

2023 Best Practices for Produced Water Management associated with Shale and Unconventional Gas Development in U.S.

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Abstract

Best practices are identified for recycling produced water in terms of hydraulic fracturing, completion fluid composition, considerations for produced water minimization to disposal wells, future beneficial reuse application, avoidance of environmental concerns, long-term liabilities, and formation and disposal risk. Topics such as reservoir productivity, sand production, infrastructure and formation scale and corrosion control consideration, bacteria, organics, and total petroleum hydrocarbon (TPH) management will be components for this discussion.

Technical focus will be guided by findings from 2023 Technical Conferences (SPE, Produced Water Society, Texas Produced Water Recycling Consortium, New Mexico Produced Water Recycling Consortium, U.S. Department of Energy Pareto program for Produced Water Pareto Optimization, and other technical forums on the topic.)

Practices have rapidly advanced in the last two years, with a focus on cost reduction, a lowering of environmental risks with expanded opportunity for reuse in oil and gas as well as other industries (e.g., agriculture). Focus is on prescriptive treatments at minimal cost, while bounded by historic, current, and future understanding of liabilities and sound environmental management, including (future) support of beneficial reuse to other industries.

This concise study is an important reference for engineers working in produced water management, quickly directing them to “bottom line” best practices for Unconventional developments.

Introduction

Produced Water

During the hydrocarbon recovery process produced water (PW) is a necessary byproduct that results in one of the highest volume waste streams in the industrial world. However, thoughts about how to effectively manage large volumes of PW are evolving. There is the opportunity to re-classify PW from a waste stream to a resource and asset, depending on how it is managed.

The Transition: Liability to Asset

Over 57 billion barrels of produced water will be produced in 2024 according to Global Water Intelligence (GWI), with over 46 billion barrels associated with world conventional production, and over 9 billion barrels associated with Unconventional Production, mostly in the U.S. The market for PW treatment equipment is now over \$2.5 billion a year and projected to grow at over 5% per year for the foreseeable future, according to GWI (Global Water Intelligence, 2023). That is a lot of water that has the potential to be a major liability, or if properly managed, a valued annuity.

Within this paper we use the following definitions:

Produced Water includes naturally occurring formation water produced along with hydrocarbons, as well as early flowback returns from hydraulic fracturing.

Recycling (Reuse) programs within the Oil and Gas industry take produced water as influent and return a clean brine (lightly treated brine) as a base for completion fluids (used in hydraulic fracturing and other oilfield applications.)

Beneficial Reuse programs take PW (or clean brine) as influent, to be treated on a “fit for purpose” basis to achieve water quality objectives for use outside Oil and Gas. Treatment will typically include removal of heavy metals and reductions of Total Dissolved Solids, namely salts. Treatment can be expensive; costs can be many times higher than clean brine treatment costs.

Along with the economic and logistics challenges associated with massive, produced water increases, more stringent environmental regulations are coming into play, requiring methodical treatment of produced water before discharge to onshore or offshore outlets. Produced water has historically been viewed by the oil industry as a cost and potential liability that increases with time.

However, the pace of change is accelerating. Because many onshore producing fields are in water-scarce regions, reuse of produced water reduces dependence on freshwater resources, reserving them for higher value uses, like drinking water. Recycling (or reuse) of produced fluids also reduces the volumes of water injected into underground via injection wells. This helps to conserve precious pore space for higher value applications, and keeps the fluids in the hydrogeologic cycle, instead of removing them as with SWD injection.

Produced water recycling benefits within Oil and Gas are two-fold: treated produced water is generally cheaper than acquiring freshwater for a hydraulic fracturing job, and more importantly, reuse or recycling of produced water presses the right environmental buttons, with ESG (Environmental and Social Governance) driving investment and business valuations in U.S. and worldwide markets. Accordingly, PW reuse has skyrocketed in the continental U.S., with Permian reuse volumes doubling over the last five years.

Discussion

Produced Water Characterization

Produced water composition is even more variable than hydrocarbon composition, with salinity ranges running from quite low and easily addressable, (for example 10K-20K parts per million (ppm) of total dissolved solids (TDS) in parts of Arkansas, Colorado, Wyoming, and the lower U.S. Rockies) to extremely saline and quite costly to treat water (as much as 150K-210K ppm of TDS found in parts of the Permian, Haynesville, Bakken, and Marcellus plays). For reference, seawater has around 35K ppm of TDS. The heavy salt loading in PW renders it unsuitable for agriculture, and many other industrial uses, without extensive treatment to reduce the salt and other constituents. High levels of salt are a greater threat to vegetation and livestock than hydrocarbons, whose effects will diminish over time, unlike salt. The following are the main contaminants of concern in produced water:

- High level of total dissolved solids
- Oil and grease
- Suspended solids
- Heavy metals
- Scalants (examples include calcium and magnesium, which if present with sulfates, can produce complex scales which are extraordinarily difficult to remove.)
- Dispersed oil

- Dissolved and volatile organic compounds
- Dissolved gases
- Bacteria
- Chemicals (additives) used in completion and production operations such as oxidants, biocides, scale and corrosion inhibitors, friction reducers, paraffin control, and emulsion breakers (amongst others).
- Naturally Occurring Radionuclides, or NORM (may be present in formation water in varying degrees in certain geologies)

The amount of produced water, and the constituents and their concentrations vary significantly over the life of the well. Shale wells and other “tight” permeability wells that are hydraulically fractured will typically return a good portion of the completion fluid injected, from 20%-50%, within 2-5 months following completion. This component of produced water is termed “frac flowback” and carries with it much of the chemistry used in the completion job, comingled with the natural formation water. Over the first year, the chemical makeup of the produced water returns to the makeup of the natural formation water. It is generally free of completion chemistry returns at this stage.

