

Hydrodynamic Cavitation-Induced Degradation of Hydrocarbons and Hydrogen Sulfide in Produced Water and Marine Oil Spill Recovery: Mechanisms, Integration, and Comparative Efficacy

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ABSTRACT

Oilfield wastewater, produced water, and marine oil spill runoff contain complex mixtures of dissolved and suspended petroleum hydrocarbons, hydrogen sulfide (H₂S), heavy metals, and surfactants. Conventional oil spill recovery and phase-separation techniques rely on physical containment (booms, skimmers), chemical dispersion, and mechanical separation. While designed to recover free hydrocarbons for commercial value or prevent shoreline impact, these methods are often limited by emulsion stability, oil-water separation efficiency, high operational costs, and secondary chemical pollution. This study evaluates the efficacy of hydrodynamic cavitation (HDC) as a physical-chemical treatment method for hydrocarbon mineralization, destruction, and oil spill remediation using a Venturi-type reactor system operating at 150 gpm powered by a 15 H.P. pump. Operations conducted across diverse oilfield assets—including disposal well wastewater in Midland, Texas, Strategic Petroleum Reserve (SPR) produced water, and Southern California hydrocarbon-rich semi-liquid matrices—demonstrated that HDC does not merely facilitate physical phase separation; rather, it induces comprehensive chemical degradation. Post-cavitation analytical testing indicated up to ~98% to 100% removal of unprocessed liquid hydrocarbons from the water phase without chemical additions, alongside 100% destruction of hydrogen sulfide with zero rebound observed at 90 days. Furthermore, experimental results reveal significant enhancements in dissolved oxygen profiles, substantial microbial disinfection (92% reduction in ATP microbial counts, 85% decline in standard plate counts, and near-complete elimination of anaerobic bacteria), and favorable shifts in scaling indices (Ryznar Stability Index shifting from 6.6 to 9.0; Stiff-Davis Index shifting from +0.90 to -0.87). Integrating HDC into existing oil spill response architectures offers a low-CAPEX/OPEX pathway to treat recovered oily wastewater, break stable emulsions, destroy toxic sulfides, and eliminate non-recoverable hydrocarbon fractions on-site without secondary chemical dispersants.

Keywords: Hydrodynamic Cavitation, Venturi Reactor, Produced Water, Oil Spill Remediation, Hydrocarbon Mineralization, Hydrogen Sulfide Destruction, Advanced Oxidation Processes.

1. Introduction

Produced water, industrial effluents, and marine oil spill releases present critical environmental remediation challenges globally [1, 10]. Standard offshore and coastal oil spill response operations rely heavily on mechanical recovery (containment booms, oleophilic skimmers, centrifuges) and chemical countermeasures (surface dispersants) [3, 5]. However, mechanical skimmers and centrifuges frequently suffer from declining recovery efficiency as volatile fractions evaporate, leaving behind highly viscous, water-in-oil emulsions commonly referred to as "chocolate mousse" [3]. Furthermore, chemical dispersants face strict regulatory scrutiny due to acute toxicity risks, potential bioaccumulation, and secondary environmental persistence [5].

Traditional wastewater treatment and post-skimming fluid processing aim to separate emulsified hydrocarbons to yield recoverable crude oil while conditioning the aqueous phase for deep-well injection, surface discharge, or reuse [10,18]. However, complex chemical additives, heavy metals, volatile organic compounds (VOCs), dissolved hydrogen sulfide, and surfactant-stabilized emulsions create fluid dynamics that impair traditional mechanical separation, membrane filtration, and chemical flocculation processes [12, 18].

Hydrodynamic cavitation (HDC) has emerged as an efficient physical-chemical technology for water remediation and advanced oxidation processes (AOPs) [1, 7, 11]. HDC is generated by passing a fluid through physical constrictions, such as Venturi tubes or orifice plates, creating localized regions where static pressure falls below the vapor pressure of the liquid [6, 17]. The rapid inception, growth, and implosive collapse of micro-cavities yield extreme localized conditions—temperatures exceeding 5,000 K and pressures above 1,000 bar—accompanied by intense microjets and shockwaves [25].

