INTERPRETING SRB MONITORING DATA FROM PRODUCED WATER HANDLING SYSTEMS

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ABSTRACT

The growth of sessile SRB in biofilms in produced water systems, with the concomitant production of hydrogen sulfide, is know to cause a range of problems including; corrosion, toxic gas production, reservoir souring and formation damage. The optimisation of control of SRB is generally based on data produced by monitoring planktonic SRB numbers and is invariably ineffective. The basic principals of microbiology are often ignored due to a lack of training of the responsible personnel and a general lack of microbiology expertise in the field. This paper introduces the concept of applying basic microbiological models to aid in the interpretation of field data and the design of optimised biocide treatments.

INTRODUCTION

Bacterial growth, in particular the growth and activity of Sulfate-reducing Bacteria (SRB) can result in sulfide generation and associated problems in produced water handing systems. Depending on the system temperature, both thermophilic and mesophilic bacterial growth may result in problems in the same system, requiring possibly more than one course of remedial action. Where the produced water is to be injected into the formation for pressure support, the presence of an already enriched population of SRB may exacerbate reservoir souring and also result in formation damage.

Whilst these problems are well known throughout the oil industry, many attempts to control SRB growth end in failure, with large sums of money expended on seemingly ineffective biocide treatments. The corrosion failures and souring of produced oil and gas associated with the activity of SRB cost the industry $ 10's millions per annum in lost production, downtime, replacement parts and treating chemicals. To exacerbate the problem, increasing environmental legislation is restricting the use of biocides and alternative technologies are having to being considered.

Despite the huge costs described above, however, bacterial monitoring still receives only lip service at many field locations. Often monitoring programmes are dismissed as 'useless' due to the perception that they are producing at best meaningless, and at worst misleading, results. Much of this is not due to poor methods (although this is the case in many situations) but is the result of a lack of understanding or training in basic microbiology of the field personnel tasked with maintaining bacterial control. The overall effect is to downgrade bacterial monitoring to an absolute minimum, often with very costly repercussions. A bacterial problem will always cost multiples more expenditure to resolve than the cost of preventing it is the first place.

BASIC MICROBIOLOGY

In order to win the battle to control bacterial growth in the oilfield, we must understand the enemy. All to often the response to a bacterial contamination problem is to apply a treatment chemical in much the same way as one would respond to a chemical scale or corrosion event. This can be the first mistake. It is essential to remember that bacteria are living organisms; the rules of biology and biochemistry apply and these may require a much different approach than that applied to a purely chemical problem.

The aim of this paper is to introduce how two basic bacterial metabolism parameters – growth rate and metabolic sulfide production rate can be applied to demonstrate the extent of bacterial activity in a given situation, thereby aiding in identifying the source of a particular problem and helping in the development of an effective treatment regime. In the short time available it is not possible to cover the subject in detail and obviously some oversimplification (for the ease of explanation) is inevitable.

The paper assumes that the reader understands that it is the sessile populations of bacteria in biofilms that have to be controlled and not the planktonic bacteria that, in general, are the subject of any monitoring data.

Bacterial Growth

Bacterial growth is an increase in the number of cells in a population, rather than an increase in the size of its individual members. The growth of a pure bacterial culture can be modelled according to first-order kinetics of a chemical reaction. Growth rate is often referred to in terms of the doubling time; that is the time taken for the number of cells present to increase two-fold. The doubling time will be dependent on the type of bacteria and also on the environment in which the bacteria are growing. Important environmental parameters are nutrient concentration, pH, temperature, salinity, etc.

A generalised growth curve can be used to describe the growth of a bacterial culture in liquid medium. This sigmoidal growth curve is divided into four regions:

Lag Phase: If bacteria are transferred to fresh medium, there is a time delay before growth is initiated. This is often due to the synthesis of new molecules to enable utilisation of the new compounds. This is known as the lag phase and is of variable length.

