electrical current. The conductivity of a solution depends on the presence and concentration of ions and the temperature of the water. Conductivity can provide a reliable method of determining the reduction of ions in the water through each treatment process but not the specific ion composition. The method for the analysis of conductivity is Standard Methods 2510 B. Both benchtop and inline conductivity meters are available, with multiple manufacturers to choose from.
Particle Count	A particle counter is used for water quality control and can size and count particles in a water stream. Particle counters are useful in tracking the performance of filters by counting and sizing the particles in the filter effluent. Particle counters are more sensitive to the detection of particles than turbidimeters and thus can identify degradation in filter performance faster than a turbidimeter. The methods for the analysis of particles in water include Standard Methods 2560 B, 2560 C, and 2560 D. Both benchtop and inline particle counters are available, with multiple manufacturers to choose from.
Total Organic Carbon (TOC)	TOC is the measure of organic carbon in water. The measurement of TOC can indicate the organic load of an industrial wastewater and helps assess the efficiency of the treatment processes. The methods for the analysis of conductivity include Standard Methods 5310 B, 5310 C, and 5310 D. Both benchtop and inline TOC analyzers are available, with multiple manufacturers to choose from.
Ionic Species	Ion chromatography (IC) is used to identify specific anion (e.g., Cl ⁻ , SO ₄ ²⁻ , CO ₃ ²⁻ , etc.) and cation (e.g., Na ⁺ , Ca ²⁺ , Mg ²⁺ , etc.) species in water. The methods for the analysis of anions by IC include EPA 300.0 and Standard Methods 4110 B and 4110 C. Benchtop and inline IC analyzers are available, with multiple manufacturers to choose from. Inline IC instruments are generally near-real-time measurements since the analysis takes time to complete. In practice, inline IC data points will lag 15 to 45 minutes behind the sample time depending on the specific configuration of the instrument. Similarly, the species that can be detected with IC will depend on the instrument's configuration, and it may not be possible to combine all of measurements of interest into a single instrument.

Producing Formation Composition Adjustment

While BTTF is located in the Bakken shale play, the issue of PW management extends to other unconventional plays across the United States, each with their own PW composition characteristics. Shipping PW from other formations to BTTF for technology testing has been performed for previous test campaigns. This option is considered to be far more cost-effective than establishing an equivalent test facility in another region since the investment in foundational infrastructure, permitting, safety systems, etc., has already been made for BTTF.

An alternative to shipping PW from afar is to blend water at BTTF to simulate the characteristics of other water sources. A comparison was made to see if the Bakken PW available at BTTF could be used to emulate PW from the Permian Basin in West Texas and eastern New Mexico since the Permian is the most productive oil field in the United States, producing over 40% of total U.S. output (U.S. Energy Information Administration, 2025a), and it also faces PW management challenges including induced seismicity (Hennings and Smye, 2024). Basin-averaged compositions for Permian and Bakken PWs are presented in Table 5 (Scanlon, 2020b), and the major cation and anion data are shown graphically in Figure 3. Average Bakken water has a higher TDS content compared to the Permian, roughly 230,000 mg/L compared to 148,000 mg/L. However, if Bakken water is diluted to match the TDS content of Permian water as in the calculated composition in Table 5, its major ionic composition closely resembles Permian water as indicated by the dashed boundary in Figure 3.

Sodium chloride is the dominant dissolved salt in both water sources, followed by calcium chloride. Other anions like sulfate and bicarbonate are relatively low in both waters. The variations in minor cations including potassium, magnesium, and barium are not expected to have a significant impact on treatment technologies that either desalinate or dewater PW since they will minimally impact bulk fluid properties such as density, vapor pressure, saturation index, etc. On the other hand, magnesium may have a targeted effect on lithium recovery since it is a key interferent for many approaches to lithium separation.

Table 5. Comparison of Average PW Compositions (Scanlon, 2020b)

Parameter	Units	Permian Tight Oil	Bakken Tight Oil	Diluted Bakken (calculated)
Averaged Samples	No.	859	327	—
TDS	mg/L	147,500	229,200	147,500
Cl ⁻	mg/L	95,820	142,816	91,908
Na ⁺	mg/L	51,520	72,299	46,527
Ca ²⁺	mg/L	6627	13,520	8701
Mg ²⁺	mg/L	1311	1181	760
SO ₄ ²⁻	mg/L	1024	514	331
K ⁺	mg/L	841	4386	2823
HCO ₃ ⁻	mg/L	440	238	153
Ba ²⁺	mg/L	167	67	43

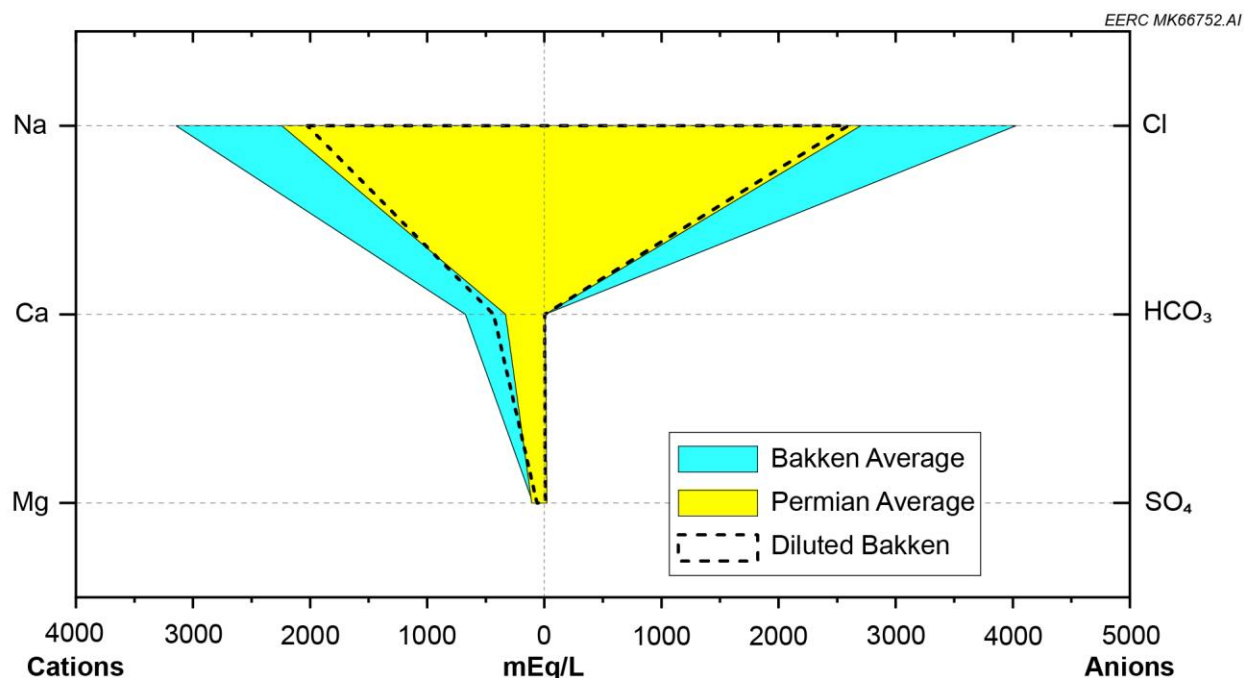


Figure 3. Stiff diagram comparison of average Permian and Bakken water compositions, and a calculated composition for Bakken water diluted to match the Permian's dissolved solids.

Lithium is a CEM that could be extracted from PW in significant quantities, particularly Permian PW, given the large aggregate quantity of water produced there, even though the lithium content is not as high as elsewhere (Smith et al., 2024). The EERC reviewed lithium concentration data for individual samples of Bakken PW from the BTTF extraction well and a sample of Permian PW from a prior technology test evaluation at BTTF. These data are summarized in Figure 4 and show that the lithium content in Bakken water appears to be proportionally more concentrated such that its diluted lithium content is comparable to that in the Permian sample. However, Bakken water is relatively lower in magnesium compared to Permian water, and its molar ratio of magnesium to lithium is approximately half that of the Permian sample. Magnesium is a strong interferent for lithium recovery (Nikkhah et al., 2024), and the ratio of magnesium to lithium is used as an indicator of difficulty in lithium recovery. Therefore, it might be desirable to increase the magnesium content of diluted Bakken PW if it is intended as a Permian surrogate for lithium recovery testing. This effect could be achieved by injecting diluted Bakken PW with a soluble magnesium compound like MgCl_2 to bring the magnesium-to-lithium ratio within a range more typical of Permian water.

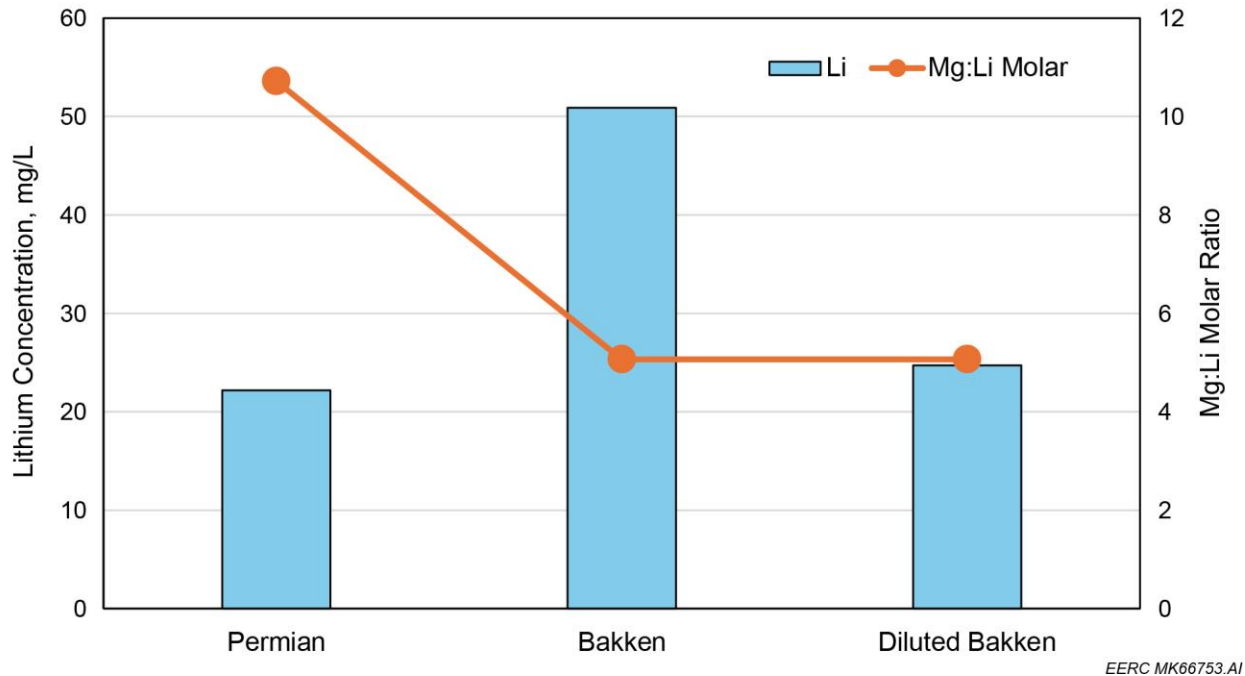


Figure 4. Comparison of lithium concentration and the Mg:Li ratio for a sample of Permian PW and a sample from the BTTF E-1 extraction well; the diluted Bakken is a calculated composition based on diluting the Bakken E-1 sample so that its TDS concentration matched that of the Permian sample.

High-Value Mineral Recovery

The dissolved solids composition in unconventional oil and gas PW is typically dominated by relatively few dissolved species as demonstrated by the Permian and Bakken examples in Table 5 (Scanlon, 2020b). However, these waters also typically contain a multitude of minor constituents, some of which are valuable CEMs. Given the growing importance of sourcing CEMs domestically, recovery methods were reviewed to ensure that the pretreatment needs of such systems were included in the BTTF retrofit design along with the water quality needs for modular PW treatment system testing previously discussed. A recent study examined the potential for recovering five CEMs from unconventional U.S. PW: cobalt, lithium, magnesium, manganese, and nickel (Smith et al., 2024) and concluded that the greatest opportunity lies with recovering lithium and magnesium based on data available at the time. Lithium recovery from PW has been reviewed (Nikkhah et al., 2024), and the identified pilot and/or commercial processes are summarized in Table 6. It was found that all of the approaches reviewed for lithium recovery have analog sensitivities to the more general PW treatments reviewed in Table 2 and that the proposed segmentation of the BTTF treatment train in Figure 2 will be suitable for the addition of lithium CEM recovery.

Table 6. Reviewed Lithium Recovery Methods Applicable to PW*

Technology	Key Operational Sensitivities	Anticipated Stage of BTTF Integration
Solvent Extraction	Divalent cation interference.	Following primary treatment to address interferences.
Chemical Precipitation	Minimal, but coprecipitation of with Mg expected.	Following primary treatment to address interferences; following pretreatment possibly acceptable with recovery of impure precipitates.
NF	Surface fouling.	Within secondary treatment; fouling expected without upstream colloidal solids removal.
Selective Adsorption	Surface fouling; high TDS.	Following primary treatment or within a secondary treatment configuration.

* Nikkhah et al., 2024.

BTTF CURRENT CONFIGURATION

Description of Demonstration Facility

The BTTF treatment test facility was originally established to enable further development and evaluation of brine treatment technologies capable of addressing high-TDS brines associated with geologic CO₂ storage targets. Specific objectives for the treatment facility were to enable the development, pilot testing, and advancement of commercially viable extracted water and PW treatment technologies that can meaningfully reduce brine disposal volumes and provide an alternate source of water and/or salable product(s) for beneficial use. The treatment facility was constructed at a commercially operated SWD facility and is located near Johnsons Corner, approximately 13 miles east of Watford City, North Dakota.

BTTF includes a permanent heated environmental enclosure measuring 60 by 80 feet, with 18-foot wall height, equipped with two large automatic overhead doors. The building is constructed on a sealed concrete pad with drainage containment and was designed with a large demonstration bay that can accommodate up to semi (tractor-trailer)-sized technology skids. Figure 5 shows the treatment facility building exterior and associated tank and piping infrastructure.



Figure 5. BTTF (front and back).

BTTF was integrated with active reservoir management (ARM) and SWD infrastructure and operations, which allowed for access to PW and extracted brines as well as concentrated brine reinjection capabilities. Flow capacities up to 25 gpm are possible, with the ability to blend brines and freshwater to achieve TDS concentrations ranging from 500 mg/L up to approximately 330,000 mg/L. A salinity concentration of approximately 180,000 mg/L TDS was targeted for purposes of the initial project research; however, tailored blends are possible to suit capabilities and/or limitations of selected technologies or research objectives.

The building is designed with a demonstration bay area having a Class 1, Division 2, electrical rating and a liquid collection sump pit and pump with a Class 1, Division 1, rating in the event of accidental release of flammable vapors or gases from technology testing. These spaces, along with an electrically unclassified adjacent office and control room area for project supervision and management activities, are shown in the plan view of Figure 6. The classified demonstration bay was equipped with a gas-monitoring system to warn against the formation of hazardous atmospheres during testing of treatment technologies, some of which may potentially not be Class 1, Division 1, electrically rated. The gas-monitoring system comprised five separate alarm monitors designed to detect hydrogen sulfide (H_2S), nitrous oxide (NO_2), carbon monoxide (CO), methane (CH_4), and ethylene (C_2H_4), which are the most likely hazardous components that could be encountered during anticipated operations. A power shunt fail-safe within the integrated supervisory control and data acquisition (SCADA) system was designed to immediately disconnect power to the building in the event a hazardous atmosphere was detected and triggered an alarm.

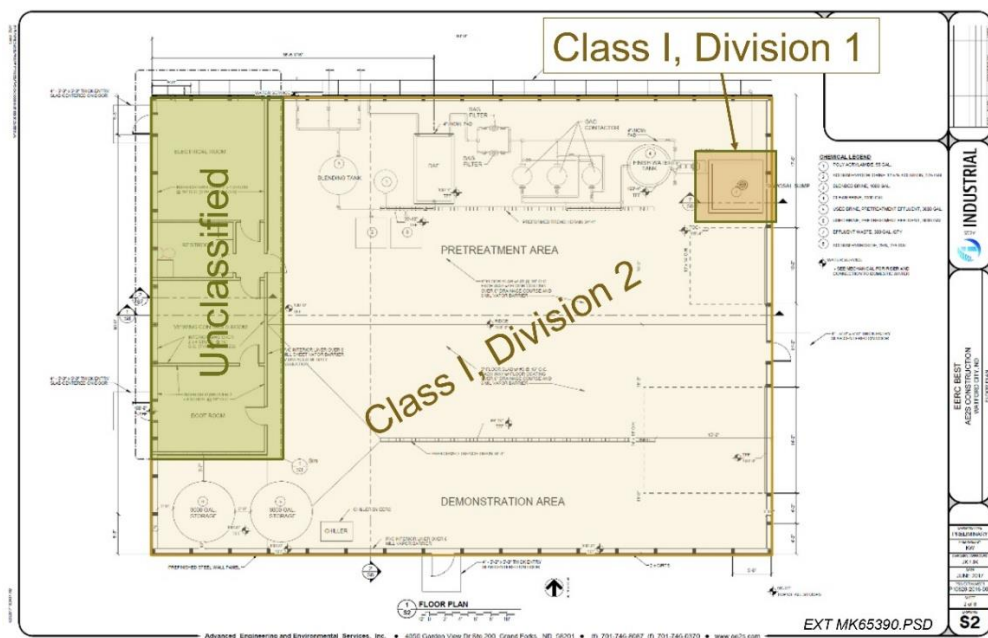


Figure 6. Layout and electrical rating of test bed treatment facility.

