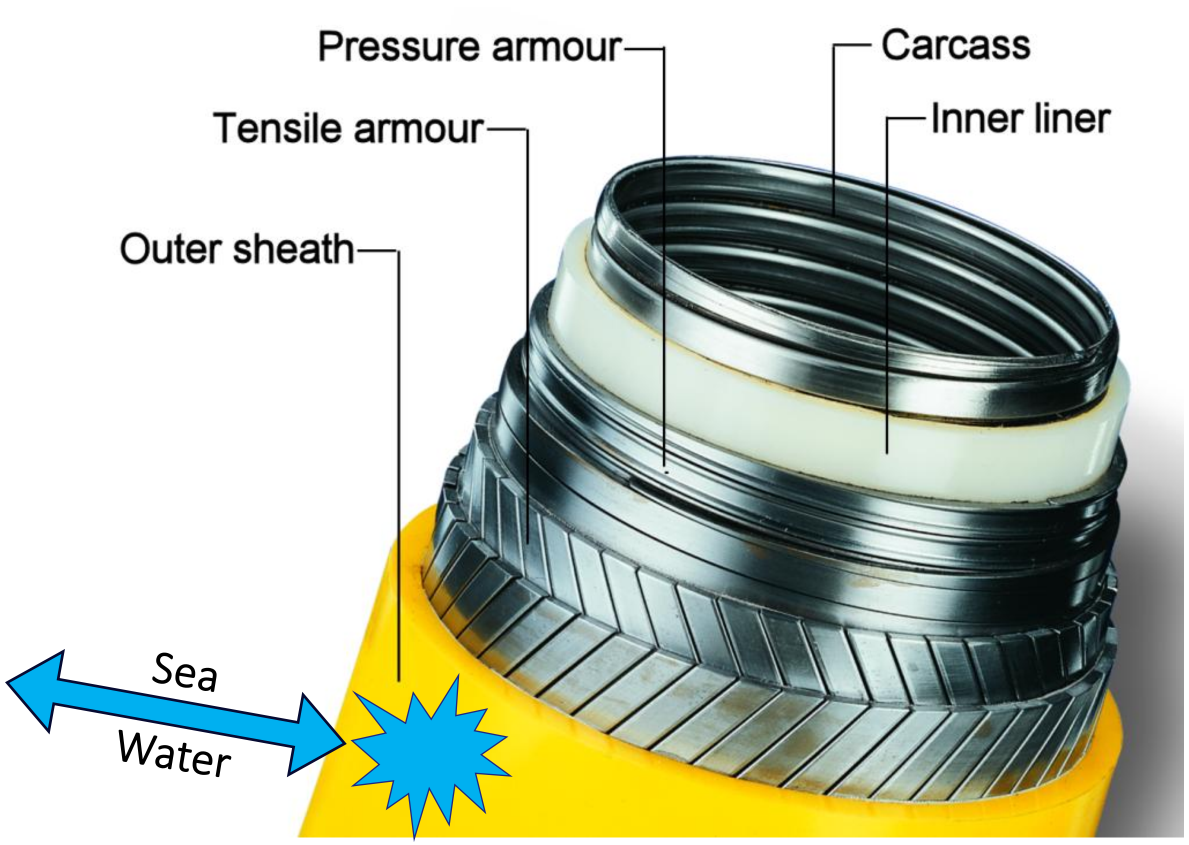
16.11.2025

Fagdag om fleksible røyr, integritetsstyring og aldring,
HAVTIL Stavanger 26 th November 2025

Corrosion of armour wire steel in the annulus of flexible pipes - an overview of mechanisms

Arne Dugstad
arne.dugstad@ife.no

Corrosion modes / mechanisms



Confined environment

- **V/S < 0.1 ml/cm²**

Diffusion:

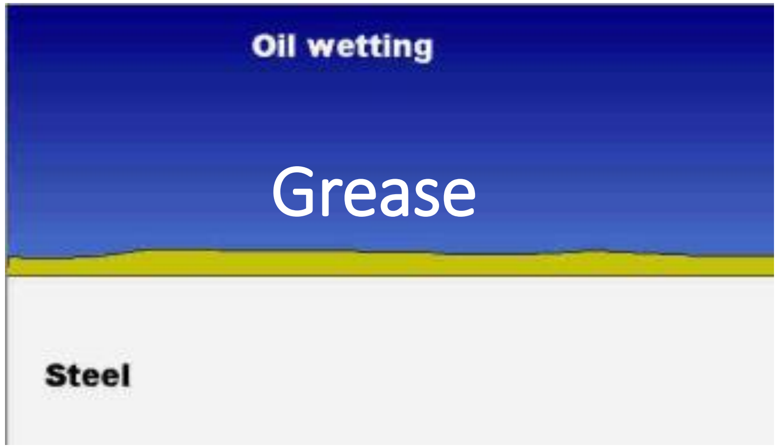
- **H_2O (high RH%- liquid)**
- **CO_2**
- **H_2S**
- **CH_4 +++**

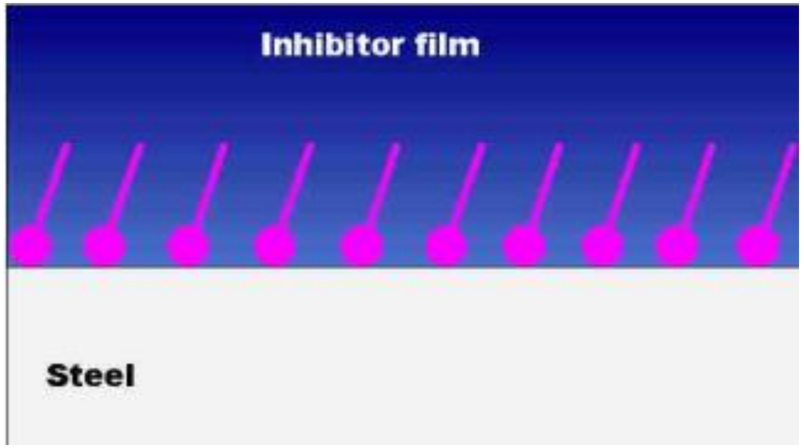
Air (O_2) through vent port

Damaged outer sheath:

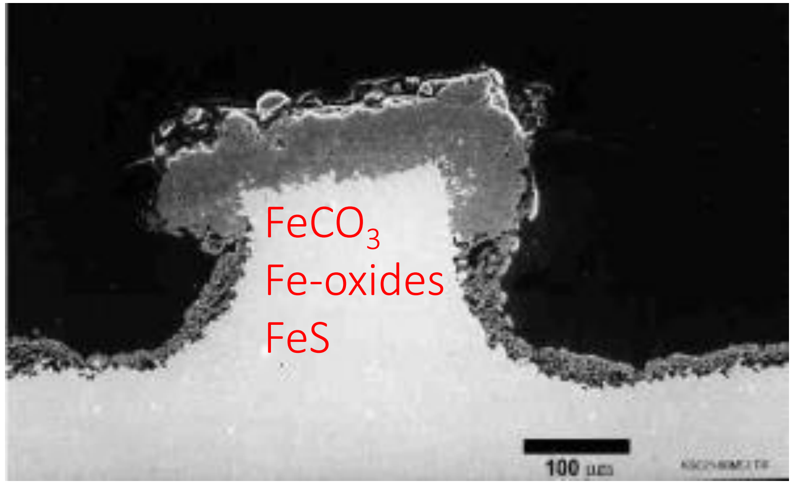
- **air (20 % O_2)**
- **sea water (0-10 ppmw)**

Carbon steel exposed to water + $CO_2/H_2S/O_2$ in the annulus corrodes >>0.01 mm/y unless it achieves a protective layer on the surface





CP?



