Predicting, Controlling and Monitoring MIC in Seawater Injection Systems  
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Abstract

Even after over 30 years of practical field experience, the inability to effectively control microbiologically influenced corrosion (MIC) continues to lead to failures resulting in unplanned shut-downs, and repair and replacement costs. In ageing fields, where barrels of seawater injected can be measured against barrels of oil produced, the economic impact of not meeting injection targets has raised the profile of integrity, maintenance and flow assurance in seawater injection systems which were previously frequently regarded with less immediacy. Even now, basic frequently asked questions such as ‘… should we have been aware? What treatments work? How do we measure?’ illustrate that the current performance for predicting, controlling and monitoring MIC in seawater systems is such that it is not effectively managed. MIC is often seen as impossible to predict and uneconomic to control which, when coupled with badly designed monitoring and inappropriate data interpretation results in a somewhat defeatist attitude to MIC mitigation. This paper presents an MIC management strategy which ensures that MIC is appropriately predicted, that the controls applied are sufficiently robust to mitigate the predicted MIC and that the monitoring undertaken provides useful measurement of the efficacy of the controls applied.

Key-word: microbiologically influenced corrosion, MIC, seawater injection.

Introduction

Currently the models presented for predicting the rate of pitting resulting from microbiologically influenced corrosion (MIC) associated with the activity of Sulphate-reducing Bacteria (SRB) are severely hampered by the fact that there is no universally accepted mechanism to explain the pitting and localised corrosion observed [1]. Not only is there little agreement on the pitting rate; the location, intensity and pit morphology often associated with an incidence of MIC attack do not lend themselves to any pattern which might be described as 'characteristic' [2].

It is clear from field experience that there can be significant SRB growth and activity within a system where no significant MIC has been encountered [3]. Equally, a similar degree of SRB contamination and activity can be concluded as the root cause of very severe pitting [4]. With such completely contradictory field evidence, it is unlikely that a unified mechanism for SRB corrosion will be available in the very near future.

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This is further complicated by several common misconceptions that are often produced as fact within oil company internal documents and guidance notes, often due to these documents not being reviewed with sufficient frequency to remain current with our knowledge and understanding of microbial corrosion processes and advances in environmental microbiology. The result is that many operators currently monitor and attempt to control SRB growth, but do not actively mitigate MIC. There was seen to be a requirement, therefore, to develop a system or tool to manage MIC mitigation. Based on the premise that we cannot manage what we cannot measure, then all parameters employed within the tool had to be capable of being verified by measurement. The tool had to be able to make a MIC prediction, evaluate the effect of a control and measure the degree of mitigation of MIC achieved by that control.

### Predicting MIC due to SRB Activity

A qualitative MIC model had previously been developed by Pots et al [5] which attempted to link MIC to a range of proposed influencing factors.

\[
CR = C \times F^p
\]

Equ. 1

where:
- \( CR \) = corrosion rate
- \( C \) = MIC constant (assumed or measured)
- \( F = (f_1 \times f_2 \times f_3 \times \ldots \times f_n) \) (MIC influencing factors/parameters)
- \( p \) = power factor (0.57)

In total, Pots presented 15 different parameters (Table 1), both biotic (10) and abiotic (5), to which a factorial value ranging from 0.0001 to 5 is applied depending upon whether the parameter condition inhibited or promoted MIC. Running the model required a 'Yes' or 'No' answer or the input of a field determinable metric for each of the 15 parameters. Whilst only qualitative, the model provided very useful guidance and it was seen to be quite widely applied for such by several operators. By applying a MIC constant the model appears to be semi-qualitative, but the author qualifies this by stating that the rate calculated is 'very approximate'.

Maxwell [6] amended the Pots model to reduce the parameters from 15 to 4. This has been further developed to determine a measure of MIC stimulation (S) or mitigation (M) achieved as follows:

\[
SM_t = (F_{MIC} \times F_{SOLIDS} \times F_{O2} \times F_{VAR})^p
\]

Equ. 2

where:
- \( SM_t \) = Degree of Stimulation/Mitigation during time period (t)
- \( F_{MIC} \) = factorial for potential for MIC to initiate
- \( F_{SOLIDS} \) = factorial for presence of deposited solids
- \( F_{O2} \) = factorial for dissolved oxygen concentration
- \( F_{VAR} \) = factorial for other system specific factor(s) (Age, History, etc.)
- \( p \) = power factor (0.57) allowing application/comparison to Pots model

Combining all the biotic parameters from Pots model in a microbiological model, produced an output of the rate of sulphide production which could theoretically predict the concentration of iron sulphide in the biofilm on the metal surface at a given time. The rate of sulphide production was determined from kinetic and thermodynamic modeling of SRB growth (cell yield) and activity (product yield). It was assumed that all hydrogen sulphide produced was immediately reacted with available iron and precipitated as iron sulphide in the biofilm. Using
a standard spectrophotometric assay for acid volatile sulphide, a limit of detection of 10 µg sulphide per cm$^2$ is possible. This allows the ability to measure and, therefore, manage this parameter. Therefore, this value is currently assumed to produce the microbiological condition where MIC could be initiated and is used to determine the $F_{\text{MIC}}$ factorial.

