

Evaluation of the effects of iron sulfide on THPS-mediated souring mitigation using high pressure sand-packed reactors

Renato M. De Paula¹, Chris Jones², Stephanie Edmunds², Matt Streets³, Kerry Lillis³, Muna Mohamud³, Bob Eden³

¹ SNF Oil & Gas, The Woodlands, TX 77381, USA

² SNF Oil & Gas, Oldbury, B69 4LN, United Kingdom

³ Rawwater Engineering Company Limited, Warrington, WA3 4JE, United Kingdom

Abstract

Reservoir souring remains one of the most elusive and challenging issues in the oil and gas industry. The variation of reservoir conditions, complex sub-surface parameters and limited understanding of the microbiome under reservoir conditions make it difficult to achieve expected results even with well calculated strategies. The use of nitrate treatments is an example, with reported success in certain reservoirs, but poor outcome in other instances.

Tetrakis (hydroxymethyl)phosphonium sulfate (THPS) is a common biocide used to maintain microbial control in production systems. Additionally, THPS has been demonstrated to control souring by blocking the metabolism of SRPs when dosed at low concentrations, akin to a specific inhibitor. Nonetheless, questions remain about the feasibility of using THPS in sour reservoir conditions and indeed the ability of THPS to control SRP in the presence of iron sulfide. As a potent iron chelator, THPS reacts with iron sulfide particles, dissolving the mineral scale and forming a complex with Fe^{2+} , which does not affect the microorganisms.

In this study, we evaluated the ability of a proprietary THPS formulation to block SRP activity in the presence of high levels of iron sulfide scale. Sour, sand-packed reactors containing 3% w/w iron sulfide (troilite and pyrite mixture) were treated with formulated THPS for several weeks. Hydrogen sulfide, residual iron, volatile fatty acids and microbial counts were measured, and community analysis was performed. The results indicated that the type of

iron sulfide scale has a significant impact on how souring progresses over time, and different forms of iron sulfide have distinct ability to scavenge H₂S on the mineral matrix. Moreover, we found that even in the presence of high percentage levels of iron sulfide species, the formulated THPS is still effective to block the activity of the sulfate-reducing microorganisms and stop souring from occurring. Taken together, these results shed light on an important question on how effective THPS-based chemistry can be deployed in soured reservoirs with no further capacity for iron-induced H₂S scavenging.

Introduction

Reservoir souring refers to the undesirable increase in hydrogen sulfide (H₂S) concentrations in oil reservoir fluids that were originally “sweet” (i.e., low in H₂S). This phenomenon is of significant concern in the petroleum industry because H₂S is highly toxic, corrosive to infrastructure, and severely reduces the economic value and safety of hydrocarbon production and processing operations. Souring typically occurs when water-based injection fluids — often seawater or reservoir brine used for pressure maintenance during secondary and tertiary oil recovery — introduce both sulfate and sulfate-reducing microorganisms into the reservoir environment. In the anoxic conditions of a subsurface reservoir, these microorganisms, particularly sulfate-reducing bacteria (SRB) and related sulfate-reducing prokaryotes (SRP), catalyze the reduction of sulfate to sulfide, leading to biogenic production of H₂S over the life of the field (Sugai et al., 2020).

The underlying mechanisms of reservoir souring include both biological and abiotic processes: microbial sulfate respiration can occur where organic electron donors are available, while thermochemical reduction processes may also contribute under high-temperature conditions, although microbial activity is often the dominant cause in waterflooded systems (Basafa and Hawboldt, 2019). The onset and severity of souring are influenced by a combination of microbiological, geochemical, and reservoir engineering factors, including the composition of injected fluids, reservoir temperature, and the presence of organic substrates and minerals that interact with sulfide species (Alkan et al., 2024). Understanding these processes and their implications is critical not only for predicting H₂S formation but also for developing mitigation strategies to protect production infrastructure, ensure worker safety, and maintain oil quality throughout the life of a reservoir.

Downhole treatments commonly include continuous or batch nitrate injection to stimulate nitrate-reducing bacteria that outcompete SRB, and targeted biocide application to suppress microbial populations (Hubert and Voordouw, 2007). In addition, sulfate removal units (SRUs) are widely implemented in seawater-injection systems — particularly in offshore developments such as the North Sea — to reduce sulfate concentrations before injection, thereby limiting the electron acceptor required for SRB metabolism and preventing H₂S formation at the source (Krebs et al., 2019). On the surface, produced H₂S is managed through gas sweetening (e.g., amine treatment) to meet environmental and safety standards (Pudi et al., 2022). Additionally, biocide treatments, and real-time monitoring provides a robust, long-term solution for controlling reservoir souring while protecting asset integrity and production efficiency.

Tetrakis(hydroxymethyl)phosphonium sulfate (THPS) is widely used in oilfield operations to control reservoir souring by targeting sulfate-reducing bacteria, the primary producers of H₂S. THPS is a fast-acting, broad-spectrum biocide that disrupts microbial cell metabolism and membrane integrity, leading to rapid reduction of viable SRB populations in injection water systems and near-wellbore regions. It is particularly valued for its effectiveness under a wide range of salinity conditions and for its relatively favorable environmental profile compared with some traditional biocides, as it degrades into less persistent byproducts. Laboratory and field studies have demonstrated that properly dosed THPS treatments can significantly reduce sulfide production rates and delay the onset of souring, especially when applied as part of a continuous or batch treatment program (McDonnell & Russell, 1999; Jones et al., 2011; De Paula et al., 2023).