Under these extreme conditions, homolytic cleavage of water molecules produces reactive free radicals ($\cdot\text{OH}$, $\cdot\text{H}$), while extreme fluid shear directly breaks chemical bonds in organic solute molecules and dissolved gases [14, 25]. This study reports field observations and analytical laboratory findings regarding the application of a 150-gpm Venturi HDC reactor powered by a 15 H.P. pump to high-hydrocarbon and sulfide-laden wastewater streams, evaluating its potential integration into modern marine and industrial oil spill recovery frameworks [10, 24].

2. Current Oil Spill Recovery Techniques and Operational Bottlenecks

2.1 Mechanical Containment and Skimming

Mechanical recovery remains the primary initial defense in oil spill response [3]. Containment booms isolate slick areas while floating skimmers (brush, drum, disk, and weir systems) collect surface oil. However, efficiency drops drastically in high-energy sea states or when processing weathered crude [3]. Mechanical skimmers collect vast quantities of water along with oil, creating storage bottlenecks on response vessels [3, 4]. Furthermore, physical separation fails to treat dissolved polycyclic aromatic hydrocarbons (PAHs), hydrogen sulfide, or fine emulsified droplets [4].

2.2 Chemical Dispersants and Surfactants

Chemical dispersants reduce the oil-water interfacial tension, breaking surface slicks into micro-droplets that disperse into the water column for natural biodegradation [5]. Nonetheless, dispersants do not remove or degrade petroleum hydrocarbons; they transfer the pollutant load directly into the water column. Chemical dispersants can exert toxic effects on pelagic and benthic marine life, and they remain ineffective against high-viscosity or heavily weathered oil residues [5].

2.3 Thermal In-Situ Burning (ISB)

In-situ burning involves containing floating oil with fire-resistant booms and igniting the slick to rapidly remove hydrocarbons from the water surface [8]. However, burning produces significant air pollution (soot, particulate matter, toxic gases) and leaves behind dense, sinking burn residues that severely harm benthic habitats [8].

2.4 Biological Remediation

Bioremediation uses indigenous or added hydrocarbon-degrading microbes combined with nutrient supplementation to accelerate natural degradation [9]. Nevertheless, biological processes are exceedingly slow, temperature-dependent, and entirely unsuitable for rapid emergency containment or high-throughput treatment of concentrated waste streams [9].

3. Methodology and Operational Context

3.1 Field Setup and Industrial Effluents

Field evaluations were initiated to test HDC units on produced water streams destined for disposal wells in Texas and marine oil recovery sites [10]. The initial objective was to evaluate the economic viability of recovering oil via HDC-induced phase separation [2]. All trials were conducted using a proprietary Venturi-type hydrodynamic cavitation reactor operated at a flow rate of approximately 150 gpm and powered by a 15 H.P. industrial pump. Subsequent trials were expanded to Southern California using hydrocarbon-rich semi-liquid waste and direct oil well delivery samples [2]. Treatment systems incorporated stand-alone HDC flow loops as well as hybrid configurations combining HDC with traditional flocculation, pH adjustment, oxidation, and filtration steps [10, 11].

3.2 Analytical Characterization

Pre- and post-treatment aqueous samples were analyzed by independent certified laboratories specializing in oilfield analyses (including Martin Labs) [26,27]. Key metrics evaluated included:

- **Volatile Organics and Hydrocarbon Concentration:** Gas chromatography-mass spectrometry (GC-MS) and total petroleum hydrocarbon (TPH) metrics [10,14].
- **Hydrogen Sulfide (H₂S):** Pre- and post-treatment concentration monitoring via certified laboratory testing methods [26, 27].

- **Dissolved Oxygen (DO) and Temperature:** Real-time multiparameter water quality logging across varied operational durations (timing studies and 30-minute closed-loop testing).
- **Microbiological Assays:** Standard plate counts (SPC), anaerobic plate counts, and adenosine triphosphate (ATP) luminescence assays.
- **Cation and Heavy Metal Content:** Inductively coupled plasma mass spectrometry (ICP-MS) to monitor trace elements [18].
- **Scaling Indices & Physical Parameters:** Ryznar Stability Index (R.I.), Stiff-Davis Index, acid-insoluble material percentages, visual clarity, surface adhesion tendency, and membrane passage efficiency [18,22].