Similarly, sub-models are employed to determine the other factorials. The $F_{\text{SOLIDS}}$ is determined after taking into account the water chemistry, scaling tendency, filter performance, general corrosion rates, velocity, cleaning pigs, etc. $F_{\text{O}_2}$ can utilise historic data, current monitoring or Monte Carlo predictions to decide on the relevant factorial(s). $F_{\text{VAR}}$ considers influencing factors possibly unique to individual systems; such as age, previous operational history, etc.

Being careful not to claim that the models are able to calculate an MIC pitting rate, it is important to provide engineers with an output which provides a useful estimate of potential MIC rates. Applying the Maxwell model (Equ.2) factorials to Pots model (Equ.1) produces:

$$CR = C \times SM_t$$  \hspace{1cm} \text{Equ. 3}$$

where 
- $CR$ = corrosion rate 
- $C$ = constant for MIC 
- $SM_t$ = stimulation/inhibition factorial over stated time (t) period(s) 
  ($SM > 1$ = MIC stimulated; $SM < 1$ = MIC mitigated)

Figure 1 presents a prediction for sulphidic biofilm development in a seawater injection system which is not treated with biocide (Table 2, condition D). The model predicts that the SRB numbers in the biofilm will increase rapidly to $10^6$ cm$^{-2}$ in 5 weeks and that the sulphide concentration will exceed 10 µg cm$^{-2}$ after 37 weeks. Both the sessile SRB numbers and the rate of development of the sulphide film predicted are comparable to field data from North Sea seawater injection systems operating at temperatures around 20-30°C.

Applying Pots model (Equ.1) predicts a corrosion rate of 0.53 mmpy averaged over the year; i.e. a penetration depth of 0.53 mm after 12 months operation. Applying Equ.3 predicts a corrosion rate of 0.000 mmpy for the first 37 weeks and 5.55 mmpy for the remaining 15 weeks; i.e. a penetration depth of 1.60 mm after 12 months operation.

**Controlling Sulphidic Biofilm Development with Biocide**

Complete control is assumed if continuous biocide treatment is applied. As soon as planktonic SRB attach to a surface and become sessile, the contact time with the continuous biocide dissolved in the water phase becomes infinite. Given that the concentration is sufficient to be biostatic then these sessile SRB will remain inactive and will not grow. If the concentration is sufficient to kill the SRB within time (t); where $t < \infty$, then the SRB will remain inactive, will not grow and ultimately will be killed. A continuous treatment strategy which applies a biostatic or biocidal concentration will, according to the model, prevent MIC.

Figures 2 and 3 present predictions for sulphidic biofilm development in a seawater injection system D which is treated with the same batch biocide treatment, either once per week (D1) or twice per week (D2). It is assumed that each biocide dose is capable of killing 90% of the sessile bacteria present each time the dose is applied. The model predicts that the SRB numbers in the biofilms in D1 will increase to $10^6$ cm$^2$ in 12 weeks and that the sulphide concentration will exceed 10 µg cm$^{-2}$ after 65 weeks. For D2, the model predicts that sessile
SRB will be controlled at very low numbers and that the sulphide concentration will not exceed 0.00003 µg cm\(^{-2}\).

Applying Pots model (Equ.1) predicts a corrosion rate of 0.21 mmpy averaged over the year for both D1 and D2, despite doubling the biocide volume added; i.e. a penetration depth of 0.21 mm after 12 months operation and 0.42 mm after two years.

Applying Equ.3 for D1 predicts a corrosion rate of 0.000 mmpy for the first 65 weeks and 5.55 mmpy thereafter; i.e. a penetration depth of 0.000 mm after 12 months operation, but 5.55 mm by the end of year two. For D2 the model predicts that there will be no MIC in year one or year two.

Controlling Sulphidic Biofilm Development with Pigging and Biocide

Figure 4 presents a prediction for sulphidic biofilm development in seawater injection system D which is not treated with biocide but which is efficiently pigged (90% removal of sulphide film) once per month. The model predicts that the SRB numbers in the biofilm will increase to \(10^6\) cm\(^{-2}\) in around 5 weeks but that the sulphide concentration is maintained at or below 2 µg cm\(^{-2}\).

Figure 5 presents predictions for sulphidic biofilm development in seawater injection system D1 (treated with biocide) also with monthly pigging. In this case, the model predicts that the SRB numbers will plateau at \(10^6\) cm\(^{-2}\) but only after 80 weeks and that the sulphide concentration will not exceed 0.2 µg cm\(^{-2}\).

Applying Pots model (Equ.1) to the D and D1 systems with monthly pigging predicts average corrosion rates of 0.01 and <0.01 respectively. Applying Equ.3 also predicts that MIC will be completely mitigated in both situations.