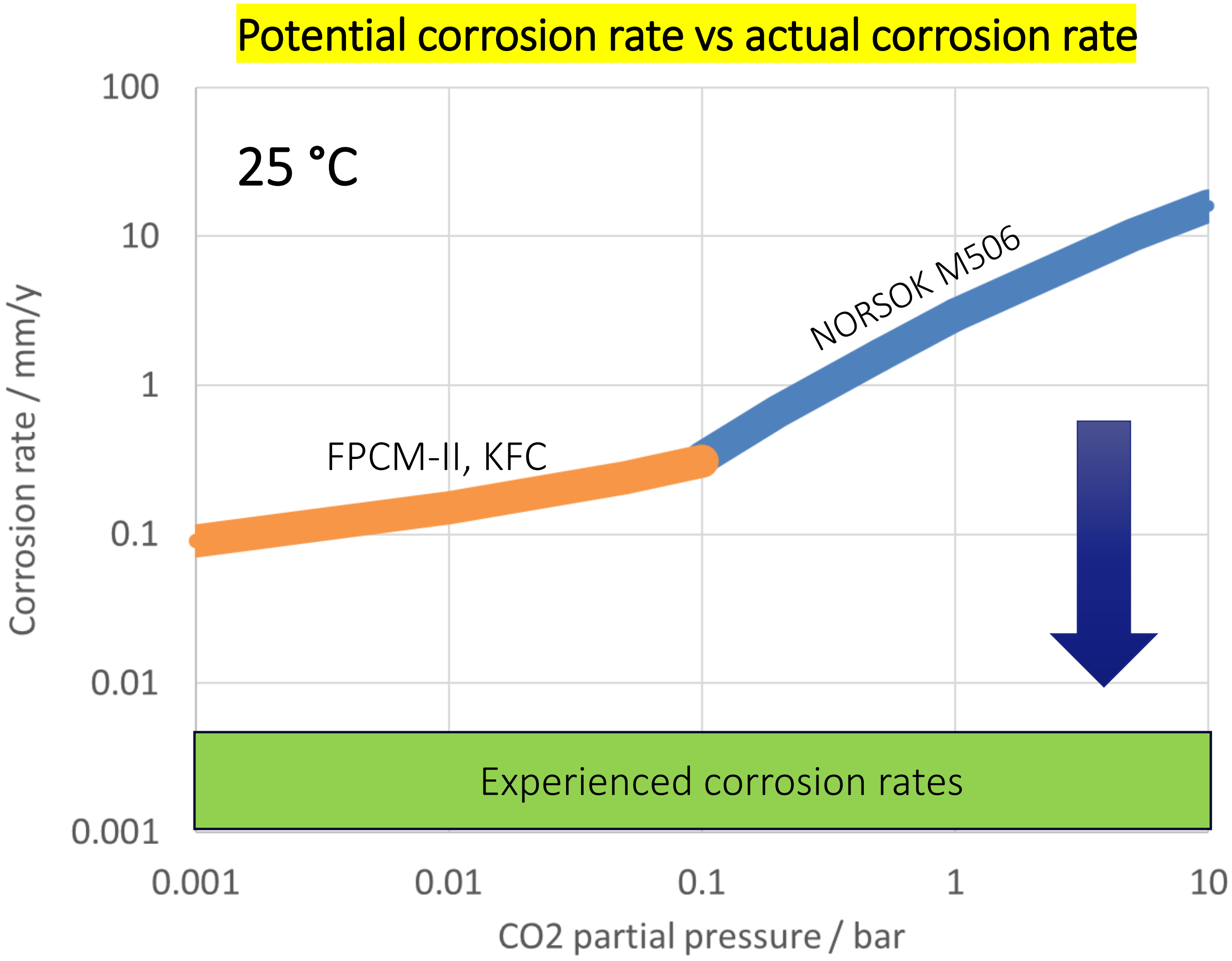
Local corrosion rates for water wet wire surfaces

Temp °C ↓	*pCO_2 →*	*<0.01*	*0.01-0.1*	*0.1-0.5*	*>0.5*	*Air (amb)*
		Corrosion rate mm/y				
< 30	High Fe^{2+}	< 0.01	< 0.01	< 0.01	< 0.01	<0.15
	Low Fe^{2+}	< 0.15	< 0.4	< 1	> 1	
	Post repair	< 0.05?	< 0.05?	< 0.05?	< 0.05?	
30-50	High Fe^{2+}	< 0.01	< 0.01	< 0.01	< 0.01	<0.20
	Low Fe^{2+}	<0.25	<0.8	<1.5	>1.5	
	Post repair	< 0.05?	< 0.05?	< 0.05?	< 0.05?	
50-70	High Fe^{2+}	< 0.01	< 0.01	< 0.01	< 0.01	<0.30
	Low Fe^{2+}	<0.25	<1	<2	>2	
	Post repair	< 0.05?	< 0.05?	< 0.05?	< 0.05?	
>70	High Fe^{2+}	< 0.01	< 0.01	< 0.01	< 0.01	<0.30
	Low Fe^{2+}	<0.25	<1.2	<2.5	>2.5	
	Post repair	< 0.05?	< 0.05?	< 0.05?	< 0.05?	