A brine pretreatment system was installed to ensure all technology evaluations used brine with similar and consistent compositions. The pretreatment system was designed to remove particulates, organics, and potential scale-forming constituents and consisted of chemical addition, dissolved air flotation (DAF), bag filters, GAC filtration, and associated instrumentation to monitor quality of the treated brine for all demonstrated technologies.

The pretreatment system consists of an automated blending configuration that uses pneumatic control valves on each supply line for extracted brines, Bakken PW, and freshwater to achieve varying blend chemistries and salinity concentrations. Sodium hydroxide (30%) and bleach (sodium hypochlorite 12%) are metered into the brine mixture during the blending process to adjust the pH of the brine to approximately 10.5. After blending and desired salinities are achieved, a coagulant and polymer solution are metered into the brine prior to a DAF system where flocculated particulates and bottom sludge are skimmed off and pumped out of the process to an external poly sludge tank adjacent to the treatment building. The DAF process is designed to remove any unstable scale-forming components of brine chemistry that may inhibit proper treatment in follow-on technologies. The DAF effluent flows through a set of sock filters (~10 μ m) to remove remaining particulate and is then routed through a series of GAC beds to remove any dissolved organics, including dissolved hydrocarbons. The filtered brine is then considered “finished” and flows into a 1000-gallon storage tank from which it is fed to the technology skid being evaluated. Throughout the pretreatment process, conductivity meters are positioned in the flow lines to accurately understand the conductivity of the treated brine. Additionally, there are several sample ports throughout the system where samples can be collected to evaluate pH, particulate content, and dissolved organic constituents that may indicate the need to change out the GAC in the GAC vessels or make other adjustments to the pretreatment system.

After the “finish” water tank, there are a final flowmeter, conductivity meter, and turbidity meter to accurately assess the quantity and quality of the brine being fed into the technology skid. This information is also tracked and recorded in the SCADA system associated with the building and pretreatment system. Once the brine has been processed through a demonstration technology, samples can be routinely collected for analysis and the excess effluent streams are diverted into two separate tanks, one each for the concentrated brine and the clean treated water. For disposal of the test effluents, a series of flow lines and transfer pumps are able to recombine the fluids and transfer them out of the building and into the reinjection flow system. Figure 7 shows several views of the entire demonstration bay, including the office area and effluent storage tanks (upper left), pretreatment system (upper right), sump pump system and brine delivery piping components (lower left), and demonstration bays available for test system setup (lower right).



Figure 7. Various photos and angles of the treatment facility.

Electrical requirements for each demonstration are supplied through a separate power transformer that was isolated from the rest of the building electrical supply. A separate junction box with sufficient 440-volt power supply and an associated step-down transformer for lower voltage requirements (i.e., 220 and 110 volt) allowed for continual integrated monitoring and recording of power consumption variables (i.e., total watts, kWh, etc.) for each technology evaluation. Each demonstration technology was connected and disconnected to the power system by a contracted certified electrician, and data recording was controlled through software and the integrated SCADA system on-site.

Several components of the building operations, brine supply infrastructure, and pretreatment system are operated and monitored using an EERC-developed SCADA system. The SCADA system efficiently and accurately controlled operations, allowed for easy integration of new sensors and equipment, and enabled remote operation of some components. Figure 8 (bottom) shows the SCADA system control area. The system has a modular design and ensured continuous data collection and storage. Components/parameters that were controlled, monitored, and/or data-recorded included system temperature and pressure, tank level, turbidity in flow lines, EC (salinity inferred) of brine, flow status and rate, safety and alarm systems, and power consumption parameters for demonstration activities. Figure 8 (top) shows the specific SCADA control screens for the pretreatment system configuration. Overall site and treatment facility capabilities for the original BTTF configuration are illustrated and detailed in a presentation in Appendix A.

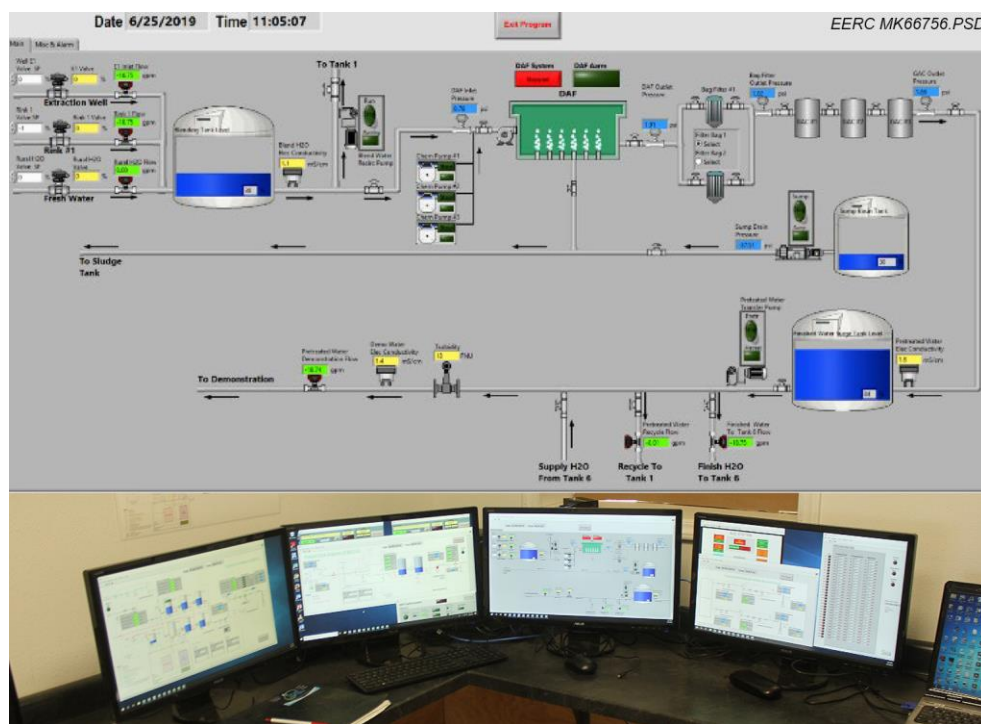


Figure 8. SCADA system control area with multiple computer displays.

The original BEST project was conducted in two phases starting in 2015. The first phase was a 15-month design study, and the follow-on second phase was the construction and implementation of field-based extraction/injection wells and associated test facility infrastructure. The facility was utilized to conduct technology testing evaluations on treatment technologies potentially applicable to high-TDS PWs and additionally for providing a platform for non-project-related research conducted through NETL and Leidos-sponsored efforts. Figure 9 shows some of the technology evaluations conducted over the years.



Figure 9. Images of previous demonstration activities in the facility.

Current Status of Capabilities and Infrastructure

BTTF was put into an idled state in 2024 under Activity 2 of Subtask 3.3. An agreement was reached with the site operator, Select Water, that allows continued access to the facility and payment of operating expenses including utility costs and site maintenance. No infrastructure has been removed.

The facility was assessed by AE2S in 2025, and its full assessment is included in its design study in Appendix B. In summary, the overall site and building are in good condition, and no modifications were recommended. Exterior piping and tank storage appear to be in usable condition, but their leak integrity needs to be verified. Similarly, the effluent piping and finished water storage inside the building also appear to be in usable condition. Components at or near the end of their service life include the DAF system and GAC contactors; both are recommended to be decommissioned and removed. Potentially reusable components include the supply piping, blending system, and filter housings, provided they control within the lower flow range specified for the upgraded facility. Serviceability of the process instrumentation needs to be assessed at the time of detailed design. Reusing the SCADA system, while functional, was judged to be cost-prohibitive compared to starting new given limitations in finding compatible hardware and the need for expansion to monitor and control the increased number of treatment modules within the upgraded design.

PRELIMINARY FACILITY DESIGN

AE2S created a preliminary retrofit design for BTTF, with input from the EERC and direct feedback from representatives at DOE and NETL. Based on these discussions, the planned flow range for the retrofit facility will be 1 to 5 gallons per minute, or approximately 40 to 170 bbl/day of conditioned PW for testing. All processing equipment and instrumentation design and price estimates were based on this assumption. This preliminary design description is based on the study provided by AE2S, which is included in Appendix B along with supporting materials provided by AE2S.

Treatment Train Configuration

The AE2S design is presented according to the four conditioning stages presented in Figure 2: PW blending, pretreatment, primary treatment, and secondary treatment. Characteristic water composition and potential testing uses for each stage of conditioning are presented in Table 3. The AE2S study in Appendix B includes a high-level process diagram for the proposed system that provides added detail within each stage.

PW Blending

As in the original BTTF configuration, on-site sources of PW, extracted Dakota formation water, and potable-quality dilution water will be supplied to a blending manifold. Source water options will also include feed from an external source such as a bulk container or tanker truck. Flowmeters will be installed on each feed line to measure both the instantaneous flow rate and the totalized flow into the blending manifold, which will either directly feed the next stage of the treatment train or fill a mixing tank that can also be used as the treatment train feed source. The mixing tank will be provided with a variable-speed mixer and automatic valves to mix the water prior to treatment. A sample tap will be installed within the mixing tank to allow for the analysis of the raw water prior to treatment.

A minimum of three injection points will be provided on the dilution water line to allow chemical injections for composition adjustment of the test water. Chemical feed systems including tanks and pumps will need to be acquired to perform chemical injection. Sample taps will be installed to allow for the analysis of the composition-adjusted water. The dilution water will also be plumbed to feed the treatment train directly for posttest flushing and cleanout of the entire system or individual modules by bypassing inactive circuits. A separate cleanout skid with a pump is also proposed that can circulate dilution water through isolated parts of the treatment train for extended times. This skid will include provisions to inject cleaning or conditioning agents (caustic, acid, or other chemicals depending on the application) into the circulating solution.

Pretreatment

The PW pretreatment system will be used for the removal of oil, organics, and suspended solids. Pretreatment is not designed to remove dissolved solids; however, some dissolved organics classified as TOC may be removed through certain treatment systems depending on the processes and/or chemicals selected. The proposed pretreatment systems include an oil–water separator, a coagulation/flocculation/sedimentation (CFS) unit, and filtration with sand and/or GAC. A DAF could also be added back into the process should it be wanted or required. Each of these processes have the capability to remove oil, organics, and suspended solids. An automated pH adjustment system is also proposed. The system will be designed such that the pretreatment units can be placed in series, parallel, or bypassed altogether. The following paragraphs describe the pilot units proposed for BTTF in more detail.

- **Oil–Water Separator:** Oil–water separators are designed to separate free and dispersed oils from a wastewater stream. The unit selected for BTTF is made from stainless steel, with the internal coalescing media pack and oil skimmer parts made from polyvinyl chloride (PVC) for corrosion protection. The unit comes with an inlet, outlet, adjustable oil skimmer, air vents, and a removable lid. If required, it can be designed with slant rib clarification plates to assist with the removal of settleable solids. A collection tank could be provided to store the settled solids.
- **CFS:** Coagulation is the process by which chemicals are added to the water to aid in the removal of suspended particles. Chemicals such as aluminum sulfate, ferric chloride, ferric sulfate, or polymers are coagulants and are added to create floc particles. These chemicals destabilize the charges on suspended particles, allowing them to form larger floc particles. Flocculation is the process by which the floc particles can then grow even larger under the right mixing conditions. After flocculation, the particles are allowed to settle (i.e., sedimentation) to the bottom of the tank where they are collected and disposed of. CFS is an excellent process for the reduction of oil droplets and TSS. This process can also remove a portion of the dissolved organic carbon, but this application requires additional process optimization. The unit selected for BTTF is an integrated skid consisting of three separate tank systems: a three-stage rapid mix tank, a three-stage flocculation tank, and a plate settler-based sedimentation tank. All tanks come with variable-speed mixers, and the sedimentation tank is equipped with an automatic sludge removal system. The unit comes with chemical feed systems which can be configured for flow pacing, closed-loop proportional integral derivative (PID) or trim control. The skid will be controlled through an integrated control panel that includes many options for inline water

quality monitoring and data logging as well as remote operation via a wireless cellular connection.

- **Filtration:** Filtration is a physical process that uses sand or other types of media to strain out particles from water. The filters typically use coarse sand and anthracite as the filtering material, but other media such as GAC is also used for dual benefit of particle removal and organic reduction. The filters are periodically cleaned using a process called backwashing by pumping clean water up through the filter media to wash away the collected solids. Filtration usually comes after the CFS process, although other configurations could be used. The filtration unit selected for BTTF comes as an integrated skid with two to six filter columns that are 6-inch, 8-inch, or 10-inch diameter. Flow can be directed to a single filter or a group of filters for either series or parallel operation. The skid will be controlled through an integrated control panel that includes many options for inline water quality monitoring and data logging as well as remote operation via a wireless cellular connection.
- **GAC Contactors:** As stated above, the filter media in the filtration columns can be exchanged for GAC to assist with the removal of organic chemicals. GAC is effective in the removal of volatile organic chemicals, synthetic organic chemicals, and natural organic matter measured as TOC. The GAC contactors will operate in the same manner as described above for the filtration skid.
- **DAF (optional):** DAF is a treatment process that uses the coagulation and flocculation process to grow larger particles, but instead of separating them through sedimentation, compressed air is bubbled through the water to assist the particles to float to the top of the tank. The particles are then skimmed off the top of the tank, and any heavier sludge that is formed is removed from the tank bottom. DAF is used for the removal of both suspended oil and suspended solids. It can also be effective for removing unstable dissolved solids that become saturated during air equilibration. Analogous to the CFS skid, the proposed DAF unit for BTTF will consist of three separate tank systems, including a three-stage rapid mix tank and a two-stage flocculation tank but a DAF clarification tank substituted for a sedimentation tank. Other operational features for the DAF unit are similar to the CFS skid.
- **pH Adjustment:** Water treatment can be influenced by many factors including pH, which influences corrosion, bacteria growth, and chemical reactions. A pH adjustment skid is proposed for BTTF to control this parameter prior to any subsequent treatment step. Piping connections will be rapidly reconfigurable so that the pH skid can feed any other system in the treatment train. The skid will be a one-, two-, or three-stage continuous flow-through system and completely automated. Its operation can be integrated with an external control or data management system. Instrumentation will include flow rate and influent and effluent pH levels. A minimum of two chemical feed systems will be provided to dose an acid or base chemical.

Primary Treatment

The PW primary treatment system will be used for the removal of heavy metal contaminants and scale-forming divalent cations. The primary treatment systems selected include heavy metal and divalent cation removal (i.e., softening) with chemical precipitation, ion exchange resins, and

membrane systems such as NF. Each of these processes has the capability to remove divalent cations and heavy metals under a certain range of operating conditions. The primary treatment system will be designed such that the individual units can be placed in series, parallel, or bypassed altogether. The following paragraphs describe the pilot units proposed for BTTF in more detail.

- **Chemical Precipitation and Ion Exchange:** Chemical precipitation followed by ion exchange is a common method used for the removal of heavy metals from water. Chemical precipitation is the process where a chemical is added to water to convert the dissolved metal ions into an undissolved form. The resulting particles settle and are removed. The most commonly used chemicals for metals precipitation include hydroxide, sulfide, carbonate, and phosphate ions. Ion exchange is then used as a polishing step where the resin beads are coated with a negatively charged functional group which will attract and exchange a positively charged heavy metal ion. Once the resin becomes saturated with metal ions, it is readied for reuse by passing a concentrated solution containing sodium or hydrogen ions through the bed to recharge it with the proper functional group. The proposed unit for BTTF includes a first-stage pH adjustment tank followed by a second stage of tanks for chemical feed, mixing, and precipitation/settling of the metal-laden sludge. Third-stage ion exchange tanks provide polishing metals removal that can be combined with activated carbon for volatile organic compound (VOC) removal, if desired. The skid will be controlled through an integrated control panel that includes many options for inline water quality monitoring and data logging as well as remote operation over the Internet.
- **Softening:** PW contains elevated concentrations of calcium and magnesium, also known as hardness. The primary treatment system will include a water-softening option to remove these primary cations, and others like strontium and barium, from solution. Recovery of lithium from PW is hindered through interaction with magnesium, making the softening process necessary for the recovery of some CEMs. Hard water reduction is also required before any RO processing can be achieved. Water-softening skids for industrial processes are ubiquitous; however, these systems are primarily based on ion exchange, which greatly limits their applicability to treating PW. Typically, ion exchange softeners have limits on incoming TDS levels that are usually well below the TDS of some PW, including PW from the Bakken and Permian plays. A softening alternative for BTTF is to employ a second stage of chemical precipitation, likely based on carbonate chemistry, to remove the bulk of calcium, magnesium, and other scaling divalent cations.
- **Ultrafiltration:** Ultrafiltration membranes are a solution to treat colloidal solids which are defined as suspended solids that can pass through a 2- μ m filter. These membranes utilize a pressure gradient to force clean water, i.e., permeate, through the membrane while rejecting the colloidal solid contaminants along with the concentrate, or reject stream. The primary benefit with membrane technology in general is that it is a physical barrier that rejects particles at a precise size. The drawback of this alternative is the fouling that can occur depending on the water constituents and their concentration. For example, upstream microfiltration will be required to remove larger suspended solids before water can be fed into the ultrafiltration membrane. Failure to remove larger solids and other contaminants such as emulsified oil would quickly foul downstream screening. Ultrafiltration unit design depends heavily on the expected feed conditions and concentrations, upstream microfiltration conditions, and desired permeate

product quality. As such, a notional ultrafiltration system has been included in the BTTF design, but specific equipment features will not be determined until a detailed design is performed.

Secondary Treatment

Proposed units within the secondary treatment stage are capable of reducing the TDS of PW under certain conditions, potentially extending to the point of producing clean, desalinated water in the case of RO. Appropriate technologies include RO and another membrane-based approach of NF and electrodialysis reversal (EDR). The following paragraphs describe the pilot units proposed for BTTF in more detail.