From a production perspective, the well will return very high volumes (4,000 BPD and greater) of flowback and produced water immediately following completion, quickly declining as much as 80-90% within a matter of months, with a very long water production “tail” for the life of the well.

Following the initial flowback period, typically, the produced water to oil (hydrocarbon) ratio (WOR) is relatively low in the early stages of production but increases in proportion and in many cases volume (as the well “waters out”) over the life of the well. In parts of the Delaware Basin in Texas, the WOR for a young well may start as low as 2 or 3 over time increasing to 6-8. Eastern areas of the Delaware basin can be considerably higher. Other areas, like the Midland basin, generally have low WORs of 1-3, with many less than 2.

Produced Water Treatment

Due to the dynamic, long term nature of these changes, regular monitoring of volumes and water quality (component measurements) are requirements for any effective water management program, and specifications for produced water treatment facilities, and storage, should account for future volume and compositional changes in the fluids.

Produced water process flows, treatment preferences, and target outcomes for the fluids vary across the western hemisphere. Experience and economics of recycling, and availability of SWD or EOR also vary quite substantially from region to region. (The enormous Marcellus gas play in Pennsylvania has essentially no disposal wells in the state.) Notwithstanding, operators in the Permian historically had good access to SWD wells, and have recently heavily leaned

into recycling, with recycling of PW for flowback considered “Standard Operation Procedure” amongst Tier 1 and Tier 2 operators. EOR has historically been a dominant outlet (exceeding SWD) in many areas in North America, although the conventional EOR fields are waning as aging fields are shut in and will play a decreasing role going forward.

The end-use or disposition of the produced water within Oil and Gas will determine what type of treatment is required (Figure 1).

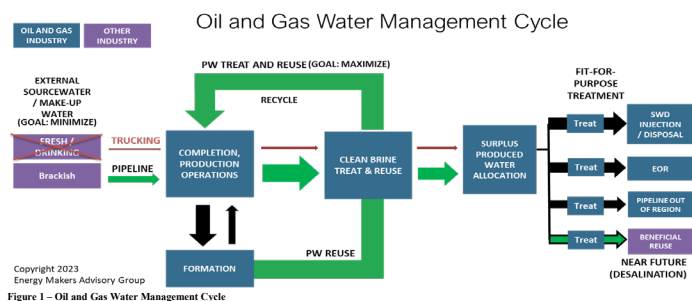


Figure 1 - Oil and Gas Water Management Cycle

- **Produced water recycling for reuse as Hydraulic Fracturing fluid base (also commonly referred to as “Pre-Treat”):** will typically involve removal or reduction of oil and grease (hydrocarbon recovery has value and can be resold), suspended solids, heavy metals, bacteria, and possibly scalants (Figure 2).

Current Practices: Clean Brine Pre-Treat for Completion Fluid

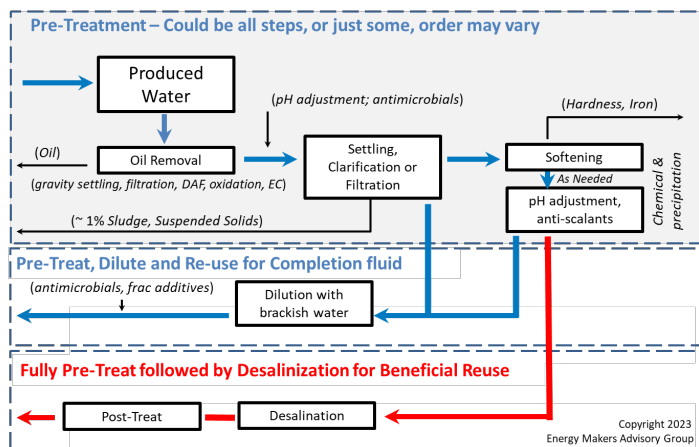


Figure 2 - Pretreatment of Produced Water for Fracturing

- **Desalination for Alternate or Beneficial (other industry) Use:** A second, more complex and expensive level of treatment, is to remove nearly all the constituents in the water to very low or non-detect levels. The dominant component in produced water (and ocean water) are salts (95%+); this class of

technology is generally referred to as Desalination, as with seawater desalination plants. Desalination is preceded by Pre-Treatment (see above) and followed by polishing or post-treatment to address any remaining residuals, such as light organics. Desalination has been adopted in low-TDS regions like Colorado for decades, whereas Desalination is just beginning to be considered in the Permian, with dozens of pilot programs underway.

