An Understanding of Reservoir Souring and Management

Institute of Corrosion : ICorr Technical Event

Tuesday 29th October 2019

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Overview

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

2. **Development of Souring in the Field**
   - The importance of souring forecasting

3. **Souring Control and Mitigation**
   - What options are available to Operators?

4. **Case Study**
   - From Laboratory to Field

5. **Conclusions**

Figure 1. Sample Collection in Pressurised Bioreactor Suite

1. Introduction to Oilfield Reservoir Souring

Definition of Souring

An increasing mass of hydrogen sulphide (H_2S) in the total produced fluids, in excess of 3ppmv in the gas phase at Standard Temperature and Pressure (STP)

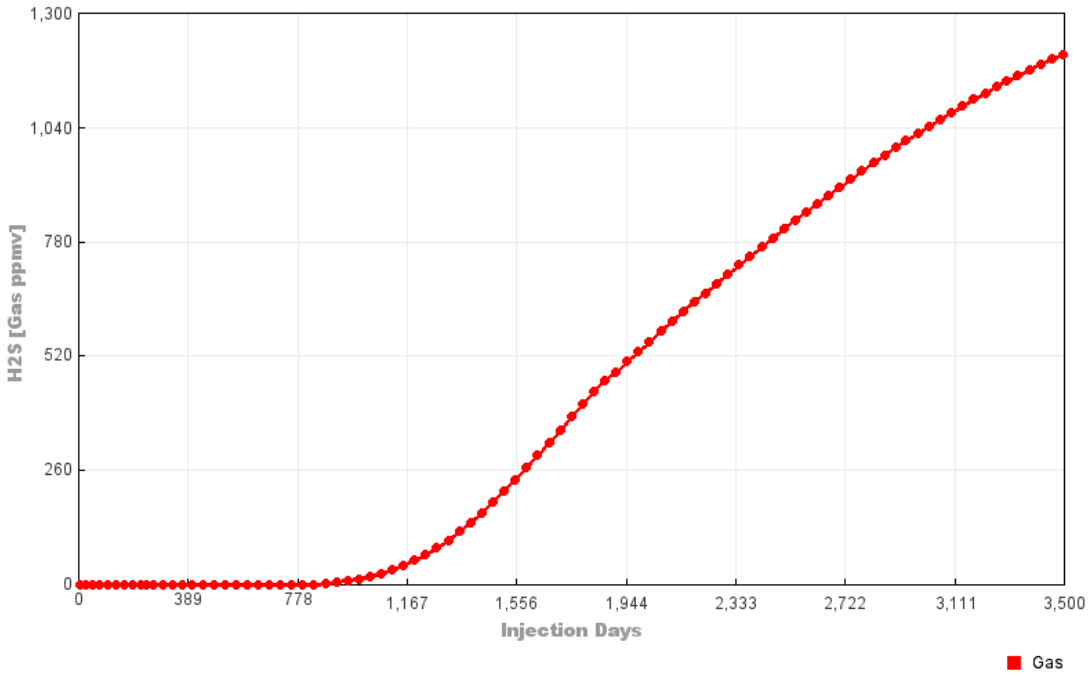

Figure 2. Typical Souring Forecasting Profile

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

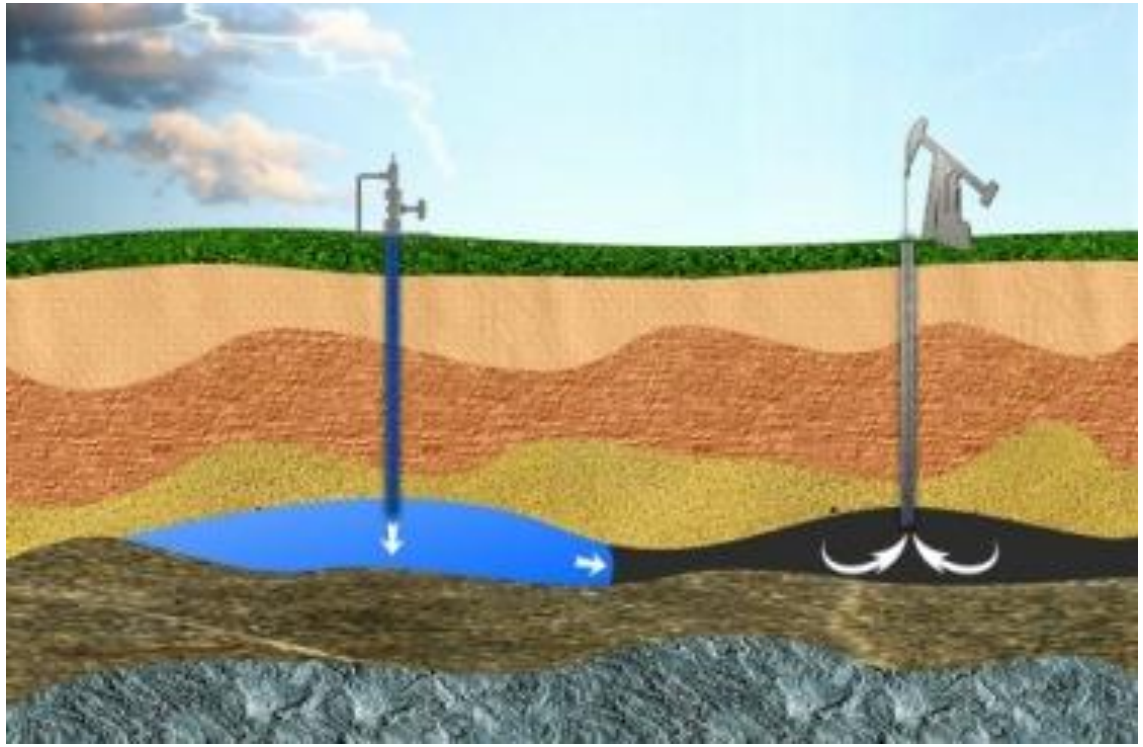

Figure 3. Secondary Recovery through Waterflooding
http://www.amerexco.com/recovery.html

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

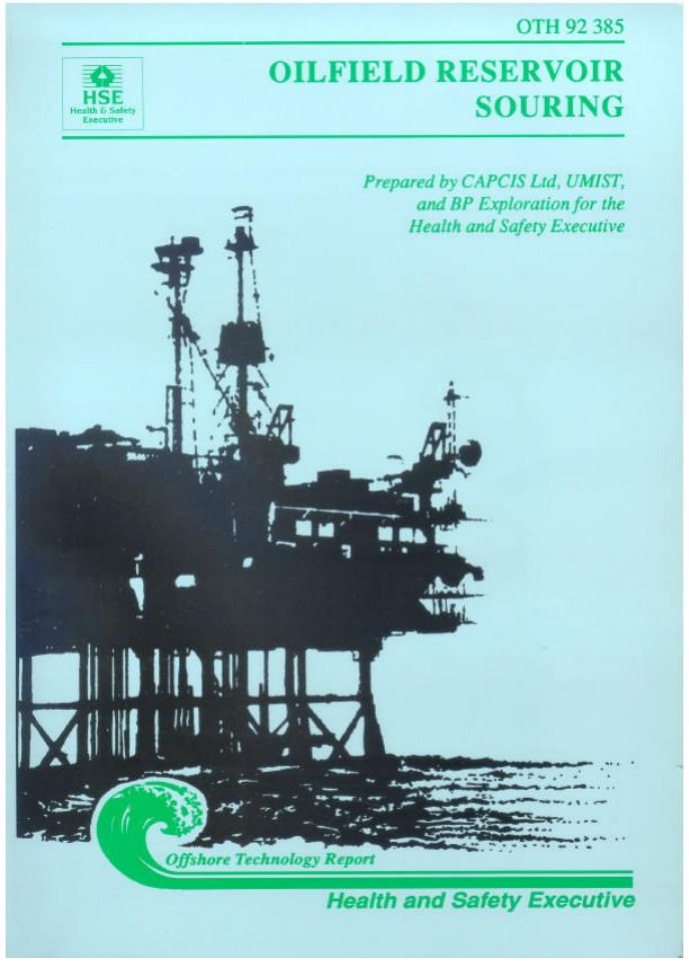

Figure 4. The Oilfield Reservoir Souring Programme
http://www.hse.gov.uk/research/othpdf/200-399/oth385.pdf

1. Introduction to Microbiological Oilfield Reservoir Souring

Top 5 Requirements

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

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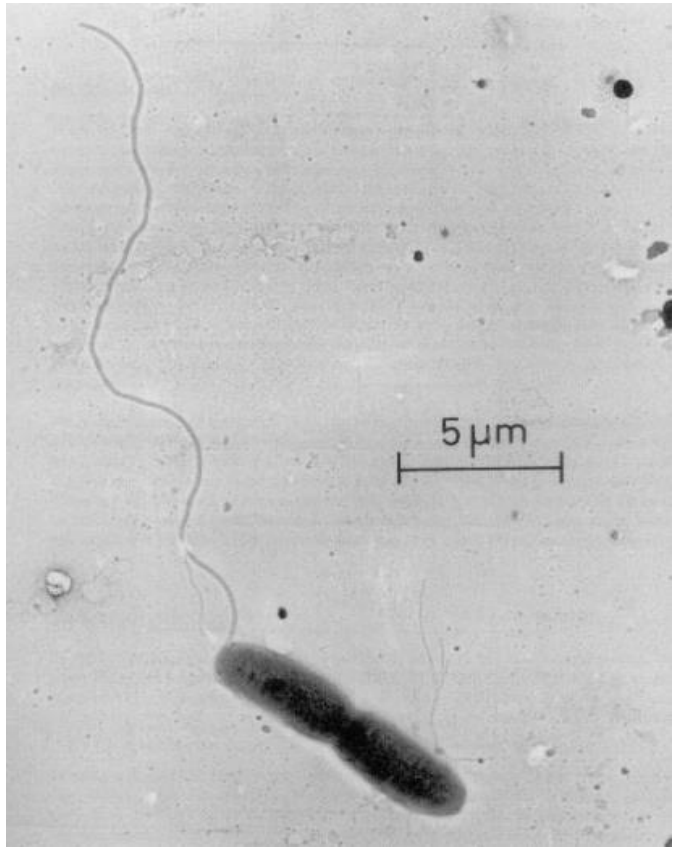

Figure 5. SRM recovered from the Thistle Field
http://www.hse.gov.uk/research/othpdf/200-399/oth385.pdf

1. Introduction to Microbiological Oilfield Reservoir Souring

Top 5 Requirements

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- Organic Food Source

Figure 6. Seawater in the Strait of Malacca
https://en.wikipedia.org/wiki/Seawater

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Figure 7. Crude Oil Souring Propensity Bottle Test

1. Introduction to Microbiological Oilfield Reservoir Souring

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- Anoxic Conditions
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Reservoir Factors

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

$$CH_3COO^- + SO_4^{2-} \rightarrow 2HCO_3 + HS^-$$

Acetic Acid + **Sulphate** → Bicarbonate + **Bisulphide**

1. Introduction to Microbiological Oilfield Reservoir Souring

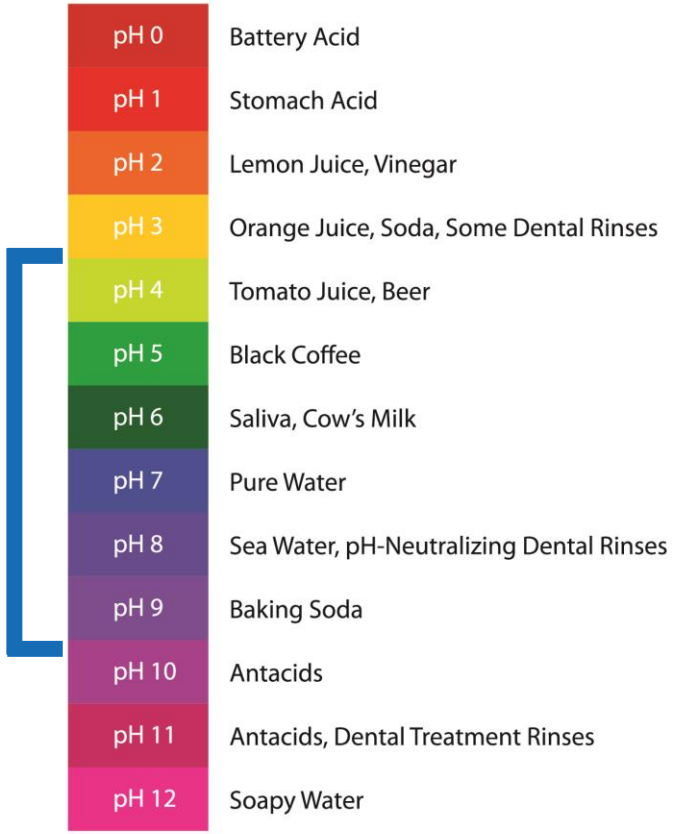


Figure 8. pH Scale
https://www.pinterest.com/pin/486459197220981014/

Water Physiochemistry

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

1. Introduction to Microbiological Oilfield Reservoir Souring

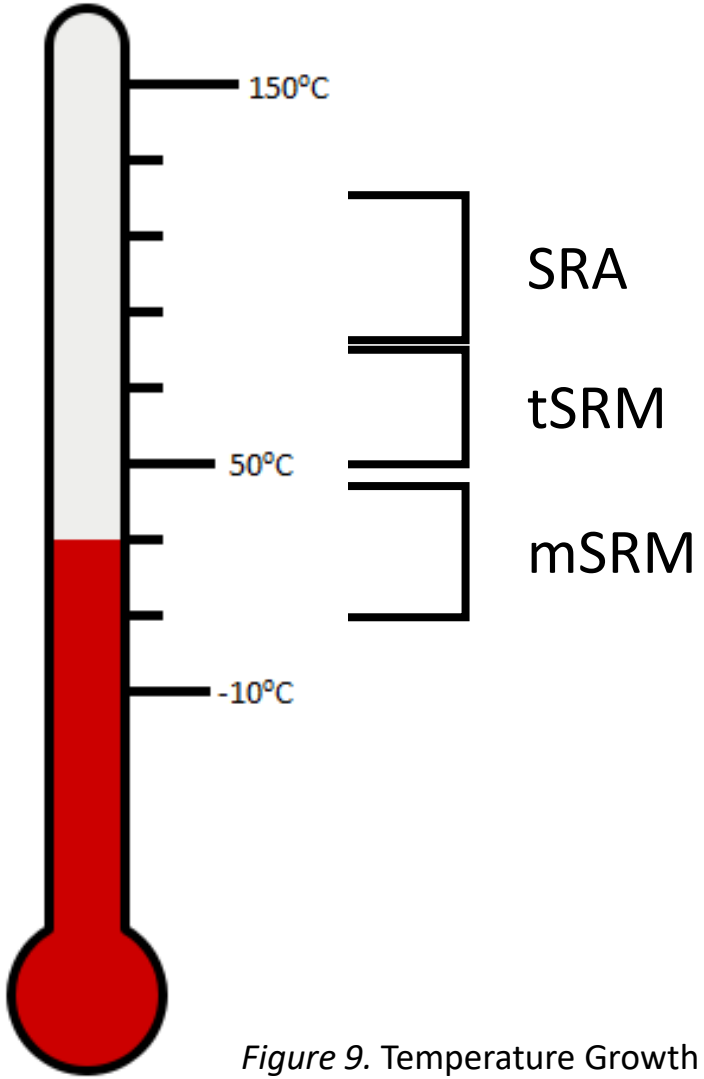


Figure 9. Temperature Growth Ranges

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

1. Introduction to Microbiological Oilfield Reservoir Souring

Figure 10. Pressure Maintenance in Pressurised Bioreactor Suite

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

Figure 11. Hydrogen Sulphide Warning Sign
http://www.blakelycc.com/news/know-the-facts-about-hydrogen-sulfide/