Exponential Phase: Once initiated, bacterial growth is exponential i.e. the total population doubles over each generation time. Populations seldom maintain exponential growth for long. The reason is apparent if the consequences are considered. A single bacterium, with a doubling time of 20 minutes would, after only 48 hours exponential growth, produce progeny of 2.2×10^{31} g; roughly 4000 times the weight of the earth. Exponential growth is limited, therefore, by the exhaustion of a nutrient or by the accumulation of toxic by-products. A typical doubling time in the lab for an SRB might be 3 – 6 hours.

Stationary Phase: At the end of exponential phase the growth rate declines and cell division eventually stops. At this point the bacteria are said to be in a stationary phase. Stationary phase cells have a different chemical composition from exponential phase cells. In general this allows the stationary phase cells to become more resistant to adverse physical conditions and chemical agents.

Death Phase: Eventually cells held in a non-growing state will die. The death rate is variable and will depend on the environment as well as the particular bacteria.

Metabolic Sulfate Reduction to Sulfide

SRB require, in common with all other life forms, a balanced diet in order to perform their metabolic functions and grow. The key parameter that results in them being such a problem in industrial systems, is that instead of oxygen they utilise sulfate. Therefore, instead of respiring oxygen to water, they respire sulfate to hydrogen sulfide.:

$$\text{Carbon} + SO_4 \rightarrow CO_2 + H_2S + \text{ENERGY} \quad \text{SRB}$$
$$\text{Carbon} + O_2 \rightarrow CO_2 + H_2O + \text{ENERGY} \quad \text{Aerobic Bacteria}$$

The rate of metabolic activity will vary due to environmental parameters such as temperature, pH, osmotic pressure, nutrient availability, etc. However, wide ranging environmental studies have indicated that, on average, an individual SRB cell is capable of producing $10^{-13} - 10^{-14}$ moles of sulfide per 24 hour period.

SRB IN PRODUCED WATER HANDLING SYSTEMS

In order to effectively control a bacterial contamination problem using chemical treatments, it is essential to apply the biocide at the correct point, in sufficient quantity and with the required frequency. This requires the field engineer to identify where the bacteria are growing (and where they originated); identify a suitable dose rate of the biocide that will significantly reduce that problematic population of bacteria to a level where the problem is halted and then to reapply the treatment with sufficient regularity to ensure that the problematic level of the population does not develop again.

Source of Bacteria

As far as SRB contamination of the process system is concerned, it is generally considered that the most likely source of bacterial contamination originates from 'somewhere upstream'; and in many cases the producing wells or oil reservoir. However, the original source of bacterial contamination may be due to one or a combination of historic and/or current events such as, the recirculation of drains fluid; jetting of the separators (particularly with seawater); poor chemical control during hydrotest operations, contamination of the drilling mud or other such processes.

If the initial production is 'hot' (greater than 45°C), but the temperature in the flowlines and separators is 'cool' (less than 45°C) then the thermophilic bacteria which would be active in the hot wells would not be capable of growth in these cool areas and may be irrelevant in the corrosion or souring problems identified in the production system. It is critical, therefore, to segment the system into areas of defined bacteriological risk and identify the key parameters controlling bacterial activity. In some cases each of these areas may have a different control strategy.

Many formation waters contain appear to contain all the nutrients required for SRB growth (although many are depleted in the key nutrient – sulfate), yet initial production may be sweet. The production of sulfide and souring of the system, particularly where seawater is used for pressure support, may only become apparent several months or even years into production. In seawater waterfloods, it is proposed that the sulfate introduced via the seawater is the key to reservoir souring. However, in the production system, any source of water containing sulfate; i.e. drains water, jetting water, etc. can initiate the production of significant levels of hydrogen sulfide from SRB activity and, therefore, sulfide production in these areas may be independent of the changes occurring due to waterflooding.

It is clear, therefore, that bacterial problems in production systems can be incorrectly attributed to certain locations based on a mistaken interpretation of monitoring data or the misapplication of a monitoring technique; i.e. inappropriate incubation temperature, sample abuse prior to analysis, etc. A basic knowledge and understanding of microbiology is, therefore, a prerequisite to an effective treatment.