- **Treatment for EOR Injection:** will typically include removal of Oxygen (to reduce corrosion), oil and grease, suspended solids, and if present, bacteria and possibly scalants. Paraffins and asphaltenes are not a dominant problem in the Permian as they are in other parts of the world.
- **Treatment prior to injection by Salt Water Disposal (SWD) wells** is quite minimal, and generally includes only removal of free oil and grease and suspended solids. Commercial (or high volume) well operators will also proactively extend the useful life of a SWD with periodic maintenance routines that may include injection of corrosion inhibitors, scale inhibitors, and acidization to help with wellbore plugging and fouling.

Pre-Treatment of PW for completion fluid is SOP throughout the unconventional O&G industry. With the noted exception of Desalination, Pre-Treatment, EOR treatment, and treatment for SWD are relatively simple and are achieved at a relatively low cost, generally well below \$0.30/barrel, with some simple treatments available at a small fraction of that cost (for example: application of oxidant and natural settling/gravity separation.)

However, the issue is that these consumptive uses of PW in the oil and gas industry are each limited in terms of the relative volume (or capacity) compared to the growing surplus of water being produced:

- Use of produced water to generate a clean brine for hydraulic fracturing is limited based on current trading prices and completion activity, which can be cyclic.
- EOR fields are declining in volume and numbers, requiring less water.
- Disposal wells are the more significant outlet currently, but also associated with increasing environmental risk and issues including pressurization and induced seismicity.

Supply-Demand Gaps for Produced Water will Require Beneficial Reuse

Throughout the Permian, coinciding with the development of unconventional resources, the increases in PW production are now faced with decreasing capacities of PW applications, such that the “tried and true” outlets for PW can no longer keep up with production volumes. In Southeast New Mexico,

Energy Makers Advisory Group estimates 2 million barrels of produced water is generated each day in excess of available New Mexico local injection capacity, and therefore piped down into Texas by midstream operators for disposal. This growing surplus of produced water here, and elsewhere, must find new outlets for use, outside the Oil and Gas Industry (such as productive uses of former wastes called “Beneficial Reuse”). This involves a variety of fit for purpose treatments of PW for use in other industries and applications.

Increasing concerns about Salt Water Disposal (SWD) well integrity and their role in fluid isolation have driven the industry to substantially increase PW recycling in Oil and Gas completions, as a means to reduce volumes (and costs) going to SWD wells. The same driver is now forcing the industry to accelerate development of options for beneficial uses (outside of oil and gas applications) for this surplus of PW.

The vision is that these efforts will achieve four purposes:

- 1) Leverage the action as part of the operator’s ESG and Sustainability platform,
- 2) reduce unnecessary oil and gas consumption of fresh and brackish fluids,
- 3) maintain freedom to operate (continue to produce oil and gas) and,
- 4) in time, allow for a lower cost of overall operations.

It Used to be so Easy....

Since the inception of the Oil and Gas industry, EOR and Salt Water Disposal (SWD) wells have been integral to maintaining oil and gas production. The fact that they are collocated on lease or on nearby oilfields also allowed injection of the fluid in near real-time with nominal storage requirements for a low cost. The massive volumes of PW are too great to store for long periods of time (which could create a long-term environmental liability).

The ability to “get rid” of thousands of barrels of water with no overt impact to the operator was a valued asset. After successful use of these assets for many decades, a number of challenges are adversely impacting SWD and EOR as a reliable outlet for PW, causing great concerns to onshore operators in the most prolific oil production regions, namely the Permian Basin in Texas and New Mexico.

Salt Water Disposal Well Challenges

In the Permian, daily water production has increased to over 15 M barrels per day, now injecting over 5.5 billion annually, according to B3 Insight (Procyk, 2023). An increase in induced seismicity in recent years has paralleled the increases in injection Figure 3.