Product Inhibition

- High concentrations of H_2S can be toxic to SRM
  - mSRM ~700mg/L
  - tSRM ~200mg/L
  - SRA ~ 50mg/L

1. Introduction to Microbiological Oilfield Reservoir Souring

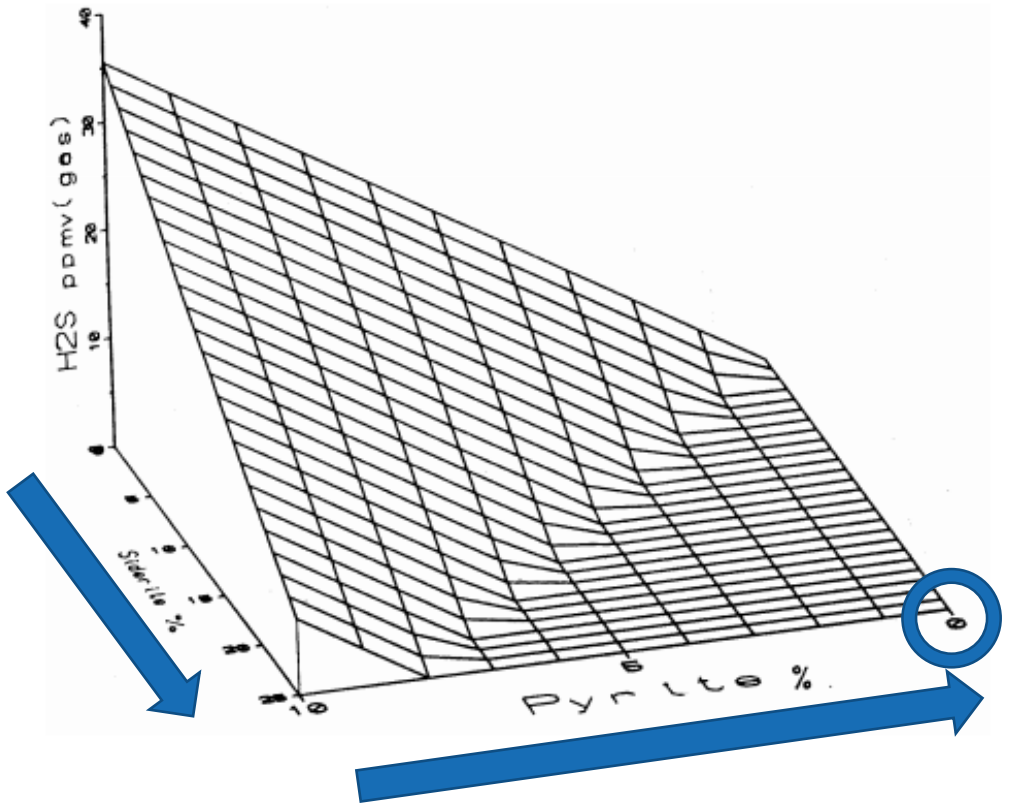


Figure 12. The 'Siderite Shield'
http://www.hse.gov.uk/research/othpdf/200-399/oth385.pdf

Natural Sulphide Scavengers

- The downhole mineralogy can have a significant sulphide scavenging capacity

Beneficial Scenario

- High Siderite %
- Low Pyrite %

1. Introduction to Microbiological Oilfield Reservoir Souring

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

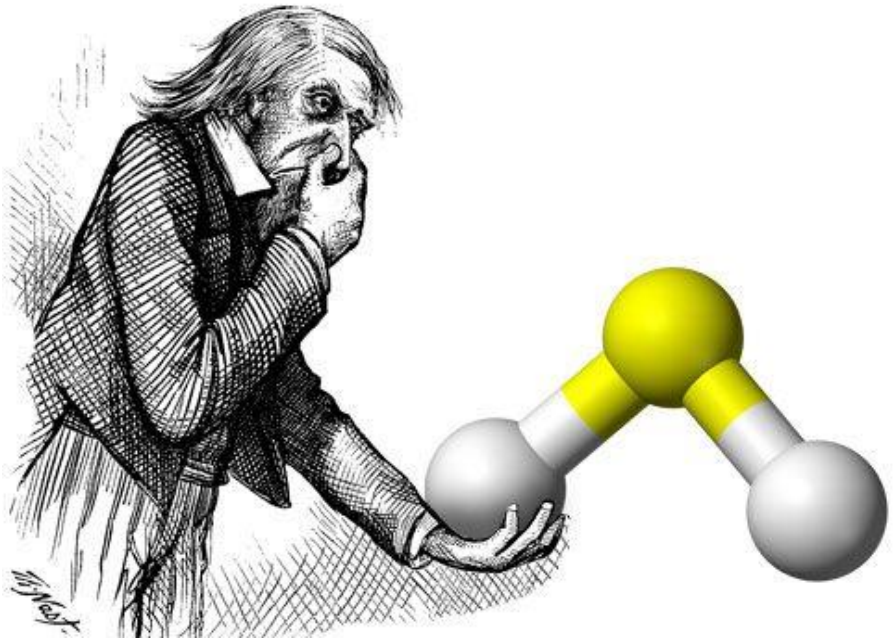


Figure 13. Pungent H_2S smell
https://www.stevejenkins.com/blog/2015/02/fix-rotten-egg-smell-in-your-water/

1. Introduction to Microbiological Oilfield Reservoir Souring

Why Does it Matter?

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

Figure 14. H_2S Gas Phase Concentrations and Symptoms
https://www.biologicalwasteexpert.com/blog/hydrogen-sulfide-can-rapidly-go-from-nuisance-odors-to-danger

Further information can be found here:
http://www.hse.gov.uk/offshore/infosheets/is6-2009.htm
http://www.hse.gov.uk/pubns/guidance/oce6.pdf

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

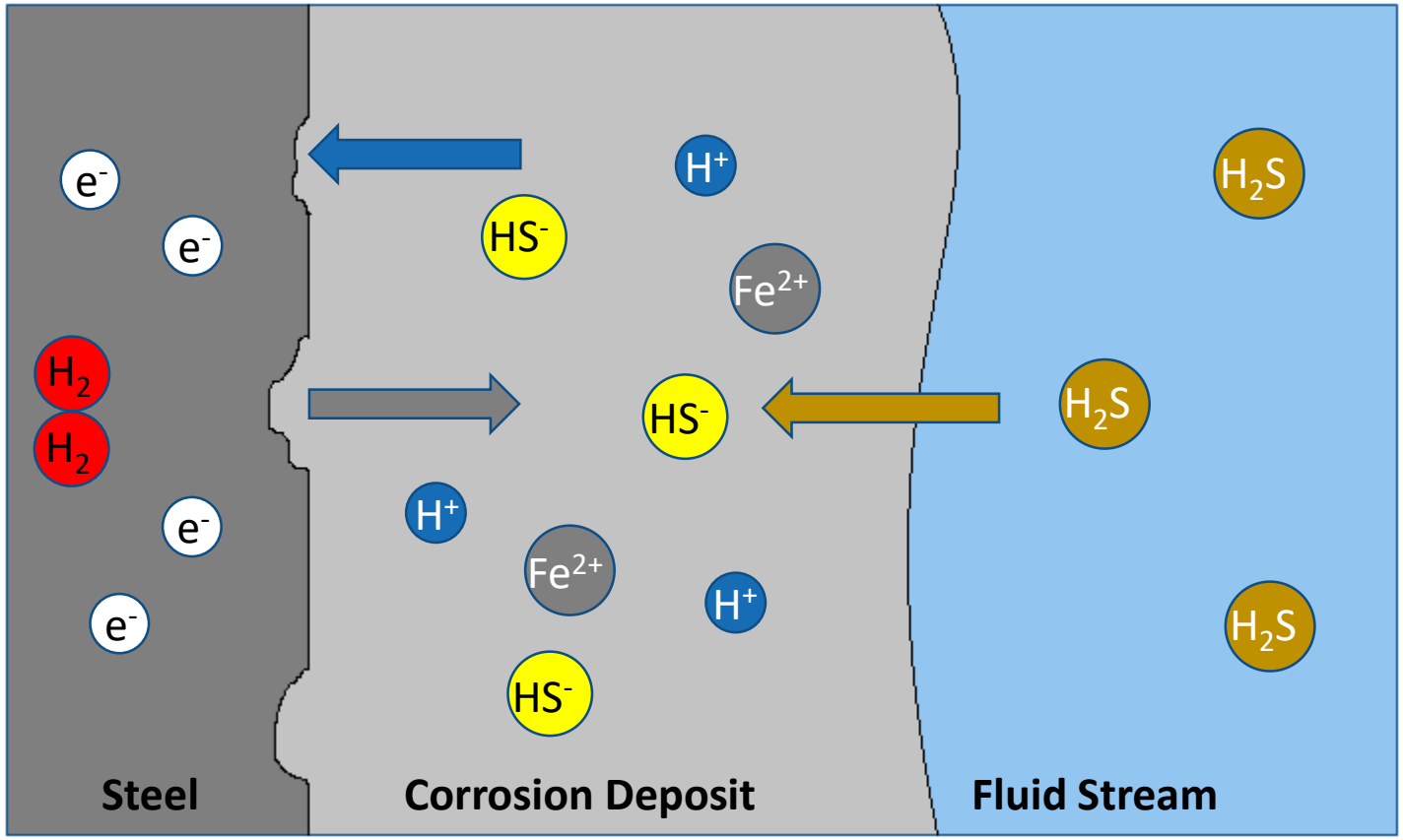


Figure 18. Schematic of Hydrogen Cracking

NACE MR175 for Corrosion Resistant Alloys for Sulphide Service

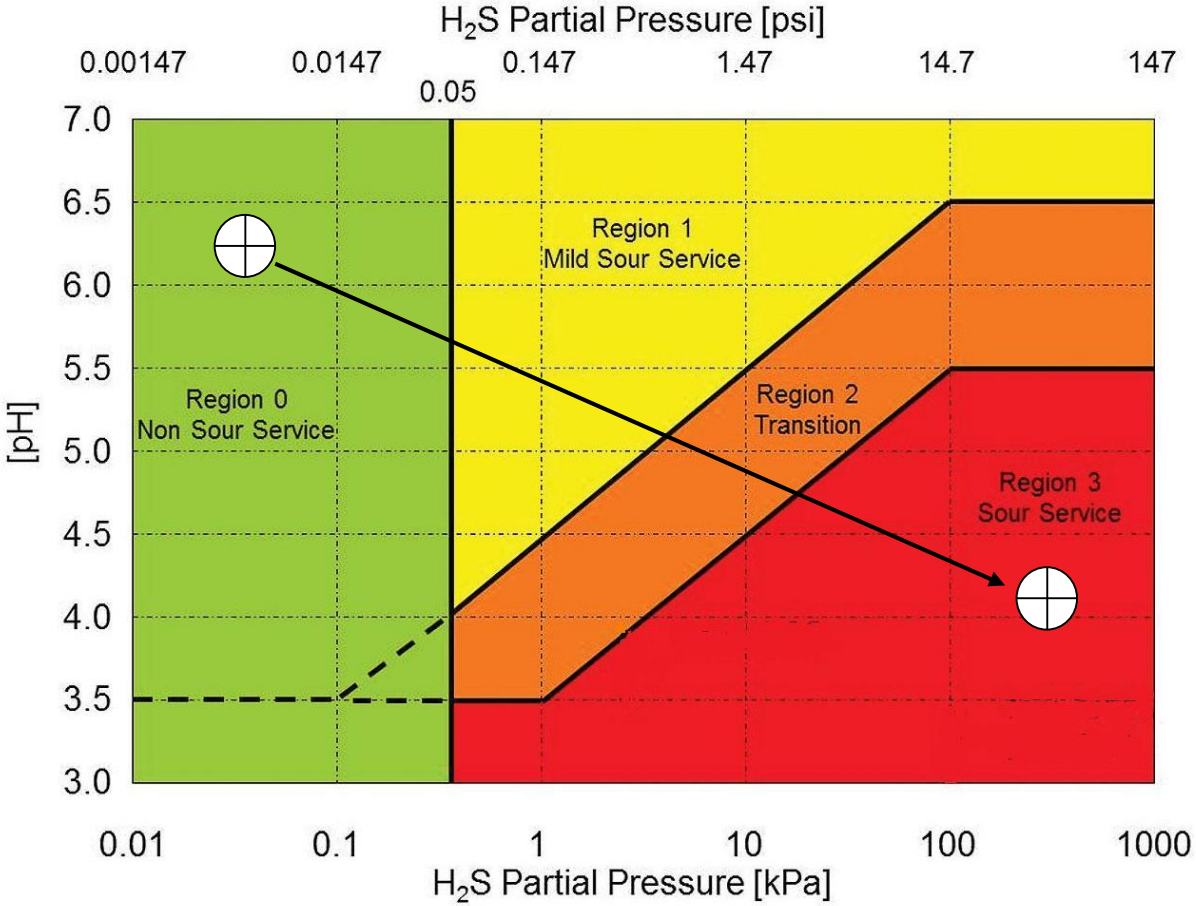
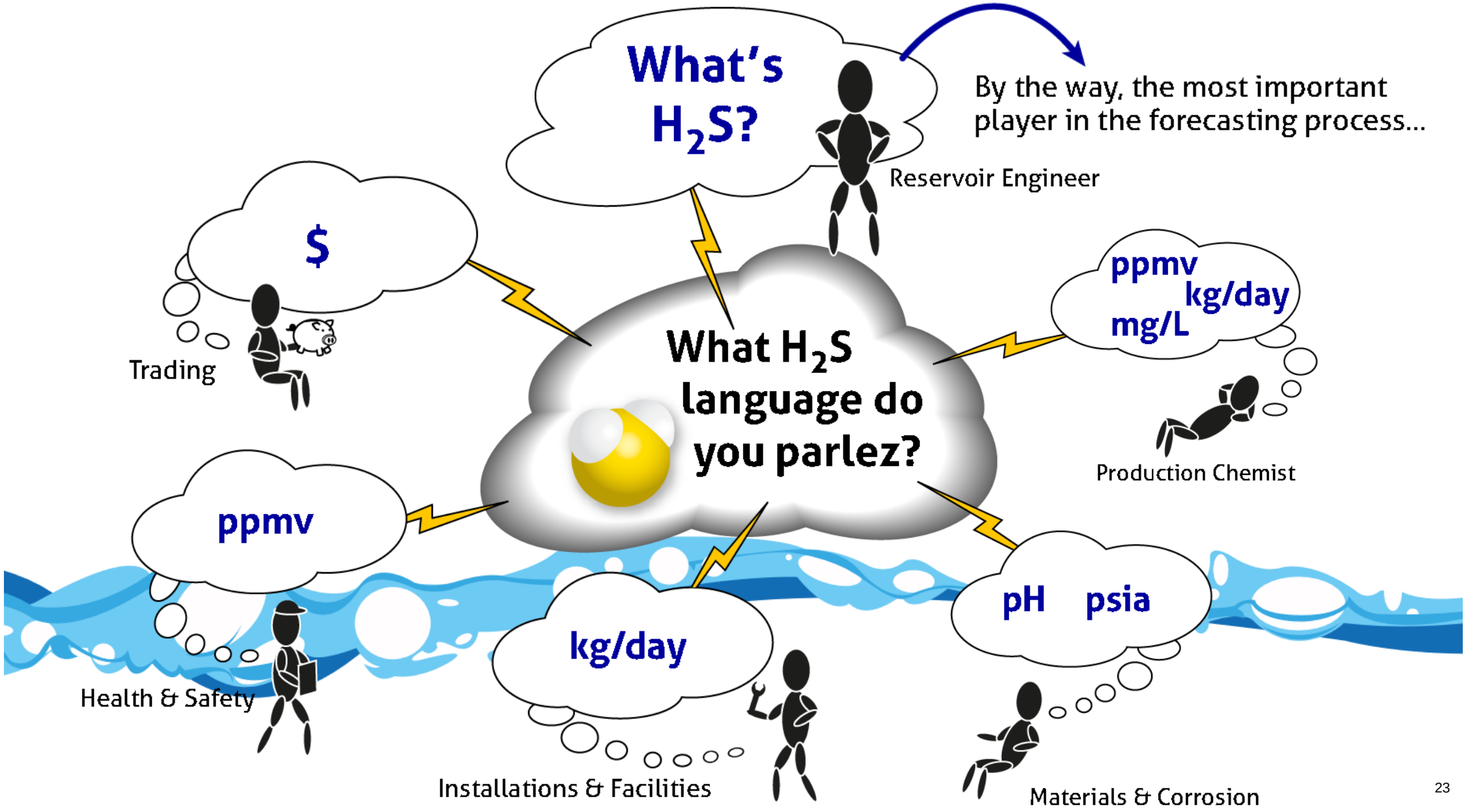


