An Understanding of Reservoir Souring and Management

Institute of Corrosion : ICorr Technical Event

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Overview

1. Introduction to Oilfield Reservoir Souring
   • What is it and why does it matter?

2. Development of Sourcing in the Field
   • The importance of souring forecasting

3. Sourcing Control and Mitigation
   • What options are available to Operators?

4. Case Study
   • From Laboratory to Field

5. Conclusions
1. Introduction to Oilfield Reservoir Souring

Definition of Souring

An increasing mass of hydrogen sulphide (H₂S) in the total produced fluids, in excess of 3ppmv in the gas phase at Standard Temperature and Pressure (STP).

But what is the origin of this sour gas?
1. Introduction to Oilfield Reservoir Souring

• In order to continue production, water is often introduced to maintain downhole operating pressure

• Historically, the origin of sour gas production had been linked with secondary recovery

• In the 1980s, many oil operators had associated injection water breakthrough with observations of souring

Figure 3. Secondary Recovery through Waterflooding
http://www.amerexco.com/recovery.html
1. Introduction to Oilfield Reservoir Souring

- In the summer of 1987, the Oilfield Reservoir Souring Programme was launched.
- Aim to review ideas and developments in souring, and to resolve the microbiological/geochemical souring debate.
- First programme in the world to identify the critical role which microbiology plays in oilfield reservoir souring.

Figure 4. The Oilfield Reservoir Souring Programme
1. Introduction to Microbiological Oilfield Reservoir Souring

Top 5 Requirements

• Sulphate-Reducing Microorganisms
• Water
• Sulphate
• Anoxic Conditions
• Organic Food Source
1. Introduction to Microbiological Oilfield Reservoir Souring

Top 5 Requirements

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• Anoxic Conditions
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Figure 5. SRM recovered from the Thistle Field
1. Introduction to Microbiological Oilfield Reservoir Souring

Top 5 Requirements

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• **Water**
• Sulphate
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• Organic Food Source

*Figure 6. Seawater in the Strait of Malacca*
https://en.wikipedia.org/wiki/Seawater
1. Introduction to Microbiological Oilfield Reservoir Souring

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*Figure 7. Crude Oil Souring Propensity Bottle Test*
1. Introduction to Microbiological Oilfield Reservoir Souring

Top 5 Requirements

- Sulphate-Reducing Microorganisms
- Water
- Sulphate
- Anoxic Conditions
- Organic Food Source

Reservoir Factors

- Water Physiochemistry
- Temperature
- Pressure
- Product Inhibition
- Natural Sulphide Scavengers

\[
\text{CH}_3\text{COO}^- + \text{SO}_4^{2-} \rightarrow 2\text{HCO}_3^- + \text{HS}^-
\]

Acetic Acid + Sulphate \(\rightarrow\) Bicarbonate + Bisulphide
1. Introduction to Microbiological Oilfield Reservoir Souring

**Water Physiochemistry**

- pH 4 to 9
  - **Seawater = 8.3**
- Salinity 0 to 475,000 TDS
  - **Seawater = 35,000 TDS**
- Redox below -100mV
  - **Reservoir = -230mV**

*Figure 8. pH Scale*
https://www.pinterest.com/pin/486459197220981014/
1. Introduction to Microbiological Oilfield Reservoir Souring

Temperature

- General Microorganisms
  -10°C to +150°C
- SRM
  - mSRM 10°C to 45°C
  - tSRM 50°C to 80°C
  - SRA 80°C to 120°C

*Figure 9. Temperature Growth Ranges*
1. Introduction to Microbiological Oilfield Reservoir Sourcing

Pressure

- SRM
  - mSRM  1atm to 500atm
  - tSRM  1atm to 500atm
  - SRA    tolerate slightly higher pressures

- SRM can survive high pressure environments
1. Introduction to Microbiological Oilfield Reservoir Souring