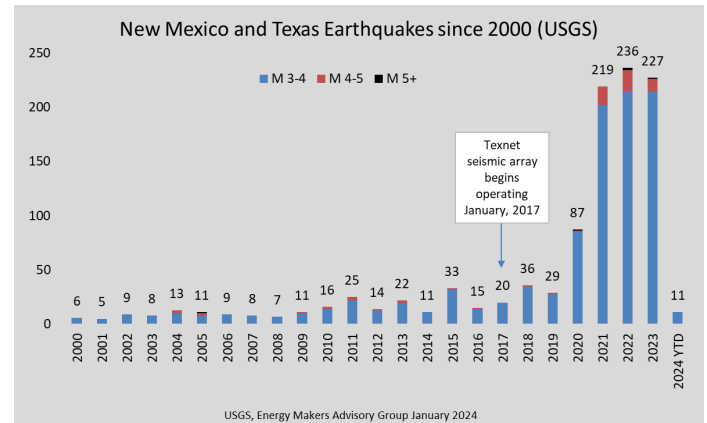


Figure 3 – Increase in recorded earthquakes since 2000

Recent occurrences of seismic events of over 4.0 (Moment) Magnitude in the Midland and Delaware basins have resulted in increased scrutiny of all SWD activity. Regulators, namely the Texas Railroad Commission (RRC) and the New Mexico Oil Conservation Division have responded to the earthquakes with regional policy changes including SWD daily volumetric restrictions or outright cessation if injection into deep, or zones. Although not conclusive, the consensus opinion is that deep SWD injection is more likely to be the cause of oilfield earthquakes. Fortunately, at this point most of the events have not occurred near high population centers which has helped mitigate risk. However, populations near Midland and SE New Mexico are now occasionally beginning to feel regional earthquakes, and concerns are mounting. Thus, alternatives to SWD injection must rapidly be developed as part of the framework of good water management stewardship.

A summary of recent issues arising from decades of underground injection into SWD and EOR wells include:

- **Diminishing injection capacity in shallow SWD wells** – the formations cannot reliably process as much water as they used to. Decreases in capacity may or may not be overcome with higher pumping pressure which could also contribute to over-pressurization.
- **Pressurization of SWD and EOR formations** – increase in PW injection volumes is driving higher pressures in many formations. The essential role of SWD wells is to protect (more shallow) potable and freshwater formations from contamination. A concern is that uncapped pressure increases could compromise the formation structure, and potentially allow for contamination of nearby aquifers.
- **Correlations and possible causation of earthquakes** – in certain regions, produced water injection (particularly in deep underpressured strata) have been

associated with induced, or man-made, earthquakes. While physical damage to humans or infrastructure has to date been modest (oil and gas field are generally in unpopulated regions), the concern is that the threat may be growing, and that a significant earthquake causing real damage may occur if trends are left unabated.

- **Leaks, losses, and lost circulation zones** – anecdotes point to wellbore integrity issues, along with injection pressures exceeding area frac pressures, which could lead to fluid migration to unintended zones.
- **Proximity to adjacent wells and communication with compromised oilfield infrastructure** – inadequately plugged abandoned wells (orphan wells) and long-running inactive wells a major environmental threat in the U.S. Due to aging cement, corroded tubulars and other integrity issues, these hundreds of thousands of aging wells (many unknown, and many with unknown locations, not visible at the surface) could serve as subsurface conduits, allowing saline produced water to contaminant shallower formations via compromised wellbores spanning multiple formations.
- **Uncertain freedom to operate** – Disposal wells used to have a very long predictable life, spanning decades. In the Permian, issues spanning from pressurization, production interference and induced seismicity has led state regulators to issue abrupt restrictions to disposal well operations, ranging from reduced injection limits to outright closure. Investments in SWDs ranging from \$3 M to \$30 M (large, deep, commercial SWD) can be lost “overnight” due to unpredictable environmental issues and regulatory responses.
- **Escalating Costs of Disposal and Transportation** - As a result of the increasing environmental and geopolitical constraints, operators in seismically active areas may lose access to local injection capacity and have to haul their water much further via truck to receptive SWDs, or invest in pipelines to do the same, increasing Capex and/or Lease Operating Expenses (LOE) associated with disposal well costs.

The only positive news across these many challenges is that as a result of dwindling supply versus demand, **increasing disposal costs are making recycling a more economical alternative than disposal in many cases, in turn improving the industry’s overall ESG (Environmental and Social Governance) scorecard.** The next pricing milestone for even

broader produced water treatment will be when desalination and mineral reuse reach parity with full disposal costs.

Finite Pore Space (and shortages) requires Long Term Management

According to EnergyMakers Advisory Group, approximately 35% of SWD wells in the Midland Basin appear to be losing injection capacity, and as a result, operators are beginning to tailor production programs around their ability to manage water. In some areas, if additional outlets for PW are not developed, operators may be forced to shut-in production due to lack of adequate disposal or other PW outlets.

The demand for isolated, subsurface pore space is also increasing. More produced water is being generated with aging production and new completions, and there are seemingly enormous U.S. government appetites for carbon sequestration and blue hydrogen, each requiring water treatment and piped access to isolated pore space, as is available in oil and gas plays. In addition to these future demands for pore space, providing clean water for Beneficial Reuse programs will require an outlet for the recovered salty effluent, or concentrate. The composition of the effluent will be a strategic driver in its handling, also affecting overall plant and treatment economics. Currently, most planners believe that SWD wells could accommodate effluent with 250K-275K TDS, and therefore design desalination recovery levels to manage waste TDS levels at these levels. It remains to be seen whether higher levels of salinity adversely impact SWD performance; we don’t know yet.

Because pore space is a finite resource, it needs to be conserved for the highest value applications. For example, we may want to reserve disposal capacity for concentrate from Beneficial Reuse, injecting more saline concentrate and saving and retaining half a barrel of fresh water for every barrel produced.