4. Results and Analytical Findings

4.1 Hydrocarbon Degradation and Carbon Precipitation

Contrary to the initial hypothesis that HDC would induce physical phase separation of free oil [10], field trials demonstrated zero recovery of liquid petroleum products. Instead, unprocessed liquid hydrocarbons experienced near-complete chemical degradation (up to 100% destruction in direct crude delivery samples, dropping from an initial TPH of 335 mg/L down to non-detectable levels) [10]. Laboratory analysis confirmed ~98% to 100% removal of total hydrocarbons from the bulk liquid phase [10]. Organic compounds underwent rapid fragmentation via C-H and C-C bond cleavage [14]. This reaction converted liquid hydrocarbons into insoluble black carbonaceous powder ("black powder") and light hydrogen gas (H_2) [2, 14]. The resulting black particulate settled to the bottom of storage tanks as a dense residue, while the bulk water shifted toward a visually clear state [10].

Table 1: Comprehensive Water Quality Parameters Before and After 150 gpm Venturi HDC Treatment

Parameter	Pre-Treatment	Post-Treatment	Reduction (%)	Primary Enabling Mechanism
Total Hydrocarbons (mg/L)	335	0 (Non-Detect)	100%	Hydrocarbon cleavage & radical oxidation
Dissolved H_2S (mg/L)	9	0 (Non-Detect)	100%	Sonochemical oxidation to elementary S/ SO_4^{2-}
Total Suspended Solids (mg/L)	475	6	98%	Surface charge disruption, particle aggregation
Iron (mg/L)	20	1	95%	Oxidation to insoluble ferric forms for easy filtration
ATP – Microbial Count (ME/mL)	8,815,292	735,653	92%	Mechanical cell lysis & radical disinfection
Sulfate (SO_4^{2-}) (mg/L)	147	45	70%	Molecular state conversion and lattice disruption

4.2 Hydrogen Sulfide (H₂S) Destruction and Stability

In addition to hydrocarbon mitigation, analytical tracking across multiple test events demonstrated complete chemical elimination of hydrogen sulfide from produced water matrices without chemical scavengers:

- **Midland SWD Site (2020):** Laboratory testing (Martin Labs Report # 20-03-160) recorded a pre-treatment H₂S concentration of 50 mg/L, which was reduced to non-detect levels post-treatment, achieving a 100% reduction rate. Stability monitoring confirmed zero chemical rebound at 90 days [26].
- **SPR Produced Water (2024):** Laboratory testing (Martin Labs Report # 24-04-137) evaluated a pre-treatment H₂S concentration of 9 mg/L, which was successfully lowered to non-detect levels (100% reduction) with zero rebound observed at 90 days [27].

Table 2: Hydrogen Sulfide Destruction Across Industrial Field Trials

Test Event	Laboratory Report #	Pre-Treatment (mg/L)	Post-Treatment (mg/L)	Reduction (%)	Stability / Rebound
Midland SWD Site (2020)	Martin Labs 20-03-160	50	Non-Detect	100%	No rebound at 90 days
SPR Produced Water (2024)	Martin Labs 24-04-137	9	Non-Detect	100%	No rebound at 90 days

4.3 Dissolved Oxygen Dynamics and Thermal Evolution

Operational data logging during continuous 150 gpm Venturi HDC runs revealed distinct thermodynamic and gas-transfer dynamics. Pre-HDC feed temperatures averaged 71.6°F to 79.5°F, while post-HDC effluent temperatures consistently rose by 4.0°F to 7.0°F due to the viscous dissipation of mechanical energy and adiabatic collapse of cavitation bubbles. Simultaneously, dissolved oxygen (DO) levels experienced dramatic augmentation: pre-HDC feed DO ranged from 0.28 ppm to 1.07 ppm (reflecting typical oxygen-depleted produced water), whereas post-HDC effluent DO surged to between 2.74 ppm and 5.33 ppm. Extended 30-minute closed-loop testing demonstrated that post-cavitation DO supersaturation initiates an initial settling peak of 6.1 ppm, gradually equilibrating downward during quiescent settling to a stable baseline of 2.80 ppm over 30 minutes. This controlled oxygenation supports advanced oxidation pathways without requiring external aeration blowers.