Biocide Application

Biocide chemicals may be one of the least scientifically applied treatments. Laboratory 'time v kill' tests are performed on unspecified bacterial populations with little of no recourse to system temperature, pH, salinity, etc. Following these tests, the optimum kill concentration (if determined) is rounded to the nearest 100 ppm and a few hours are added to the time component for 'assurance' of effectiveness. Lastly, a treatment frequency based on the calendar week or month is selected and thus the biocide treatment programme is developed. In the field, this programme will generally be amended to suite operational parameters resulting in a final treatment regime that bears little or no resemblance to the finding of the laboratory tests.

APPLYING BASIC MICROBIOLOGICAL MODELS

Consider the basic microbiology presented above. How can this, in conjunction with a simple monitoring programme be applied to aid in the development of an effective treatment programme? The following scenarios are based on real systems where the basic models were used to aid in interpreting the data.

SCENARIO ONE
SULFIDE METABOLISM AS A MONITORING TOOL

A production system, where SRB monitoring has indicate the presence of planktonic SRB in the fluids entering and exiting the Separators was showing increasing levels of H_2S in the sales gas. The corrosion implications on the gas export flowline were causing significant concern and as the production wells had historically being showing low levels of H_2S it was assumed, based on the presence of SRB, that the reservoir was souring. An aggressive biocide dosing regime into the production flowlines was ineffective.

Using the rate of sulfide production per SRB cell per day, it was demonstrated to the operator that the 10 Kg of sulfide being produced each day required a population of population of between $10^{15} - 10^{16}$ SRB cells. If densely packed, this population would occupy a volume of less than 10 litres. In light of this finding, a mass balance of sulfide was performed and it was determined that the majority of the sulfide was produced from the separator and not from the wells. An aggressive biocide treatment directed at the separator allowed the increasing sulfide level to be controlled. Planktonic SRB numbers were not affected significantly.

SRB can only be active in an aqueous environment. If all the sulfide is from SRB activity then it all must have been produced as dissolved sulfide. A mass balance of sulfide is required to detect sulfide in the gas, water and hydrocarbon phases. This can then be used to calculate the total bacterial sulfide production and from this the population can be estimated.

In many cases, accurate monitoring of sulfide concentration, together with an understanding of its partitioning characteristics, can present much more useful data than SRB numbers alone.

SCENARIO 2
USING REGROWTH RATES TO OPTIMISE TREATMENTS

Laboratory testing has proven beyond doubt that a certain biocide is capable of killing a wide range of types of SRB as long as a minimum concentration is achieved and a minimum exposure time maintained. With this information, it has been decided that the application in the field will be to inject the biocide at the maximum rate that the injection pump will allow. At this rate the budget for chemical will allow 150 hours of pumping in a calendar year. The frequency of treatment, however, cannot be agreed with differences of opinion ranging from one treatment per month for 12.5 hours to once per week for 2.88 hours.

The defining criteria for the frequency of the treatment must be that each treatment should be applied to a significantly reduced population than the previous treatment. The parameters that dictate this are the Log reduction in numbers achieved by each treatment and the doubling time of the population during regrowth between treatments.

To demonstrate how doubling times can be used to assist in determining dosing frequency, consider a clean 1 cm^2 metal coupon installed into the system immediately after a biocide treatment. One SRB cell is present on the coupon at time = 0 and this grows with a doubling time of 12 hours (0.5 days). After 5 days there are 10^3 SRB per cm^2; after 30 days, 10^6 and after 45 days, 10^9. This basic consideration of doubling time would indicate immediately that treatments should be more frequent than even once per week.

Consider a dirty system, were an SRB population already exists. In this case 1 cm^2 of surface may already be contaminated with 10^6 SRB. Assuming that the biocide treatment is 99.99% effective, the population would drop to 10^2. However, with the same 12 hour doubling time as above, the population would return to pre-treatment levels in only 7 days. Thus, in this case a weekly treatment would not result in a gradual clean-up of the system, but would merely maintain the *status quo*.