In practice, THPS is often integrated with complementary souring mitigation strategies such as nitrate injection and sulfate removal to enhance long-term control. While THPS provides rapid microbial knockdown, nitrate promotes competitive exclusion of SRB by nitrate-reducing bacteria (NRB), creating a more sustainable suppression mechanism. Alternatively, THPS can be used to replace nitrate treatment, when the latter is no longer effective as a competitive exclusion agent (De Paula et al., 2024). Field applications have shown that combining chemical biocides like THPS with monitoring programs — including microbial population analysis and sulfide concentration tracking — improves treatment optimization and reduces chemical overuse. However, careful management is required to minimize the risk of microbial adaptation and to account for reservoir temperature, pH, and

compatibility with production chemistry. When applied within a comprehensive souring management framework, THPS remains a critical tool for controlling SRB activity and protecting infrastructure from H₂S-related corrosion and safety hazards (Hubert & Voordouw, 2007; Gieg et al., 2011).

Despite the well-established efficacy of THPS to control SRB activity, one critical question is whether its effectiveness remains in an already soured reservoir, where iron sulfide has accumulated over time. The well-known capability of THPS to dissolve FeS and chelate iron ions raises the concern that not enough THPS would be available to attack SRB cells in the presence of high levels of iron sulfide. In this study we evaluate the ability of a formulated THPS product to control SRB metabolism and prevent/remediate reservoir souring even in the presence of high levels of iron scaling.

Methodology

Pressurised, Sand-Packed Bioreactor Set-up and Operation

A total of twelve (12) pressurised, sand-packed bioreactors operated in four triplicate groups for the duration of the 13-week study at the Rawwater UK laboratories. The pressurised bioreactors and the associated injection and production jewellery were constructed of 316L stainless steel, pressure rated with a maximum working pressure of 3,000 psig (207 barg). This methodology has been used extensively for the accurate evaluation of microbial souring as it replicates the key physical and chemical conditions present within the downhole reservoir environment (Dutta et al., 2020; Jones et al., 2011, 2014; Streets & Eden, 2024).

All twelve of the pressurised, flowing bioreactors were packed with a homogenised mixture of 25% w/w pre-established sand and 75% w/w fresh, low-iron sand. Six of these bioreactors were further amended with a mixture of 1.5% w/w troilite and 1.5% w/w pyrite, 90-100 mesh. A second version of the experiment was later set up with 3% w/w pyrite only (see results for explanation). The pre-established inoculating sand consisted of core matrix from decommissioned, pressurised bioreactors from Rawwater's pressurised bioreactor suite, and therefore contained a mature pre-established oilfield microbial sessile consortium capable of VFA utilisation, oil degradation, nitrate reduction and sulfate reduction (R. De Paula et al., 2023; R. M. De Paula et al., 2024; Streets et al., 2025).

The bioreactors were operated at 1,000 psig (69 barg), and the temperature was maintained at 30°C (+/- 1°C) through controlled heat within an insulated mesophilic incubator in order to simulate a microbiologically active near wellbore environment. Influent was delivered using pneumatic pumps at a target batch flow rate of 5.00 ml/min over 15 minutes (80 ml per injection cycle) to ensure a full replacement of the average swept volume during each injection cycle. The baseline influent water injected was anoxic, synthetic produced water, with a target mixed volatile fatty acid (VFA) concentration of 60 mg/l (ratios of 50 mg/l acetate, 5 mg/l propionate, and 5 mg/l butyrate) and was introduced as the primary carbon source to support microbial sulfate reduction.

Injection chemistry for biocide shot dosing of the selected THPS product formulation (PS70AN) was prepared immediately prior to injection on day 63.

Pressurised Bioreactor Treatment

In order to assess whether shot dose of the selected THPS formulation would be effective for souring remediation in both the presence and absence of pyrite, the twelve pressurised, sand-packed bioreactors were assigned to one of four triplicate group conditions:

Table 1: Overview of bioreactor groupings, including pyrite addition to the starting packing matrix and application of the THPS shot dose on day 63

Bioreactor Group Description	Addition of 3% w/w pyrite in packing matrix?	THPS shot-dose treatment (4-hour application on day 63)?
Controls	No	No
FeS Controls	Yes	No
Tests	No	Yes
FeS Tests	Yes	Yes

Water samples from the effluent end of each pressurised bioreactor were collected over the course of the study for total sulfide analysis. Samples were collected directly onto zinc acetate, which reacted with the sulfide species in solution to form a zinc sulfide precipitate, preserving the total sulfide concentration (limit of detection (LoD) set to 0.1 mg/l and limit of

quantification (LoQ) set to 0.5 mg/l total sulfide concentration). The sulfide was then regenerated in acid for a methylene blue colourimetric test. This test was calibrated using the standard iodometric sulfide titration method.

Both the injection water and the bioreactor effluent water were analysed for individual VFA concentrations (acetate, propionate, and butyrate), using in-house ion chromatography. The LoQ for all individual VFA component concentration analysis through ion chromatography was 0.2 mg/l.

Influent and effluent THPS concentration analysis was conducted using the 'THPS Test Kit' and 'THPS Reagent Pack' supplied by Lovibond. Using the standardised procedure, THPS concentration measurements were taken of the injection water and of the bioreactor effluent water following the 4-hour contact period (Table 2).

At the conclusion of the 13-week study, core sand samples were recovered anoxically from each of the twelve bioreactors to characterise the sessile (biofilm) microbial communities and benchmark their development against the original inoculum packing matrix. Quantitative PCR (qPCR) was used to determine the abundance of total bacteria and total sulfate reducing bacteria in each core expressed as cells/g, while 16S rRNA gene next-generation sequencing (NGS) was applied to resolve community composition (LuminUltra Technologies Ltd., Canada). The NGS data were used to describe both the dominant taxa present in each sample and the relative contribution of key metabolic groups across the bioreactor systems.