Figure 19. NACE MR0175 / ISO15156
https://www.drillingcontractor.org/research-expands-as-sour-gas-completion-challenges-increase-19044


What's H_2S?
By the way, the most important player in the forecasting process...
Reservoir Engineer
$
Trading
What H_2S language do you parlez?
ppmv
kg/day
mg/L
Production Chemist
ppmv
Health & Safety
kg/day
Installations & Facilities
pH
psia
Materials & Corrosion

2. Development of Souring 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 H_2S and appearance at facilities under specific operating conditions
- Rawwater has continually developed the model through further research

http://www.hse.gov.uk/research/othpdf/200-399/oth385.pdf

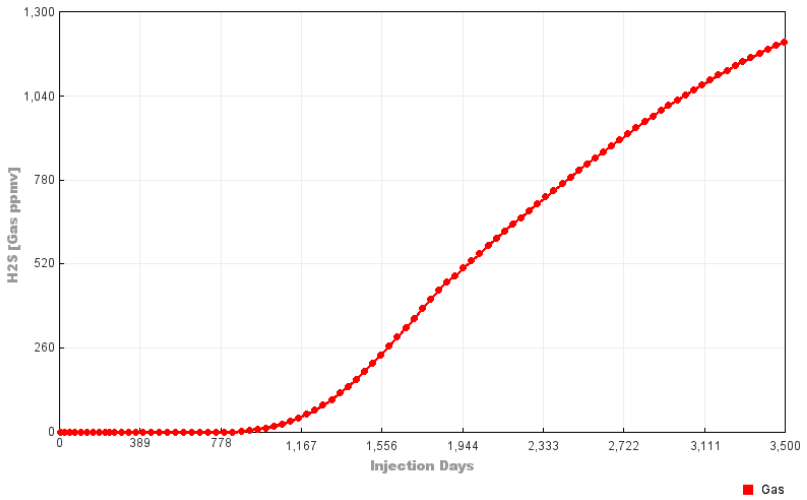


Figure 2. Typical Souring Forecasting Profile

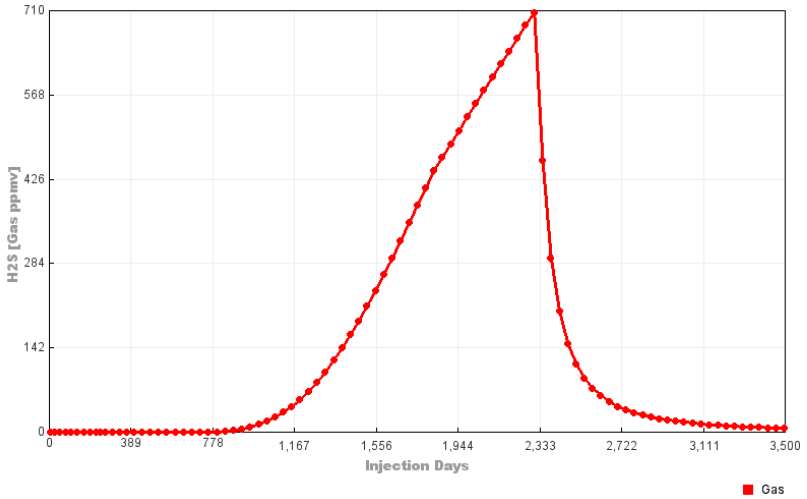


Figure 21. Typical Souring Forecasting Profile 2

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

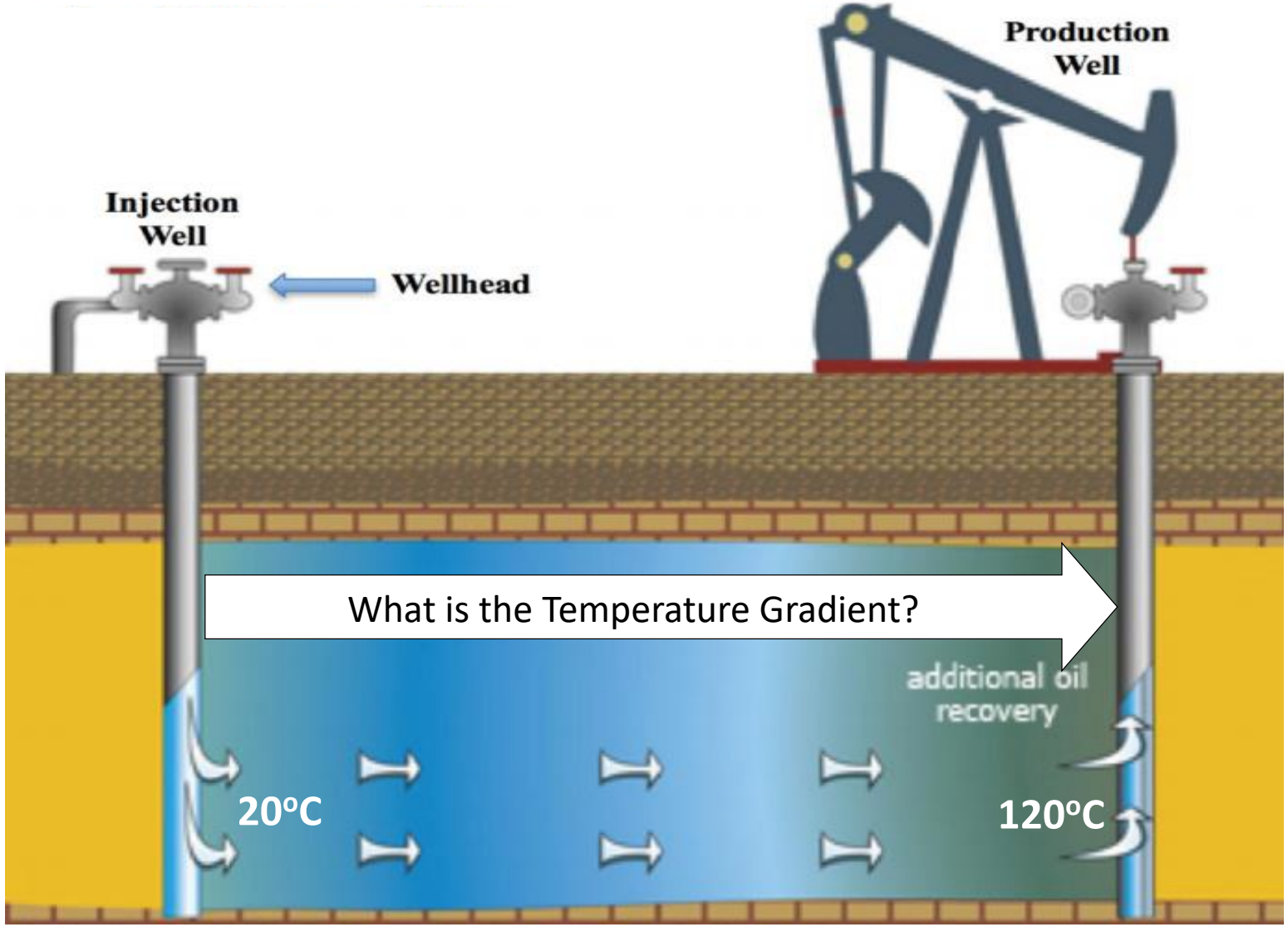
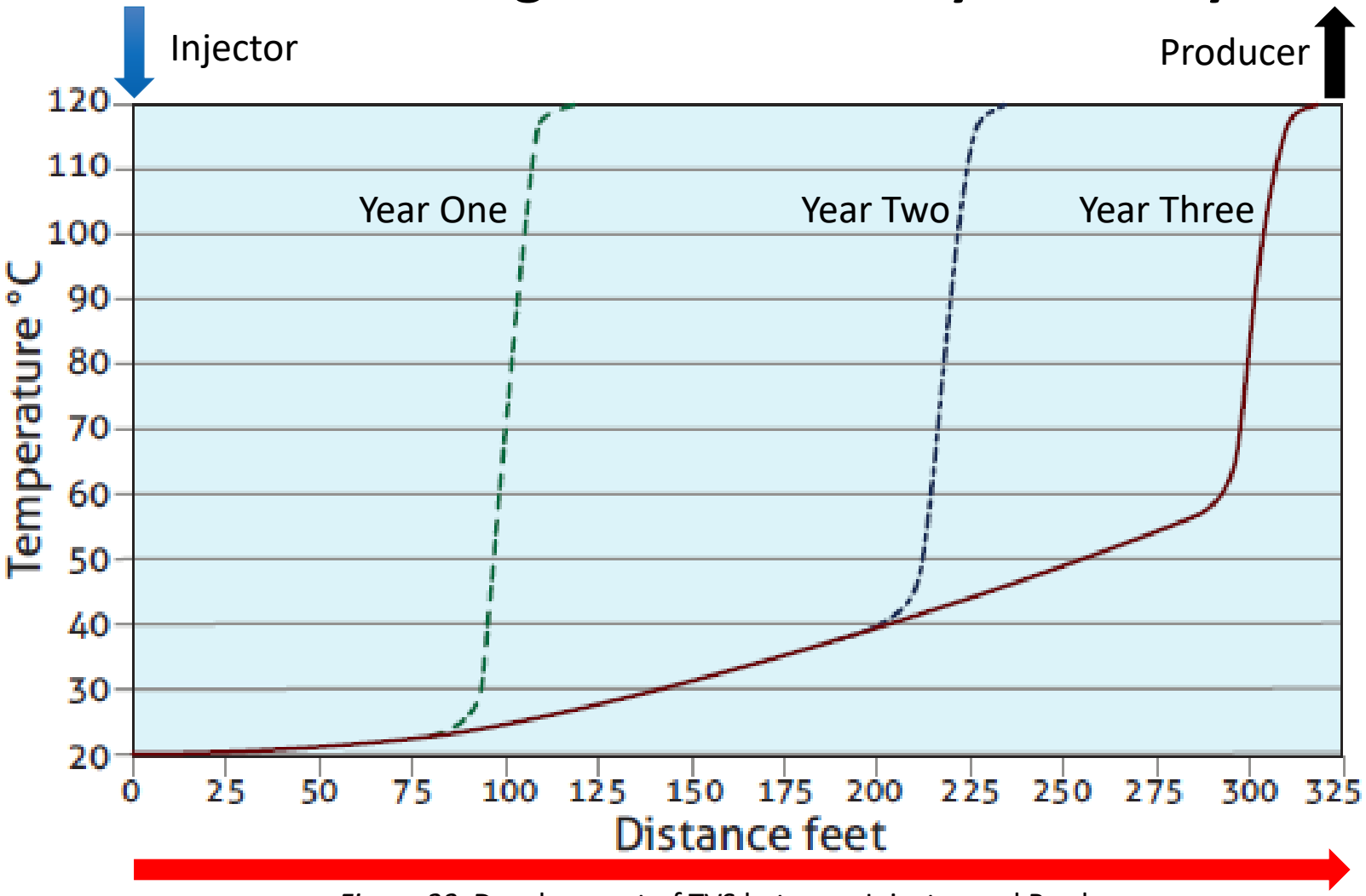


Figure 22. Secondary Recovery through Waterflooding

https://www.resilience.org/stories/2017-08-09/this-is-the-drilling-method-for-most-us-oil-but-regulators-offer-almost-no-oversight/

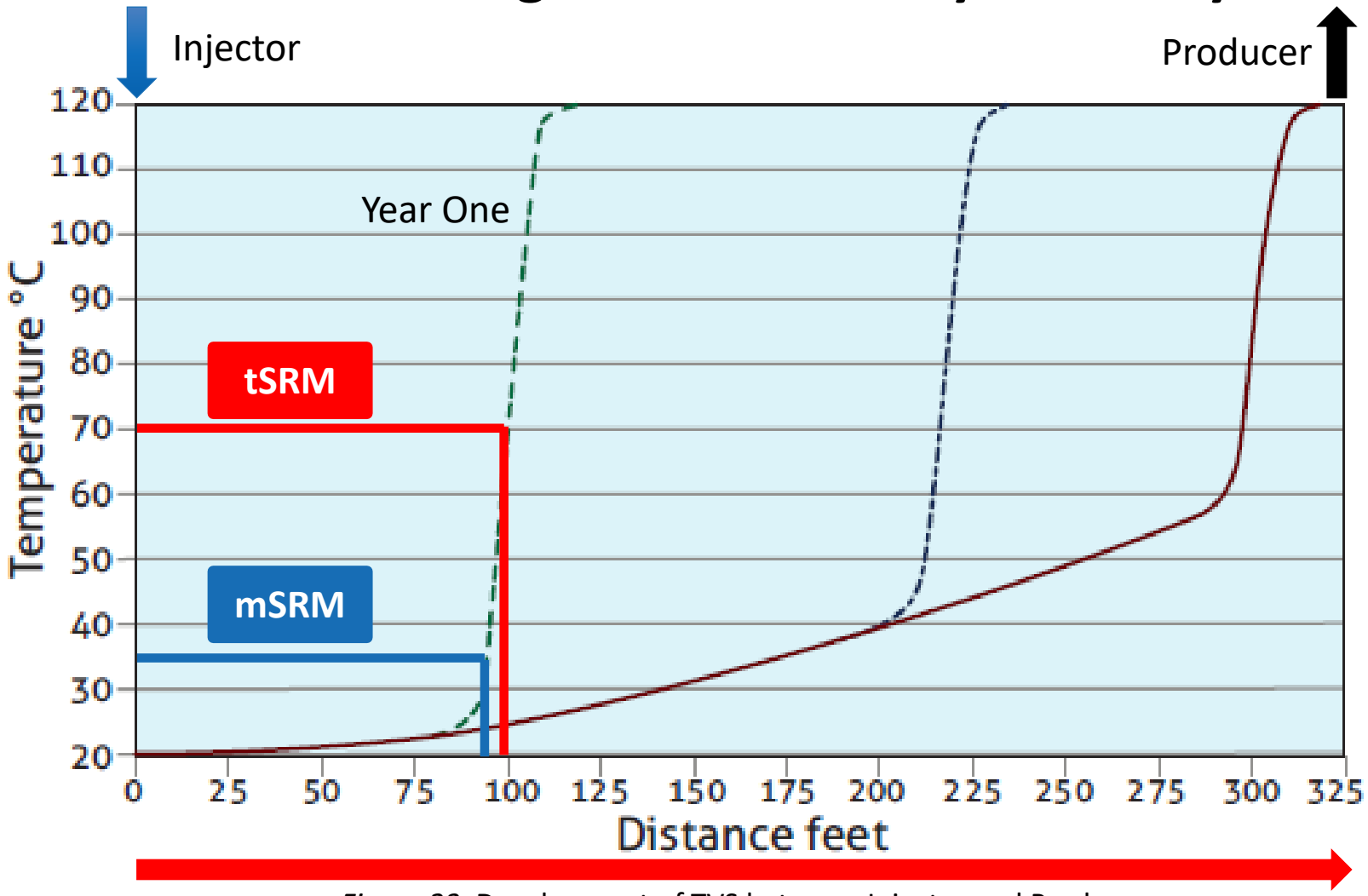
i. Oilfield Reservoir Cooling from Secondary Recovery