- **RO and NF Membranes:** RO and NF are both considered secondary treatment alternatives that provide a polishing step to further clean the water after primary treatment. Both RO and NF operate similarly to ultrafiltration membranes but with a smaller pore size to remove dispersed organics, divalent cations, and even chloride salts in the case of RO. The difference between RO and NF is pore size: NF typically can remove solids in the 0.001–0.01-micrometer range where RO pores are approximately 0.0001 micrometers. This pore size difference allows RO to remove chloride salts but also increases fouling potential compared to NF. The benefits and drawbacks of RO and NF are like those of ultrafiltration. For example, ultrafiltration is typically required upstream of RO and NF just as microfiltration is recommended upstream of ultrafiltration. The design of RO and NF secondary treatment systems depends heavily on the expected feed conditions and concentrations, upstream membrane conditions, and desired permeate product quality. As such, a notional RO/NF system has been included in the BTTF design, but specific equipment features will not be determined until a detailed design is performed.
- **EDR:** EDR is another secondary treatment technology that is designed to focus on the removal of chloride salts. Electrodialysis is a membrane process that is driven by an applied electric field where anion contaminants will move toward the anode and cation contaminants will move toward the cathode. Anion-selective and cation-selective membranes placed between the anode and cathode allow the passage of ions with the same charge but block those of opposite charge. As a result, each set of membranes forms a cell where ions are concentrated outside the membranes and clean water is left in between. An EDR unit will contain a stack of these cells to match the treatment capacity. Charged suspended solids will also be impacted by the electric field and captured by the membrane, which can result in fouling. Charge reversal can clean membranes and reverse fouling to reduce the need for chemical cleaning and prolong membrane life. Manufacturers that produce EDR units are limited, and few of them offer systems sized for the BTTF flow rate. Most likely, an EDR unit will have to be sourced outside the United States, with system specifics determined at the time of detailed design.

PW Chemistry Determination

The proposed BTTF design includes the inline instrumentation and grab sample collection ports necessary to fully characterize operation of the treatment train. Real-time or near-real-time inline instrumentation reviewed by AE2S was presented in Table 4. Table 7 presents the proposed

Table 7. Proposed Schedule of Inline PW Instrumentation

Parameter	Proposed Sampling Locations
Turbidity	Mixing tank effluent, pretreatment effluent, primary treatment effluent, and secondary effluent. Select individual treatment systems will also have an instrument installed.
TSS	Mixing tank effluent, pretreatment effluent, primary treatment effluent, and secondary effluent. Select individual treatment systems will also have an instrument installed.
pH	Mixing tank effluent, pretreatment effluent, primary treatment effluent, and secondary effluent. Select individual treatment systems will also have an instrument installed.
EC	Mixing tank effluent, pretreatment effluent, primary treatment effluent, and secondary effluent. Select individual treatment systems will also have an instrument installed.
Particle Count	Filtration and GAC contactor effluent and at the effluent of any membrane filtration system.
TOC	Mixing tank effluent, pretreatment effluent, primary treatment effluent, and secondary effluent. Select individual treatment systems will also have an instrument installed.
Ionic Species	Mixing tank effluent, pretreatment effluent, primary treatment effluent, and secondary effluent.

sampling locations for each instrument type. Conditioned water from the treatment train will generally represent the inlet water conditions for technologies under test. It will also be possible to monitor test system effluent with the inline instrumentation by discharging test effluent into one of the instrumented effluent manifolds that are planned for each of the major treatment stages.

In addition to inline instrumentation installed throughout the treatment train, AE2S identified PW parameters for which no inline measurement option is currently available. These parameters are listed in Table 8 along with descriptions of their analysis. Numerous sample taps are included throughout the proposed facility design to collect water for these offline analyses. To minimize the time for grab sample measurement feedback, all of the analyses in Table 8 could feasibly be performed on-site at BTTF by trained personnel and after a modest investment in basic laboratory infrastructure such as a demineralized water supply and fume ventilation system.

Table 8. Review of PW Grab Sample Analyses

Parameter	Description
Emulsified Oil	Oil in water analysis provides a quick and accurate determination of the amount of oil in a water sample. PW can have detectable concentrations of oil that need to be removed before the water can be discharged. Methods for the analysis of oil in water include ASTM International D7066, EPA 413.2, and EPA 418.1. A benchtop unit is available, with several manufacturers to choose from.
VOCs	Many VOCs in water can be analyzed using a purge and trap with a gas chromatograph–mass spectrometer (GC/MS). It is proposed the pilot plant project be provided with a purge and trap GC–MS for the analysis of VOCs. The list of VOCs that can be detected by purge and trap GC–MS number nearly 60 compounds. The method for the analysis of VOCs is EPA Method 524.2 or Standard Methods 6200 B.
Heavy Metals	Inductively coupled plasma–optical emission spectroscopy (ICP–OES) can analyze a number of different metals and divalent cations in water. It is proposed the pilot plant project will be provided with ICP–OES to analyze the different metals and divalent cations that may be found in the PW stream. The method for the analysis of metals by ICP–OES is EPA 200.7 or Standard Methods 3120 B.
Microbial Activity	The need to determine the type and count numbers for different microbial communities in PW is critical for understanding the effect of microbial communities on corrosion and fouling. Tests have been developed that use adenosine triphosphate (ATP), which can be tied directly to microbial population in water. Results can be achieved within minutes instead of days as required by culture-based testing. Another method to detect iron bacteria, sulfate-reducing bacteria, and slime-forming bacteria within water is the biological activity reaction test (BART). This test can be performed in the laboratory, and results can be achieved within 8 days.

System Automation and Data Acquisition

Conceptual design of the automation package includes a supervisory control panel (SCP), human–machine interface (HMI) module and control software, and integrated process and equipment-specific controllers. This control scheme enables the development of a feature-rich system that is both robust and cost-efficient. HMI software, connecting through the SCP, will oversee all subsystems throughout the facility and log time-stamped process data for postprocessing and analysis. Most or all process equipment packages will be sourced with control systems required to operate that particular process area. These local controllers will be integrated with the SCP to receive control direction and upload process data such as flow rates, flow totals, analytical data, pressures, alarms/alerts, run times, power consumption, etc. Process instrumentation, valves, and other devices that are not specifically included within a process area equipment package will be directly connected to the SCP. Existing hazardous gas and leak sensors within the demonstration area will be integrated into the SCP to provide warnings and trigger overall facility shutdown in the event an unsafe condition is detected.

The control system architecture will be designed with utmost flexibility in mind to accommodate the evaluation of not only PW treatment technology, which may have its own interfacing needs, but also advanced instrumentation for PW monitoring that is under

development. Identifying a suitable PW stream for instrument evaluation and collecting data with it will be a straightforward matter given the flexible configurability proposed for the treatment train. Deeper integration of a novel instrument signal into the SCP or one of the equipment skid controllers will require an evaluation by an instrumentation engineer to determine feasibility. Integration at the SCP level will likely be more feasible than within one of the individual skid controllers because the SCP will allow greater access to the HMI control programming and the panel itself will be designed with an expectation of future potential expansion. Such evaluations will need to be done on a case-by-case basis.

Preliminary Retrofit Project Cost Estimate

High-level construction cost estimates for each stage of the proposed BTTF retrofit are shown in Table 9 along with an overall estimated total cost for construction of the retrofit described in AE2S's design study. Costs are divided into categories of treatment skids, instrumentation, electrical, mechanical, process piping, and a budget for unidentified design elements and cost escalation. These estimates include some conservative assumptions to account for potential price increases prior to starting a retrofit project. Optional treatment and instrumentation equipment that was priced but not included in the recommended design has a zero quantity. Obviously, changes to the design requirements that eliminate other units or that add optional items will impact the estimated total as well.

Table 9. Estimated Construction Costs for the BTTF Retrofit

General Requirements				
Insurance, Bond, Mobilization, etc.	1	\$50,000	\$50,000	\$156,000
			Subtotal	\$156,000
Treatment Skids				
Oil–Water Separator	1	\$75,000	\$86,250	\$86,300
Coagulation, Flocculation, and Sedimentation Pilot Skid	1	\$196,000	\$225,400	\$225,400
Granular Media Filtration and GAC Contactor Pilot Skid	1	\$184,000	\$211,600	\$211,600
pH Neutralization Skid	1	\$49,800	\$57,270	\$57,300
Ion Exchange/Heavy Metals Skid	1	\$110,000	\$126,500	\$110,000
Softening Skid	1	\$75,000	\$86,250	\$86,300
Ultrafiltration Skid	1	\$150,000	\$172,500	\$172,500
RO Skid	1	\$150,000	\$172,500	\$172,500
Electrolytic Cell Pilot Skid (EDR)	1	\$250,000	\$287,500	\$287,500
Superfiltration Skid (Nanofiltration)	1	\$150,000	\$172,500	\$172,500
			Subtotal	\$1,581,900
Optional Treatment Skids				
Adsorption Pilot Skid	0	\$96,000	\$110,400	\$–
Ozonation Pilot Skid	0	\$196,000	\$225,400	\$–
DAF Pilot Skid	0	\$200,000	\$230,000	\$–

Continued . . .

Table 9. Estimated Construction Costs for the BTTF Retrofit (continued)

Description	Qty	2025 Unit Price	2025 Installed Unit Price	Total Estimated Cost
Instrumentation				
Particle Counter	1	\$8,855	\$10,190	\$10,200
HACH 3700 Electrodeless Conductivity Sensor	3	\$8,000	\$9,200	\$27,600
InfraCal 2 (emulsified oil) – InfraCal 2 Instrument	1	\$8,000	\$9,200	\$9,200
HACH Solitax Turbidity Probe with Controller	2	\$15,000	\$17,250	\$34,500
HACH Solitax TSS Probe with Controller	2	\$15,000	\$17,250	\$34,500
HACH LuminUltra ATP	1	\$8,000	\$9,200	\$9,200
Sievers InnovOx Online TOC Analyzer	2	\$45,000	\$51,750	\$103,500
Analytik-Jena Plasma Quant 9100 ICP OES (heavy metals/cations)	1	\$300,000	\$345,000	\$345,000
Metrohm 2060 IC Process Analyzer (anions/cations)	1	\$280,000	\$322,000	\$322,000
GC–MS (volatiles)	0	\$210,000	\$241,500	\$–
Tank Level Transducers	3	\$1,800	\$2,070	\$6,300
			Subtotal	\$902,000
Electrical				
Control Panel	1	\$65,000	\$84,500	\$84,500
Instrumentation Wiring	17	\$1,200	\$3,000	\$51,000
Valves and Miscellaneous Device Wiring	44	\$800	\$1,040	\$45,800
Skid Wiring	9	\$4,000	\$5,200	\$46,800
Pump Starters and Wiring	6	\$4,000	\$5,200	\$31,200
Networking Equipment and Wiring	1	\$30,000	\$60,000	\$60,000
Control Software and SCADA Hardware	1	\$15,000	\$30,000	\$30,000
Instrumentation and Controls Programming	1	\$175,000	\$175,000	\$175,000
			Subtotal	\$524,300
Mechanical				
Mechanical System Maintenance and Refurbishment	1	\$50,000	\$65,000	\$65,000
			Subtotal	\$65,000
Process				
Piping	500	\$50	\$70	\$45,500
Pumps	6	\$1,500	\$2,250	\$13,500
Valves – Electric Actuated	44	\$500	\$750	\$33,000
			Subtotal	\$92,000
Complete System Estimate				
Construction Subtotal				\$3,322,000
Contingency		20%		\$665,000
Opinion of Total Probable Construction Costs (\$2025)				\$3,987,000
Engineering/Construction Administration/Procurement		15%		\$599,000
EERC Project Oversight and System Shakedown Testing				\$410,000
Total Project Cost				\$4,996,000

Note: Estimated costs subject to change based on current market conditions and material pricing.

CONCLUSIONS

PW management presents additional challenges for unconventional oil and gas production compared to conventional production, primarily due to the fact that unconventional PW cannot typically be reinjected back into the producing formation and must be disposed of elsewhere or reused. Reuse options for this PW could include hydraulic fracturing, enhanced oil recovery, nonenergy applications such as chemical production, and potential alternate water supply scenarios like surface water discharge or groundwater recharge. Recovery of critical materials from PW, particularly lithium and magnesium, could also become an important domestic supply of these elements in the future. These developing areas of PW reuse will generally require higher-quality PW treatment than what has been acceptable for disposal and reuse for hydraulic fracturing.

BTTF has many attractive features to continue to serve as a test and development facility for PW treatment technologies. The facility is located at a commercial SWD operation and has access to several water sources for blending test water, and it has installed flow lines to directly dispose of any wastewater generated during testing. Bakken PW available at the facility is generally more concentrated than water from other unconventional plays, and when diluted it can approximate the bulk composition of other PW sources, particularly Permian PW. Targeted injections of specific compounds can further be used to increase the compositional similarity of key species. The facility is also set up to receive and use PW transported in bulk containers and tanker trucks.

Adapting BTTF to evolving PW treatment testing needs and using it to emulate PW from other formations will likely be more cost-effective than rebuilding a facility with equivalent capabilities in another unconventional play. During a site assessment by AE2S, the BTTF building and fixed infrastructure were determined to be in good condition, including exterior and interior brine holding tanks and related piping. Individual pieces of equipment from the original conditioning system are at the end of their useful life and cannot be reused. Similarly, the original control system, while functional, would likely not be cost-effective to reuse in the event of a significant expansion of the conditioning system's capabilities. The proposed facility retrofit will restore and expand test capabilities of the conditioning system to allow a wider range of water quality to be generated for treatment technology testing.

A Class 3-level (i.e., -20% to +30%) construction budgetary estimate for the as-described BTTF retrofit is approximately \$5,000,000, which includes conservative assumptions to account for potential price increases prior to starting a retrofit project. The estimate also includes the prerequisite detailed design effort and associated labor needed to finalize design requirements, and that will include full equipment specifications, bill of materials, and price quotations for the to-be-configured equipment and/or systems, as well as EERC project management and oversight and system shakedown testing upon completion. The EERC management will include oversight of design and construction activities with the engineering subcontractor and interfacing with DOE project/program management and site owner, Select Water, to ensure all desired system modifications are completed in an efficient and timely manner. Should DOE decide to fund the recommended site modifications in the near future, a detailed project proposal with updated cost estimates, based on current market conditions, would be prepared and submitted for consideration.

MILESTONES

The completed milestone table can be found in Table 10.

Table 10. Milestones

Milestone Title/ Description	Planned Completion Date	Actual Completion Date	Verification Methods	Comments
M1 – Subcontracts and Site Access Agreement Complete	10/15/2024	10/29/2024	Documented in quarterly report	Finalizing the agreements took longer than anticipated.
M2 – Preliminary Engineering Design (conceptual) and Cost Estimate Documents Complete	4/30/2025	4/30/2025	Documented in quarterly report	
M3 –Topical Report with Engineering Design (conceptual) and Cost Estimate Submitted	5/31/2025	5/30/2025	Topical report submitted to NETL	

REFERENCES

- Abdelhamid, C., Latrach, A., Rabiei, M., and Venugopal, K., 2025, Produced water treatment technologies—a review: *Energies*, v. 18, <https://doi.org/10.3390/en18010063>.
- Able, C., Schmitt, T., Siefert, N., and Fritz, A., 2025, Baseline cost analysis of energy wastewater treatment with preliminary feasibility analysis of critical mineral recovery: *Minerals*, v. 15, <https://doi.org/10.3390/min15030213>.
- Amakiri, K., Canon, A., Molinari, M., and Angelis-Dimakis, A., 2022, Review of oilfield produced water treatment technologies: *Chemosphere*, v. 298, <https://doi.org/10.1016/j.chemosphere.2022.134064>.
- Cole, G., Robbins, C., Grauberger, B., Garland, S., Tong, T., Bandhauer, T., and Quinn, J., 2022, Optimization of mobile oil and gas produced water treatment unit deployment logistics to achieve economic feasibility: *Resources, Conservation & Recycling*, v. 181, <https://doi.org/10.1016/j.resconrec.2022.106249>.
- Conrad, C., Yin, Y., Hanna, T., Atkinson, A., Alvarez, P., Tekavec, T., Reynolds, M., and Wong, M., 2020, Fit-for-purpose treatment goals for produced waters in shale oil and gas fields: *Water Research*, v. 173, <https://doi.org/10.1016/j.watres.2020.115467>.
- Energy & Environmental Research Center, 2024, Produced water management and recycling options in North Dakota: https://cms.oilresearch.nd.gov/image/cache/G-51-09FR_2.pdf (accessed Dec 15, 2024).
- Ghafoori, S., Omar, M., Koutahzadeh, N., Zendehboudi, S., Malhas, R., Mohamed, M., Al-Zubaidi, S., Redha, K., Baraki, F., and Mehrvar, M., 2022, New advancements, challenges,

- and future needs on treatment of oilfield produced water—a state-of-the-art review: *Separation and Purification Technology*, v. 289, <https://doi.org/10.1016/j.seppur.2022.120652>.
- Ground Water Protection Council, 2025, Modern oil & gas development – 2023 update: www.gwpc.org/wp-content/uploads/2023/12/GWPC-Modern-Oil-and-Gas-Primer-Update_FINAL.pdf (accessed May 2025).
- Hennings, P., and Smye, K., 2024, Knowns, questions, and implications of induced seismicity in the Permian Basin: AAPG, <https://doi.org/10.1306/08292424051>.
- Khatoon, R., Raksasat, R., Ho, Y., Lim, J., Jumbri, K., Ho, C., Chan, Y., Abdelfattah, E., and Khoo, K., 2023, Reviewing advanced treatment of hydrocarbon-contaminated oilfield-produced water with recovery of lithium: *Sustainability*, v. 15, <https://doi.org/10.3390/su152216016>.
- Nath, F., Chowdhury, M., and Rhaman, M., 2023, Navigating produced water sustainability in the oil and gas sector—a critical review of reuse challenges, treatment technologies, and prospects ahead: *Water*, v. 15, <https://doi.org/10.3390/w15234088>.
- Nikkhah, H., Ipekci, D., Xiang, W., Stoll, Z., Xu, P., Li, B., McCutcheon, J.R., and Beykal, B., 2024, Challenges and opportunities of recovering lithium from seawater, produced water, geothermal brines, and salt lakes using conventional and emerging technologies: *Chemical Engineering Journal*, v. 498, <https://doi.org/10.1016/j.cej.2024.155349>.
- Scanlon, B.R., Ikonnikova, S., Yang, Q., and Reedy, R.C., 2020a, Will water issues constrain oil and gas production in the United States?: *Environmental Science & Technology*, v. 54, <https://doi.org/10.1021/acs.est.9b06390>.
- Scanlon, B.R., Reedy, R.C., Xu, P., Engle, M., Nicot, J.P., Yoxtheimer, D., Yang, Q., and Ikonnikova, S., 2020b, Can we beneficially reuse produced water from oil and gas extraction in the U.S?: *Science of the Total Environment*, v. 717, <https://doi.org/10.1016/j.scitotenv.2020.137085>.
- Select Water AquaView, 2025, AquaView technology: www.selectwater.com/technology/aquaview/ (accessed May 2025).
- Smith, K.H., Mackey, J.E., Wenzlick, M., Thomas, B., and Siefert, N.S., 2024, Critical mineral source potential from oil and gas produced waters in the United States: *Science of the Total Environment*, v. 929, <https://doi.org/10.1016/j.scitotenv.2024.172573>.
- Tetra Automation and Monitoring, 2025, Water management automation and monitoring: <https://onetetra.com/energy-services/water-management/automation-and-monitoring/> (accessed May 2025).
- U.S. Energy Information Administration, 2025a, Petroleum and other liquids: www.eia.gov/dnav/pet/pet_crd_crpdn_adc_mbbldpd_m.htm (accessed May 2025).