Results

Microbial Souring in Pressurised Bioreactors

THPS is a potent chelator of divalent metal ions, especially, iron, zinc and copper. It has been widely used in the oil & gas industry to dissolve amorphous iron sulfide sludge besides its intended use as a biocide. The reaction of THPS towards iron and amine groups in microbial cells is driven by steric hindrance, kinetics and thermodynamics. Thus, the availability of THPS to act on microbial cells can be affected by the presence of free iron and iron scales. Nonetheless, it is unknown to which extent this can impact the microbial effectiveness of

THPS. To address this, we set up experiments to determine the impact of iron sulfide on the ability of a THPS formulation to control SRB activity in simulated souring conditions.

To determine the efficacy of the selected THPS formulation to control microbial sulfide generation in simulated, near wellbore subsurface environments, the bioreactors were operated at mesophilic temperatures to facilitate significant growth and activity of the pre-established sand matrix inoculum.

In the initial experimental set up, a mixture of 1.5% w/w troilite (FeS) and 1.5% w/w pyrite (FeS₂), totalling 3% w/w of iron scale. This is considered a high level of iron scaling predicted to be present in soured reservoirs.

In all bioreactors, consumption of injected mixed VFA was used to infer microbial activity, along with the measurements of H₂S generated by the microbial activity. In the first 25 days of operation, consumption of mixed VFA was observed in all bioreactors. Nonetheless, H₂S was only measured in the bioreactors that did not contain 3% w/w iron sulfide mixed in the sand matrix (Figure 1). This was indicative that, although the SRB microbial population was active, consuming VFAs and likely generating H₂S, the sour gas had been scavenged by the iron sulfide scale. In fact, the ability of troilite (FeS) to further react with H₂S to produce the fully reduced form of pyrite (FeS₂) is well described in the literature (Heinen and Lauwers, 1996).

Based on this observation, the experiment was stopped, and the bioreactors were cleaned and repacked with 3% w/w pyrite (FeS₂). This change would avoid further scavenging of H₂S produced by microbial activity and would simulate a reservoir with exhausted iron-induced H₂S scavenging.

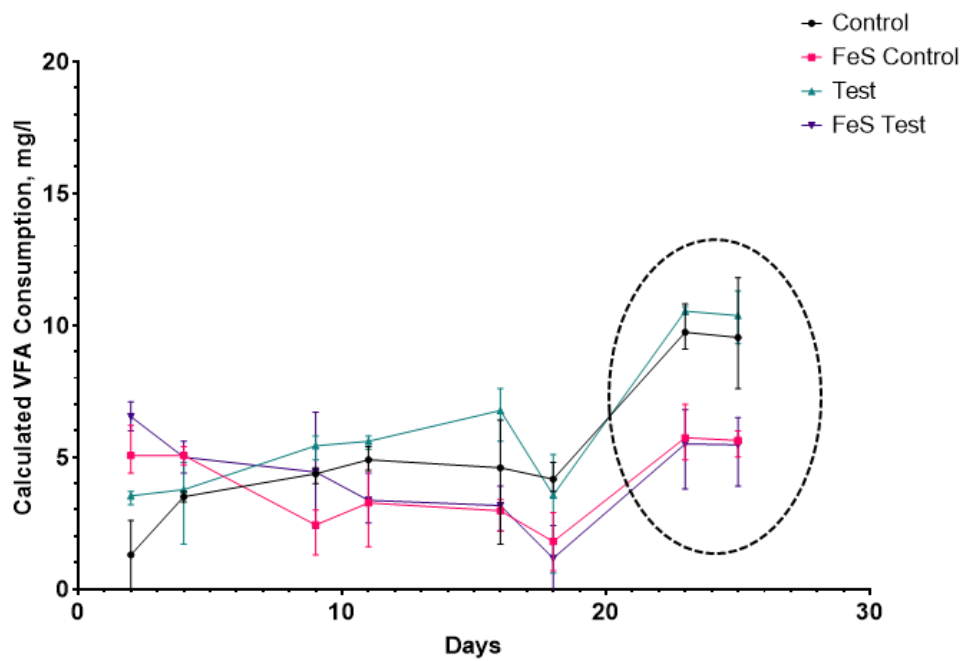
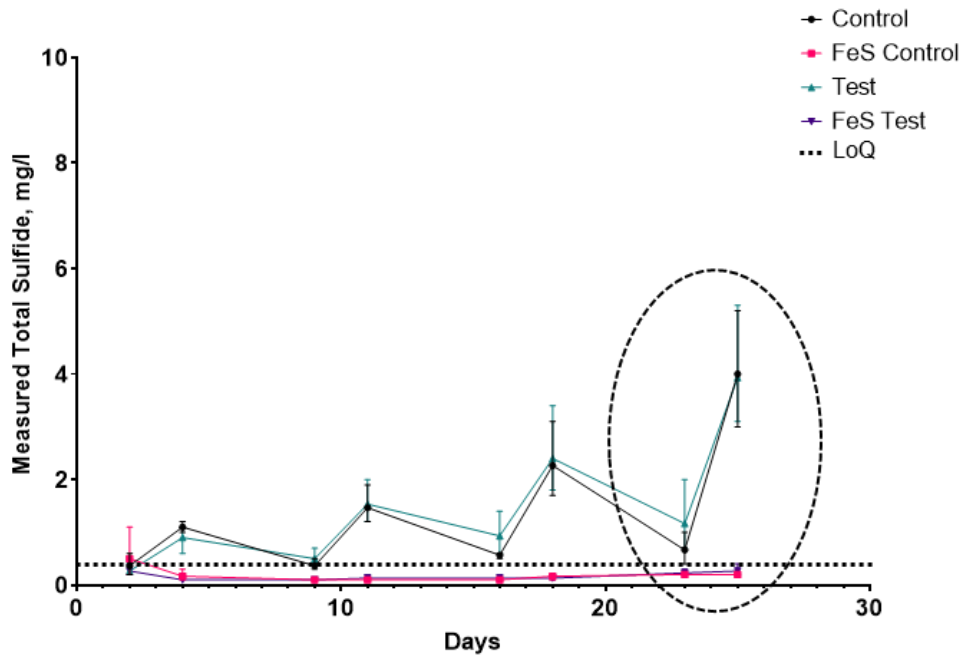