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



tSRM
Thermophilic Sulphate-Reducing Microorganisms

mSRM
Mesophilic Sulphate-Reducing Microorganisms

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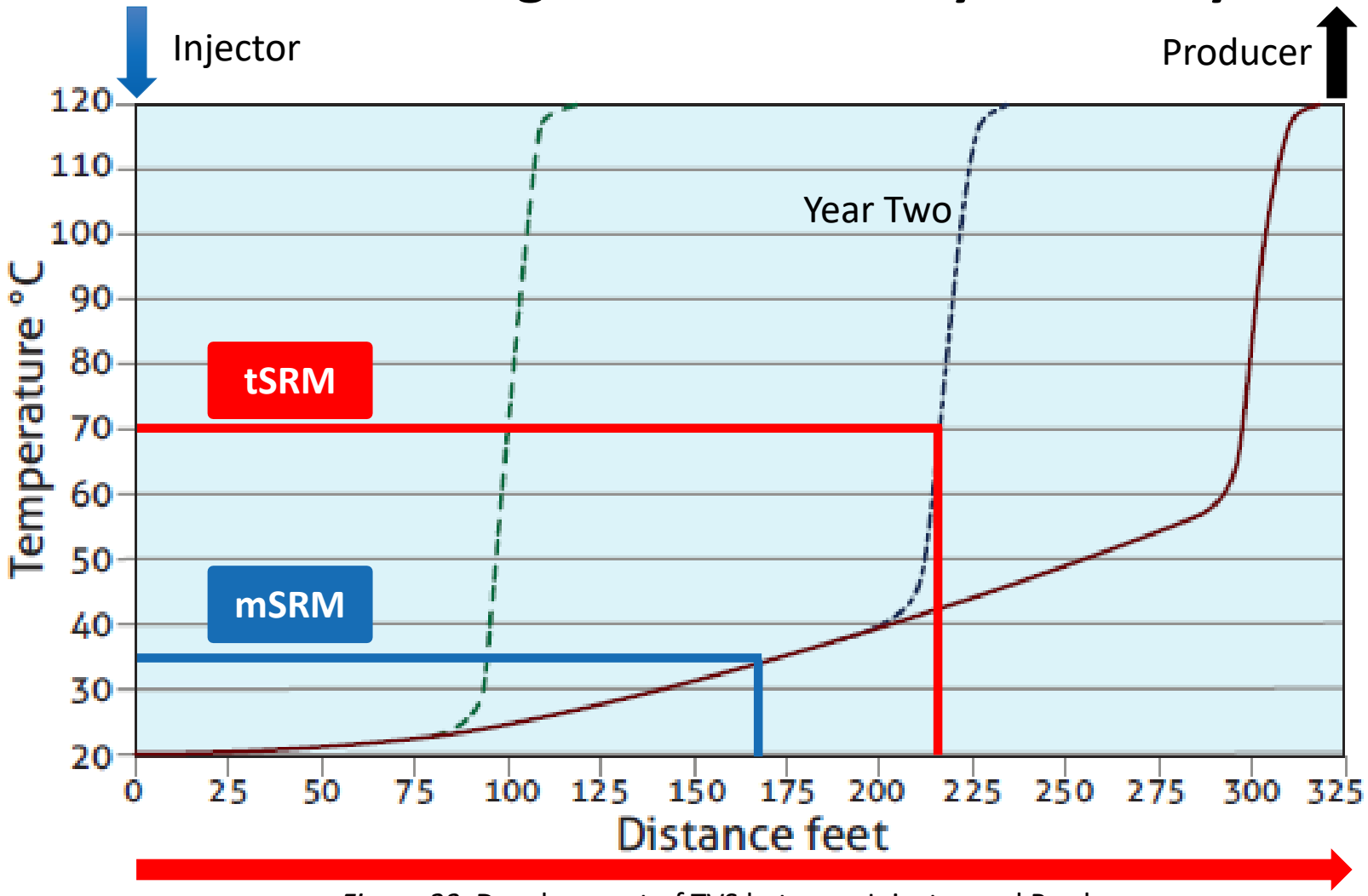

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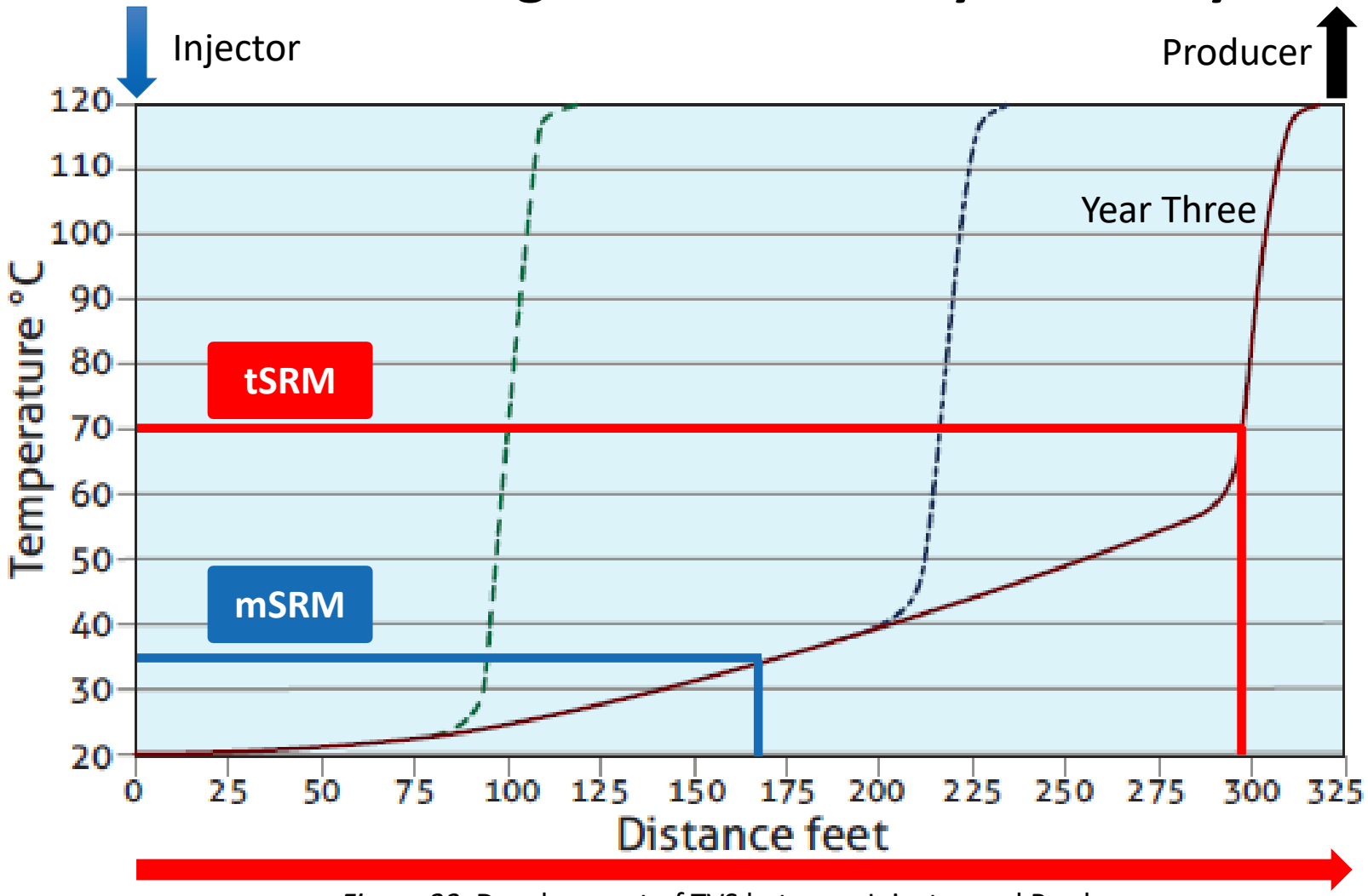

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Radial Flood of Injected Water

Representative flow of injection water from injector to producer

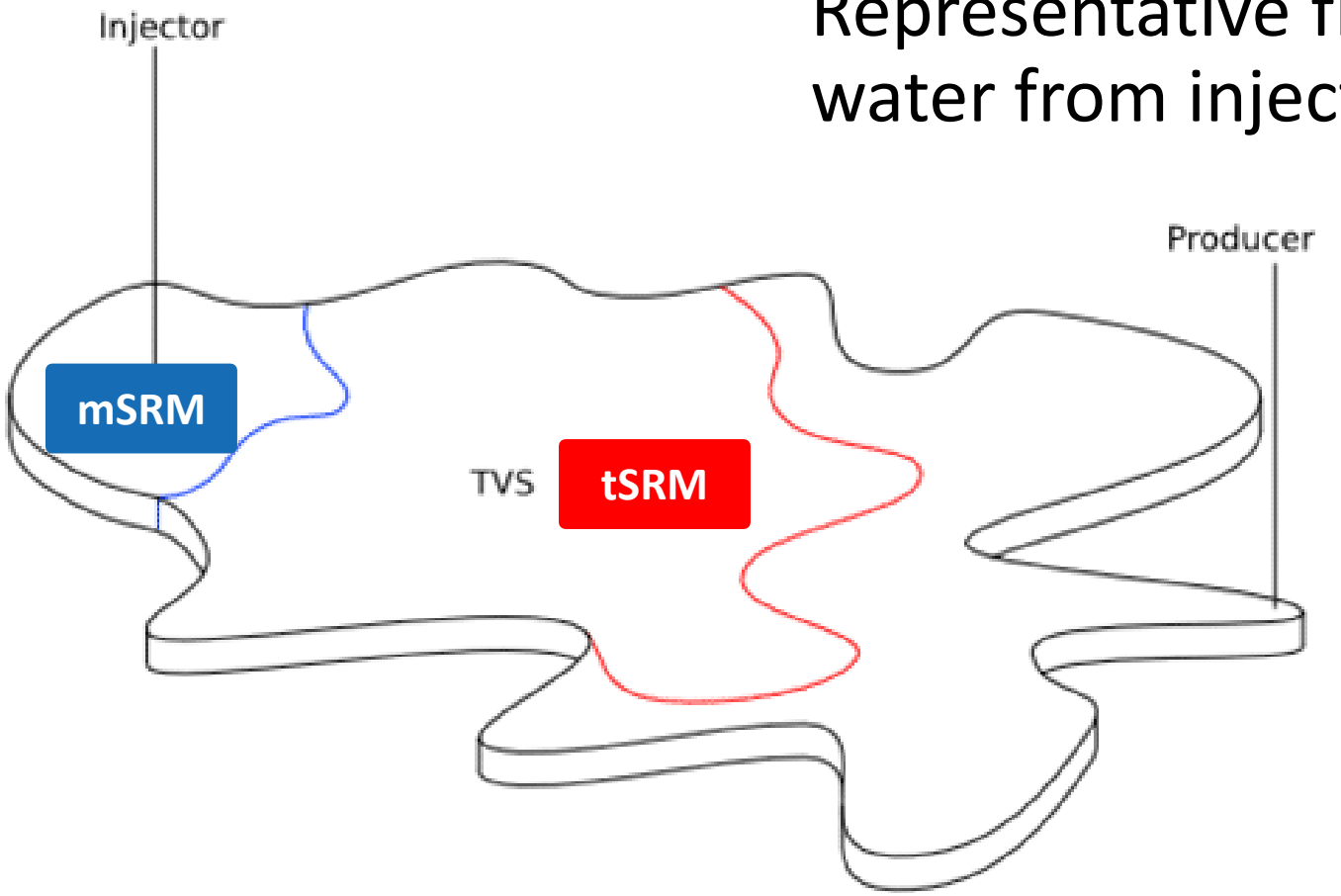

Figure 24. Model Illustrating Radial Flood of Injection Water
Adapted from HSE Document 'OTH 92 385'