Beneficial Reuse Cost Reduction and the Need for Rapid Adoption - Next-level industry challenges are to reduce the cost of treatment (namely desalination) for beneficial reuse, such that beneficial reuse can also grow to become the preferred economic and environmental alternative to disposal wells. Currently, efforts towards beneficial reuse are very early stage, with state regulators cautiously evaluating paths forward. Many in industry believe there could be a collision course ahead which could result in oil production shut-in across parts of the Permian, if safe and regulated alternatives to SWD are not brought on quickly. (Note that Permian injection issues do not universally apply to all oil and gas fields. Many other oil and gas markets may have decades of disposal capacity assets; each field is different, as is the surrounding geology.)

Recommended Best Practices During the Energy Transition

Full Costing

Cost management still rules the oilfield; however, the definition of “full cost” has evolved to reflect related upstream and downstream costs, along with environmental and societal costs and liabilities tied to world financial markets. “Really green” is now a mandate in U.S. and European public financial markets, and even influencing industry to now consider ESG costs and liabilities in addition to the standard framework of lowest cost selection historically employed.

Measure and Monitor

Every aspect of the produced water life cycle must be quantified and recorded on a time-appropriate frequency, including volumes and flow rates, pressures, temperatures, and chemical composition, in order to accurately develop optimal treatments and provide solutions on an “overall” lowest cost basis, including upstream and downstream impacts. In the long term, it is cheaper to automate measurement and monitoring with simple SCADA systems as opposed to relying on field personnel. Lowering field service visits with automated monitoring also improves ESG scores.

When it comes to SWD risk management, automated (real-time) monitoring of pressures and volumes can provide early insights into operational anomalies, allowing for pre-emptive remediation. In Texas, voluntary seismic monitoring (with transparent reporting to tracking systems) helps with earlier insights into induced seismicity, and operators who volunteer to implement around SWD operations will be given positive consideration (higher injection limit) when Texas RRC regulators set permit injection limits for the monitored SWD wells.

Characterize in Detail and at appropriate Frequencies to maintain Optimal Operations

Produced water cost management requires consideration of chemistry, energy, labor, and equipment, along with minimization of waste streams depending on available outlets, each of which must be evaluated in the overall cost assessment.

Produced water gathered in oilfield operations is often highly variable, depending on the nature of daily operations. Water treatment is typically a two to five-stage process. The beginning and endpoint of the process requirements depend on understanding the specific chemistry, and chemistry ratios, of the fluids coming into the system, and the specific chemistry (or more likely, range of chemistry) from each exit stream, or effluent, of the system. In addition, the chemistry at each treatment interval within the proposed design must be evaluated and understood. Lastly, the potential variability or range of concentration of each component at each stage must be known.

Depending on the number of analytes being sampled and analyzed, accredited laboratory costs can range from as little as \$20/ sample up to \$2,000 or more/ fluid sample, if an exhaustive list of tests are conducted and more elements are characterized. Testing for bacteria and Naturally Occurring Radioactive Materials (NORM) can also add additional turn-around time, and for NORM, drives higher testing costs.

General Characterization is not Sufficient, Characterize the Details

Broad characterization like measurements of TDS is insufficient for water planning. Not only should each element on the periodic table be periodically characterized, if relevant and present, so should the ionic variants. As an example, treatment of Fe^{2+} is different than treatment of Fe^{3+} . Heavier hydrocarbons can be removed with lower cost systems than light hydrocarbons like Benzene or Toluene. In general, hydrocarbons, bacteria, any type of scalants, divalent cations (i.e. magnesium, calcium) and heavy metals (i.e. iron, barium, strontium) should all be characterized in sufficient detail to allow prescriptive treatment planning.

Manage to Minimize Waste Volumes and Potential Liabilities

In the soon-to-be heavily regulated emerging Beneficial Reuse world, both the treated effluent and concentrate streams will also have to be characterized with frequency to maintain regulatory compliance, and to manage waste programs. In Texas, leadership within the Texas Railroad Commissions have suggested “real time” characterization may be required for some parameters, going forward. Both the clean stream and the waste streams need to be continuously characterized during treatment programs. Managing waste should be among the very top drivers in designing a water treatment program.

For example, non-hazardous waste has limits on arsenic, barium, and benzene. If concentrations of these chemicals are found in the waste stream at the hazardous limit or greater, and the (entire) waste stream is therefore characterized as hazardous, waste management costs could increase from two to twenty-fold. Thus, much of water management costs is waste management engineering and costing.

Radionuclides (i.e. radium-226, radium-228) and NORM (i.e. uranium, thorium), naturally present in the underground formation water, are other possible components in PW requiring thoughtful and proactive waste management. If kept in solution at low concentrations, and not allowed to concentrate in tubulars or flow lines, low levels of radionuclides are easily managed, as they are in municipal drinking water plants. If allowed to concentrate over years of aggregated use, they can grow to not only escalate waste costs (radioactive waste is more expensive than other hazardous wastes) but also become growing future liabilities. This is the classic example of an “ounce of prevention” being worth a “pound of cure.”