Figure 1: Measured sulfide generation (top) and calculated average VFA consumption (bottom) in the four triplicate bioreactor groups. Bioreactors were packed with or without 3% w/w total iron sulfide (1.5% w/w FeS and 1.5% w/w FeS₂). Error bars represent the standard deviation of measurements obtained from each triplicate incubation at each timepoint

Similarly, as in the first set of experiments, during the initial 9-weeks of microbial establishment, calculated mixed VFA consumption concentrations were relatively stable from all four groups prior to shot dose of formulated THPS treatment (Figure 2). Microbial VFA consumption remained relatively stable in the two triplicate groups which did not receive shot dose THPS treatment until the end of the project ('Controls' and 'FeS Controls'). H₂S generation was observed in all the bioreactors prior to the injection of THPS – indicating that in these conditions, the microbial activity (as observed by VFA consumption) correlated to the production of H₂S without the effect of iron sulfide scavenging the biologically produced H₂S.

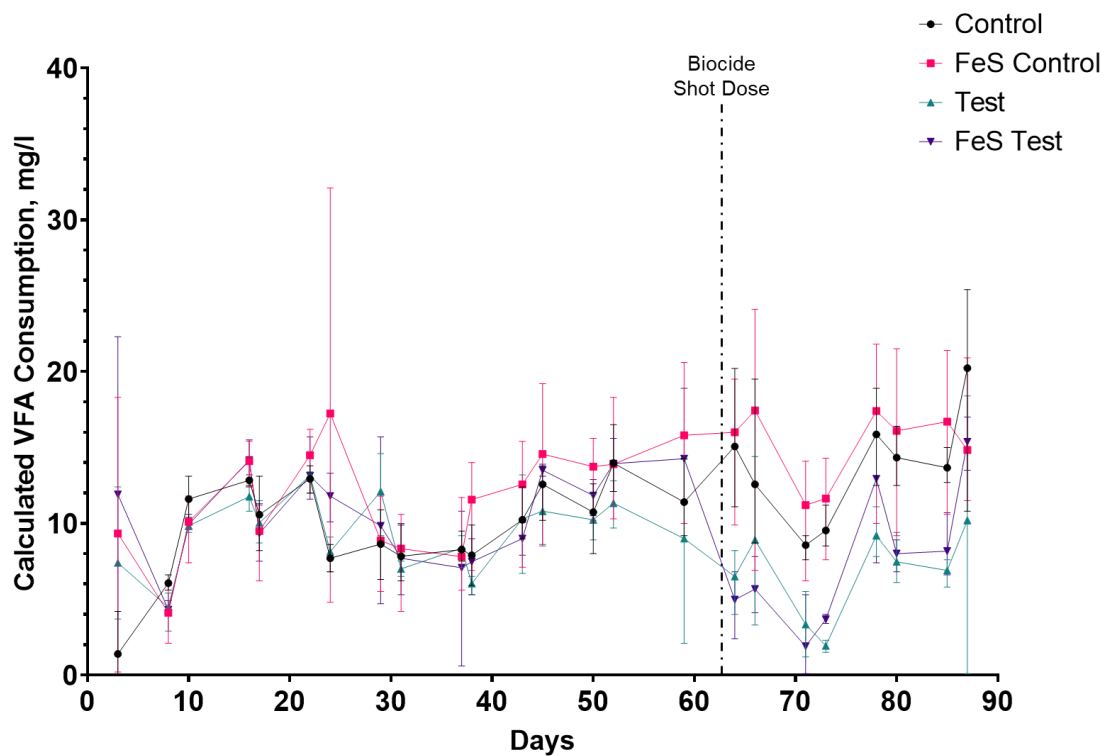


Figure 2: Calculated average VFA consumption concentration for the four triplicate groups. Bioreactors were packed with or without 3% w/w FeS₂. Error bars represent the standard deviation of measurements obtained from each triplicate incubation at each timepoint

From the start of the study through to the THPS shot dose on day 63, average produced water sulfide concentrations across the four triplicate groups increased gradually and remained broadly comparable between all groups (Figure 3). In the bioreactor groups which did not receive THPS treatment, sour gas production continued until the end of the project.

These findings suggested that microbial VFA consumption and sulfide generation under simulated subsurface pressure and temperature conditions were not significantly impacted by the presence of 3% w/w pyrite in the bioreactor packing matrix.