U.S. Energy Information Administration, 2025b, Monthly crude oil and natural gas production: www.eia.gov/petroleum/production/#ng-tab (accessed May 2025).

U.S. Energy Information Administration, 2025c, Annual energy outlook 2025: www.eia.gov/outlooks/aeo/tables_ref.php (accessed May 2025).

Walsh, F.R., and Zoback, M.D., 2015, Oklahoma's recent earthquakes and saltwater disposal: Science Advances, <https://doi.org/10.1126/sciadv.1500195>.

APPENDIX A

BEST DEMONSTRATION TEST SITE OVERVIEW



Energy & Environmental Research Center (EERC)

**BRINE EXTRACTION AND STORAGE TEST (BEST)
DEMONSTRATION TEST SITE
DE-FE0026160**

U.S. Department of Energy National Energy Technology Laboratory
Water Technologies Project Review Meeting
September 17, 2020 – 1:30 p.m. ET

John Hamling
Assistant Director, Integrated Projects

NORTH DAKOTA

BRINE TREATMENT USER FACILITY



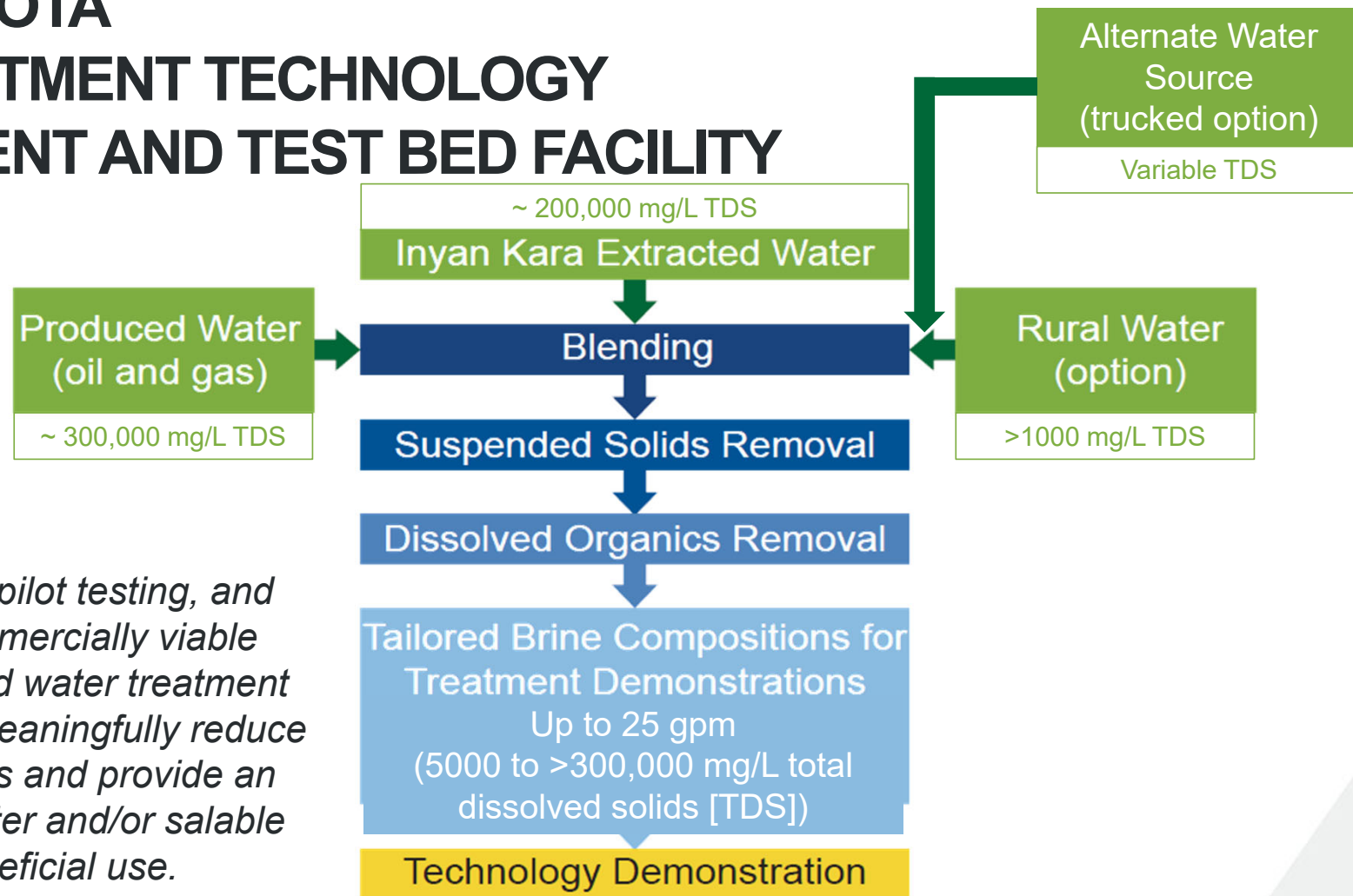
UNIVERSITY OF
NORTH DAKOTA



NORTH DAKOTA BRINE TREATMENT TECHNOLOGY DEVELOPMENT AND TEST BED FACILITY

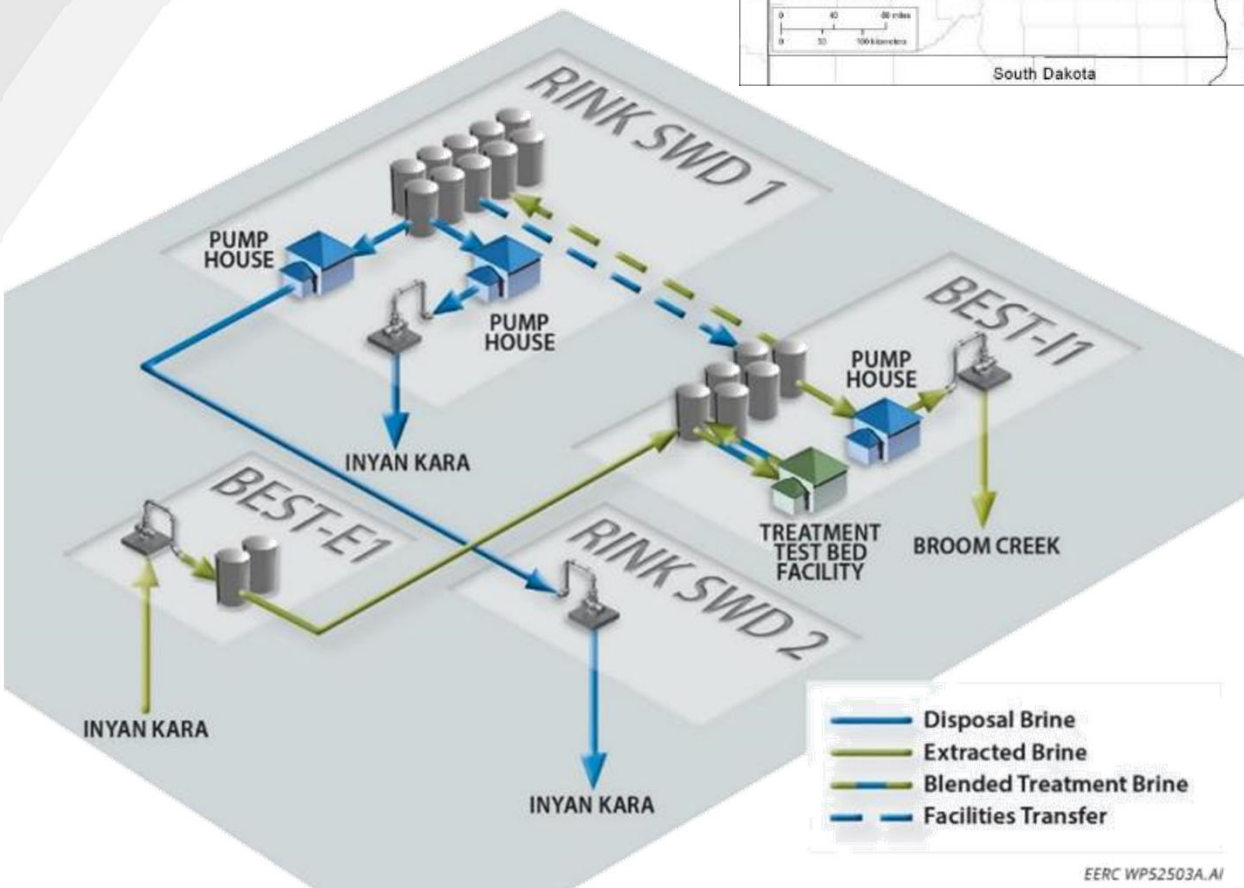
Implement and operate a brine treatment technology development and test facility to enable development of brine treatment technologies capable of treating high-total dissolved solids (TDS) brines associated with geologic CO₂ storage targets.

NORTH DAKOTA BRINE TREATMENT TECHNOLOGY DEVELOPMENT AND TEST BED FACILITY



Enable development, pilot testing, and advancement of commercially viable extracted and produced water treatment technologies that can meaningfully reduce brine disposal volumes and provide an alternate source of water and/or salable products for beneficial use.

THE SITE



EERC
LND NORTH DAKOTA



A photograph of a water treatment facility. In the foreground, there are two large, vertical, cylindrical storage tanks. To the right of the tanks is a small, single-story building with a brown roof. The ground is reddish-brown dirt. In the background, there is a flat landscape under a clear sky.



John Harding, Mark Kim, Pam Klappelch, Lorry Jacobsen, and Robert Janssen

undarc.org



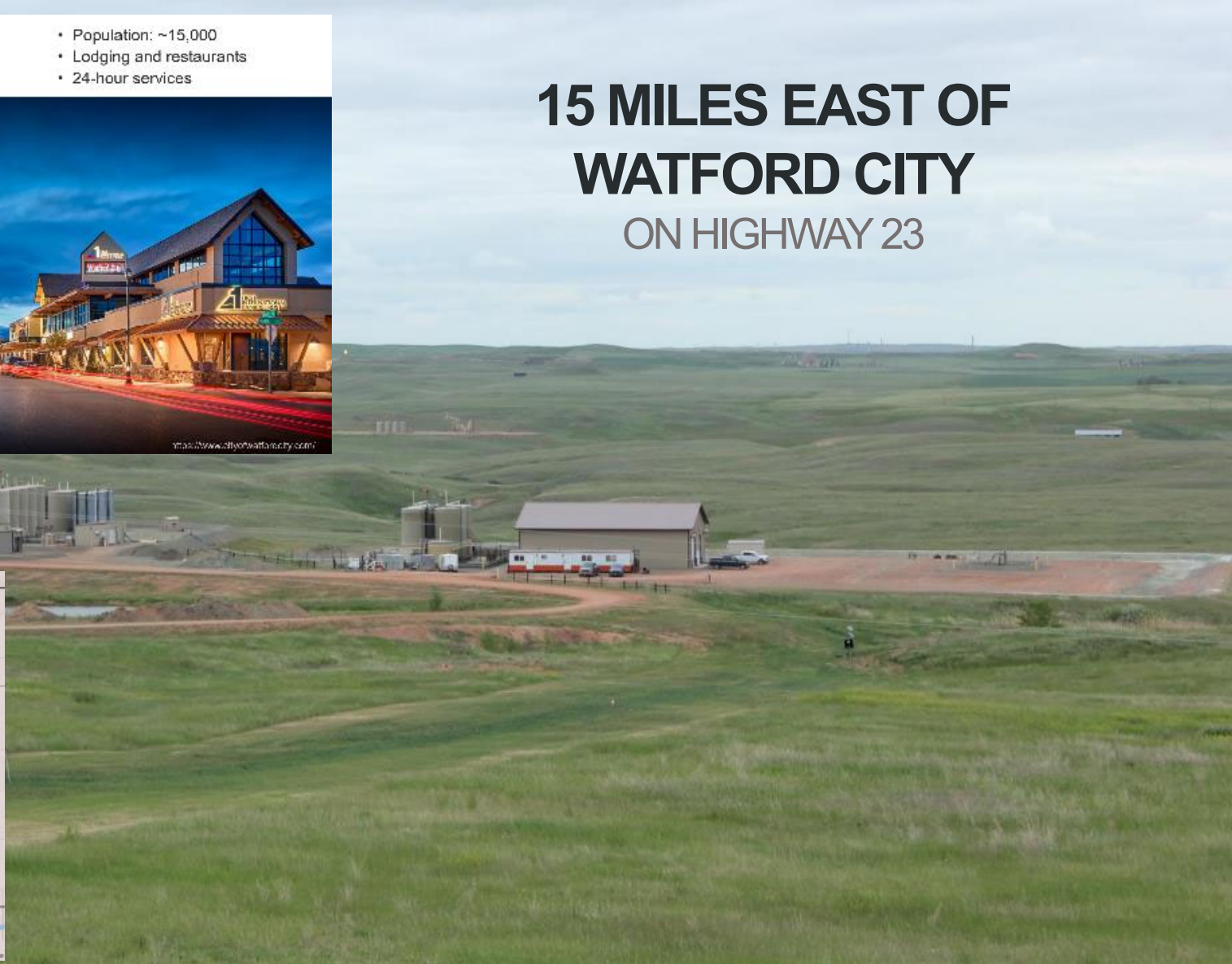
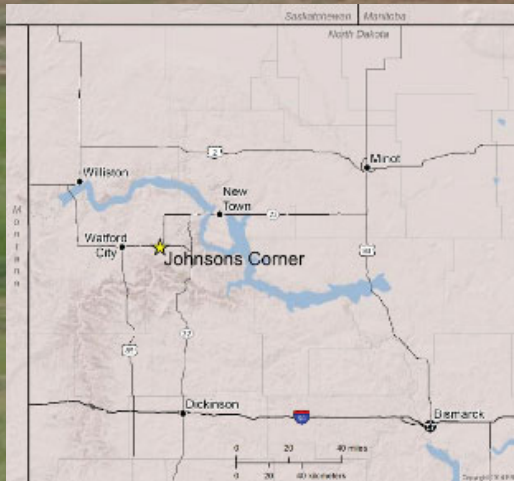
WATFORD CITY, NORTH DAKOTA

Oil & Gas Industrial Hub

- Population: ~15,000
- Lodging and restaurants
- 24-hour services



15 MILES EAST OF WATFORD CITY ON HIGHWAY 23



WATER TREATMENT DEMONSTRATION FACILITY



- Permanent environmental enclosure (24/7/365 ready)
 - 60' x 80' (18' wall height)
 - Air-handling and exchange
 - Class I Division 2-rated
- 53' demonstration bay with concrete floor
- Two overhead doors
- Integrated with active reservoir management (ARM) and saltwater disposal (SWD) infrastructure
- Treatment rates up to 25 gpm (bench to pilot)
- Blending and pretreatment

- Sized to accommodate up to a semi-tractor-trailer-sized demonstration
- 300 kW electric power
- Waste management
- Propane (5000-gal tank)*
- Noncontact cooling water (30 gpm)*

* Can be accommodated.