**Product Inhibition**

- High concentrations of H$_2$S can be toxic to SRM
  
  - mSRM $\sim$ 700mg/L
  - tSRM $\sim$ 200mg/L
  - SRA $\sim$ 50mg/L

*Figure 11. Hydrogen Sulphide Warning Sign*
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Natural Sulphide Scavengers

• The downhole mineralogy can have a significant sulphide scavenging capacity

Beneficial Scenario

• High Siderite %
• Low Pyrite %

Figure 12. The ‘Siderite Shield’
1. Introduction to Microbiological Oilfield Reservoir Sourcing

Why Does it Matter?

- Highly flammable and toxic gas
- Pungent (rotten egg smell)
- Irritation of eyes, nose and throat
- Workplace Exposure Limits (WELs)
  
  - 5ppmv for 8-hour time weight average
  - 10ppmv for 15-minute time weighted average

Figure 13. Pungent H₂S smell
https://www.stevejenkins.com/blog/2015/02/fix-rotten-egg-smell-in-your-water/
1. Introduction to Microbiological Oilfield Reservoir Sourcing

Why Does it Matter?

<table>
<thead>
<tr>
<th>Concentration (ppm)</th>
<th>Symptom/Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01 – 1.5</td>
<td>Odor threshold</td>
</tr>
<tr>
<td>2 - 5</td>
<td>Prolonged exposure may cause nausea, tearing of the eyes, headaches or loss of sleep</td>
</tr>
<tr>
<td>20</td>
<td>Possible fatigue, loss of appetite, headache, poor memory, dizziness</td>
</tr>
<tr>
<td>100 – 150</td>
<td>Loss of smell (olfactory fatigue or paralysis)</td>
</tr>
<tr>
<td>500 – 700</td>
<td>Staggering, collapse in 5 minutes. Serious damage to the eyes in 30 minutes. Death in 30 – 60 minutes.</td>
</tr>
<tr>
<td>700 – 1000</td>
<td>Rapid unconsciousness, immediate collapse within 1 to 2 breaths, death in minutes</td>
</tr>
</tbody>
</table>

*Figure 14. H₂S Gas Phase Concentrations and Symptoms*

Further information can be found here:

http://www.hse.gov.uk/offshore/infosheets/is6-2009.htm
1. Introduction to Microbiological Oilfield Reservoir Souring

Why Does it Matter?

*Figure 15. Cracking of Pre-Heater Tube*
https://www.met-tech.com/images/preheater-tube-failure-3.jpg

*Figure 16. Cracking of Steel Pipeline*

*Figure 17. Cracking of Steel Pipeline*
https://www.slideshare.net/hsupouway/nace-32427380
1. Introduction to Microbiological Oilfield Reservoir Souring

Schematic of Hydrogen Cracking

Figure 18. Schematic of Hydrogen Cracking
NACE MR175 for Corrosion Resistant Alloys for Sulphide Service

Figure 19. NACE MR0175 / ISO15156
https://www.drillingcontractor.org/research-expands-as-sour-gas-completion-challenges-increase-19044
What's $H_2S$?

By the way, the most important player in the forecasting process...

What $H_2S$ language do you parlez?

- Reservoir Engineer
- Production Chemist
- Health & Safety
- Installations & Facilities
- Materials & Corrosion
2. Development of Sourcing in the Field

During secondary recovery, the cold water introduced into the downhole formation creates a cool zone, known as the **Thermal Viability Shell (TVS)**

The size of the downhole TVS is dynamic, changing overtime based on field operations

The TVS can be thought of as a ‘downhole bioreactor’, supporting the growth of the SRM within the formation

*Figure 20. Oil Platform*
2. Development of Souring in the Field

Rawwater’s DynamicTVS© Souring Forecasting Model

• Developed in the late 1980’s at UMIST, published in 1993

• Describes production of H₂S and appearance at facilities under specific operating conditions

• Rawwater has continually developed the model through further research

2. Development of Souring in the Field

i. Oilfield Reservoir Cooling from Secondary Recovery

ii. Growth of Sulphate-Reducing Microorganisms (SRM)

iii. Transport of $H_2S$ to the Producer

iv. Partitioning of $H_2S$ from the water to the oil and gas phases at specified conditions
2. Development of Souring in the Field

i. Oilfield Reservoir Cooling from Secondary Recovery

- Temperature
- Flow Rate
What is the Temperature Gradient?