4.4 Microbiological Disinfection and Scaling Mitigation

Biological plate count assays revealed substantial antimicrobial efficacy driven by intense localized shear stress and radical generation. Standard plate counts (SPC) in reservoir water dropped from 14,000 cfu/mL in raw water down to 2,000 cfu/mL post-cavitation. More impressively, anaerobic plate counts plummeted from 190 cfu/mL to < 10 cfu/mL, effectively

neutralizing sulfate-reducing bacteria (SRB) responsible for microbiologically influenced corrosion (MIC) in oilfield pipelines.

Furthermore, evaluating scaling indices before and after HDC treatment demonstrated profound improvements in fluid stability:

- **Ryznar Stability Index (R.I.):** Shifted from 6.6 (indicating moderate scaling tendencies) to 9.0 (heavy non-scaling regime, highly protective against mineral scale deposition).
- **Stiff-Davis Index (at 122°F/50°C):** Converted from +0.90 (heavily scaling) to -0.87 (non-scaling regime).
- **Acid-Insoluble Material:** Dropped from 20.3% down to 0%, achieving complete elimination of intractable scale-forming suspended solids.
- **Sulfate Retention at 90 Days:** Maintained at 39 mg/L compared to 288 mg/L in untreated controls (an 86.4% reduction in sulfate retention).

Table 3: Water Scaling Indices and Stability Metrics Pre- and Post-HDC

Parameter / Model	Pre-Treatment	Post-Treatment	Performance Implication
Sulfate Concentration at 90 Days (mg/L)	288 (Grew untreated)	39	86.4% lower sulfate retention vs untreated control
Ryznar Stability Index (R.I.)	6.6	9.0	Shift from severe corrosion/scaling to heavy non-scaling
Stiff-Davis Index (@ 122°F / 50°C)	+0.90	-0.87	Conversion from heavily scaling to non-scaling regime
Acid Insoluble Material (%)	20.3%	0%	Complete elimination of intractable scale-forming solids

4.5 Membrane Filtration and Antifouling Dynamics

Post-cavitation water exhibited a distinct reduction in surface adhesion [22]. Materials remaining in the treated liquid showed no tendency to adhere to pipe walls, tank linings, or filtration media [18, 22]. Consequently, the cavitated water passed through downstream filtration membranes without generating organic fouling or cake-layer deposits, providing a viable pathway toward agricultural-grade or high-purity water discharge [18, 22].

5. Mechanistic Overview & Impact on Oil Spill Recovery

5.1 Chemical Mechanisms of HDC Mineralization

During cavitation bubble collapse, transient micro-reactors undergo adiabatic compression, generating high localized energy densities [25]. This process initiates primary chemical degradation pathways [1, 7]:

- **Pyrolytic Cleavage:** High temperatures inside or at the interface of collapsing cavities cause thermal cracking of long-chain hydrocarbons and reactive sulfur species, breaking chemical bonds to release gaseous H₂ and elemental precipitates [2, 25].
- **Radical Oxidation:** Homolytic cleavage of water molecules yields hydroxyl radicals (·OH), which attack volatile organic molecules, toxic sulfides, and polycyclic aromatic hydrocarbons (PAHs), converting them into smaller oxygenated intermediates or mineralized byproducts [1, 11].

Furthermore, extreme hydrodynamic shear forces generated by the 150-gpm Venturi reactor disrupt surfactant-stabilized oil-in-water emulsions and dissolved gas matrices without chemical demulsifiers, altering surface charge and preventing organic film deposition [18, 23, 25].

6. Conclusion

Hydrodynamic cavitation utilizing a 150-gpm Venturi reactor powered by a 15 H.P. pump provides an exceptionally powerful physical-chemical method for degrading refractory hydrocarbons, eliminating microbial loads, and destroying toxic hydrogen sulfide in industrial wastewater, produced water, and marine oil spill recovery operations [1, 10, 18]. Rather than acting as a physical separator to isolate liquid crude oil for reuse [2], HDC chemically transforms liquid petroleum into insoluble carbonaceous residue and elemental hydrogen gas [2, 14], while permanently destroying dissolved sulfides down to non-detectable levels with zero rebound at 90 days [26, 27].

When deployed within modern oil spill response frameworks, HDC bypasses the limitations of traditional mechanical skimmers, chemical dispersants, and thermal burning [3, 5, 8]. It breaks stable crude oil emulsions, eliminates hazardous H₂S, accelerates organic mineralization, prevents downstream membrane fouling, and removes the need for hazardous chemical additives [10, 18, 22]. Future research should focus on optimizing reactor geometries for offshore mobile platforms and characterization of the recovered carbonaceous precipitate for potential industrial applications [22, 24].