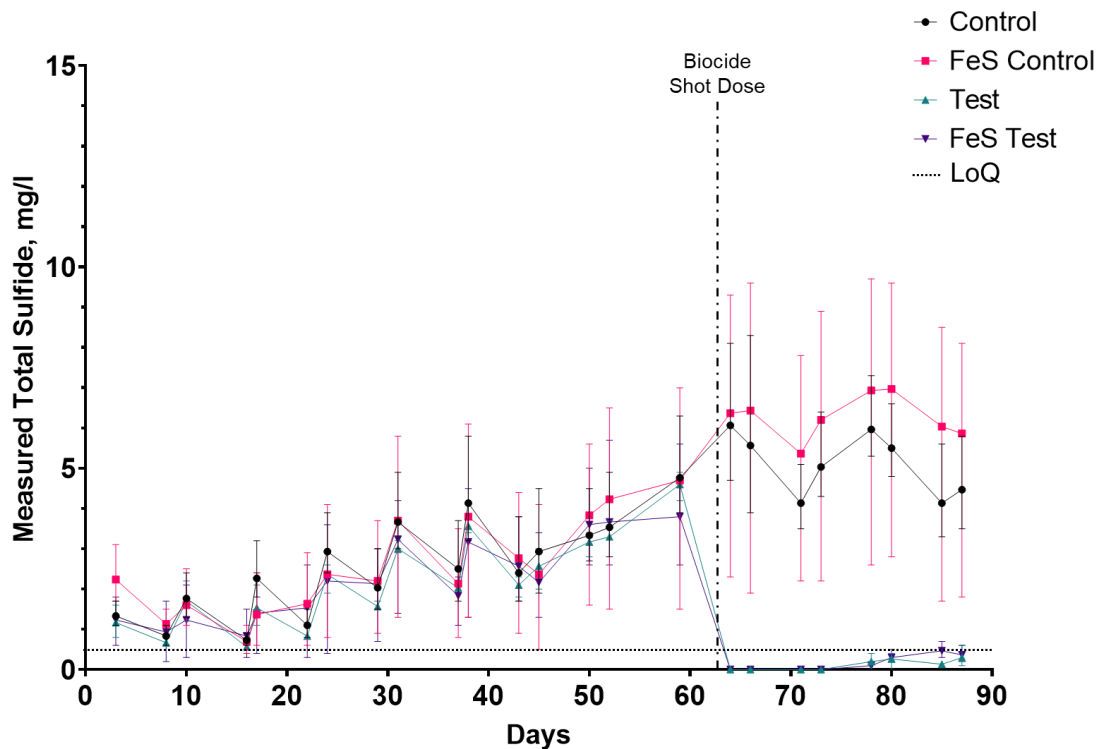


Figure 3: Average measured H₂S generation for the four triplicate groups. Error bars represent the standard deviation of measurements obtained from each triplicate incubation at each timepoint

Microbial Souring Remediation by Biocide Application

Two of the triplicate groups (labelled as ‘Test’ and ‘FeS Test’) were used to determine the impact of the presence of iron sulfide on a single shot dose of formulated THPS to control microbial souring.

On project day 63, the ‘Test’ and ‘FeS Test’ group bioreactors all received a 4-hour, 50ppm (mg/l) active of a 3rd generation THPS formulation containing a proprietary polymer to aid in scale and biofilm control. This formulation has previously been shown to have significant better performance compared to generic THPS (Jones et al., 2010). An immediate response was observed on project day 64, with a significant decrease in the average calculated VFA consumption relative to the ‘Control’ and ‘FeS Control’ groups. Nonetheless, a recovery in VFA consumption was observed in both bioreactor groups treated with the biocide, regardless

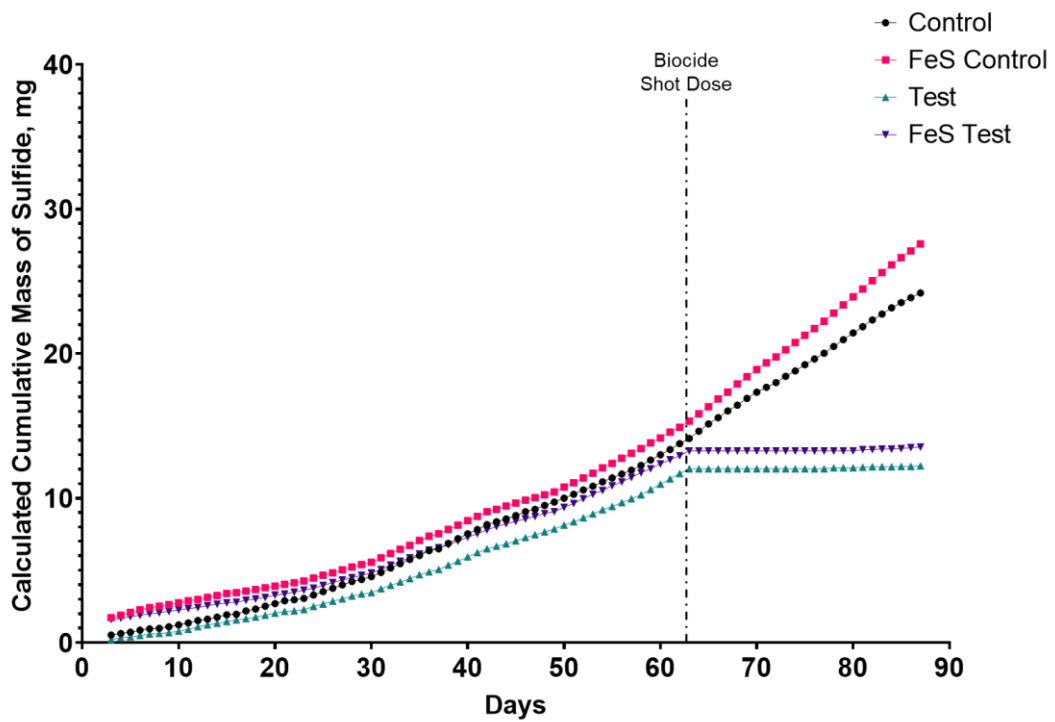
of the presence of absence of iron sulfide in the matrix. This indicated that although a single treatment with the formulated THPS product reduced microbial activity, that reduction was transient and was recovered after the product was flushed from the system (Figure 2).

Concomitant with the reduction in VFA consumption, a single dosage of formulated THPS drastically reduced the H₂S levels in both test groups (plus or minus FeS₂). The H₂S levels were reduced to below detection levels, with a significant low dosage (50mg/L). The presence of 3% w/w FeS₂ in the matrix of one set of bioreactors did not prevent the product to act on the microbial population and blocking H₂S production. More importantly, H₂S levels were never recovered to the levels prior to injection of the biocide, despite the microbial community metabolically recovering, as determined by the VFA consumption. For the remaining period of the experiment (23 days), the treated bioreactors maintained “sweet” conditions. These results indicate that THPS, even a low dosage, can block production of H₂S in sulfate-reducing communities, independent of the presence of high levels of pyrite.