“Pie Slice” Flood of Injected Water

Simplified flow of injection water from injector to producer

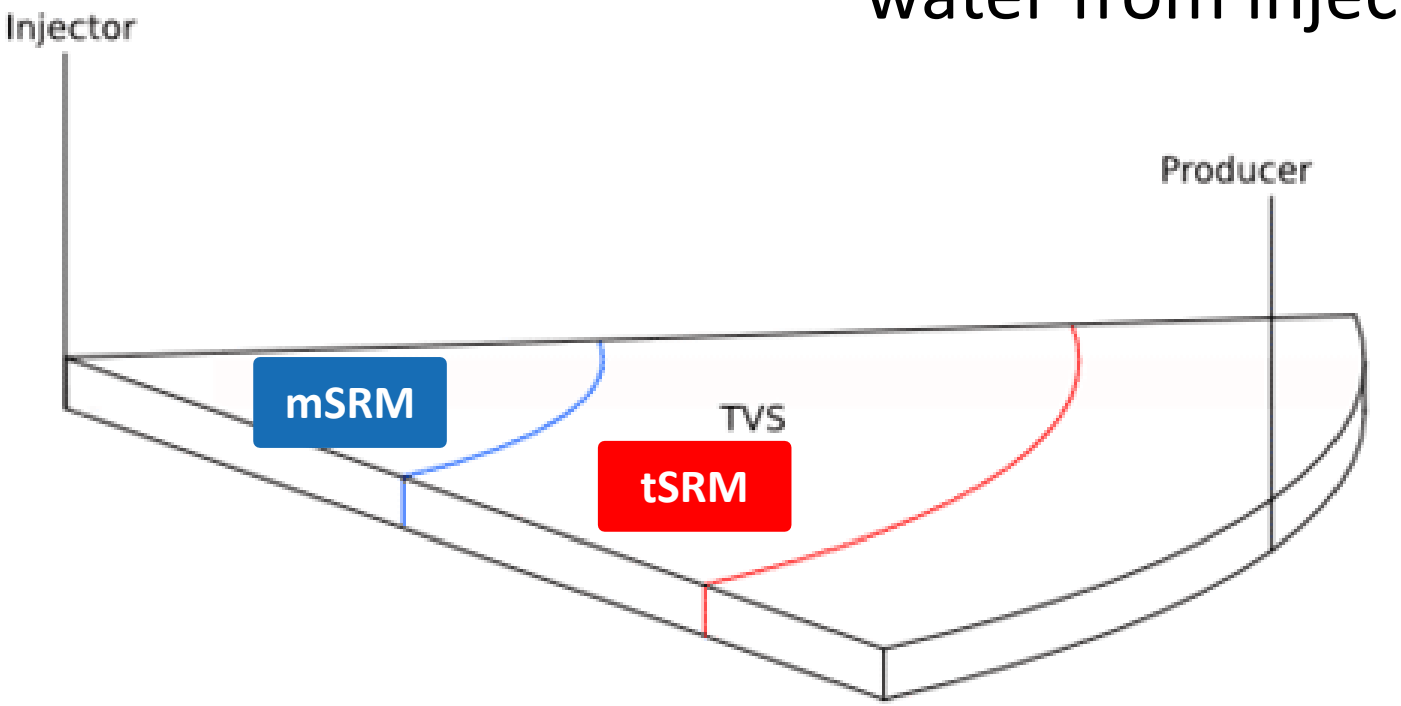

Figure 25. Model Illustrating Injection Water Swept into a Single ‘Pie Slice’
Adapted from HSE Document ‘OTH 92 385’

2. Development of Souring in the Field

ii. Growth of Sulphate-Reducing Microorganisms

- Pressure / Temperature Conditions
- Surface Area

ii. Growth of Sulphate-Reducing Microorganisms

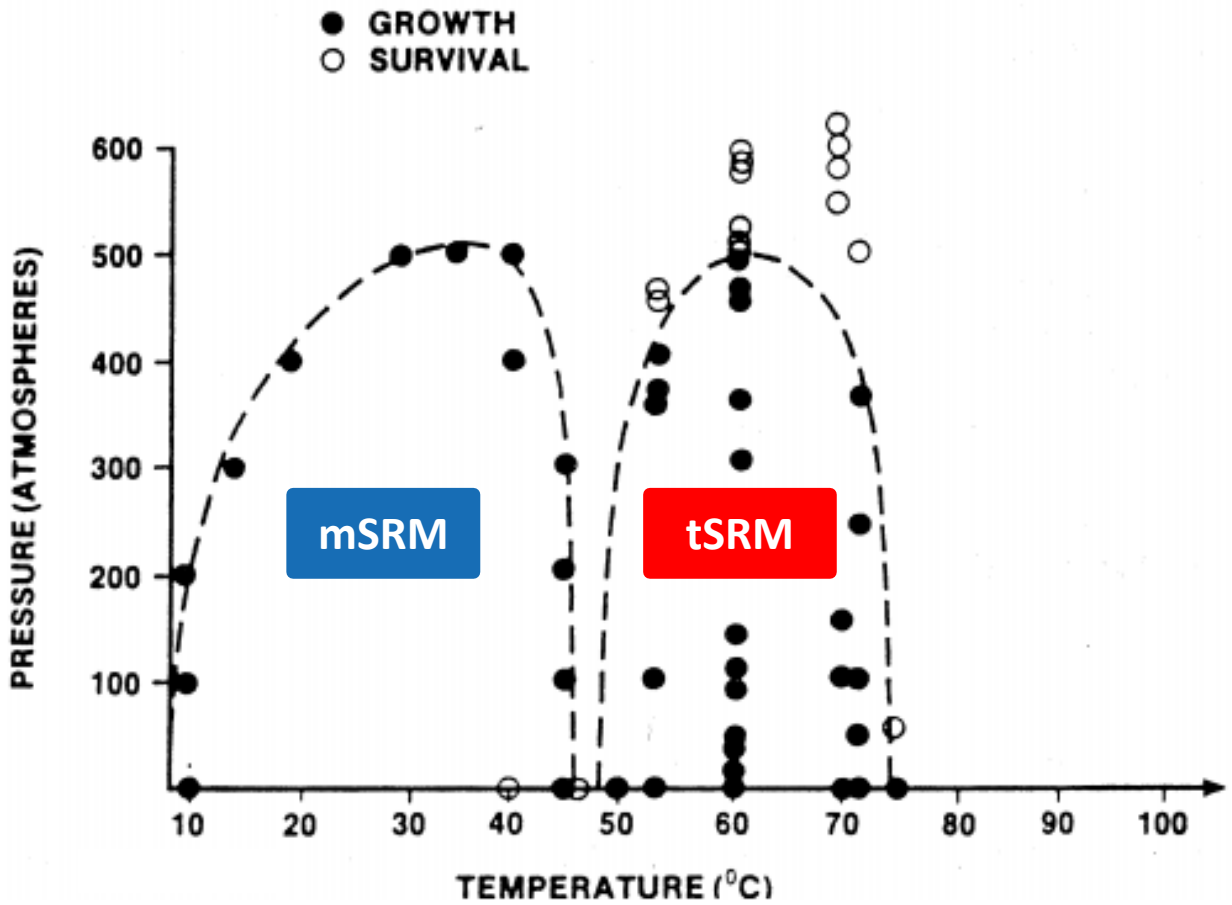

Figure 26. Pressure vs. Temperature Growth Domains for mSRM and tSRM Cultures
Adapted from HSE Document 'OTH 92 385'

ii. Growth of Sulphate-Reducing Microorganisms

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

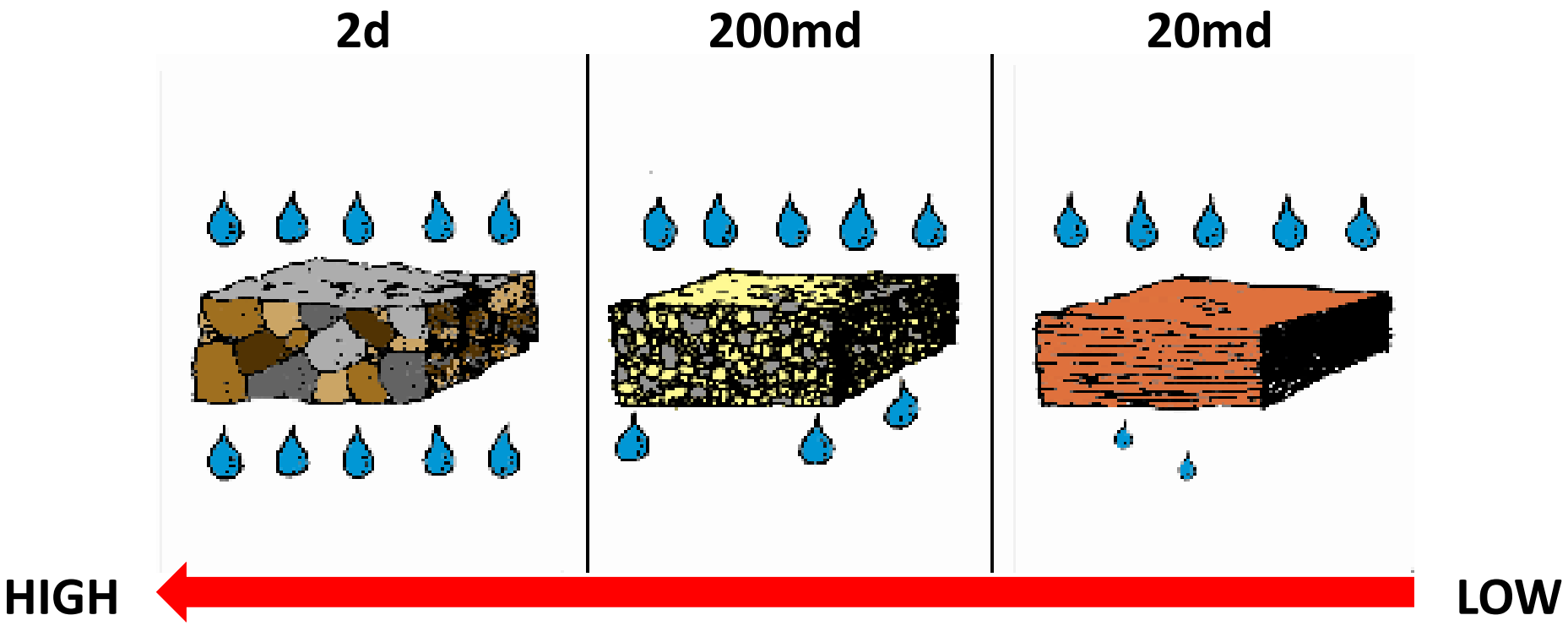

Figure 27. Varying Rock Formations and Permeabilities
https://blogs.egu.eu/network/water-underground/2015/09/03/how-easily-does-our-understanding-of-crustal-permeability-flow-a-new-geofluids-special-edition/

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)

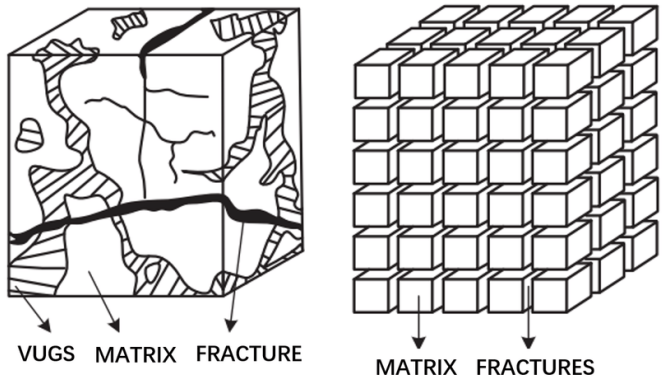

Figure 28. Varying Rock Formations and Permeabilities
https://www.researchgate.net/figure/The-double-porosity-model-proposed-by-Warren-and-Root_fig1_316772637

Higher degree of fracturing → Greater Surface Area for Microbial Colonisation

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2. Development of Souring in the Field