20°C  120°C

Figure 22. Secondary Recovery through Waterflooding

https://www.resilience.org/stories/2017-08-09/this-is-the-drilling-method-for-most-us-oil-but-regulators-offer-almost-no-oversight/
i. Oilfield Reservoir Cooling from Secondary Recovery

Moving thermal front over time during secondary recovery

Figure 23. Development of TVS between Injector and Producer Platenkamp curves adapted from HSE Document ‘OTH 92 385’
i. Oilfield Reservoir Cooling from Secondary Recovery

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- Thermophilic Sulphate-Reducing Microorganisms (tSRM)
- Mesophilic Sulphate-Reducing Microorganisms (mSRM)

Moving thermal front over time during secondary recovery.
Radial Flood of Injected Water

Representative flow of injection water from injector to producer

Figure 24. Model Illustrating Radial Flood of Injection Water
Adapted from HSE Document ‘OTH 92 385’
“Pie Slice” Flood of Injected Water

Simplified flow of injection water from injector to producer

Figure 25. Model Illustrating Injection Water Swept into a Single ‘Pie Slice’
Adapted from HSE Document ‘OTH 92 385’
2. Development of Sourcing in the Field

ii. Growth of Sulphate-Reducing Microorganisms

• Pressure / Temperature Conditions

• Surface Area
ii. Growth of Sulphate-Reducing Microorganisms

![Graph](image)

*Figure 26. Pressure vs. Temperature Growth Domains for mSRM and tSRM Cultures Adapted from HSE Document ‘OTH 92 385’*
ii. Growth of Sulphate-Reducing Microorganisms

- **Permeability**: The ease with which a fluid can move through rock

*Figure 27. Varying Rock Formations and Permeabilities*

ii. Growth of Sulphate-Reducing Microorganisms

• Fracturing

In addition to natural fractures, there are two key modes of fracturing from Operations:

1. Thermally-Induced Fracturing (TIF)

2. Pressure-Induced Fracturing (PIF)

Higher degree of fracturing ➔ Greater Surface Area for Microbial Colonisation

Figure 28. Varying Rock Formations and Permeabilities

https://www.researchgate.net/figure/The-double-porosity-model-proposed-by-Warren-and-Root_fig1_316772637
2. Development of Sourcing in the Field

i. Oilfield Reservoir Cooling from Secondary Recovery

ii. Growth of Sulphate-Reducing Microorganisms (SRM)

iii. Transport of $\text{H}_2\text{S}$ to the Producer

iv. Partitioning of $\text{H}_2\text{S}$ from the water to the oil and gas phases at specified conditions
2. Development of Sourcing in the Field

*Figure 2. Typical Sourcing Forecasting Profile*
Figure 19. NACE MR0175 / ISO15156

https://www.drillingcontractor.org/research-expands-as-sour-gas-completion-challenges-increase-19044
2. Development of Sourcing in the Field

Benefits of Forecasting

• Provides **insight** for implementing **mitigation** plans

• Vital for **optimised, cost-effective treatment** of sour gas fluid management

*Figure 2. Typical Sourcing Forecasting Profile*

*Figure 21. Typical Sourcing Forecasting Profile 2*
3. Sourcing Control and Mitigation

‘Tried-and-tested’ methods of mitigating issues associated with sour gas production in the O&G industry are limited.