When the cumulative generation of H₂S in all bioreactor groups is plotted, we can see a clear distinction between the groups treated with formulated THPS. By the end of the 13-week period, the ‘FeS Control’ group (bioreactors containing iron sulfide and not treated with THPS) produced the greatest cumulative mass of sulfide during the study, reaching a calculated 27.6mg by project day 87 (Figure 4). In comparison, the ‘Control’ group (no iron sulfide, no THPS treatment) reached a calculated 24.2mg (87.7% of the ‘FeS Controls’). For the THPS-dosed bioreactor groups, the ‘Test’ group (no iron sulfide) peaked at a calculated 12.2mg (50.6% of the ‘Controls’) and the ‘FeS Test’ group (iron sulfide present, THPS treated) reached 13.5mg (49.0% of the ‘FeS Controls’) over the same 87-day period. Thus, THPS clearly decreases the total H₂S accumulation, and that the effect is not impacted by the presence or absence of iron sulfide scale.

These findings indicated that the application of a 4-hour, 50 mg/l formulated THPS shot dose under simulated subsurface pressure and temperature conditions to remediate and control

microbial souring was not affected by the presence of 3% w/w pyrite in the bioreactor packing



matrix.

Figure 4: Calculated cumulative mass of sulfide dataset for the four triplicate groups

During this study, THPS residual measurements were made before and after the 4-hour THPS shot dosing of the pressurised, flowing bioreactors (Table 2), and delta calculations were conducted to determine measurable changes in influent and effluent THPS concentration.

Table 2: THPS residual concentration analysis using the Lovibond THPS test kit

Triplicate Condition	Individual Bioreactor	Measured THPS in Injection Water, mg/L	Measured THPS in Produced Water, mg/L	Calculated THPS Loss, mg/L (%)	Average THPS Loss, mg/L (%)
Tests	Test A	49.0	38.8	10.2 (20.8%)	10.9 (22.2%)
	Test B	49.0	36.7	12.3 (25.1%)	
	Test C	49.0	38.8	10.2 (20.8%)	
FeS Tests	FeS Test A	49.0	30.6	18.4 (37.6%)	19.1 (38.9%)
	FeS Test B	49.0	30.6	18.4 (37.6%)	
	FeS Test C	49.0	28.6	20.4 (41.6%)	

Microbial Sessile Community Analysis Following Biocide Application

To determine possible changes in the microbial community composition in response to treatment with the THPS formulation, community analysis was performed on core samples from all bioreactors at the end of the experiment. The core sand samples were extracted from the depressurised bioreactors and analysed for qPCR and 16S NGS to determine the total number of bacteria and sulfate-reducing bacteria (SRB) in each core sample, as well as the relative abundance of the most abundant organisms in each sample.

qPCR for total prokaryotes and SRB from the starting inoculum and from the core samples for all bioreactors are shown in Figure 5. The results indicated that although the overall population remained at high levels ($>10^8$ cells/unit) in the initial inoculum and in all bioreactors, the total SRB population seemed to be slightly reduced in the bioreactors treated

with formulated THPS, particularly in the reactors containing iron sulfide. Although the differences seem to be small, it is important to note that the qPCR analysis can detect genetic material from both viable (living) and non-viable (dead) cells. Thus, the true effect of formulated THPS on SRB cells can be masked by false positives resulting from the detection of DNA from dead cells.

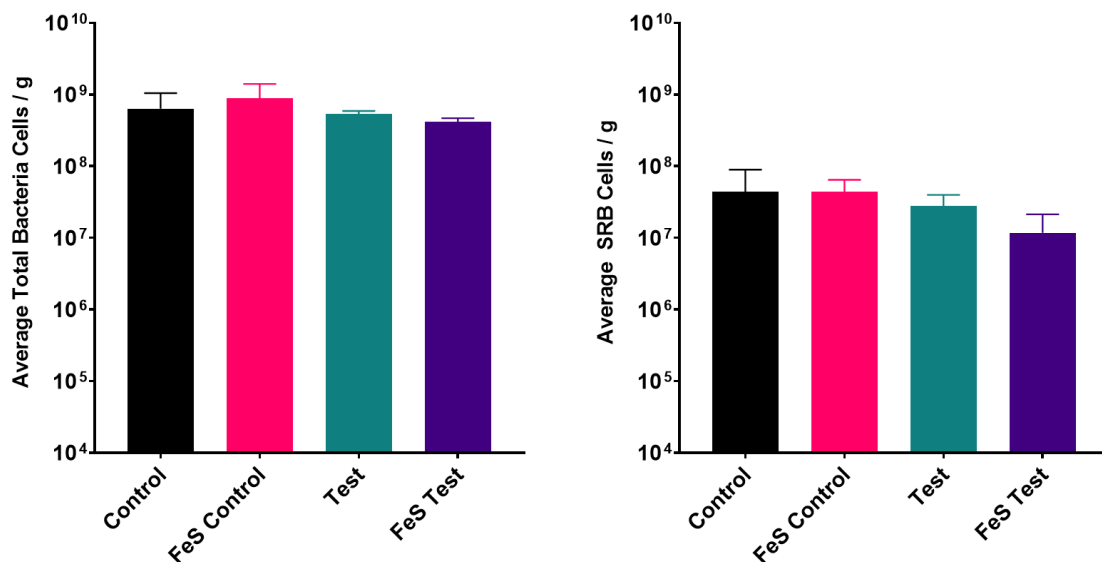


Figure 5: qPCR dataset for the starting pre-established sand inoculum and the average triplicate group samples from the decommissioned, pressurised bioreactors for total bacteria (left) and sulfate reducing bacteria (right) in cells/g matrix material. Error bars for the four triplicate groups represent the standard deviation of measurements obtained from each triplicate incubation at the final timepoint

Further evidence of the effects of THPS on the SRB population comes from the microbial community distribution, determined by 16S taxonomy. Figure 6 describes the population distribution of the five most common taxa groups of the sessile bioreactor community at the end of the bioreactor study, demonstrating a significant shift from the starting inoculum and the end-point decommissioned core samples.