BLENDING AND PRETREATMENT

Blending of water to a target TDS level of 180,000 mg/L

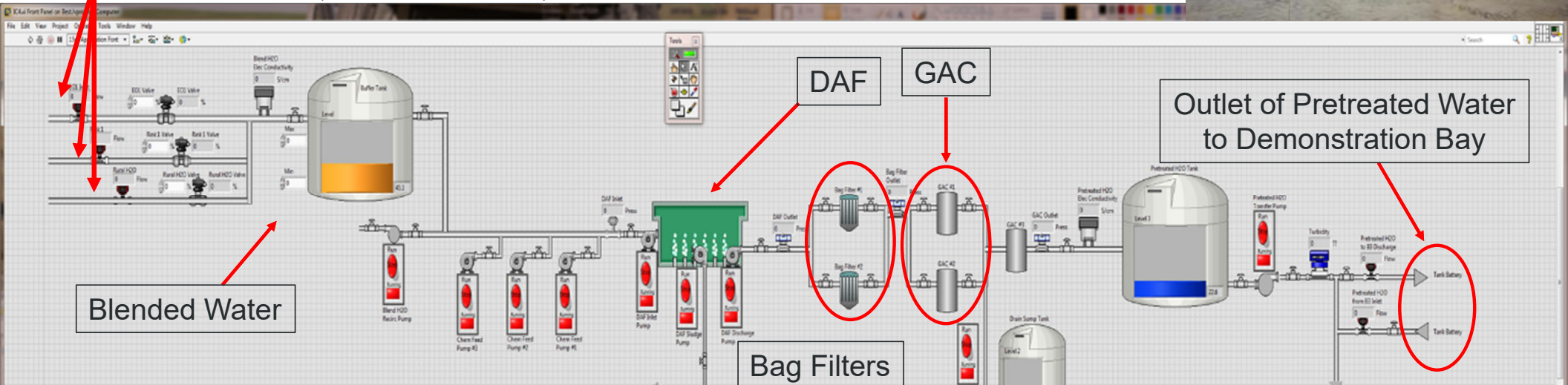
... or tailored blends
<5000 mg/L TDS
to
>300,000 mg/L TDS

to suit capabilities and/or
limitations of selected
technologies.

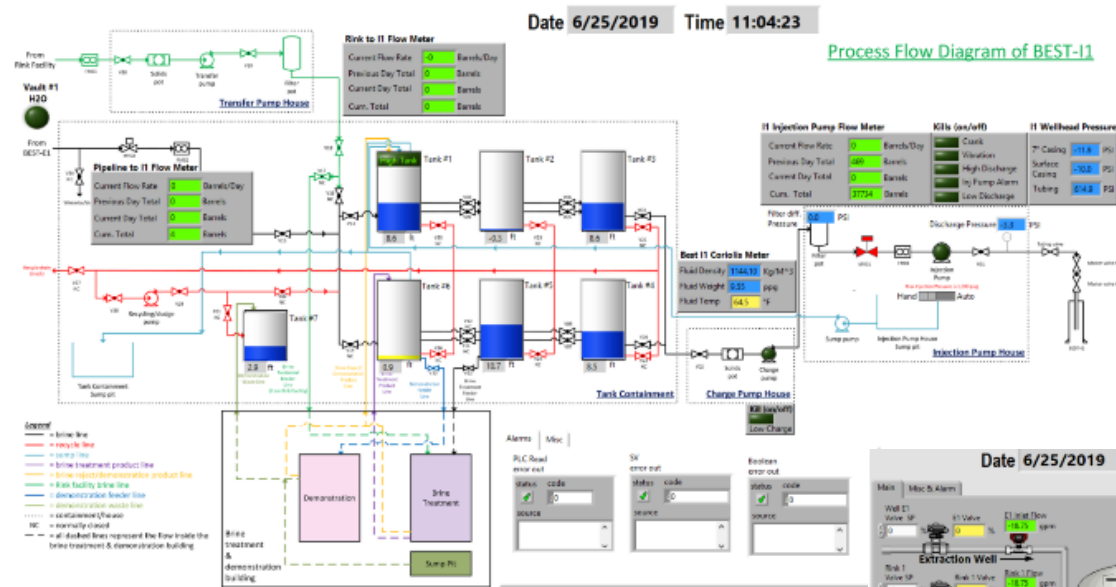
- Suspended solids removal (dissolved air flotation [DAF]).
- Filter bags.
- Dissolved organics removal (granular activated carbon [GAC]).
- Facility can be adapted for use with alternate fluid compositions and treatment/prereatment processes.



EXTRACTED, PRODUCED, AND FRESHWATER SOURCE



SCADA, REMOTE MONITORING AND CONTROLS



Water Blending and Pretreatment

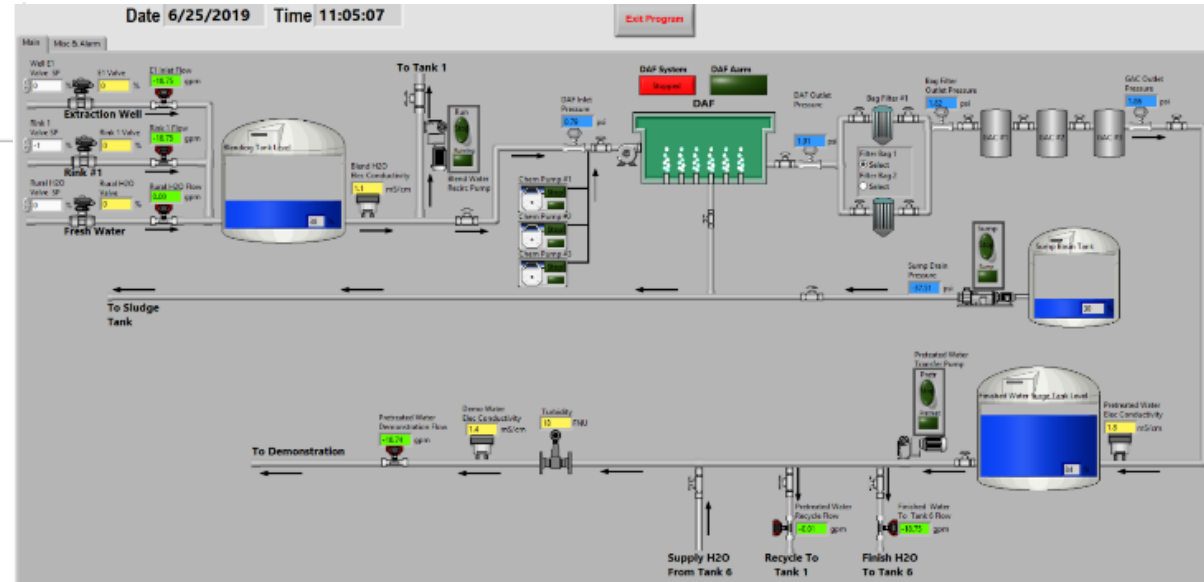


Finished Water Supply for Demonstrations

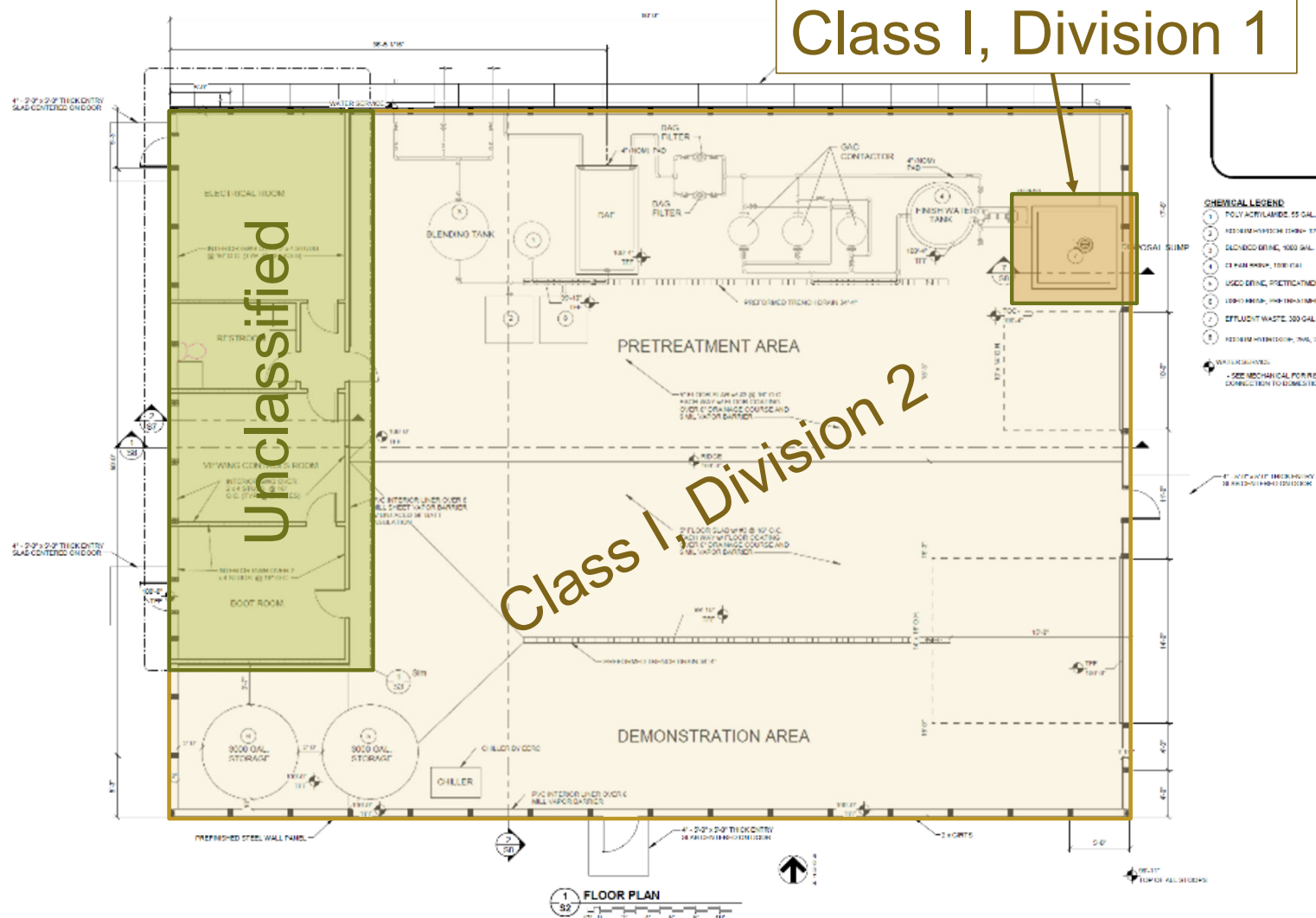
BLENDING AND PRETREATMENT

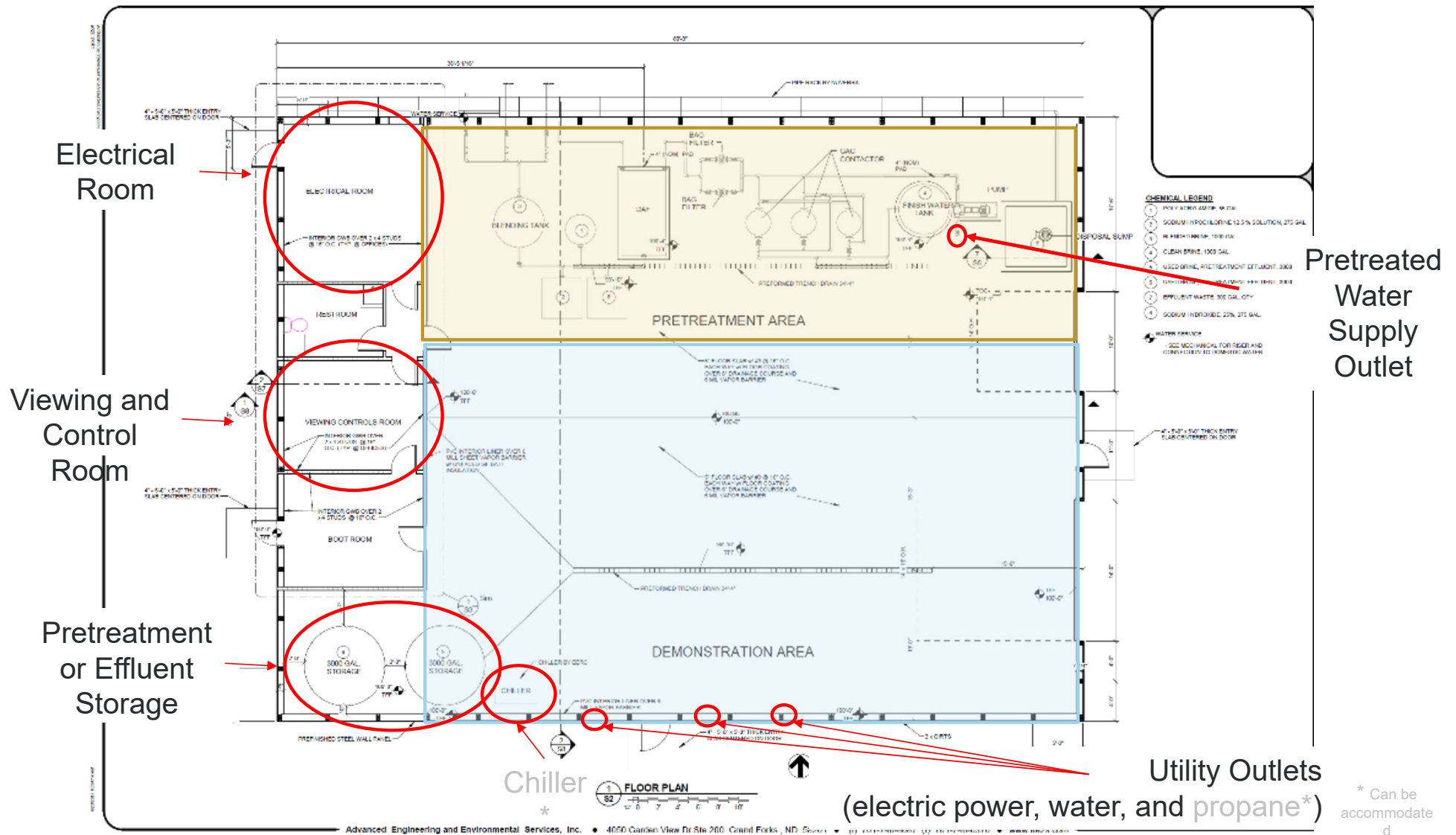
FACILITIES

- Influent and effluent flow rates and composition
- Chemical usage
- Energy and thermal use/load
- HSE and operability systems (e.g., pretreatment systems, hazardous environmental monitoring...)
- Remote, real-time, secure access



Class I, Division 1

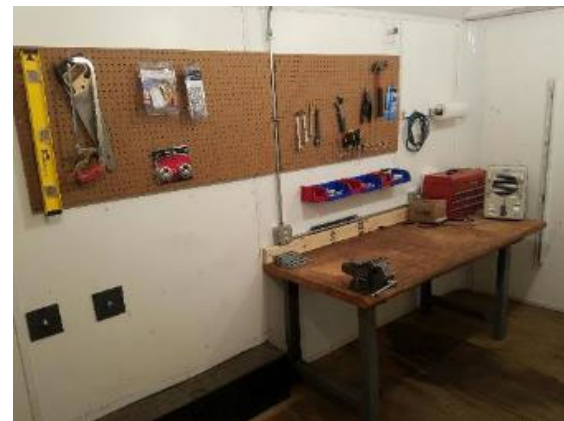




* Can be accommodate

MOBILE WORKSHOP AND COMMAND CENTER

MULTIUSE OFFICE, MEETING AND
WORKSPACE





- Seeking to develop and test two or more brine treatment technologies at the North Dakota brine treatment technology development and test bed facility.
- Enable development of brine treatment technologies capable of treating high-TDS brines associated with geologic CO₂ storage targets. (~180,000 mg/L TDS).
 - Alternate source of water
 - Reduced disposal volumes
 - Salable products for beneficial use
- Cost offsets may be made available for highly qualified technologies.

WILLISTON BASIN WATER TREATMENT TECHNOLOGY TEST BED

WE SEEK TO PILOT-TEST TECHNOLOGIES CAPABLE OF TREATING HIGH-TDS WATER.

TREATMENT AND HANDLING of high-TDS (total dissolved solids) waters associated with energy production are challenging and not readily or economically accomplished using conventional water treatment techniques. Geologic injection is often required to effectively manage fluids associated with electrical power generation, oil and gas production, and active reservoir management for geologic CO₂ storage.

As part of a public-private collaboration, a facility is being constructed in western North Dakota to pilot-test high-TDS water treatment technologies that can:

- Produce alternate sources of water for industrial or domestic use.
- Produce salable products.
- Meaningfully reduce brine disposal volumes.

Pilot testing provides critical understanding of technology performance under field operating conditions. This understanding enables the advancement and commercial adoption of viable technologies capable of treating these challenging waters for beneficial use.

The Energy & Environmental Research Center (EERC) is seeking companies interested in pilot-testing water treatment technologies at the facility. This is a collaborative effort with Nuverra Environmental Solutions (Nuverra) and the U.S. Department of Energy (DOE) National Energy Technology Laboratory.

The extracted water treatment test bed facility is located approximately 13 miles east of Watford City, North Dakota, immediately adjacent to North Dakota Highway 23 on the Johnsons Corner site, a Nuverra-operated commercial saltwater disposal (SWD) facility.

The test bed will feature the ability to blend extracted and produced waters in order to generate tailored brine compositions ranging from ~4500 to ~300,000 mg/L TDS.

EERC engineering staff will be on-site during all demonstration activities to assist with connections to the test bed facility and to monitor and gather process performance data. Technology developers are expected to provide their own operations staff. During steady-state operation, EERC engineering staff will conduct energy and material balances (power consumption, process flows, and influent and effluent quality analyses).

A report summarizing demonstration activities and detailing performance data and technology capabilities will be prepared and submitted to DOE. Nondisclosure and site access agreements between the EERC, Nuverra, and technology developers will be negotiated prior to demonstration.