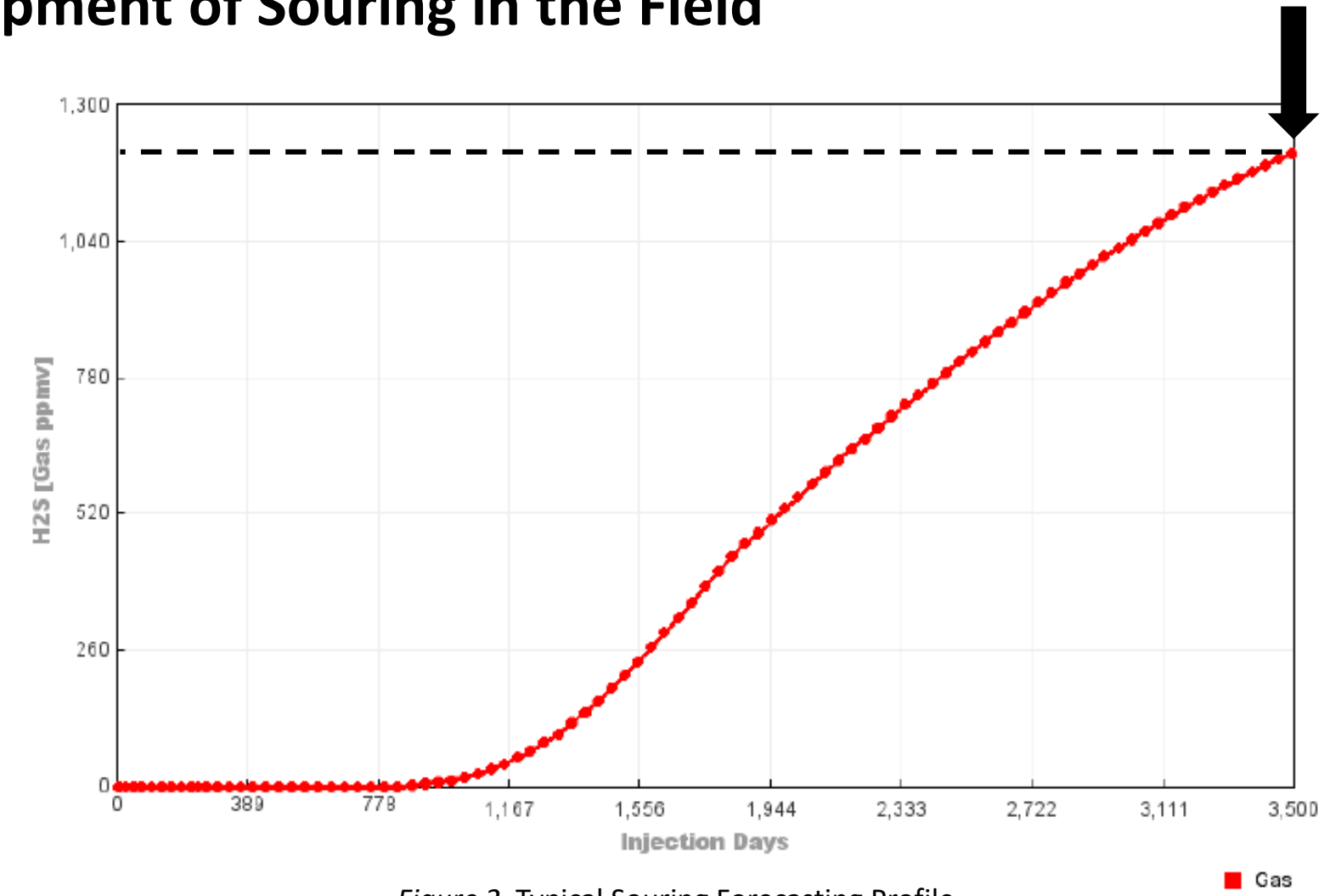


Figure 2. Typical Souring Forecasting Profile

NACE MR0175 Standard

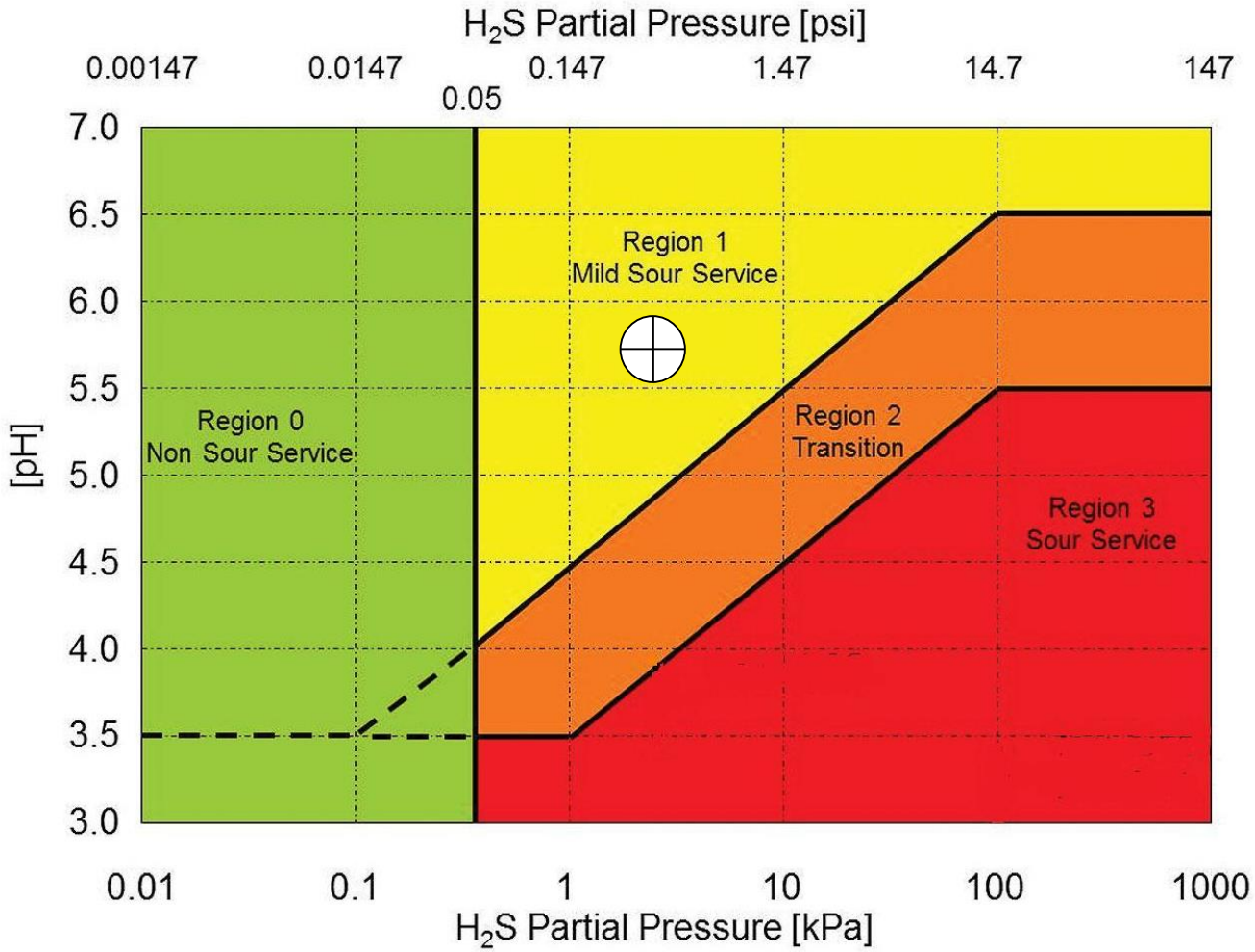


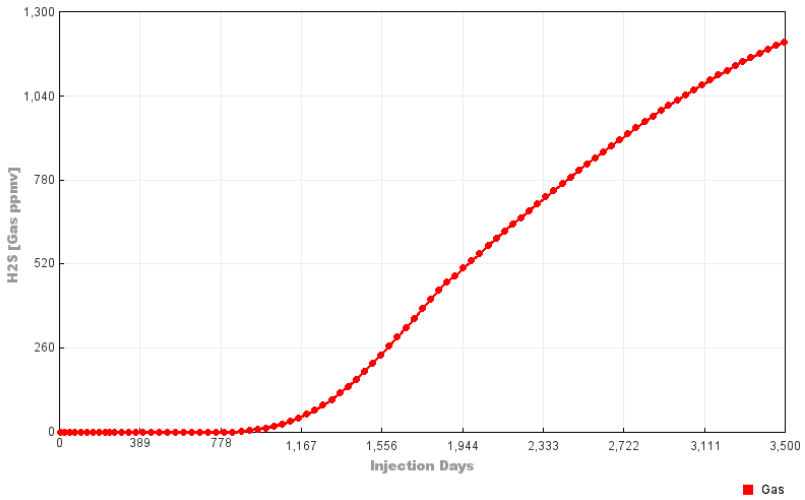
Figure 19. NACE MR0175 / ISO15156

https://www.drillingcontractor.org/research-expands-as-sour-gas-completion-challenges-increase-19044

2. Development of Souring in the Field

Benefits of Forecasting

- Provides **insight** for implementing **mitigation** plans
- Vital for **optimised, cost-effective treatment** of sour gas fluid management



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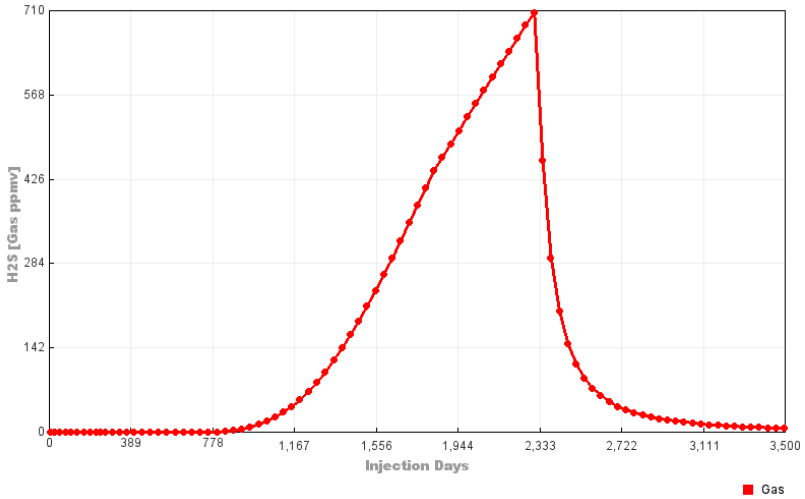
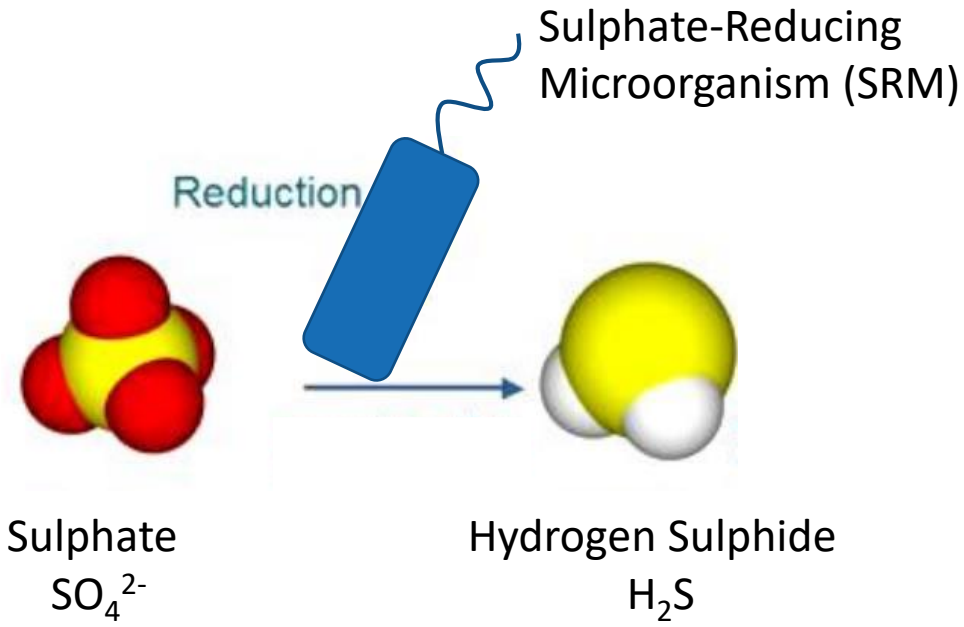


Figure 21. Typical Souring Forecasting Profile 2

3. Souring Control and Mitigation

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

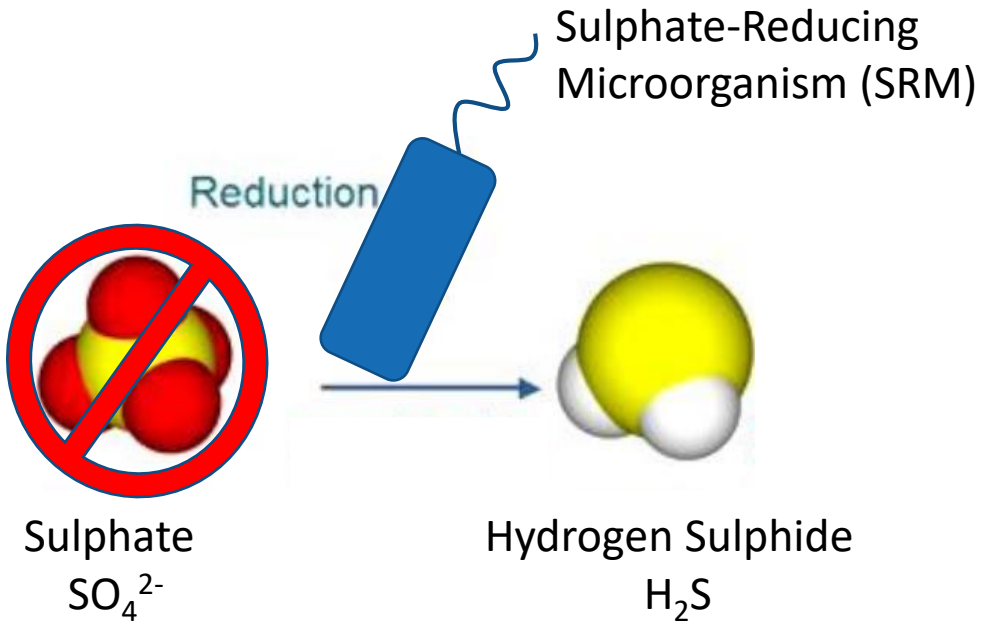
- Water Injection Management
- Production Water Management



3. Souring Control and Mitigation; Water Injection Management

Sulphate Removal from Injection Water

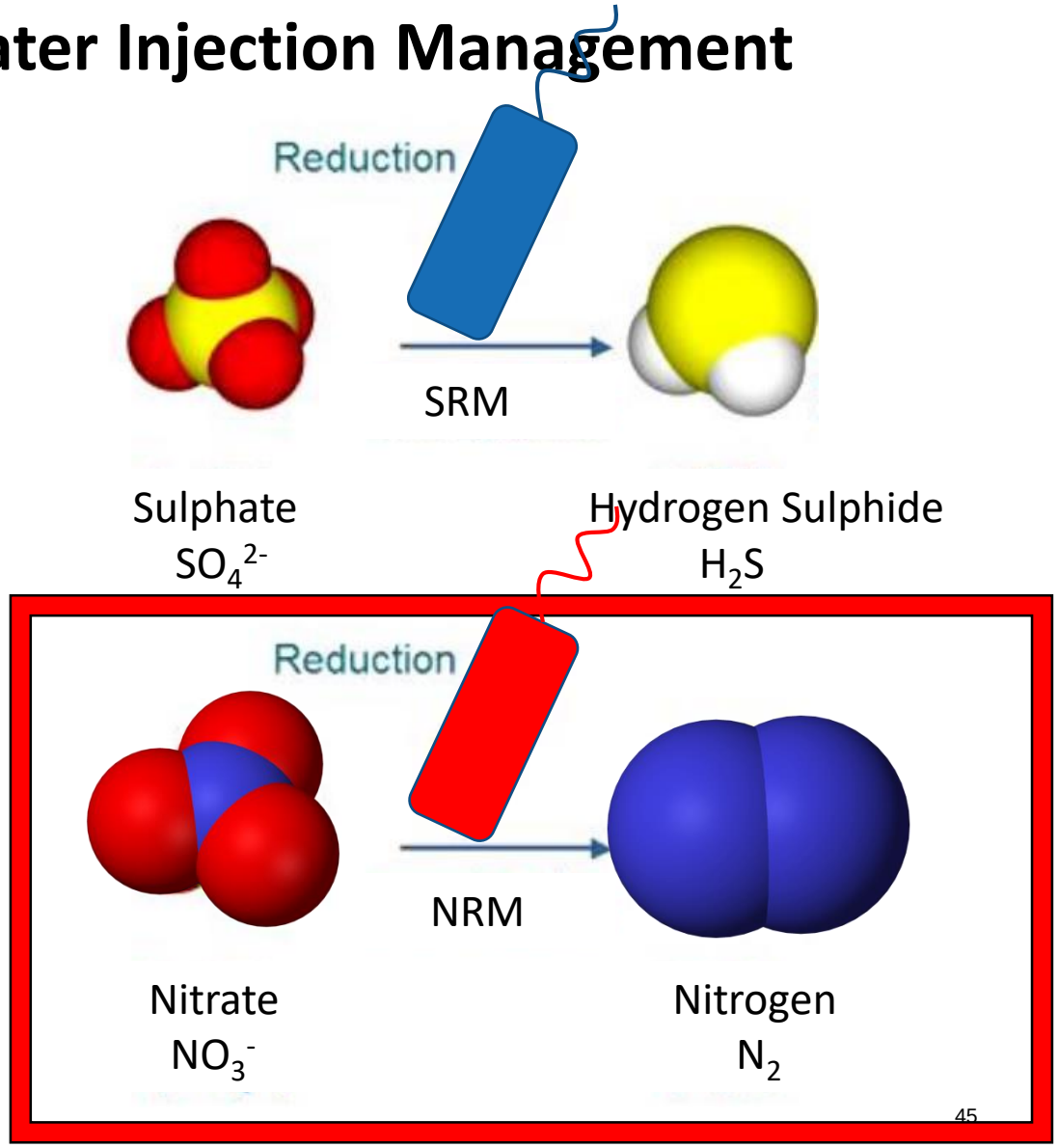
- Historically for scale control
- Significantly reduces biogenic souring
- Enhanced oil recovery benefits
- Expensive
- Removal of sulphate from produced water (PW) not currently possible



3. Souring Control and Mitigation; Water Injection Management

Nitrate Dosing in Injection Water

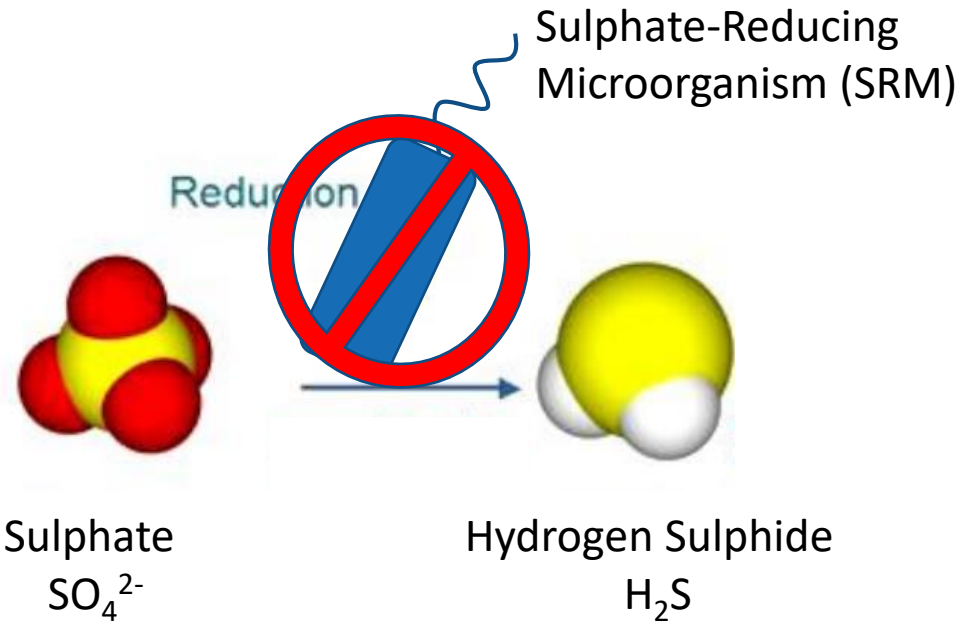
- Microorganisms preferentially reduce nitrate
- Nitrogen production rather than sulphides
- Continued growth of downhole microbiology
- Remediation of sour field possible, but delayed response