Various wastes will be output at each stage of the treatment process; the key is combining or managing (or in some cases diluting) the waste streams to minimize volumes and costs while staying below regulatory designated (chemical) limits. Chemistry, equipment, and retention times and treatment processes should be chosen with an understanding of their impact on waste volumes, character, and costs.

Solids Handling Strategies for Clean Brine to reduce Long Term Liability

Generation of a solids-based waste stream (sand, sediment, sticks and stones, bacteria and sludge, other suspended solids) from PW generally happens in the following onshore scenarios:

1) Prior to SWD and EOR injection, basic filtration (mesh filter, cartridge filter, walnut shells, other) is applied to reduce Total Suspended Solids (TSS) and minimize formation plugging. Solids are captured in the filtering material and discarded (along with the filtering material, often), most likely to a landfill.

2) Clean Brine for Reuse; Treatment in Lined Impoundments with Oxidants – the most common method of generating a clean brine is to skim off free oil and grease, followed by addition of one or more oxidants to the PW in a lined impoundment. The PW may also be filtered for solids removal before being treated in the impoundment. The “treated” water is typically then pumped out of the lined impoundment by one or more pumps which pull from the middle of the pond, avoiding materials which float or sink. Solids are allowed to accumulate within the impoundment, until the time the impoundment is closed, where they are treated as a sludge or solid waste (if dewatered). This clean brine treatment method is relatively inexpensive and requires no specialized equipment. Large, lined impoundments or ponds require residence time for oxidation and settling to take place. Large, exposed surface areas and interaction with the chemistry in air play a role, and evaporation rates impacting volumetrics and dosing levels should also be considered. In the future, state environmental regulators may play a role in monitoring possible air emissions associated with this approach, in regions including New Mexico.

3) Clean Brine for Reuse; Treatment with Dissolved Air Floatation (DAF) Systems, Clarifiers, Micro-bubble separation systems, and Chemistry. This more equipment-intensive approach to clean brine treatment allows for higher-throughput, higher-rate water treatment, with a vastly reduced surface footprint by eliminating the need for long residence time and impoundments. In these systems, a typically inert gas is introduced as tiny bubbles in the system (typically air or nitrogen) and used to speed up reaction and residence time. The bubbles along with cavitation help the introduced chemistry to mix and react with the water and speed coagulation and or flocculation effects, if chemical accelerants are added, which is typical of these systems. Waste streams will typically flocculate and coagulate at the surface of the vessel, where they

are skimmed off or otherwise removed from the system. They may be transported as sludge waste or dewatered and sent to a landfill. These types of high throughput, higher-specification, and smaller footprint systems have rapidly grown in adoption and can produce a higher quality brine (for example lower TSS or better removal of light hydrocarbons.) Large midstream companies providing high-volume clean brine services are more likely to use systems like DAFs. DAFs and similar equipment are relatively expensive to operate and maintain (with large systems costing \$500,000 - \$1,000,000 and more), and frequent and recurring staff training.

Managing Solids Liabilities

In scenarios #1(Filtration) and #3 (DAF) above, the solids are removed and separated from the fluid, and sent to a landfill or waste facility. They are not allowed to collect and aggregate for long periods of time and no liability is accrued.

In Scenario #2, (Clean Brine Treatment in Lined Impoundments) the solids are separated out with the use of chemistry but remain in the impoundment for the life of the operation (or until cleaned, which rarely happens.) If used for a small number of months before closure, there is limited liability from aggregated solids. But if, for example, the impoundment is used for many years, and there are low levels of radioactivity present in the fluids and solids, or other heavy metals or hazardous wastes are present, there could be an aggregation or concentration of affected solids such that the density of contaminants (in this case radioactive particles) over time rises above allowable limits for non-hazardous waste facilities.

There is growing long-term liability in maintaining this type of facility. Over time, the waste liability of the pond may grow to be many multiples of its original costs, with hazardous waste disposal prices often costing two to twenty times more than those of non-hazardous waste, and radioactive disposal much higher.

Hazardous waste includes a broad range of materials that exhibit characteristics such as toxicity, reactivity, ignitability, or corrosivity. Examples of hazardous waste include certain solvents, heavy metals, pesticides, and certain types of industrial byproducts. One way to mitigate liabilities from solids build-up is to periodically close impoundments for cleaning and maintenance, such that solids are removed and properly disposed (long before elements of concerns are allowed to “concentrate up” beyond allowable limits). This type of remediation could also require liner disposal and replacement, which can be expensive.

Solids Handling Strategies for Desalination and Beneficial Reuse

In the three scenarios discussed above, for underground injection and clean brine treatments, the relative percentage of solids generated are relatively minimal, and typically less than

1% of fluid volume. In these scenarios all the salts, the dominant component, are left dissolved in the injected or treated clean brine fluid.

However, under much more stringent Beneficial Reuse use applications, 99% or more of the salts may need to be removed, contributing to a significant and highly saline waste stream (called “concentrate”). Industry is just beginning to develop methods to minimize waste streams from desalination.