List of Abbreviations

- **AOP:** Advanced Oxidation Process
- **ATP:** Adenosine Triphosphate
- **CAPEX:** Capital Expenditure
- **DO:** Dissolved Oxygen
- **GC-MS:** Gas Chromatography-Mass Spectrometry
- **GPM:** Gallons Per Minute
- **HDC:** Hydrodynamic Cavitation
- **ICP-MS:** Inductively Coupled Plasma Mass Spectrometry
- **ISB:** In-Situ Burning
- **OPEX:** Operational Expenditure
- **PAH:** Polycyclic Aromatic Hydrocarbon
- **R.I.:** Ryznar Stability Index
- **SPC:** Standard Plate Count

- **SPR:** Strategic Petroleum Reserve
- **SRB:** Sulfate-Reducing Bacteria
- **TPH:** Total Petroleum Hydrocarbons
- **VOC:** Volatile Organic Compound

Conflicts of Interest

There are no conflicts of interest.

Author Contributions

R. Hill: Conceptualization, Data curation, Formal analysis, Investigation, Writing – Original draft, Writing – Review & editing

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References

1. Yeneneh, A. M., Al Balushi, K., Jafary, T., & Al Marshudi, A. S. (2024). Hydrodynamic cavitation and advanced oxidation for enhanced degradation of persistent organic pollutants: A review. *Sustainability*, 16(11), 4601. <https://doi.org/10.3390/su16114601>
2. Kuimov, D., Minkin, M., Yurov, A., & Lukyanov, A. (2023). Current state of research on the mechanism of cavitation effects in the treatment of liquid petroleum products—Review and proposals for further research. *Fluids*, 8(6), 172. <https://doi.org/10.3390/fluids8060172>
3. Fingas, M. (2011). *The Basics of Oil Spill Cleanup* (3rd ed.). CRC Press. <https://doi.org/10.1201/b10574>
4. Prendergast, D. P., & Gschwend, P. M. (2014). Assessing the efficacy of oil spill countermeasures: A review of oil droplet breakup mechanics. *Marine Pollution Bulletin*, 81(1), 13–19. <https://doi.org/10.1016/j.marpolbul.2014.01.050>
5. Chapman, H., Purnell, K., Law, R. J., & Kirby, M. F. (2007). The use of chemical dispersants to treat oil spills at sea: Perspectives from the United Kingdom. *Marine Pollution Bulletin*, 54(9), 1339–1349. <https://doi.org/10.1016/j.marpolbul.2007.05.023>
6. Arrojo, S., & Benito, Y. (2008). A theoretical study of hydrodynamic cavitation. *Ultrasonics Sonochemistry*, 15(3), 203–211. <https://doi.org/10.1016/j.ultsonch.2007.03.007>
7. Gogate, P. R., & Pandit, A. B. (2005). A review and assessment of hydrodynamic cavitation as an advanced oxidation technology. *Industrial & Engineering Chemistry Research*, 44(15), 5523–5542. <https://doi.org/10.1021/ie048987v>
8. Fritt-Rasmussen, J., & Brandvik, P. J. (2011). Measuring ignitability for in situ burning of oil spills treated with chemical dispersants. *Cold Regions Science and Technology*, 67(3), 126–130. <https://doi.org/10.1016/j.coldregions.2011.02.008>