3. Souring Control and Mitigation; Water Injection Management

Biocide Dosing in Injection Water

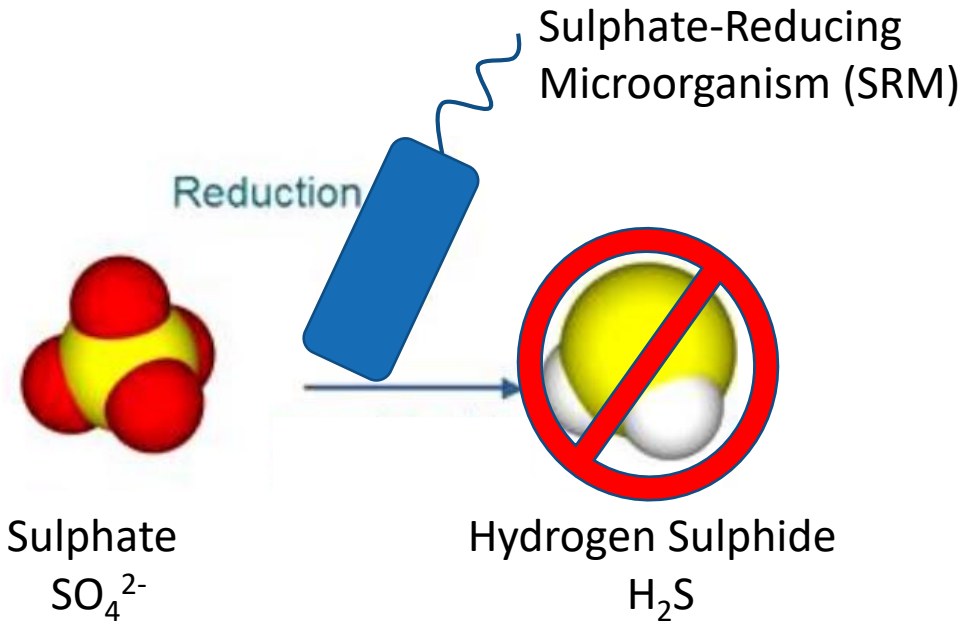
- Beneficial in maintaining downhole injectivity
- Demonstrates effective facilities souring control
- No enhanced growth of downhole microbiology
- Downhole reservoir souring control is still unproven



3. Souring Control and Mitigation; Production Water Management

H_2S Scavenger Chemistries

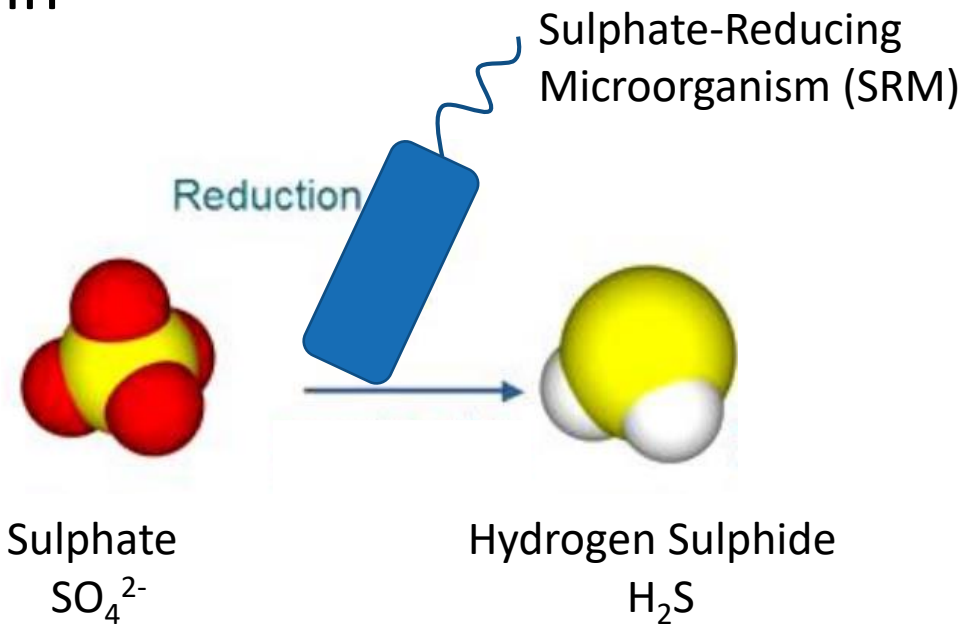
- Common end-of-pipe control measure
- Financial benefits in low souring fields
- Mitigation strategy as opposed to direct control
- H_2S scavenger demand increases over time



3. Souring Control and Mitigation; Production Water Management

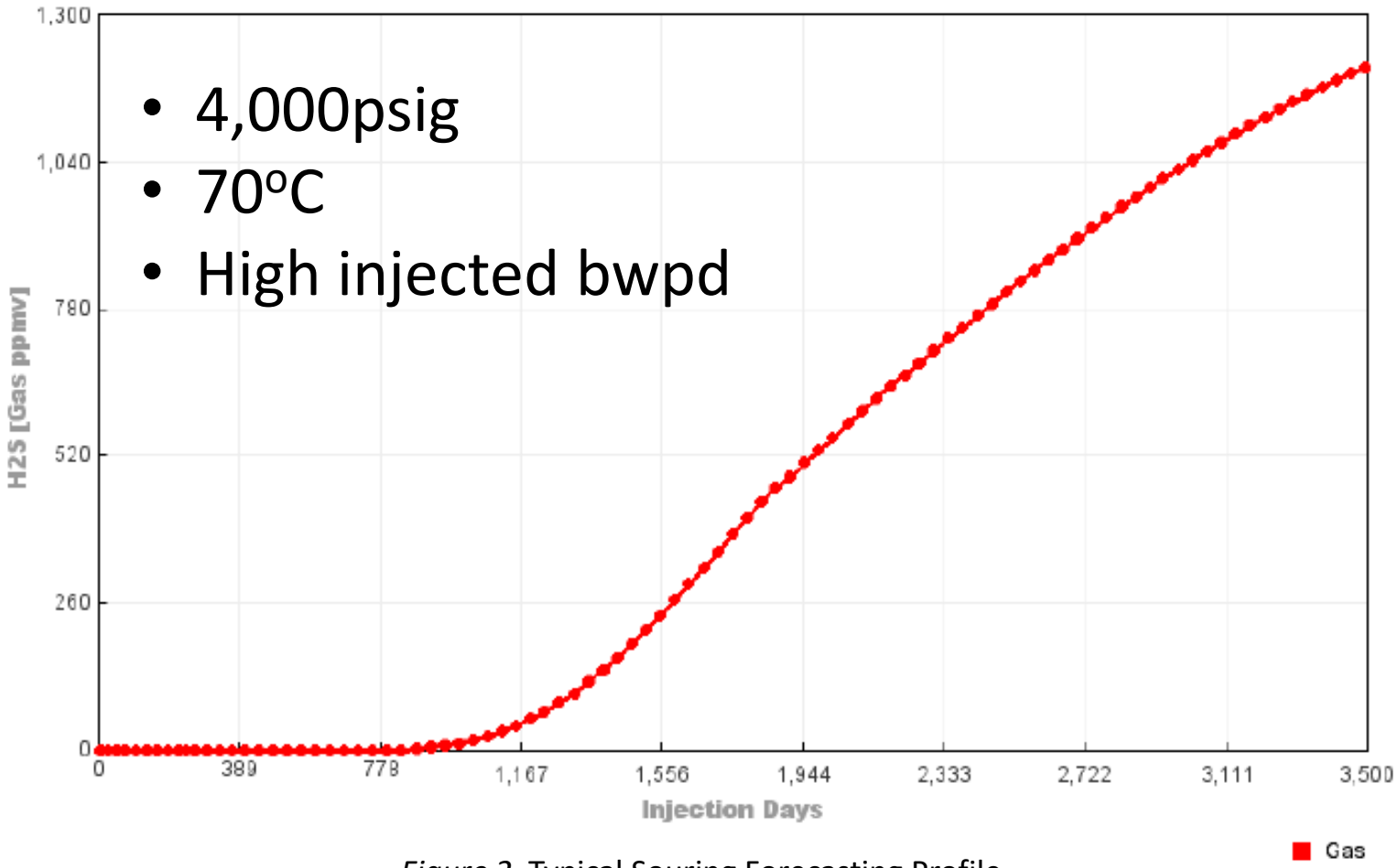
Each injector / producer pair is unique in its souring propensity

- 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 Souring Forecasting Profile

4. Case Study: A 'Typical' Souring Profile

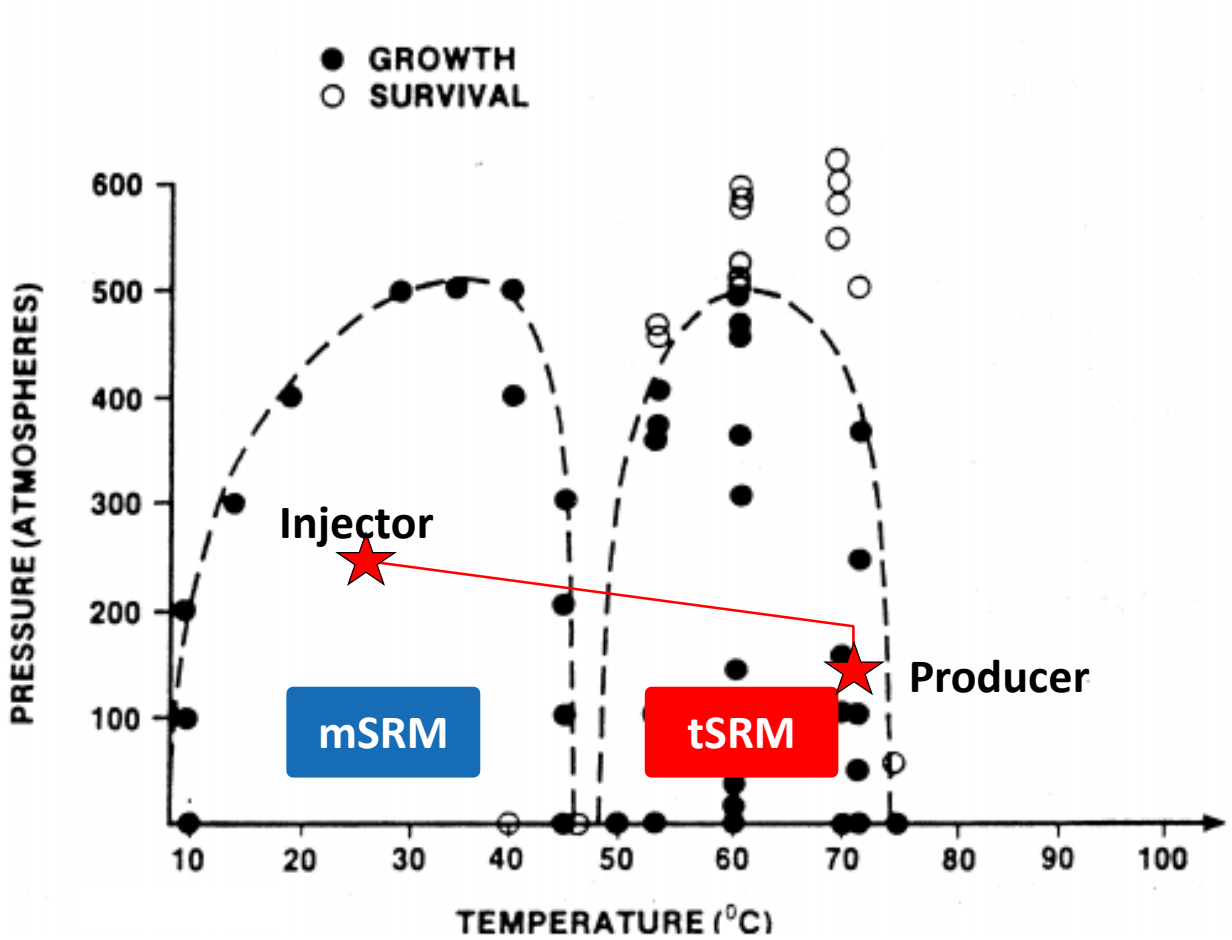


Figure 26. Pressure vs. Temperature Gradient from Injector to Producer
Adapted from HSE Document 'OTH 92 385'