Mineral Harvesting: Recovery of Rare Earth Metals and other valuable Byproducts from Concentrate

The enormous volumes of complex salts and intermingled materials and heavy metals could turn to a liability if appropriate applications are not developed for their separation and recovery. The most promising alternative is separating out and harvesting the useful byproducts, or components of the waste stream, for sale. For example, in the Northeast U.S., the concentrate from desalination processes has been successfully treated to recover salts for de-icing programs, and calcium chloride salts as a weighting base for drilling fluids. Clean brine concentrate may also be recovered and sold as ten-pound brine for other industrial uses. Much discussion is held around the potential for lithium recovery in certain brines and produced water. Dense brines, such as those found in the Arkansas and Louisiana Smackover formation, having concentrations more than 80 ppm (some as high as 150 ppm or greater) are generally believed to be economically recoverable, given sufficient capital budgets. However, it is still uncertain whether lithium recovery can be made economic for typical Permian produced waters, which are more likely to have brine concentration levels under 10-20 ppm. To make the economics work for Lithium and other mineral harvesting programs, it is likely we will have to separate out and find commercial uses for the higher volume materials like calcium and magnesium, likely to extract along with the Lithium, which would otherwise have high disposal costs due to their volumes. A further question remains as to the size of local markets for these recovered byproducts.

Because the volume of concentrate from PW is projected to be very high, mineral harvesting programs are in their technical infancy, initially the vast majority of “waste concentrate”, (about 50% if of the total volume of influent produced water), is still designated for SWD wells due to lack of a better alternative. There is high urgency to come up with more effective ways to separate out useful byproducts from desalination concentrate, and to lower the overall volumes (and costs) of waste in order to make Beneficial Reuse economic to all stakeholders.

Think “Long Term, Human Life Toxicity, and ESG” – The likely pathway for Permian Oil and Gas production includes future dependence on Beneficial Reuse to maintain current oil and gas production levels. Accordingly, PW management strategies should contemplate long-term thinking

regarding all chemistries (and their residual effects) introduced and used to treat produced water.

The likely adoption pathway for use of fit-for-purpose treated PW outside of Oil and Gas applications includes the following near term versus longer term applications, reverse-ranked for their potential to cause toxicity in humans and human food chains.

Near term Beneficial Reuse Applications (Non-Consumptive)

- Industrial use (influent to industrial process)
- Closed loop / zero discharge applications.
- Mining extraction / Dissolution mining
- Aquifer recharge for future use
- Surface discharge for non-consumptive crops – examples include cotton, hemp, switchgrass, oilseed, etc.

Longer term Beneficial Reuse Applications

- Surface discharge for agriculture and farming, including consumptive crops (corn, soy) and food animals.
- Discharge as influent for further treatment in municipal drinking water facilities (Texas and New Mexico groundwater conservation groups are forecasting decades of impending shortages in small towns across the state.)

Chemistry Selection for Consumptive Beneficial Reuse Applications

Since produced waters may ultimately find their way into consumptive applications, any additive introduced to produced water should be considered with great scrutiny. Questions to answer before considering use include: Can the additive be removed with proven treatment methods with absolute certainty? Does the presence of the additive create any undesired reactions or precipitants? If biocidal in nature, how long will the residual effect last? Does the process introduce a diluent or make-up fluid, and if so, what constituents have historically been found in the sourcewater?

There has been an awakening in the U.S. oil and gas industry with regards to avoiding chemistries which could have long or hazardous direct or residual effects. Fortunately, we have done a reasonable job of moderating such use within industry, such as minimizing use of PFAs and PFOs in completion and production fluids.

Termed “forever chemicals”, PFAS and PFOS (Per- and Polyfluorinated Substances (PFAS), Perfluoro octane Sulfonate (PFOS)) have been linked to a wide range of health risks in both human and animal studies, from hormone disruption to reproductive harm and interference with vaccine effectiveness. Unfortunately, PFAS are almost impossible to avoid in urban

settings. They are found in our homes, our offices, our supermarkets—practically everywhere. To industry’s credit, there is little evidence that PFAs or PFOs are currently used as additives in oil and gas operations currently, although less is known about their historic use.

Another example of undesired consequences comes from the use of chlorine within municipal water treatment plants. Although chlorine has been a literal lifesaver regarding world availability of drinking water, it also has the potential to form byproducts that can cause harmful health effects. Chlorine can react with organic materials in water to form disinfection byproducts (DBPs). Scientists have identified hundreds of DBPs, with several types of DBPs having limits set by the U.S. Environmental Protection Agency (i.e. trihalomethanes (THMs), halo acetic acids (HAAs), chlorite, and bromate). In both very relevant examples, exposure to the oil and gas industry from these pollutants generally come from municipal and industrial water treatment regimes, as opposed to being present in naturally occurring formation water or chemical additives used for hydraulic fracturing.

Therefore, ESG-focused oil and gas operators with long term intent to treat their produced waters for Beneficial Reuse must conduct two sets of inquiries and due diligence with regards to their water sources and selection of chemistries. From their oil and gas customers, assurances need to be made that PW and flowback are free of additives which are toxic or hazardous – throughout the supply chain.