Determining the actual doubling time of SRB populations in the field is extremely difficult and this is not being proposed. However, by consideration of the basic bacterial growth model it is possible to put scientific reasoning into the frequency of the biocide treatment thereby removing the guesswork and moving forward towards a defined set of biocide application parameters that could be applied across a wide range of different fields.

SUMMARY

In the time available, the application of bacterial growth kinetics and metabolic models to aid in the understanding of field data has necessarily been greatly simplified. However, historically, these simple tools have almost completely been overlooked in bacterial monitoring in oilfield situations. At a time when much of the industry is clamouring for more sophisticated and more rapid methods to replace those currently being applied, due to these being perceived as 'low tech' and of little use, it is important to highlight that much of this perception is not with the techniques themselves, but with the manner in which the data is interpreted.

BIBLIOGRAPHY

1. Maxwell, S. Microbially Influenced Corrosion (MIC) Resulting in Grooves in Subsea Water Injection Flowlines. Proceedings of the Corrosion 2002 Research Topical Symposium – Microbiologically Influenced Corrosion, NACE Press.

2. Maxwell, S. *et al.* In Field Biocide Optimisation for Magnus Water Injection System. NACE 2002 Proceedings.

3. Maxwell, S. MIC in Hudson & Ekofisk flowlines. Eleventh International Biodeterioration and Biodegradation Symposium, Virginia, USA. 1999.

4. Maxwell, s. Bacterial sulphide production in hydrocarbon reservoirs. Sour Service Conference, 1994, (London).13. Maxwell, S. Bacterial sulphide generation in oil production systems. Water Management Offshore, Aberdeen, 1991.

5. Georgie, W. J., Nice, P.I and MAXWELL, S. Selection, optimisation and monitoring of biocide efficacy in the Statfjord water injection systems. Corrosion '91, Manchester.

6. Maxwell, S. The assessment of sulphide corrosion risks in offshore systems by biological monitoring. SPE Production Engineering, pp. 363-8, Sep 86.

7. Maxwell, S. Effect of cathodic protection on the activity of microbial biofilms. Materials Performance, 25, 53-56, 1986.

8. Maxwell, S. and Nice, P.I. Bacterial monitoring of the three Statfjord field water injection systems. Corrosion '88, pp. 107-124, 1988.

9. Maxwell, S and Hamilton, W.A. Modified radiorespirometric assay for determining the sulphate reduction activity of biofilms on metal surfaces. Journal Microbial Methods, 5, 83-91, 1986.

10. Maxwell S. and Hamilton, W.A. Biological and corrosion activities of SRB within natural biofilms. 1st International Conference on Biologically Induced Corrosion, Washington DC, 1985.

11. Maxwell, S. Improved monitoring of bacterially mediated corrosion risks in offshore systems. Inst of Petroleum Quarterly Journal, 1-25, September 1986.

12. Maxwell, S. Effect of cathodic protection on the activity of microbial biofilms. Corrosion '85, 281-291, 1985.

13. Maxwell, S. Biocorrosion related to oil production. Norwegian Corrosion Society, Trondheim, 1987.

14. Maxwell, S. *et al.* Biological and corrosion activities of SRB associated with offshore production platforms. Marine Biodeterioration, 367-375, Oxford & IBH Publ. Co. Ltd, 1987.

SRB Growth In Production Systems

Biological sulfide production in oil reservoirs and production systems results in the production of 'sour' gas and fluids and costs the industry $ 10's millions per annum due to:

- Lost revenue from sales of gas
- Lost revenue from wells shut-in due to high sulfide
- Cost of upgrading equipment for sour service
- Failures due to sulfide corrosion
- Treatments to sweeten sour gas for export

Question?

Bacterial monitoring is a waste of time?

True ☐

False ☐

We do it, but we don't understand it?