Currently, no guarantee is offered that DOE or other funding will be available to assist interested treatment technology developers. However, the field site and facilities for water treatment demonstrations, including potential cost offsets for power, cooling water, and effluent disposal, may be made available at no or reduced cost to selected demonstrations.

Conceptual extracted water treatment flow diagram.

Critical Challenges. Practical Solutions.

TECHNOLOGY TESTING

BRINE TREATMENT DEVELOPMENT FACILITY



Critical Challenges. Practical Solutions.

NORTH DAKOTA BRINE TREATMENT FACILITY

POTENTIAL ADAPTATION FOR EXPANDED APPLICATIONS

Facility can be readily adapted for use with alternate fluid compositions or treatment processes.

- Alternate water sources trucked and offloaded at site.
- Pretreatment and conditioning can be modified to replicate broader influent specifications.
- Blending of additives to replicate target fluid chemistries.
- Application of cascade technologies (e.g., power/thermal supply, pretreatment/conditioning...).
- On-site SWD and waste handling.



NORTH DAKOTA BRINE TREATMENT FACILITY

POTENTIAL ADAPTATION FOR EXPANDED APPLICATIONS

- Oil and gas fluid conditioning (e.g., emulsion breaking, corrosion, scale inhibitors, fluid compatibility testing, etc.)
- Produced water treatment
- Electric power generation wastewater treatment
- Industrial and municipal waste and water treatment
- Mineral resource recovery
- Agricultural water treatment
- Geologic conditioning and homogenization as a means of water pretreatment
- Benchmarking the economic and technical limits of water treatment technologies (e.g., MVR)
- Collaboration with other federal, state, or industry groups





John Hamling
Assistant Director, Integrated Projects
jhamling@undeerc.org
701.777.5472 (phone)

**Energy & Environmental
Research Center**
University of North Dakota
15 North 23rd Street, Stop 9018
Grand Forks, ND 58202-9018

www.undeerc.org
701.777.5000 (phone)
701.777.5181 (fax)

A wide-angle photograph of a university campus at sunset. The sun is low on the left, casting a warm glow over the scene. Trees with yellowing leaves are in the foreground. In the background, there are several large, multi-story brick buildings and a parking lot filled with cars.

THANK YOU

Critical Challenges. Practical Solutions.

APPENDIX B

BTTF IMPROVEMENT REPORT

BTTF Improvement Report

1. Background and Introduction

Advanced Engineering and Environmental Services (AE2S) was contracted in 2017 by the Energy & Environmental Research Center to perform the process engineering, site design, piping, equipment design, layout, procurement of the water treatment technologies, and construction of the original Brine Extraction Storage Test facility located in the Williston Basin near Johnson's corner east of Watford City. This is now called the Brine Technology Test Facility (BTTF). To accommodate the demonstrations from technologies provided by others, the original objective was to blend the water to achieve an appropriate TDS, remove any suspended solids, and reduce organics as much as possible. This pretreated stream could then be conveyed to the demonstration technologies. This new phase of the BTTF project intends to evaluate the usefulness of the site, existing treatment equipment, and to propose upgrades to the pretreatment process while also providing options for enhanced treatment beyond blending and solids and organics reductions. The following report outlines AE2S' perspective as the BTTF site is being studied for possible improvements to expand the type of technologies and produced water sources that could be evaluated.

2. Study Objectives

The BTTF facility is ideally located to take advantage of multiple water sources that can be blended to represent a wide range of source waters and analyze a wide variety of treatment technologies. The goal of this study is to provide a wide range of capabilities that could provide insight into multiple reuse options of both produced waters and other deep aquifer saline water sources. Each of these objectives is summarized below:

Critical materials such as lithium, magnesium, nickel, cobalt, etc., have become an increasing area of interest as manufacturing of advanced technologies require significant amounts of these minerals. Produced water is typically considered a waste by-product of shale oil and gas extraction but it does often contain trace amounts of several critical materials which could provide value additions to the oil industry. Produced water is available in large quantities in numerous areas across the United States. One goal of this study is to identify modular process operations that may isolate critical materials from Williston Basin brines and also other formation produced waters such as the Permian Basin. The system design includes appropriately sized instrumentation to measure the range of characteristics expected from United States brines, also outlined in this report.

As source basin pressures are depleted EOR will become increasingly important to ensure hydrocarbon production is maintained. This report characterizes the level of treatment required to

provide a source of water-flood solutions from extraction brines. In addition to EOR, discussion of treatment operations is included to bring Bakken and Permian produced water up to the quality required for fracing. The unit operations and technologies are discussed including parameters, technologies, organic reduction, turbidity reduction, interfering metals reduction, TDS reduction, etc.

With a reconfigured BTTF site, investigation of treatment options and technologies to reuse Dakota Aquifer water for fracing in the Bakken would be possible. The Dakota Aquifer is the primary injection target for Bakken produced water disposal, and has become locally pressurized. Some water management concepts, such as Geologic Homogenization, Conditioning, and Reuse [GHCR], are based on producing Dakota water for fracing, or other use, as a means of pressure management. The system could also be used to formulate what processes, and their costs, would be associated with upgrading Dakota Aquifer water for use in irrigation, industrial water supply, or as drinking water.

3. Evaluation and Assessment of Existing BTTF Facility

AE2S visited the BTTF site in February 2025 to conduct a site and equipment assessment. The building structure and site remain in good condition and no upgrades are expected as part of any reuse project. (Exhibit A – Site Assessment Photos)

- a. SCADA System. The Control panel and SCADA computer look to be in good working order, however, they were designed and programmed for a specific set of process equipment. The National Instruments (NI) brand Programmable Logic Controller (PLC) series currently installed is nearing obsolescence. Therefore, sourcing compatible hardware for equipment additions will prove challenging given the timeline for construction is still likely months or years out. The NI SCADA hardware, while adept for small laboratory installations and collection of many data points, is not designed for industrial process control like what is being proposed here. Reuse/repurposing, or a combination of NI SCADA hardware with some other automation system would be extremely challenging and likely more costly than starting from scratch. AE2S would suggest replacing the main with a distributed control system of smaller control panels installed near the proposed process equipment. Final detailed design concepts would be driven by functionality required by the process equipment and what level of instrumentation would accompany the selected treatment skids.
- b. Facility electronic components – hazardous gas detectors, leak sensors, power meters for demonstration equipment, etc. All facility sensors visually appeared to be in good condition and are expected to be serviceable. These sensors can most likely be integrated into an updated control system to provide the same monitoring and trigger functions as in the original facility configuration.

- c. Process electronic components – conductivity meters, flow meters, pressure meters, etc. While visual inspections indicated no significant damage to almost all of the existing instrumentation, AE2S expects that some of these components may need replacement given changes to the system processing requirements. Some flowrate agnostic components pressure transducers and electrical conductivity meters may, pending further inspection and verification of functionality, be repurposed. Flow meters, control valves and other in-line process equipment may need replacement with appropriately sized components suitable for the lower throughput capacity of the planned process systems.
- d. Influent and water blending system. The exterior tank farm on site is in acceptable condition with only routine cleaning needed to be operational again. The influent and water blending system remain in acceptable condition, but potential automation upgrades may be desired to control and monitor the blending system. The inlet transfer pump and flow meter along with the mixing tank are sized correctly to handle the expected flow rates for this new application. An additional pump to improve flow control from the external tank battery into the blending process may be desired.
- e. Dissolved Air Flotation (DAF) system. The original BTTF system incorporated a DAF system for removal of bulk solids in the pretreatment process. The DAF consisted of a large enclosed stainless-steel vessel with inlet and outlet piping and inlet dissolved air injection to float the solids for skimming and disposal. During operational shutdown periods, the DAF would be drained and flushed with freshwater in an attempt to purge the produced water. The complex internal configuration did prevent complete cleanout of the produced water and associated residues which has caused significant corrosion of the unit. This includes corrosion of the tank and enclosure walls of the DAF. The DAF was also sized for a larger flow than what is expected in a BTTF redesign. AE2S recommends removing and disposing of the existing DAF.
- f. Granulated Activated Carbon (GAC) Contactors. Portions of the GAC contactors experienced corrosion during previous test campaigns. These units were also sized for previous efforts and are oversized for this use case.
- g. Effluent piping and finished water tankage. These components are usable for a re-designed BTTF facility. Adequate post treatment storage will be useful for potential use in follow-on demonstration units. With further operational review of the accompanying instrumentation, it is expected that these flow meters, conductivity instrumentation, piping and tankage will be adequate for future use in an upgrade BTTF facility.

4. Identification and Recommendations for Practical Applications of the BTTF Facility

The BTTF facility is unique with applicability not only to oil and gas extraction and production research but also could offer the ability to test secondary and tertiary revenue streams

through recovery of precious metals, critical minerals, and purified water for reuse. Additional funding for expansion of the BTTF site would not just benefit North Dakota oil and gas production but would expand the scope of what types of brines could be treated and tested with a modular system layout. Modularity and sampling/control automation offered in a reconfigured BTTF system would allow operators to test produced water treatment technologies processing in real time.

After visiting the site in February 2025, AE2S personnel believe there is value to keeping the BTTF facility operational with this processing upgrade. From a site perspective the facility is in very good condition. When built, the building was equipped with top-of-the-line safety features to ensure personnel a safe working environment. Features include gas and liquid leak detection, instrumentation and control, as well containment for produced water transfer and storage facilities, all of which are expected to be serviceable and could be integrated into a new control system.

The BTTF site was built with proximity to a Bakken source water well and two saltwater injection sites. With PW injection and sample extraction in proximity to the facility, a steady state condition can be tested with relatively small operating investment.

A significant feature of this facility is the ability to blend Bakken, Permian, or other produced waters for testing state-of-the-art water treatment technologies at a singular location. From AE2S' perspective and experience with our energy clients, this functionality is unique, offering a tool that could benefit many operators and energy producing states. The cost to construct a similar site in one or multiple other basins to test produced water cleanup technologies far exceeds the cost of blending or transporting brines to the BTTF site. In addition, the heavy lift of the investment, permitting, siting, building, wells, equipment, safety systems, has already been made.

To simplify the produced water cleanup process the team broke up the unit operations into three main steps and a cleaning step, each which are summarized here and covered in detail below. A high-level process diagram for the BTTF facility treatment train that correlates to this discussion is attached to the end of this report.

- a. Blending and Pretreatment system – exterior tankage, multiple injection ports, dilution water, extraction well source, produced water source, oil water separator, coagulation/flocculation system, filtration and granular activated carbon (GAC) contactors, and pH adjustment.
- b. Primary Treatment – ion exchange/heavy metal reduction, softening, and ultrafiltration (UF).
- c. Secondary Treatment - electrodialysis reversal, reverse osmosis, and super filtration.
- d. Cleaning System - The system would also include a treatment skid to flush the system after testing campaigns. AE2S suggests piping and bypass valves to be able to test various treatment techniques in cascading or parallel arrangements.

5. Treatment Processes and Instrument Discussion.

The planned flow range for this system is 1 to 5 gallons per minute. All processing equipment and instrumentation design and price estimates are based on this assumption.

Produced water (PW) can contain a mixture of suspended solids, dissolved organic chemicals, and dissolved inorganic chemicals. The PW quality can vary significantly from region to region across the United States and across the world. Suspended solids may include silt, algae, clay, sand, and other sediments. Dissolved organic chemicals can include phenol, benzene, toluene, ethylbenzene, and xylenes (BTEX). Dissolved inorganic chemicals can include barium, calcium, magnesium, sodium, potassium, and chloride. Heavy metals may include cadmium, chromium, copper, zinc, nickel, mercury, lead, manganese, and iron. ⁽¹⁾

(1) K. T. Amakiri et al. (2022) "Review of Oilfield Produced Water Treatment Technologies" Chemosphere 298, 134064.

Reagent Water. An important aspect of performing water quality analysis is the use of reagent water for creating reagents, diluting samples, and preparing blanks. Reagent water should be devoid of the chemicals of which are being analyzed along with any chemicals which may interfere with the water sample analysis. Because the proposed lab at the EERC BTTF facility will contain several lab instruments which are highly sensitive with low detection levels, it is recommended that the reagent water be of high quality that has a minimum resistivity of 18 megohms-cm at 25 C (ASTM Type 1). 18 megohms-cm water can be achieved using mixed bed deionization followed by water polishers at individual water use locations. The water polishers will employ activated carbon adsorption and ion exchange filters. The final polishing step will include ultra filtration and UV sterilization.

Laboratory Safety Systems. The health and safety of the lab personnel is the responsibility of the organization. Safety systems shall be in place to protect the health and safety of the lab personnel. The safety systems must include sufficient lab space ventilation to prevent the exposure of lab personnel to hazardous fumes, eyewash and safety showers, fume hoods, hazardous chemical spill kits, fire blankets and extinguishers and proper chemical storage cabinets. ⁽²⁾ (2) APHA (2012) Standard Methods for the Examination of Water and Wastewater, 22nd Edition.

a. Inline Water Quality Analyzers.

Inline analyzers will measure water quality in real time. The instruments will allow operators to monitor the treatment process and take immediate corrective actions on inefficient treatment. Several inline instruments will be used within the pilot plant to monitor water quality as it flows through the processes. The following sections will describe the inline analyzers that are proposed for this pilot plant.

- i. **Turbidimeter.** Turbidity is the measure of suspended solids in the water and is generally caused by clay, silt, and organic and inorganic matter. The technology to

measure suspended solids is through the detection of the amount of light scattered by the particle. Methods for the analysis of turbidity include EPA 180.1 and Standard Methods 2130 B. Both bench top and inline turbidimeters / probes are available with several manufacturers to choose from. Inline turbidimeters will be placed at the discharge end of the raw water mixing tank, the effluent of the pre-treatment step, the effluent of the primary treatment step, and the effluent of the secondary treatment step. There are several treatment skids that would also be supplied with an inline turbidimeter such as the coagulation / flocculation sedimentation skid and filtration and GAC contactor columns. As each individual pilot skid is designed, additional turbidimeters can be installed to support the monitoring of the PW water quality.

- ii. Total Suspended Solids (TSS). Total suspended solids in water refers to the undissolved portion of solids that do not settle. Like turbidity, these particles can be caused by clay, silt, and organic and inorganic matter. TSS reduces water clarity and makes the water look cloudy or murky. Generally, TSS has been measured by gravimetric analysis but more recently insertable probes have been developed that absorb and scatter light. The difference between the measurement of turbidity and TSS is that turbidity measures light scattering while TSS measures the mass of suspended solids per unit volume of water.
- iii. Inline TSS probes are available with multiple manufacturers to choose from. Inline TSS probes will be placed at the discharge end of the raw water mixing tank, the effluent of the pre-treatment step, the effluent of the primary treatment step, and the effluent of the secondary treatment step. There are several treatment skids that will also be supplied with a TSS probe such as the coagulation / flocculation sedimentation skid and filtration and GAC contactor columns. As each individual pilot skid is designed, additional TSS probes can be installed to support the monitoring of the PW water quality. It should be noted that some manufacturers produce a combination turbidity / TSS probe in one. It is anticipated that the combination turbidity / TSS probes will be used in this application.
- iv. pH measurement. pH is one of the most important and frequently used tests in the treatment of water. Nearly every process in water or wastewater treatment is dependent on pH. Methods for the analysis of pH include EPA 150.3 and Standard Methods 4500-H⁺ B. Bench top and inline pH meters are available with multiple manufacturers to choose from. Inline pH meters will be placed at the discharge end of the mixing tank, the effluent of the pre-treatment step, the effluent of the primary treatment step, and the effluent of the secondary treatment step. There are several treatment skids that will also be supplied with an inline pH meter such as the coagulation / flocculation sedimentation skid, filtration and GAC contactor columns, and the pH adjustment skid. As each individual pilot skid is designed,

additional pH meters can be installed to support the monitoring of the PW water quality.

- v. Conductivity (surrogate for TDS). Conductivity is the measure of the ability of a solution to carry an electrical current. The conductivity of a solution depends on the presence and concentration of ions and the temperature of the water. Conductivity can provide a reliable method of determining the reduction of ions in the water through each treatment process. The method for the analysis of conductivity is Standard Methods 2510 B. Both bench top and inline conductivity meters are available with multiple manufacturers to choose from. Inline conductivity meters will be placed at the discharge end of the mixing tank, the effluent of the pre-treatment step, the effluent of the primary treatment step, and the effluent of the secondary treatment step. There are several treatment skids that will also be supplied with inline conductivity meters such as the coagulation / flocculation sedimentation skid and the filtration and GAC contactor columns. As each individual pilot skid is designed, additional conductivity meters can be installed to support the monitoring of the PW water quality.
- vi. Particle Counter. A particle counter is used for water quality control and can size and count particles in a water stream. Particle counters are useful in tracking the performance of filters by counting and sizing the particles in the filter effluent. Particle counters are more sensitive to the detection of particles than turbidimeters and thus can identify degradation in filter performance faster than a turbidimeter. The method for the analysis of particles in water include, Standard Methods 2560 B, 2560 C, and 2560 D. Both bench top and inline particle counters are available with multiple manufacturers to choose from. An inline particle counter will be placed at the effluent of the filtration and GAC contactor columns and at the effluent of any membrane skid.
- vii. Total Organic Carbon (TOC). TOC is the measure of organic carbon in water. The measurement of TOC can indicate the organic load of an industrial wastewater and helps assess the efficiency of the treatment processes. The methods for the analysis of conductivity include Standard Methods 5310 B, 5310 C, and 5310 D. Both bench top and inline TOC analyzers are available with multiple manufacturers to choose from. Inline TOC analyzers will be placed at the discharge end of the mixing tank, the effluent of the pre-treatment step, the effluent of the primary treatment step, and the effluent of the secondary treatment step. As each individual pilot skid is designed, additional TOC analyzers can be installed to support the monitoring of the PW water quality.
- viii. Ion chromatography (IC). IC is the analysis of specific analytes in water including calcium, magnesium, lithium, sodium, ammonium, potassium, fluoride, chloride, nitrite, ortho-phosphate, bromide, nitrate, sulfate, bromate, chlorite, and chlorate. Not all anions are specific to PW and need to be analyzed. The methods for the

analysis of anions by IC include EPA 300.0, Standard Methods 4110 B and 4110 C. Bench top and inline IC analyzers are available with multiple manufacturers to choose from. Inline IC analyzers will be placed at the discharge end of the mixing tank, the effluent of the pre-treatment step, the effluent of the primary treatment step, and the effluent of the secondary treatment step.

b. Grab sample analysis

Grab samples could be collected manually throughout the treatment system and provide water quality data at that specific time and place. Grab samples will be analyzed for specific chemicals either within an onsite lab or sent to a contract lab. It is proposed that the onsite lab will provide instrumentation to allow for analysis of the following parameters.