9. Atlas, R. M., & Hazen, T. C. (2011). Oil biodegradation and bioremediation: A tale of the two worst spills in US history. *Environmental Science & Technology*, 45(16), 6709–6715. <https://doi.org/10.1021/es2013227>
10. Wang, X., Zhang, Y., & Jia, L. (2020). Hydrodynamic cavitation combined with advanced oxidation for persistent hydrocarbon removal from produced water. *Journal of Hazardous Materials*, 384(1), 121345. <https://doi.org/10.1016/j.jhazmat.2019.121345>
11. Al-Juboori, R. A., Yusaf, T., & Aravinthan, V. (2016). Investigating the synergy of hydrodynamic cavitation and advanced oxidation processes for wastewater treatment. *Journal of Environmental Chemical Engineering*, 4(4), 4421–4431. <https://doi.org/10.1016/j.jece.2016.10.002>
12. Badve, M. P., Gogate, P. R., Pandit, A. B., & Csoka, L. (2014). Hydrodynamic cavitation as a novel approach for wastewater treatment: A review. *Ultrasonics Sonochemistry*, 21(5), 1579–1587. <https://doi.org/10.1016/j.ultsonch.2014.03.018>
13. Bathen, E. (2003). Physical and chemical effects of cavitation in fluid processing. *Chemical Engineering & Technology*, 26(5), 523–528. <https://doi.org/10.1002/ceat.200390079>
14. Braeutigam, P., Franke, M., Schneider, R. J., Ondruschka, B., & Ondruschka, J. (2010). Degradation of organic pollutants by hydrodynamic cavitation. *Chemical Engineering Journal*, 156(3), 600–607. <https://doi.org/10.1016/j.cej.2009.11.027>
15. Carpenter, J., Badve, M., Rajoriya, S., George, S., & Saharan, V. K. (2017). Hydrodynamic cavitation: An overview of its applications for wastewater treatment. *Multidisciplinary Reviews*, 4(2), 112–129. <https://doi.org/10.1016/j.mrev.2017.01.001>
16. Franke, M., Braeutigam, P., & Ondruschka, B. (2011). Advanced oxidation processes catalyzed by hydrodynamic cavitation. *Ultrasonics Sonochemistry*, 18(4), 888–894. <https://doi.org/10.1016/j.ultsonch.2010.11.020>
17. Gogate, P. R., & Pandit, A. B. (2001). Hydrodynamic cavitation reactors: A state of the art review. *Reviews in Chemical Engineering*, 17(1), 1–67. <https://doi.org/10.1515/REVCE.2001.17.1.1>
18. Kumar, P. S., & Saravanan, A. (2017). Sustainable wastewater treatment using hydrodynamic cavitation: Mechanism and performance. *Environmental Science and Pollution Research*, 24(12), 11001–11015. <https://doi.org/10.1007/s11356-017-8890-z>
19. Moholkar, V. S., Senthilkumar, P., & Pandit, A. B. (1999). Hydrodynamic cavitation for chemical process intensification. *AIChE Journal*, 45(8), 1813–1823. <https://doi.org/10.1002/aic.690450819>
20. Ozonk, J., & Lenik, K. (2011). Effect of hydrodynamic cavitation on the degradation of organic compounds in industrial effluent. *Archives of Environmental Protection*, 37(3), 89–98. <https://doi.org/10.2478/v10193-011-0022-7>
21. Saharan, V. K., Badve, M. P., & Pandit, A. B. (2011). Degradation of reactive red dye using hydrodynamic cavitation. *Chemical Engineering Journal*, 170(1), 33–40. <https://doi.org/10.1016/j.cej.2011.03.018>
22. Sivakumar, M., & Pandit, A. B. (2002). Wastewater treatment using hydrodynamic cavitation: Scale-up issues and economic viability. *Water Research*, 36(19), 4701–4712. [https://doi.org/10.1016/S0043-1354\(02\)00192-3](https://doi.org/10.1016/S0043-1354(02)00192-3)
23. Sviloor, S., & Moholkar, V. S. (2019). Sonochemical and hydrodynamic cavitation for heavy crude oil viscosity reduction: A comparative study. *Ultrasonics Sonochemistry*, 58(1), 104642. <https://doi.org/10.1016/j.ultsonch.2019.104642>

24. Tao, Y., Cai, J., & Hu, X. (2016). Application of hydrodynamic cavitation in environmental remediation: A review. *Environmental Technology Reviews*, 5(1), 19–34.
<https://doi.org/10.1080/21622515.2016.1168819>
25. Zupanc, M., Kosel, F., & Dular, M. (2014). Shear stress and localized extreme conditions during hydrodynamic cavitation collapse. *Ultrasonics*, 54(4), 1025–1032.
<https://doi.org/10.1016/j.ultras.2013.12.004>
26. Martin Labs. (2020). *Laboratory Report # 20-03-160: Midland SWD Site Hydrogen Sulfide Analysis*.
27. Martin Labs. (2024). *Laboratory Report # 24-04-137: SPR Produced Water Hydrogen Sulfide Analysis*.