The sulfide-producing genus, *Desulfotignum*, was detected in all twelve decommissioned bioreactor core samples at the end of the 13-week study and, in many cases, constituted the dominant taxon. The taxon family, *Desulfobacteraceae*, known also to reduce

sulfate to sulfide in strict anoxic environments, was also present in relatively high abundance in eleven of the twelve decommissioned bioreactor core samples; the ‘FeS Test B’ replicate was also characterised by the presence of this family within the decommissioned core sample, albeit at a substantially lower relative abundance (2.6%).

Finally, *Desulforomusa*, another sulfidogenic genus, was detected in all six bioreactors that did not receive the THPS shot treatment but was present at sufficiently high abundance to rank within the top five taxa in only one of the six biocide-treated bioreactors. This indicates THPS treatment may have significantly reduced the *Desulforomusa* population, which can explain the decrease in H₂S levels observed in the treated reactors.

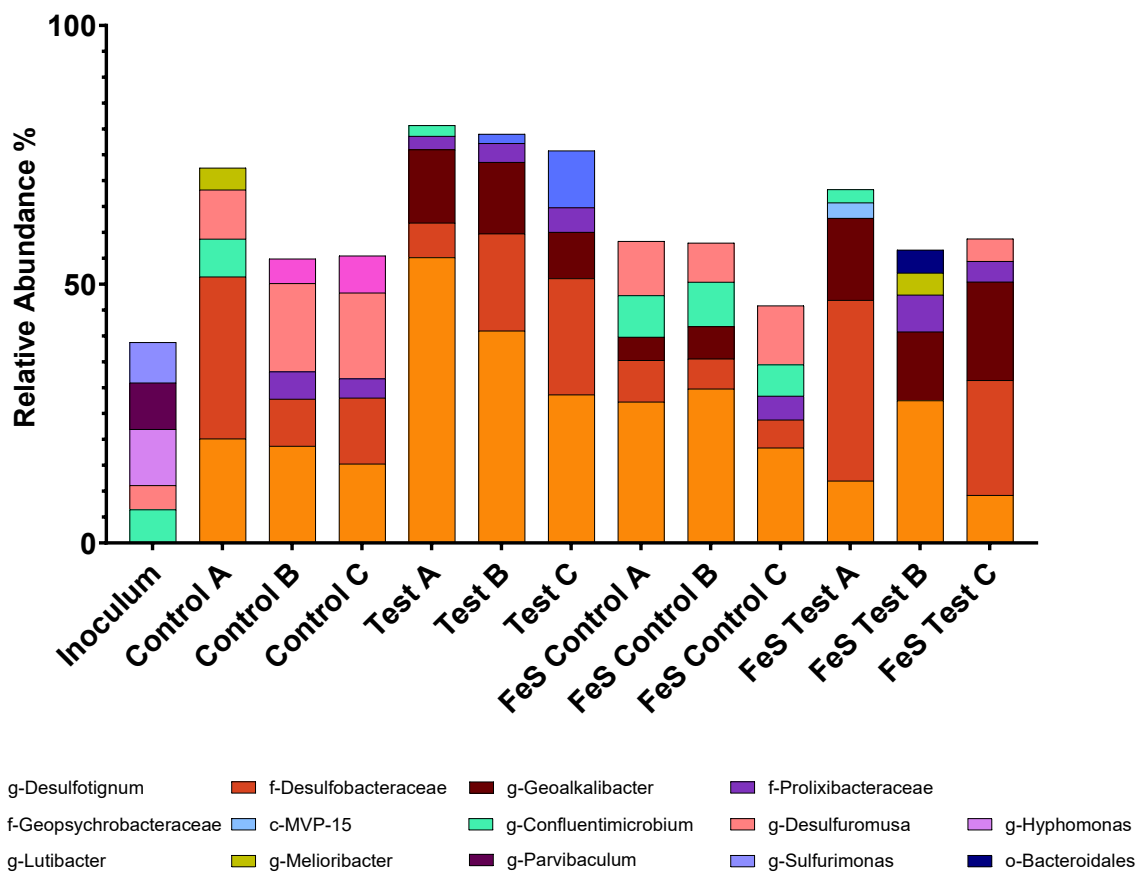


Figure 6: NGS dataset describing the top 5 taxa groups for the starting pre-established sand inoculum and the twelve core samples from the decommissioned, pressurised bioreactors

Conclusions

The concerns about the impact of iron sulfide on THPS efficacy to act as a biocide is a valid point, often raised by users of the product. The overall perception is that, in a system fouled with iron sulfide, a significant amount of THPS will be consumed by dissolving FeS and chelating iron, which would reduce the available THPS to attach to its targets in microbial cells. While, this is certainly a possibility in topside separation equipment and transmission lines, it is unclear that this concern holds in the context of reservoir souring. In reservoir conditions, most likely, H₂S will only be produced in producing wells when the reservoir exhausts its mineral scavenging capacity, a process called pyrite burial.

In this study, we showed that formulated THPS still may work, as intended, to disrupt the metabolism of sulfate-reducing microorganisms in simulated reservoir conditions, even in the presence of high levels of pyrite (FeS₂). By initially using a combination of FeS and FeS₂, we were able to show that additional H₂S scavenging is achieved in the presence of FeS, but when only FeS₂ is present, no further H₂S can be converted to sulfur mineralogy. Moreover, FeS₂ alone seems to have little to no effect on formulated THPS in reservoir conditions. This can be explained by the denser nature of FeS₂ compared to FeS, which would not favor a dissolution/chelation model as it does for the latter.