4. Case Study: A 'Typical' Souring Profile

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

- High degree of downhole cooling

<u>Conclusion</u>

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

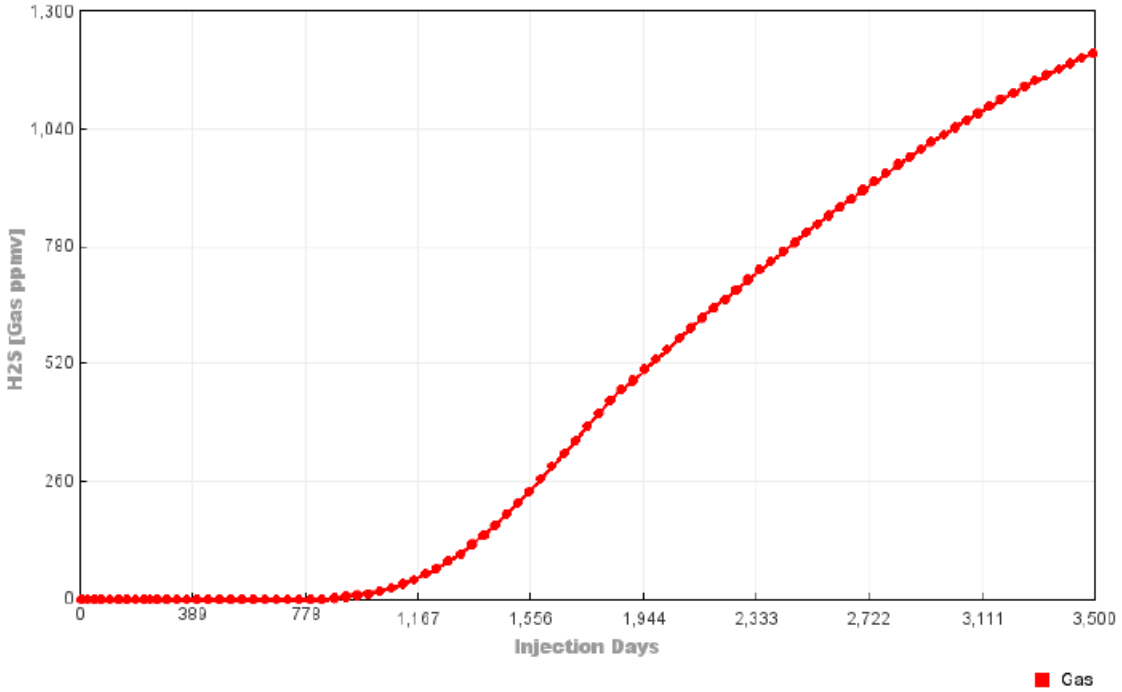


Figure 2. Typical Souring Forecasting Profile

4. Case Study: Ghanaian Souring Forecast

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

- Possible low souring potential

Figure 29. Map of Ghana
https://blog.continentalcurrency.ca/ghana-travel/

4. Case Study: Ghanaian Souring Forecast

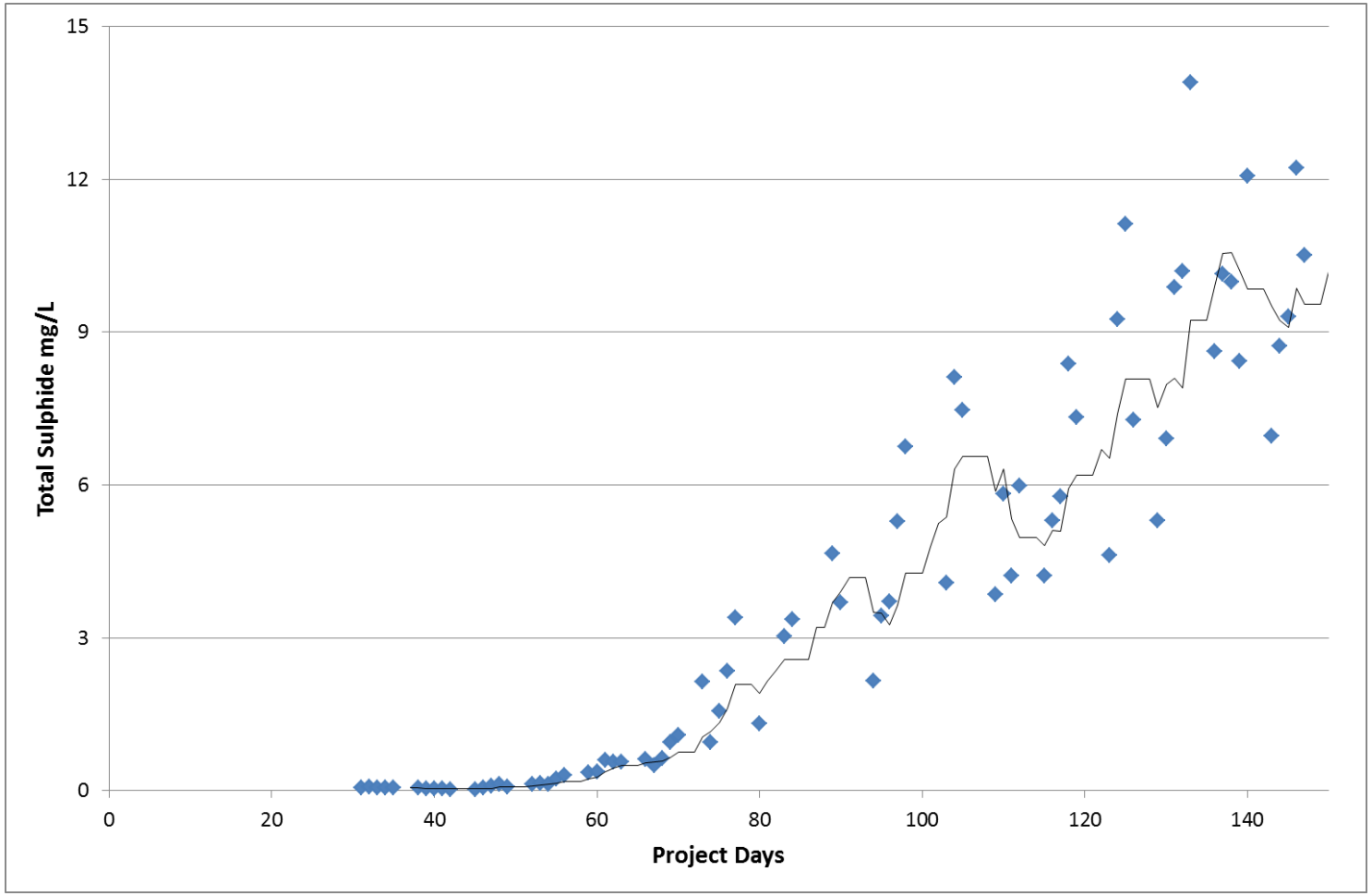


Figure 30. [Total Sulphide] Dataset from Pressurised Bioreactor Study

4. Case Study: Ghanaian Souring Forecast

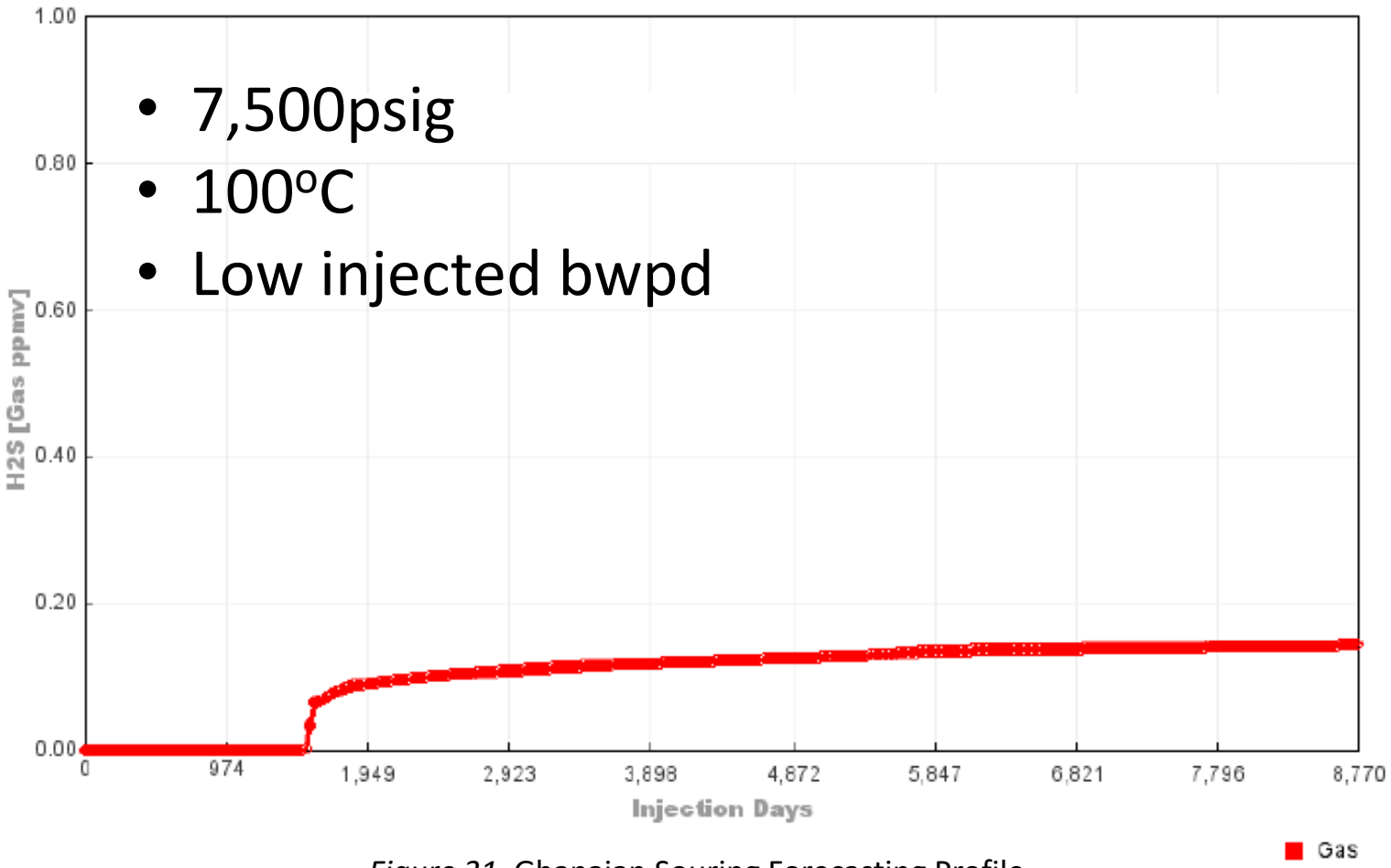


Figure 31. Ghanaian Souring Forecasting Profile

4. Case Study: Ghanaian Souring Forecast

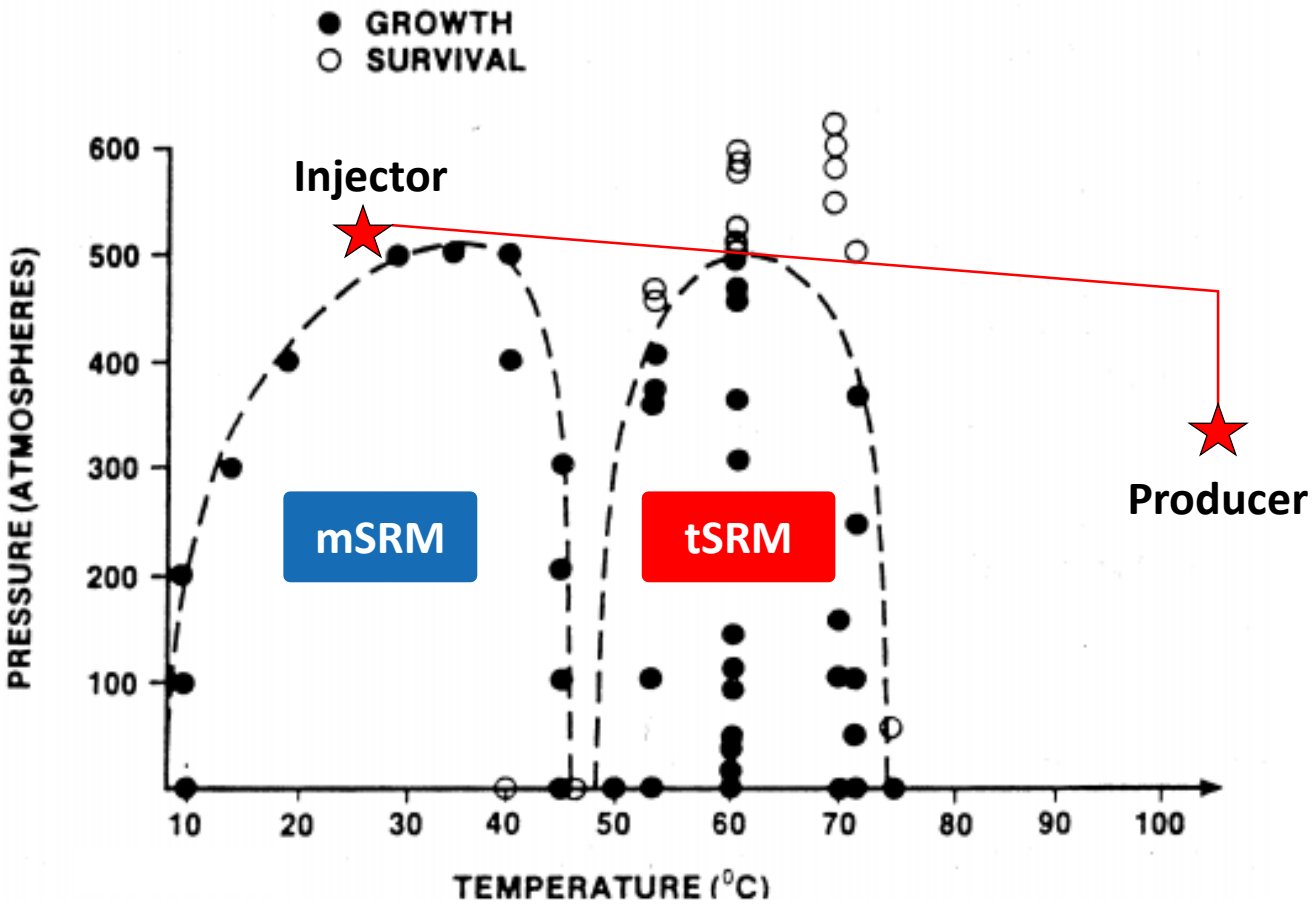


Figure 26. Pressure vs. Temperature Gradient from Injector to Producer
Adapted from HSE Document 'OTH 92 385'

4. Case Study: Ghanaian Souring Forecast

- Relatively high reservoir pressure and temperature conditions

- Low degree of downhole cooling

<u>Conclusion</u>

Despite souring crude, no significant souring at PTQ

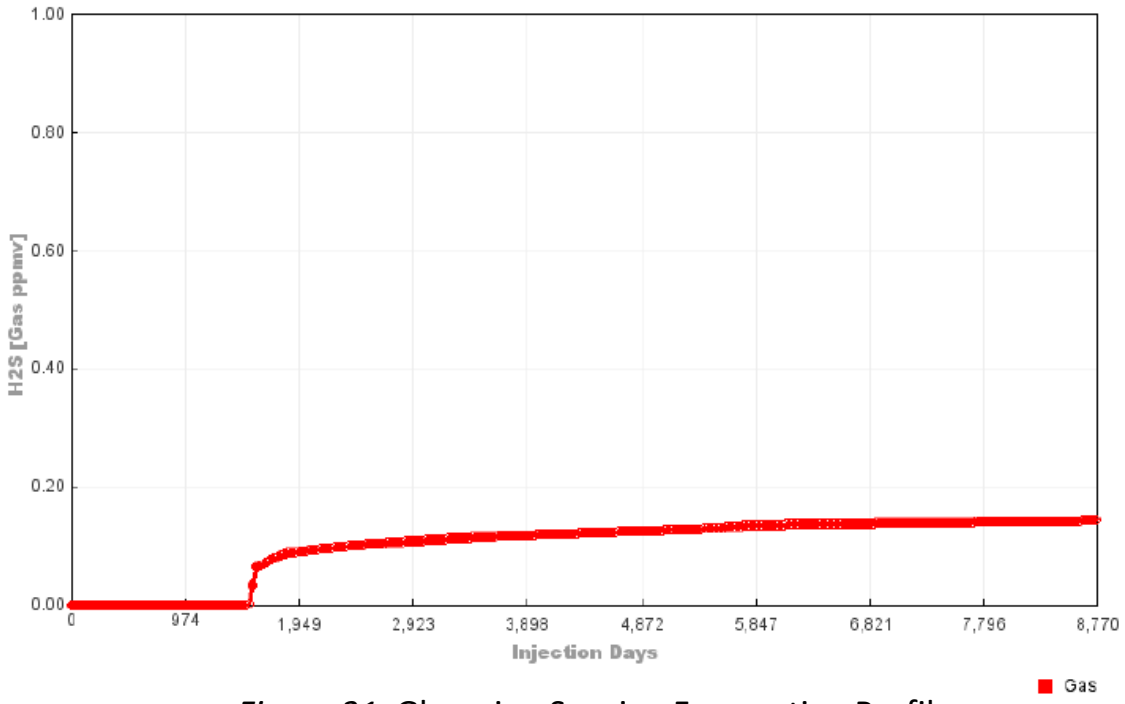


Figure 31. Ghanaian Souring Forecasting Profile

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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