• Water Injection Management

• Production Water Management

Sulphate $\text{SO}_4^{2-}$

Hydrogen Sulphide $\text{H}_2\text{S}$

Sulphate-Reducing Microorganism (SRM)
3. Sourcing Control and Mitigation; Water Injection Management

Sulphate Removal from Injection Water

• Historically for scale control
• Significantly reduces biogenic souring
• Enhanced oil recovery benefits
• Expensive
• Removal of sulphate from produced water (PW) not currently possible
3. Sourcing Control and Mitigation; Water Injection Management

Nitrate Dosing in Injection Water

- Microorganisms preferentially reduce nitrate
- Nitrogen production rather than sulphides
- Continued growth of downhole microbiology
- Remediation of sour field possible, but delayed response
3. Sourcing Control and Mitigation; Water Injection Management

**Biocide Dosing in Injection Water**

- Beneficial in maintaining downhole injectivity
- Demonstrates effective facilities souring control
- No enhanced growth of downhole microbiology
- Downhole reservoir souring control is still unproven
3. Souring Control and Mitigation; Production Water Management

**H₂S Scavenger Chemistries**

- Common end-of-pipe control measure
- Financial benefits in low souring fields
- Mitigation strategy as opposed to direct control
- H₂S scavenger demand increases over time

![Diagram showing the reaction between Sulphate (SO₄²⁻) and Hydrogen Sulphide (H₂S) to form Sulphate-Reducing Microorganism (SRM) and reduce the concentration of H₂S in the water.](image-url)
3. Sourcing Control and Mitigation; Production Water Management

Each injector / producer pair is unique in its souring propensity

- Field economics
- Field logistics
- Geographical location
- Efficacy of treatment

Combined treatments are often implemented
4. Case Study: A ‘Typical’ Souring Profile

- 4,000psig
- 70°C
- High injected bwpd

Figure 2. Typical Sourcing Forecasting Profile
4. Case Study: A ‘Typical’ Souring Profile

Figure 26. Pressure vs. Temperature Gradient from Injector to Producer
Adapted from HSE Document ‘OTH 92 385’
4. Case Study: A ‘Typical’ Sourcing Profile

- Reservoir pressure and temperature conditions suited for SRM survival and growth

- High degree of downhole cooling

**Conclusion**

This I/P pair is at high-risk of biogenic sulphide production

*Figure 2. Typical Sourcing Forecasting Profile*
4. Case Study: Ghanaian Sourcing Forecast

- Ghanaian Oilfield
  - Offshore
  - 7,500 psig
  - 110°C
  - Low injected bwpd

- Possible low souring potential

Figure 29. Map of Ghana
https://blog.continentalcurrency.ca/ghana-travel/
4. Case Study: Ghanaian Sourcing Forecast

*Figure 30. [Total Sulphide] Dataset from Pressurised Bioreactor Study*
4. Case Study: Ghanaian Souring Forecast

- 7,500 psig
- 100°C
- Low injected bwpd

*Figure 31. Ghanaian Souring Forecasting Profile*
4. Case Study: Ghanaian Souring Forecast

Figure 26. Pressure vs. Temperature Gradient from Injector to Producer
Adapted from HSE Document ‘OTH 92 385’
4. Case Study: Ghanaian Souring Forecast

- Relatively high reservoir pressure and temperature conditions

- Low degree of downhole cooling

**Conclusion**

Despite souring crude, no significant souring at PTQ

*Figure 31. Ghanaian Souring Forecasting Profile*
5. Conclusions

• Only in the last 30 years has oilfield reservoir souring been attributed to downhole microbiological activity

• Microbiological sour gas production and the risk of hydrogen or sulphide stress cracking is a global issue in the O&G industry

• All oilfield reservoirs have different souring propensities

• Reservoir souring forecasting is therefore crucial for selecting and optimising cost-effective treatment strategies

• Pressurised laboratory simulation studies can provide additional insight into the downhole microbiological activity
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