Thus, taken together, these results suggest that FeS₂ is unlikely to be a concern during treatment with formulated THPS for reservoir souring mitigation applications, and other parameters may be more important to define the success of the product. These most likely would be communication between injection and producing wells, channelling and breakthrough time, amongst others.

References

- Alkan, H.; Kögler, F.; Namazova, G.; Hatscher, S.; Jelinek, W.; Amro, M. Assessment of the Biogenic Souring in Oil Reservoirs under Secondary and Tertiary Oil Recovery. *Energies* **2024**, *17*, 2681.
- Basafa, M., Hawboldt, K. Reservoir souring: sulfur chemistry in offshore oil and gas reservoir fluids. *J Petrol Explor Prod Technol* **9**, 1105–1118 (2019).
- De Paula, R. M., Jones, C., Streets, M., Walker, L., Mouhamud, M., & Eden, B. (2024). Control of Reservoir Souring and Corrosion Prevention in Production Systems in Response to Nitrate injection Cessation. *AMPP Annual Conference + Expo*.
- De Paula, R., Jones, C., Armstrong, C., Streets, M., Walker, L., Mohamud, M., & Eden, B. (2023). Simulative Studies on the Control of Biofouling and Microbial Souring in the Wellbore of Injection Wells. *Proceedings - SPE International Symposium on Oilfield Chemistry, 2023-June*. <https://doi.org/https://doi.org/10.2118/213792-MS>
- Dutta, A., Smith, B., Goldman, T., Walker, L., Streets, M., Eden, B., Dirmeier, R., & Bowman, J. S. (2020). Understanding Microbial Community Dynamics in Up-Flow Bioreactors to Improve Mitigation Strategies for Oil Souring. *Frontiers in Microbiology*, *11*. <https://doi.org/10.3389/fmicb.2020.585943>
- Gieg LM, Jack TR, Foght JM. Biological souring and mitigation in oil reservoirs. *Appl Microbiol Biotechnol*. 2011 Oct;92(2):263-82.
- Heinen W, Lauwers AM. Organic sulfur compounds resulting from the interaction of iron sulfide, hydrogen sulfide and carbon dioxide in an anaerobic aqueous environment. *Orig Life Evol Biosph*. 1996.

Hubert C, Voordouw G. Oil field souring control by nitrate-reducing *Sulfurospirillum* spp. that outcompete sulfate-reducing bacteria for organic electron donors. *Appl Environ Microbiol.* 2007 Apr;73(8):2644-52

Jones, C., Downward, B., Edmunds, S., Collins, G., Curtis, T., Jones, L., & Eden, B. (2014). The Use Of Realistic Physiochemical Conditions To Demonstrate The Ability Of Third Generation THPS To Control Reservoir Souring And MIC. *CORROSION 2014*. <https://dx.doi.org/>

Jones, C., Downward, B., Edmunds, S., Hernandez, K., Curtis, T., & Smith, F. (2011, March 13). A Novel Approach To Using THPS For Controlling Reservoir Souring. *CORROSION 2011*. <https://onepetro.org/NACECORR/proceedings-abstract/CORR11/All-CORR11/NACE-11219/119641?redirectedFrom=PDF>

Jones, C.R., Downward, B.L., Hernandez, Kansas, Curtis, Tim, and Francis Smith. "Extending Performance Boundaries With Third Generation THPS Formulations." Paper presented at the CORROSION 2010, San Antonio, Texas, March 2010

Jones, Chris, Downward, Brian, Edmunds, Stephanie, Hernandez, Kansas, Curtis, Tim, and Francis Smith. "A Novel Approach To Using THPS For Controlling Reservoir Souring." Paper presented at the CORROSION 2011, Houston, Texas, March 2011

Krebs, Thomas, Ganguli, Rahul, Lage, Gustavo, Verbeek, Paul, Mehrotra, Vivek, Florido, Priscilla, and Mohamed Reda Akdim. "Solving the Operational Challenges of Sulfate Removal Units Using High-Flux, Fouling-Resistant Nanofiltration Membranes." Paper presented at the Offshore Technology Conference, Houston, Texas, May 2019

McDonnell G, Russell AD. Antiseptics and disinfectants: activity, action, and resistance. *Clin Microbiol Rev.* 1999 Jan;12(1):147-79.

Pudi, Abhimanyu & Rezaei Sarkhanlou, Mohsen & Signorini, Virginia & Andersson, Martin & Giacinti Baschetti, Marco & Mansouri, Seyed. (2022). Hydrogen Sulfide Capture and Removal Technologies: A Comprehensive Review of Recent Developments and Emerging Trends. *Separation and Purification Technology.* 298. 121448

Streets, M. D. T., & Eden, R. D. (2024). A Strategic Approach to Significant Cost Reduction Through Advanced Souring Forecasting Modelling and High-Pressure Bioreactors in H₂S Production Management. *SPE Symposium and Exhibition - Production Enhancement and Cost Optimisation*. <https://doi.org/10.2118/220660-ms>

Streets, M. D. T., Mohamud, M., Lillis, K., Eden, R. D., Rosolina, S., & Taggart, D. (2025, April 2). Evaluating Sub-Optimal Nitrate Application Under Simulated Field Conditions Using High-Pressure Bioreactors. *SPE International Conference on Oilfield Chemistry*. <https://doi.org/10.2118/224318-MS>

Sugai, Y.; Owaki, Y.; Sasaki, K. Simulation Study on Reservoir Souring Induced by Injection of Reservoir Brine Containing Sulfate-Reducing Bacteria. *Sustainability* **2020**, *12*, 4603.