- i. Emulsified Oil. Oil in water analysis provides a quick and accurate determination on the amount of oil in a water sample. PW can have detectable concentrations of oil that need to be removed before the water can be discharged. Methods for the analysis of oil in water include ASTM D7066, EPA 413.2 and EPA 418.1. A bench top unit is available with several manufacturers to choose from. Samples can be collected from taps to be installed throughout the pilot plant. This analysis would be used to determine the effectiveness of each treatment process on the removal of oil from the produced water stream.
- ii. Volatile Organic Chemicals. Many volatile organic chemicals (VOCs) in water can be analyzed using a purge and trap with a gas chromatograph / mass spectrometer (GC/MS). It is proposed the pilot plant project be provided with a purge and trap GC/MS for the analysis of VOCs. The list of VOCs capable of being detected by Purge and Trap GC/MS number nearly 60 compounds. The method for the analysis of VOCs is EPA Method 524.2 or Standard Methods 6200 B. Samples can be collected from taps to be installed throughout the pilot plant. This analysis would be used to determine the effectiveness of each treatment process on the removal of VOCs.
- iii. Metals and Divalent Cations. Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) can analyze a number of different metals and divalent cations in water. It is proposed the pilot plant project will be provided with an ICP-OES to analyze the different metals and divalent cations that may be found in the PW stream. The method for the analysis of metals by ICP-OES is EPA 200.7 or Standard Methods 3120 B. Samples can be collected from taps to be installed throughout the pilot plant. This analysis would be used to determine the effectiveness of each treatment process on the removal of metals.
- iv. Microbiological. The need to determine the type and count numbers for different microbial communities in PW is critical for understanding the effect of microbial

communities on corrosion and fouling. Tests have been developed which use Adenosine Triphosphate (ATP) which can be tied directly to microbial population in water. Results can be achieved within minutes instead of days as required by culture-based testing. Another method to detect iron bacteria, sulfate reducing bacteria, and slime forming bacteria within water is the Biological Activity Reaction Test (BART Test). This test can be performed in the laboratory and results can be achieved within 8 days. Samples can be collected from the many sample taps that will be provided throughout the pilot plant. The analysis for microbes can be used to determine the effectiveness of each treatment process on the removal of microorganisms.

c. Analytical Equipment Summary

Based on the discussion above concerning the lab equipment proposed for the EERC facility, the following table shows the parameters to be analyzed, the approved analytical method (if appropriate), the type of instrument proposed, the estimated cost of the analytical piece of equipment and the possible manufacturer.

Table 1 – List of Parameters, Analytical Methods and Estimated Costs for PW Testing.

Parameter	Measurement Techniques	Online or Near-Real-Time Potential (Unless noted)	Equipment plus Installation Cost, \$ / per unit	Manufacturer
Type 1 Lab Grade Water System	NA	NA	\$12,000	Thermo Scientific
Emulsified oil	ASTM D7066, EPA 413.2 & 418.1	InfraCal 2 (Benchtop)	\$8,000	Spectro Scientific
Unstable precipitates	EPA 180.1 SM 2130 B	Inline Turbidity Probe	\$15,000	HACH Solitax Turbidity probe + Controller
Suspended solids	NA	Inline TSS Probe	\$15,000	HACH Solitax TSS probe + Controller
Colloidal solids	SM 2560 B SM 2560 C SM 2560 D	Inline Particle counter	\$14,000	ChemTrac PC3400
Microbes	Microbiological	LuminUltra BART Tests (Bench Top)	\$8,000	HACH LuminUltra Total Living Biomass Assessment (ATP) Or BART Test

Dissolved organics	SM 5310 B SM 5310 C SM5310 D	Inline TOC analyzer	\$45,000	Sievers InnovOx On-Line TOC Analyzer
Volatiles	EPA 524.2 SM 6200 B	Purge and Trap GC/MS (Bench Top)	\$210,000	ThermoFisher
Heavy metals	EPA 200.7 SM 3120 B	ICP-OES (Bench Top)	\$300,000	Analytik-Jena PlasmaQuant 9100
Divalent cations	EPA 200.7 SM 3120 B	Inline Ion Chromatograph or ICP-OES (Bench Top)	\$280,000	Metrohm USA or Analytik-Jena PlasmaQuant 9100
Anion species	EPA 300.0 SM 4110 B	Inline Ion Chromatograph	\$280,000	Metrohm USA

NOTES:

Type 1 lab grade water will require cation and anion exchange tank system as pretreatment prior to bench top Type 1 Lab Grade Water System (Rental portable exchange tanks are available from Culligan).

Bench top ICP-OES will utilize Argon as the carrier gas.

Bench top Purge and Trap GC/MS will utilize Helium as the carrier gas.

6. Development of Raw Produced Water

The intent of the BTTF PW treatment system is to initially treat PW from the Bakken oil field. There may be instances when water from other oil fields or artificially created PW may want to be tested through this treatment train. Modification of the BTTF facility would include an area and equipment where the raw water may be modified to fit a desired initial water quality specification.

The BTTF facility could use either extraction well water or PW as the feed water for the pilot plant. The extraction well water and PW water will be delivered to the facility and stored in bulk storage tanks. Piping will be provided to bring the extraction well water and the PW water into the BTTF facility. Pumps will be used to pump the raw water into the pilot plant influent or into a mixing / blending tank. Flow meters will be installed on both raw water lines to measure both the instantaneous flow rate and the total volume pumped.

A separate water line allowing for the addition of dilution water into the system would need to be constructed. A high hazard backflow preventor will be provided on the dilution water line as it enters the facility to prevent the backflow of any water used in the facility to re-enter into the public water supply. Dilution water can be added to the mixing tank or by-passed around the tank to be used for flush/cleanout water. A flow meter will also be provided on this line to measure both instantaneous flow rate and the total volume pumped.

A minimum of three injection points will be provided on the dilution water line to allow for the addition of chemicals (composition adjustment) to create artificial PW water. Chemical feed systems including tanks and pumps will need to be acquired to allow for the addition of chemicals to create artificial PW. Sample taps will be installed to allow for the analysis of the composition adjusted water.

A mixing tank will be installed to allow the raw water to be fully mixed / blended before entering the treatment facility. The mixing tank will be provided with a variable speed mixer and automatic valves to mix the water prior to treatment. A sample tap will be installed within the mixing tank to allow for the analysis of the raw water prior to treatment.

a. Pretreatment Unit Processes

The PW pretreatment system will be used for the removal of oil, organics, and suspended solids. Pretreatment is not designed to remove dissolved solids. However, some dissolved organics measured as Total Organic Carbon may be removed through select treatment systems depending on the processes / chemicals selected.

The pretreatment systems selected also include an oil water separator, coagulation / flocculation / sedimentation, and filtration with sand and/or granular activated carbon contactors. A DAF could also be added back into the process should it be wanted or required. Each of these processes are designed to remove oil, organics, and suspended solids.

The system will be designed such that the pretreatment units can be placed in series, parallel, or bypassed altogether. The following sections describe the pilot units proposed to be provided:

- i. **Oil Water Separator.** Oil water separators are designed to separate free and dispersed oils from a wastewater stream. The oil water separator selected for this pilot plant is a high efficiency unit which requires little maintenance. The unit is made from stainless steel with the internal coalescing media pack and oil skimmer parts made from PVC for corrosion protection. The unit comes with an inlet, outlet, adjustable oil skimmer, air vents, and a removable lid. If required, the unit can be designed with slant rib clarification plates to assist with the removal of settleable solids. A collection tank could be provided to store the settled solids. The unit can be designed for between 1 to 10 gallons per minute (gpm).
- ii. **Coagulation / Flocculation / Sedimentation.** Coagulation is the process by which chemicals are added to the water to aid in the removal of suspended particles. Chemicals such as aluminum sulfate, ferric chloride, ferric sulfate, or polymers can be added to create floc particles. The chemicals destabilize the charges on the particles, allowing them to form larger floc particles. Flocculation is the process by which the floc particles can then grow under the right mixing conditions. After flocculation, the particles are allowed to

settle (sedimentation) to the bottom of the tank where they are collected and disposed of. Coagulation / flocculation / sedimentation is an excellent process for the reduction of oil droplets and total suspended solids (TSS). This process can also remove a portion of the dissolved organic carbon but requires the use of bench scale jar testing to determine the optimum coagulant and dosage. The proposed flocculation and sedimentation pilot plant will be designed for a flow rate of 1 to 10 gpm. The pilot unit will consist of three separate units including a three-stage rapid mix tank, a three-stage flocculation tank, and a plate settler-based sedimentation tank. The pilot unit piping will allow for three separate flow configurations including rapid mix only, rapid mix followed by flocculation, and rapid mix followed by flocculation and sedimentation. The unit comes with chemical feed systems which can be configured for flow pacing, closed loop PID, or trim control. All tanks come with variable speed mixers. The sedimentation tank is equipped with inclined plate settlers and an automatic sludge removal system. The pilot unit is integrated into one skid for a plug and play operation. The system can be monitored and controlled remotely via a wireless cellular connection. Data logging for water quality, flow, chemical feed dosages, and tank levels is collected and stored within the control panel. The user can specify inline water quality monitors including but not limited to flow, pH, conductivity, and turbidity.

- iii. Filtration. Filtration is a physical process that uses sand or other types of media to strain out particles from water. The filters typically use coarse sand and anthracite as the filtering material, but other media such as granular activated carbon is also used for dual benefit of particle removal and organic reduction. The filters are periodically cleaned using a process called backwashing by pumping clean water up through the filter media to wash away the collected solids. Filtration usually comes after the coagulation, flocculation and sedimentation process, although other configurations could be used. The proposed granular media filtration pilot plant will be designed for a flow rate of 1 to 10 gpm. The skid comes with a selectable number of filter columns from 2 to 6 with either 6-inch, 8-inch, or 10-inch diameter columns. The flow can be directed to a single filter or a group of filters and allow either series or parallel operation. The unit is skid mounted for a plug and play operation. The system can be monitored and controlled remotely via a wireless cellular connection. Data logging for water quality, flow, filter head loss, turbidity, backwash flow rate, and tank level, are integrated in the control unit. The user can specify inline water quality monitors including but not limited to flow, pH, conductivity, and turbidity.
- iv. GAC Contactors. As stated above, the filter media in the filtration columns can be exchanged for granular activated carbon (GAC) to assist with the removal of organic chemicals. GAC is effective in the removal of volatile organic chemicals, synthetic organic chemicals, and natural organic matter measured as total organic carbon (TOC). The GAC contactors will operate in the same manner as described above for the filtration skid.

- v. Dissolved Air Floatation Skid (Optional). Dissolved Air Floatation (DAF) is a treatment process which uses the coagulation / flocculation process to create particles and then compressed air is added to assist the particles to float to the top of the tank, overcoming the force of gravity. The particles are then skimmed off the top of the tank. DAF is used for both the removal of suspended oil and suspended solids. The proposed DAF pilot plant will be designed for a flow rate of 5 to 10 gpm. The pilot unit will consist of three separate units including a three-stage rapid mix tank, a two-stage flocculation tank, and a DAF clarification tank. The pilot unit piping will allow for two separate flow configurations including rapid mix followed by one or two stage flocculation, and then DAF clarification. The pilot unit comes with chemical feed systems which can be configured for flow pacing, closed loop PID, or trim control. All mixing tanks come with variable speed mixers. The DAF clarification tank is equipped with movable baffles and an automatic float flushing system. The pilot unit is integrated into one skid for a plug and play operation. The system can be monitored and controlled remotely via a wireless cellular connection. Data logging for water quality, flow, chemical feed dosages, and tank levels is collected and stored within the control panel. The user can specify inline water quality monitors including but not limited to flow, temperature, pH, conductivity, and turbidity.
- vi. pH Adjustment Skid. Water treatment can be influenced by many factors including pH. pH adjustment influences corrosion, bacteria growth, and chemical reactions. A pH adjustment skid is proposed to allow the pH of the water to be adjusted prior to a selected treatment process. The pH adjustment skid will be a plug and play unit and can be moved to any position within the desired treatment train. The pH pilot skid can be provided as a one, two, or three stage continuous flow through system. The skid will be a completely automatic operation and can be integrated within any control or data management system. Monitoring will include flow rate and influent and effluent pH levels. A minimum of two chemical feed systems will be provided to dose an acid or base chemical.

b. Primary Unit Processes

The PW primary treatment system will be used for the removal of heavy metal contaminants and scale-forming divalent cations. The primary treatment systems selected include softening with ion exchange resins, heavy metal reduction systems, and membrane systems such as nanofiltration. Each of these processes are designed to remove divalent cations and heavy metals. The system will be designed such that the primary treatment units can be placed in series, parallel, or bypassed altogether.

- i. Chemical Precipitation / Ion Exchange – Metal removal and recovery. Chemical Precipitation followed by ion exchange is a common method used for the removal of heavy metals from water. Chemical precipitation is the process where a chemical is added to water to convert the dissolved metal

ions into an undissolved form. The resulting particles are settled and removed. The most commonly used chemicals for metals precipitation include hydroxide, sulfide, carbonate, and phosphate ions. Ion exchange is then used as a polishing step where the resin beads are coated with a negatively charged functional group which will attract and exchange a positively charged heavy metal ion. Once the resin becomes saturated with metal ions, a highly concentrated solution of sodium or hydrogen ions is passed through the resin to recharge the resin with the proper functional group. The resin is then available for reuse. The proposed heavy metal reduction pilot plant will be designed for a flow rate of 1 to 10 gpm. The skid comes with a first stage pH adjustment tank, a second set of tanks for chemical feed, mixing, and precipitation / settling of the metal's laden sludge. Ion exchange tanks will provide final metals removal along with activated carbon for VOC removal if needed. The pilot unit is integrated into one skid for a plug and play operation. The system can be monitored and controlled remotely via the internet. Data logging for water quality, flow, pH, turbidity, and other water quality monitors can be provided.

- ii. Softening – Divalent cation removal. Produced water contains elevated concentrations of calcium and magnesium, also known as hardness. The primary treatment train would include a water softening system to remove these primary cations, and others, from solution. Water softening skids for industrial processes are ubiquitous, with systems available to meet every flow range and budget. Water softening does require fresh water for regeneration as well as salt or acid to release the cations from the adsorption resins. Recovery of lithium from produced water is hindered through interaction with magnesium making the softening process essential. Hard water reduction is also required before any reverse osmosis processing can be achieved. Produced water contains very high TDS levels which may not work with some cation exchange resins, meaning TDS would have to be reduced before using them. Industrial softening skids often require TDS that is an order of magnitude, or more, lower than what is found in Bakken or Permian brines. TDS reduction through dilution or some other chemical means would likely have to be addressed upstream of the softener. A softening alternative would be to employ a second stage of chemical precipitation to remove the bulk of calcium, magnesium, and other scaling divalents.
- iii. Ultrafiltration Membranes. Ultrafiltration membranes are a solution to treat colloidal solids. Colloidal solids are defined as suspended solids that can pass through a 2-micron filter. These membranes utilize a pressure gradient to force clean water, permeate, through the membrane which rejects colloidal solid contaminants. The contaminants are concentrated in the brine or reject water. The primary benefit to membrane technology in general is that it is a physical barrier which rejects particles at a precise size. The drawback of this alternative is the fouling that can occur depending on the water constituents and concentration. For example, upstream microfiltration will be required to remove larger suspended solids before water can be fed

into the ultrafiltration membrane. Failure to remove larger solids and other contaminants such as emulsified oil would quickly foul downstream screening.

c. Secondary Unit Processes

- i. Reverse Osmosis and Nanofiltration Membranes. Reverse Osmosis (RO) and Nanofiltration (NF) are both considered secondary treatment alternatives that provide a polishing step to further clean the water after primary treatment. Both RO and NF operate similarly to Ultrafiltration membranes but with a smaller pore size to remove dispersed organics, divalent cations, and even chloride salts in RO. The difference between RO and NF is pore size; NF typically can remove solids in the 0.001-0.01-micron range where RO pores are approximately 0.0001 microns. This pore size difference allows RO to remove chloride salts but also increases fouling potential compared to NF. The benefits and drawbacks of RO and NF are like those of ultrafiltration. For example, ultrafiltration is typically required upstream of RO and NF just as microfiltration is recommended upstream of ultrafiltration. Design of RO and NF secondary treatment systems will require expected feed conditions and concentrations, upstream membrane conditions, and desired permeate product quality.
- ii. Electrodialysis Reversal. Electrodialysis Reversal (EDR) is another secondary treatment technology that is designed to focus on the removal of chloride salts. Electrodialysis is a membrane process that is driven by an applied electric field where anion contaminants will move towards the anode and cation contaminants will move towards the cathode. Anion-selective and cation-selective membranes placed between the anode and cathode will capture the oppositely charged particles. These are considered cells which can be stacked for treatment capacity. Note that suspended solids carrying a charge will also be impacted by the electric field and captured by the membrane which can result in fouling. Charge reversal can clean membranes and reverse fouling. It also reduces the need for chemical cleaning which has a detrimental effect on membrane life. Manufacturers that produce EDR units are very limited and even more limited for pilot scale production. Most likely, an EDR will have to be sourced as a foreign made product; however AE2S was not able to secure a quote at this point in the design process. A conservative cost estimate based on experience is included below.