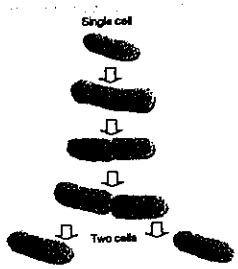
True ☐

False ☐

The Enemy

Bacterial growth

- Growth kinetics - binary fission
- Lag phase
- Exponential growth
- Stationary phase
- Death phase



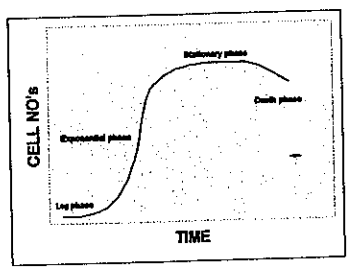
Microbiology at work ™

Doubling time - 20 minutes

0 -	1				
1 -	2	11 -	2,048	21 -	2,097,152
2 -	4	12 -	4,096	22 -	4,194,304
3 -	8	13 -	8,192	23 -	8,388,608
4 -	16	14 -	16,384	24 -	16,777,216
5 -	32	15 -	32,768	25 -	33,554,432
6 -	64	16 -	65,536	26 -	67,108,864
7 -	128	17 -	131,072	27 -	134,217,728
8 -	256	18 -	262,144	28 -	268,435,456
9 -	512	19 -	524,288	29 -	536,870,912
10 -	1,024	20 -	1,048,576	30 -	1,073,741,824

Microbiology at work ™

Bacterial growth curve



Microbiology at work ™

Sulfate Reduction (Respiration) to Sulfide

Carbon + SO4 ⟶ CO2 + H2S + Energy

Carbon + O2 ⟶ CO2 + H2O + Energy

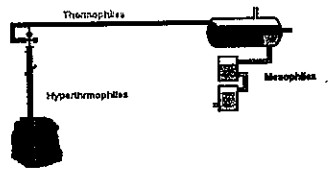
Environmental parameters

- Temperature
  - Psycrophiles (less than ~10°C [50°F])
  - Mesophiles (~10°C - ~45°C [50°F -113°F])
  - Thermophiles (~45°C - ~90°C [113°F – 194°F])
  - 'Hyperthermophiles' or Pyrophiles (greater than ~ 90°C)

Origin of SRB in System

- Indigenous – will always be there
- Reservoir (thermophiles)
- Drill mud contamination
- Water flooding (particularly seawater)
- Drains/slops
- Jetting and 'cleaning' operations
- Other

Bacteriological risk



Laboratory Biocide Tests

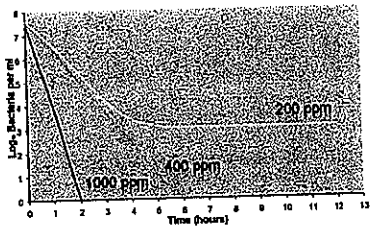
IDEAL TEST CULTURE	REALITY
• Constant quality	• Highly variable quality
• Stated composition	• Unknown composition
• Fixed incubation temp.	• Variable incubation temp.
• Measured numbers	• Not measured numbers
• Constant resistance	• Variable resistance

Scenario 1

Monitoring Data:
High planktonic SRB at wellheads and Separator outlet
Sulfide in the export gas (10 kg per day) and increasing
Conclusion: Reservoir Souring
Remedial Action: Sour Service Upgrade ($ millions)

Applying Metabolic Rate Calculation
Sulfide production = 10 kg per day
No. SRB required = 10^{15} - 10^{16} cells
Volume occupied = Less than 10 Litres
Conclusion: SRB activity in Separator
Remedial Action: Local biocide treatment ($ thousands)

Typical Time vs Kill curve (Ct)



Scenario 2

Lab Data
Use X00 ppm, for X hours for effective dose
Frequency based on calendar and operations:
Weekly? Bi-monthly? Monthly?

Applying Re-growth Calculation based on t_2
If t2 = 6 hours, population exceeds 10^3 in 2.5 days from 1 cell
If t2 = 12 hours, population exceeds 10^3 in 5 days from 1 cell
If t2 = 24 hours, population exceeds 10^3 in 10 days from 1 cell
Weekly treatments are the absolute minimum requirement - even bi-weekly should be considered

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Summary

- Even the most basic microbial kinetics have a role in interpreting monitoring data
- The fact that they are not routinely used indicates a requirement for training
- Standard monitoring methods can provide useful information – if they are applied and interpreted correctly

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