From the predictions presented above, a strategy (or strategies) for sulphidic biofilm control using biocidal chemicals and cleaning pigs can be developed and the performance predicted prior to application in the field. This potentially provides a means of assessing the cost effectiveness of biocides and pigging as controls of MIC by allowing various biocide concentrations, dose times and frequencies, and pigging frequencies to be addressed.

Monitoring MIC Mitigation

Management of MIC mitigation requires that acceptability criteria are put in place for metrics which can be directly or indirectly measured. It is important not to set Key Performance Indicators (KPI's) for all of the metrics as this brings with it microbiological complexity which may not necessarily be appreciated by the engineers and chemists who are generally responsible for assuring MIC mitigation. The KPI for the biotic component is the minimum concentration of sulphide in the biofilm that can initiate MIC. Currently this is arbitrarily set at the lower limit of detection of the assay (i.e. 10 µg cm\(^{-2}\)). However, laboratory testing is ongoing to determine if this KPI can be relaxed or indeed made more stringent [7]. The metrics associated with this KPI are acceptable numbers of sessile SRB in the biofilm and their growth and activity potential. Thus biotic metrics are concerned with sessile SRB numbers and factors which affect biofilm growth (nutrient mass balance, velocity, biocides) and activity (temperature, pH, etc.).
Abiotic metrics which are known to significantly stimulate MIC resulting from SRB activity are dissolved oxygen and solids [8]. The metric for dissolved oxygen is straightforward as this parameter can be monitored on-line using oxygen probes. However, setting acceptability criteria requires careful consideration as the acceptable concentrations of dissolved oxygen in a system containing no sulphide films may be significantly greater than those which could stimulate pitting by oxidising an iron sulphide scale and producing grains of elemental sulphur.

Solids provide a much more difficult to define metric. In addition to pigging frequency, the design of the cleaning pig, the nature of solids, the degree of hydration, etc. all may significantly impact upon the degree of stimulation of MIC produced by the presence of solids. It is anticipated that the metrics determined for solids and solids control will require significant development as attempts are made to verify the model with pitting corrosion rates determined from field experience.

Ultimately, the models need to be verified against field data. Whilst many operators employ in line weight loss coupons for corrosion monitoring, the quality of the pitting data generated is generally poor. It is often the case that only maximum pit depth is recorded, with little information on pit density and pit diameter being routinely recorded. Where intelligent pigs can be deployed, however, and generate data over a large surface area of pipe, there exists a large database of possibly useful measurements that can be applied to verify and improve MIC models.

**Conclusions**

The Bug-Tracker® model provides a useful tool for the non-microbiologist in predicting MIC in seawater injection systems and selecting the most appropriate controls for MIC mitigation.

The predictive model illustrates the theoretical effects achieved by different biocide strategies on sessile SRB control and MIC mitigation.

Implicit to the model are the metrics required, initially to run the prediction and later to verify that mitigation has been achieved. This requires the metrics to be routinely monitored thereby resulting in a system or tool which promotes the effective management of MIC mitigation.

The predictions for the incidence of MIC and the control of sessile bacteria achieved appear to be validated by field data, but further work is required to validate the MIC pitting rates predicted against field monitoring measurements from intelligent pigs and weight loss coupons.

**Bibliography’s References**

Figure 1. Uncontrolled Biofilm Development

Figure 2. 90% effective, 6 hours every week

Figure 3. 90% 6 hours twice per week
Figure 4. Effect of Pigging Only on Sulphide Film

Figure 5. Effect of Pigging with Biocide
Biotic

- pH
- Total Dissolved Solids < 6%
- If TDS > 6%, do SRB grow?
- Temperature
- If temp. > 45ºC do SRB grow?
- Sulphate conc'n
- Fatty Acid conc'n
- Utilisable Nitrogen conc'n
- Carbon:Nitrogen ratio
- Biocide routinely used?

Presence of 10 µg sulphide per cm² employing cell yield and product yield kinetics for SRB (including extremophiles) calibrated for pH, Temperature, Salinity, Nutrient conc'n & Mass balance. Inhibited by biocide and biostat effectiveness of any microbicide treatments proposed.

KPI 1. Is sulphide present in the biofilm at measurable concentrations (10 µg sulphide per cm²)?
If not, then no MIC will occur.
If yes then there is a potential for MIC to be promoted.

Abiotic

- Flow velocity
- Debris on bottom of pipe
- Pigging frequency
- Prolonged oxygen ingress
- Age of system < or > 0.5 yr

Employed for nutrient mass balance
Combined to 'cleanliness' metric aligned to pig trash produced and iron sulphide and biomass removed.
Measures dissolved oxygen
Accounted for in lag time prior to sessile bacterial biofilm development

Incorporated into model used to determine KPI 1 & 2.
KPI 2. Qualitative assessment on presence of deposit and time deposits are present.
KPI 3. Measure of mg O₂ with time.
KPI 4 Lag time dependency of MIC activity on perforation depth.

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Table 1. Comparison of manner in which inputs are applied to Pots and Maxwell models.

Table 2. Parameters applied for MIC rate predictions.