7. Automation and Data Acquisition.

Automation and data acquisition systems are essential to operating complex water treatment systems. Conceptual design of the automation package includes a Supervisory Control Panel (SCP), Human Machine Interface (HMI) module and control software, and integrated process

and equipment specific controllers. This control scheme creates a feature rich system that is both robust and cost efficient.

HMI software, through the SCP, will oversee all sub-systems throughout the facility and gather/store time-stamped process data for post processing and analysis. Process equipment packages will be sourced with control systems required to operate that particular process area. These will be integrated with the SCP, taking control direction and uploading process data such as flow rates, flow totals, analytical data, pressures, alarms/alerts, runtimes and power consumption. Process instrumentation, valves and other devices that are not specifically included within a process area equipment package will be directly connected to the SCP. Existing hazardous gas and leak sensors within the demonstration area will be integrated into the SCP to provide warnings and trigger shutdown in the event of unsafe conditions.

As technology progresses, there's a desire for modularity in the treatment process to be able to swiftly redirect flow through a new process easily. Similarly, there's a desire to be able to update or introduce new analyzer technologies. To accomplish both of these potential additions/revisions to the process flow, multiple turnout's or advanced sample tap points will be included in the final design/construction of the project. These turnouts will provide for ease in adding either treatment or analyzers swiftly and then a team of technicians will have to tackle the task of pulling in the new data into the existing SCADA system to complete the new implementation process. The control panels and SCADA system will be set up with consideration of these future additions so that final implementation step can also be completed quickly.

8. System Design Drawing and Class 3 Cost Estimate.

a. BTTF Produced Water Treatment Train Drawing.

The AE2S proposed treatment train drawing is attached at the back of this report.

b. Treatment Train Cost Estimate

AE2S assembled a Class 3 budget for the components and projected labor effort of a BTTF facility re-design, tables 2-4. The tables break costs into treatment skids, instrumentation, electrical, mechanical, process, and a budget for unidentified design elements and cost escalation. The processes were separated into three segments, pre-treatment, primary, and secondary. The pre-treatment and primary treatment unit operations would be included in a BTTF redesign. The secondary treatment processes would be an option to further the PW treatment down to a highly purified water stream.

The costs are in 2025 dollars and include a 10-30% multiplier where appropriate to address escalation. Multipliers are chosen based AE2S' years of experience designing

water and wastewater treatment facilities. AE2S suggests starting with a new instrumentation and controls system given the complexity of this design and the increased number of points to be addressed by the controls system. Also included are costs for expected Instrumentation and Control (I&C) programming, and construction.

The Class 3 budget costs included in these tables were put together as conservative numbers. Should the EERC have existing measurement instruments available or want to simplify the treatment train, the costs could be reduced. There also may be an opportunity to reuse existing BTTF instruments like flow and pressure transducers, or pumps and other systems to reduce costs.

Table 2. Pretreatment class 3 cost estimate.

	Description	Quantity	Unit	2025 Unit Price	2025 Installed Unit Price	Total Cost
General Requirements						
	Insurance, Bond, Mobilization, Etc.	1	LS	\$50,000	\$50,000	\$56,000
					Subtotal	\$56,000
Treatment Skids						
	Oil Water Separator	1	EA	\$75,000	\$86,250	\$86,300
	Coagulation, Flocculation, & Sedimentation Pilot Skid	1	EA	\$196,000	\$225,400	\$225,400
	Granular Media Filtration & GAC Contactor Pilot Skid	1	EA	\$184,000	\$211,600	\$211,600
	pH Neutralization Skid	1	EA	\$49,800	\$57,270	\$57,300
				Subtotal		\$580,600
Instrumentation						
	Particle Counter	1	EA	\$8,855	\$10,190	\$10,200
	HACH 3700 electrodeless conductivity sensor	1	EA	\$8,000	\$9,200	\$9,200
	InfraCal 2 (Emulsified Oil) - InfraCal 2 Instrument	1	EA	\$8,000	\$9,200	\$9,200
	HACH Solitax Turbidity Probe w/ controller (Unstable Precipitates)	1	EA	\$15,000	\$17,250	\$17,300
	HACH Solitax TSS Probe w/controller (Suspended Solids)	1	EA	\$15,000	\$17,250	\$17,300
	HACH LuminUltra ATP	1	EA	\$8,000	\$9,200	\$9,200
	Sievers InnovOx On-line TOC Analyzer	1	EA	\$45,000	\$51,750	\$51,800
	Tank Level Transducers	2	EA	\$1,800	\$2,070	\$4,200
				Subtotal		\$128,400
Electrical						
	Control Panel	1	EA	\$65,000	\$84,500	\$84,500
	Instrumentation Wiring	9	EA	\$1,200	\$3,000	\$27,000
	Valve & Misc Device Wiring	17	EA	\$800	\$1,040	\$17,700
	Skid Wiring	3	EA	\$4,000	\$5,200	\$15,600
	Pump Starters & Wiring	5	EA	\$4,000	\$5,200	\$26,000
	Networking Equipment & Wiring	1	EA	\$30,000	\$60,000	\$60,000
	Control Software & SCADA Hardware	1	EA	\$15,000	\$30,000	\$30,000
	I&C Programming	1	EA	\$100,000	\$100,000	\$100,000
				Subtotal		\$360,800
Mechanical						
	Mechanical System Maintenance and Refurbishment	1	EA	\$50,000	\$65,000	\$65,000
				Subtotal		\$65,000
Process						
	Piping	250	LF	\$50	\$70	\$22,800
	Pumps	5	EA	\$1,500	\$2,250	\$11,300
	Valves - Electric Actuated	17	EA	\$500	\$750	\$12,800
				Subtotal		\$46,900
				Construction Subtotal		\$1,238,000
				Contingency	20%	\$248,000
				Opinion of Total Probable Construction Costs (\$2025)		\$1,486,000
				Engineering/Construction Administration/Procurement	15%	\$223,000
				Total Project Cost		\$1,709,000

Table 3. Primary treatment class 3 cost estimate.

	Description	Quantity	Unit	2025	2025 Installed	Total Cost
				Unit Price	Unit Price	
General Requirements						
	Insurance, Bond, Mobilization, Etc.	1	LS	\$50,000	\$50,000	\$30,000
					Subtotal	\$30,000
Treatment Skids						
	Ion Exchange/Heavy Metals Skid	1	EA	\$110,000	\$126,500	\$110,000
	Softening Skid	1	EA	\$75,000	\$86,250	\$86,300
	Ultrafiltration Skid	1	EA	\$150,000	\$172,500	\$172,500
					Subtotal	\$368,800
Instrumentation						
	HACH 3700 electrodeless conductivity sensor	1	EA	\$8,000	\$9,200	\$9,200
	HACH Solitax Turbidity Probe w/ controller (Unstable Precipitates)	1	EA	\$15,000	\$17,250	\$17,300
	HACH Solitax TSS Probe w/controller (Suspended Solids)	1	EA	\$15,000	\$17,250	\$17,300
	Sievers InnovOx On-line TOC Analyzer	1	EA	\$45,000	\$51,750	\$51,800
					Subtotal	\$95,600
Electrical						
	Instrumentation Wiring	4	EA	\$1,200	\$3,000	\$12,000
	Valve & Misc Device Wiring	17	EA	\$800	\$1,040	\$17,700
	Skid Wiring	3	EA	\$4,000	\$5,200	\$15,600
	Pump Starters & Wiring	1	EA	\$4,000	\$5,200	\$5,200
	I&C Programming	1	EA	\$40,000	\$40,000	\$40,000
				Subtotal		\$90,500
Process						
	Piping	125	LF	\$50	\$70	\$11,400
	Pumps	1	EA	\$1,500	\$2,250	\$2,300
	Valves - Electric Actuated	17	EA	\$500	\$750	\$12,800
				Subtotal		\$26,500
Construction Subtotal						\$612,000
Contingency				20%		\$123,000
Opinion of Total Probable Construction Costs (\$2025)						\$735,000
Engineering/Construction Administration/Procurement				15%		\$111,000
Total Project Cost						\$846,000

Table 4. Secondary treatment class 3 cost estimate.

	Description	Quantity	Unit	2025	2025 Installed Unit Price	Total Cost
				Unit Price		
General Requirements						
	Insurance, Bond, Mobilization, Etc.	1	LS	\$50,000	\$50,000	\$71,000
					Subtotal	\$71,000
Treatment Skids						
	RO Skid	1	EA	\$150,000	\$172,500	\$172,500
	Electrolytic Cell Pilot Skid (EDR)	1	EA	\$250,000	\$287,500	\$287,500
	Superfiltration Skid (Nanofiltration)	1	EA	\$150,000	\$172,500	\$172,500
					Subtotal	\$632,500
Optional Treatment Skids						
	Adsorption Pilot Skid	0	EA	\$96,000	\$110,400	\$-
	Ozonation Pilot Skid	0	EA	\$196,000	\$225,400	\$-
	Dissolved Air Flotation Pilot Skid	0	EA	\$200,000	\$230,000	\$-
Instrumentation						
	Particle Counter	0	EA	\$8,855	\$10,190	\$-
	HACH 3700 electrodeless conductivity sensor	1	EA	\$8,000	\$9,200	\$9,200
	InfraCal 2 (Emulsified Oil) - InfraCal 2 Instrument	0	EA	\$8,000	\$9,200	\$-
	HACH Solitax Turbidity Probe w/ controller (Unstable Precipitates)	0	EA	\$15,000	\$17,250	\$-
	HACH Solitax TSS Probe w/controller (Suspended Solids)	0	EA	\$15,000	\$17,250	\$-
	HACH LuminUltra ATP	0	EA	\$8,000	\$9,200	\$-
	Sievers InnovOx On-line TOC Analyzer	0	EA	\$45,000	\$51,750	\$-
	Analytik-Jena Plasma Quant 9100 ICP OES (Heavy Metals)	1	EA	\$300,000	\$345,000	\$345,000
	Metrohm 2060 IC Process Analyzer (Divalent Cations)	0	EA	\$280,000	\$322,000	\$-
	Metrohm 2060 IC Process Analyzer (Chloride Salts)	1	EA	\$280,000	\$322,000	\$322,000
	GC/MS (Volatiles)	0	EA	\$210,000	\$241,500	\$-
	Tank Level Transducers	1	EA	\$1,800	\$2,070	\$2,100
					Subtotal	\$678,300
Electrical						
	Control Panel	0	EA	\$65,000	\$84,500	\$-
	Instrumentation Wiring	4	EA	\$1,200	\$3,000	\$12,000
	Valve & Misc Device Wiring	10	EA	\$800	\$1,040	\$10,400
	Skid Wiring	3	EA	\$4,000	\$5,200	\$15,600
	Pump Starters & Wiring	0	EA	\$4,000	\$5,200	\$-
	Networking Equipment & Wiring	0	EA	\$30,000	\$60,000	\$-
	Control Software & SCADA Hardware	0	EA	\$15,000	\$30,000	\$-
	I&C Programming	1	EA	\$35,000	\$35,000	\$35,000
				Subtotal		\$73,000
Process						
	Piping	125	LF	\$50	\$70	\$11,400
	Pumps	0	EA	\$1,500	\$2,250	\$-
	Valves - Electric Actuated	10	EA	\$500	\$750	\$7,500
				Subtotal		\$18,900
				Construction Subtotal		\$1,474,000
			Contingency	20%		\$295,000
			Opinion of Total Probable Construction Costs (\$2025)			\$1,769,000
			Engineering/Construction Administration/Procurement	15%		\$266,000
			Total Project Cost			\$2,035,000

Table 5. Complete system class 3 cost estimate.

Complete System Estimate	
Pretreatment System	\$1,709,000
Primary Treatment System	\$846,000
Secondary Treatment System	\$2,035,000
Treatment Skids	\$4,590,000

9. Conclusion.

This report outlines a BTTF-in-class modular treatment train and associated construction costs to rebuild the BTTF facility in western North Dakota. The objective of such a project would be to offer various levels of treatment for Bakken produced water as well as brines from other US production basins. The facility design also provides blending capability for producing various brine concentrations either through dilution or addition of constituents; or testing of produced waters hauled onto site from other basins. AE2S' treatment solution offers a modular test system which can feed various levels of purity of produced water to advanced treatment technologies aiming to domestically source critical minerals and metals as well as provide recycled water for various uses.

The proposed treatment train includes three sections. The pretreatment segment was designed to provide water at a level of purity that is acceptable to be reused for fracing. The water may also be acceptable for water-flood EOR, agricultural, or other applications, with only cursory treatment completed.

The primary treatment skids can upgrade produced water as a polishing step to address pH, hard water, and solids filtration. Advanced resins are available to isolate some metals and compounds as part of this step. The secondary process water can be withdrawn for sampling or to feed other advanced treatment technologies.

The secondary treatment processes include reverse osmosis, superfiltration, and electrodialysis reversal. These technologies can remove nanoscale suspended particles as well as target constituents by size and charge. The water output from the secondary treatment module would be fully upgraded.

AE2S also proposed appropriate instrumentation to measure the treated water after each step of the process. The final product could feed up and coming advanced treatment technologies set up on site to isolate critical minerals and metals. This type of system could provide process data and costs to supply critical minerals and recycled water from US oil and gas basins.

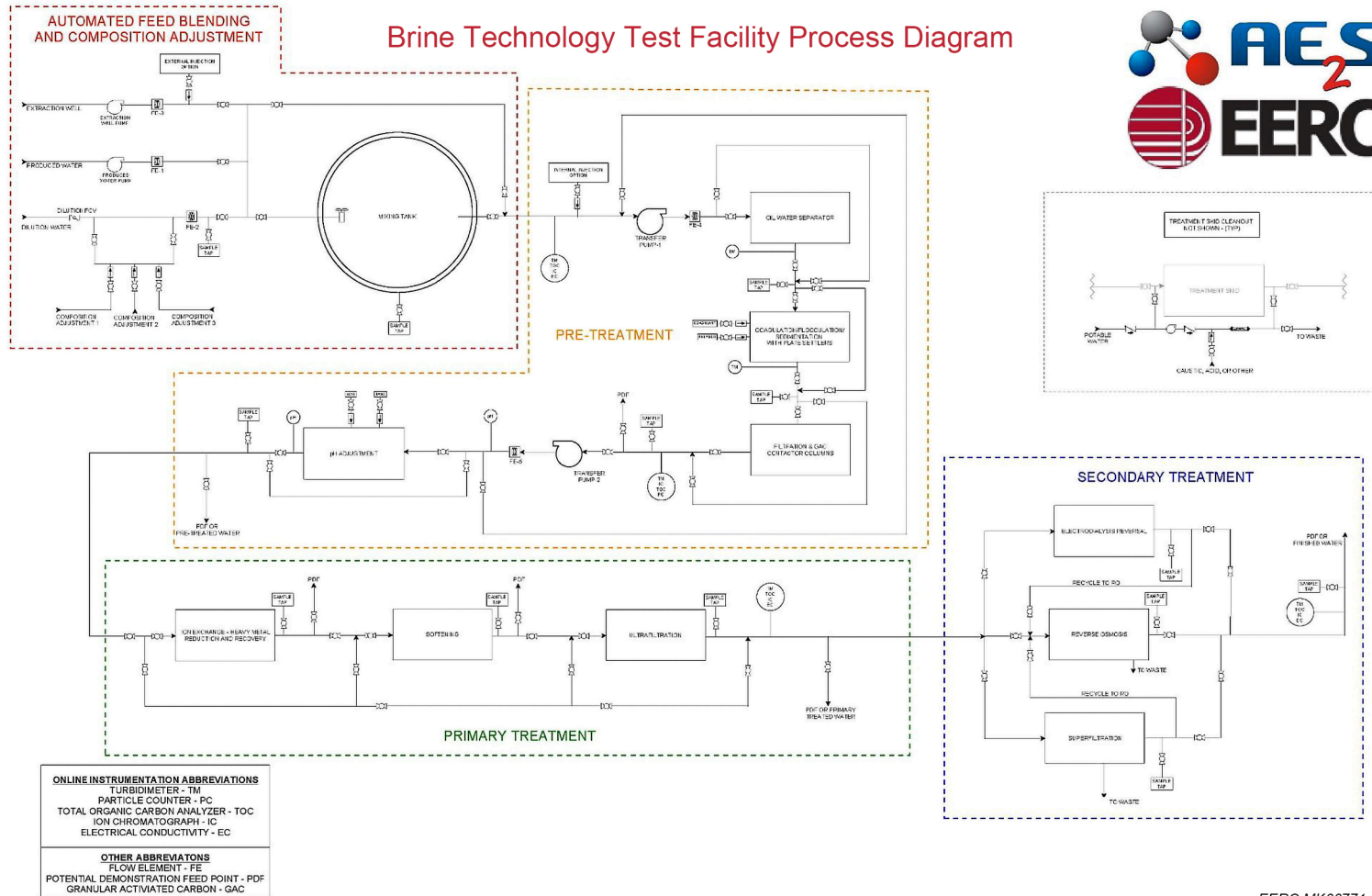
Exhibit A – Site Assessment Photos







Brine Technology Test Facility Process Diagram



EERC MK66771.PSD