Interestingly, regulatory requirements for oil and gas treated water are anticipated to be higher and more restrictive than regulations in place for U.S. drinking water. Municipal plants are also subject to a myriad of difficult to treat components ranging from illegal narcotics to hormones and prescription medications, along with PFAs and PFOs. Care should also be taken to avoid introduction of (any) treated municipal water or other make-up water used as a diluent which could have PFAs, PFOs, DBPs, dry cleaning solvents, and other elements of concern more frequently present in urban and municipal water. Adding municipal water to the mix of influent waters adds heightened regulatory exposures for operators.

Assure License to Operate with Networked Disposal and Recycling Assets (Optionality)

Many of the environmental challenges described above with SWDs, seismicity, and pressurization, are not well understood and adverse impacts tend to manifest without prior notice. A sudden restriction in SWD injection capacity could require an operator to shut-in production operations if alternative (disposal or re-use) resources are not immediately available near the well site. From an environmental perspective, while trucking or hauling provides an actionable alternative, safety issues from increased truck traffic, emissions, greenhouse gasses, and wear and tear on roads render hauling an expensive and short-lived solution.

The better “back-up plan” is to plan for the likelihood of occasional and unexpected SWD failures (whether from regulatory restrictions, proximity to earthquakes, over or under pressurization, or during maintenance/workover operations.) It is recommended that operators maintain a network of pipelined assets (permanent pipelines supplemented with leak-proof temporary layflat hose), such that if one outlet (an SWD well or recycling center) goes down for any reason, alternatives can be made quickly available, without downtime. Very importantly, pipelines need to be able to flow two ways, and care should be taking to run a diverse, geographically distributed portfolio of disposal wells and target formations (much as a balanced investment portfolio would contain a variety of different investments assets). Examples of such a networked, distributed water treatment portfolio would include:

- Contractual access to at least 20% more capacity than the operator believes is needed, such that no wells are run at full capacity; surplus capacity remains.
- Distributed, pipelined, storage and recycling capacity (to act as a buffer during periods of constraint, until new resources are brought online)
- A diverse portfolio of shallow and deep SWD wells in geographically different areas
- A diverse selection of injection formations, such that if one is “shut in”, (say, portions of the San Andres), alternative formations could be tapped, such as the Bonespring or Ellenberger.

Each operating area should have a “fall back” disposal well / PW allocation plan, such that if Plan A fails for any reason, a plan B or C is developed and actionable.

Assure Freedom to Operate: Carbon and CO₂ Management in Produced Water Treatment Programs

ESG drivers from federal and state government, regulatory agencies and financial institutions are having real-world impacts on all aspects of the oil and gas business. The same holds true for water treatment. New facility designs should contemplate emissions control and assure new sources of carbon or CO₂ or either eliminated or offset with appropriate credits. Existing facilities (treatment centers, disposal sites and flare stacks, etc.) should be ranked based on ESG profiles and exposures and prioritized for thoughtful upgrading. Exposures may be highest for acquiring companies whose target acquisitions likely deferred necessary spending in lieu of liquidation or exit strategies. A poor ESG profile can have direct material bearing on Exploration and Production (E&P) and Midstream company valuations, and their relative appeal as acquisition targets. As the ESG lexicon and associated metrics mature, it is very likely that ESG scores for midstream water treatment providers will have direct bearing on vendor selection from Operators, as well.

Summary

A new world lies ahead for Oil and Gas operators requiring complex navigation through regulatory, environmental, societal, and financial challenges, to maintain our license to operate in a hydrocarbon-dominated world now fundamentally opposed to carbon. “First movers” are already changing the stakes, with large multinational oil companies consolidating and fortifying their positions with high volume distributed treatment facilities and vast pipelined outlets for take-away. The greater challenge is for industry to educate, strengthen, and enable Tier 2 and Tier 3 oil and gas operators to achieve the same goals with fewer resources, and simultaneously, accelerate the pace of Beneficial Reuse regulations and adoption in onshore U.S. markets for production continuity.

Nomenclature

TPH = *Total Petroleum Hydrocarbon*

SPE = *Society of Petroleum Engineers*

PW = *Produced Water*

GW = *Global Water Intelligence*

SWD = *Salt Water Injection*

ESG = *Environmental and Social Governance*

TDS = *Total Dissolved Solids*

PPM = *Parts Per Million*

BPD = *Barrels Per Day*

WOR = *Water to Oil Ratio*

EOR = *Enhanced Oil Recovery*

SOP = *Standard Operating Practice/Procedure*

LOE = *Lease Operating Expenses*

SCADA = *Supervisory Control and Data Acquisition*

NORM = *Naturally Occurring Radioactive Materials*

DAF = *Dissolved Air Flootation*

PFAS (PFAs) = *Per-and Polyfluorinated Substances*

PFOS (PFOs) = *Perfluoro Octane Sulfonate*

DBP = *Disinfection Byproducts*

THM = *Trihalomethane*

HAA = *Halo acetic acid*

CO₂ = *Carbon Dioxide*

E&P = *Exploration and Production*

References

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