- **Green: Good experimental data which is supported by field observation/experience.**
- **Yellow: Extrapolated data from lab and field.**
- **Pink: Not much data, need to be addressed.**

S.A Løtveit, M. Eriksen, A. Dugstad, "Best Practice - Flexible Pipe Corrosion Assessment," SPT Congress 2023. Subsea Pipeline Technology

Normal situation, no outer damage, condensed water



- Potential corrosion rate, low [Fe^{2+}]

- No water
- Grease/Inhibitor covered steel surfaces
- Formation of corrosion products films
  - Confined environment-high [Fe^{2+}]

Normal situation, no outer damage, condensed water

Protective film formation dependent on pH, SR_{FeCO3} and concentration of dissolved corrosion product

(CO_2+H_2O)

$$Fe + 2H_2CO_3 \rightarrow Fe^{2+} + 2HCO_3^- + H_2$$

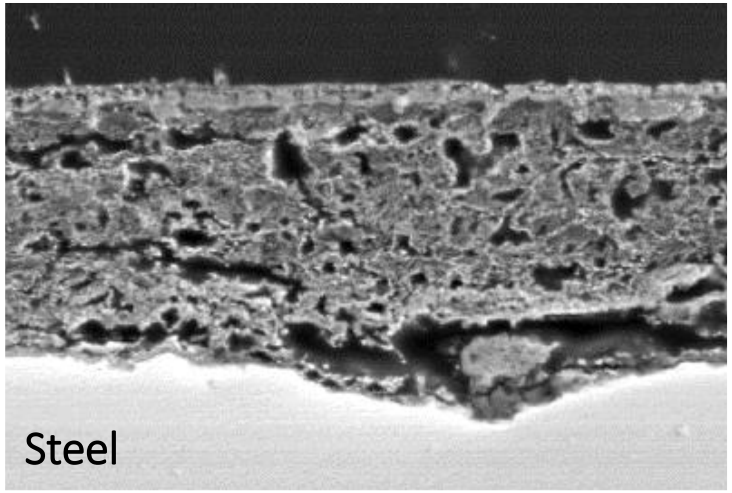
pH, SR_{FeCO3}

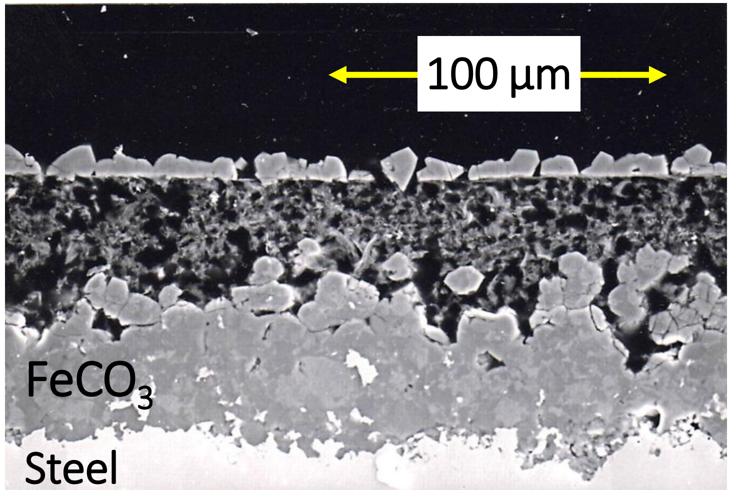
$$SR_{FeCO3} = \frac{c_{Fe^{2+}} \cdot c_{CO_3^{2-}}}{K_{sp}} > 1$$

pH, SR_{FeCO3} =100-1000

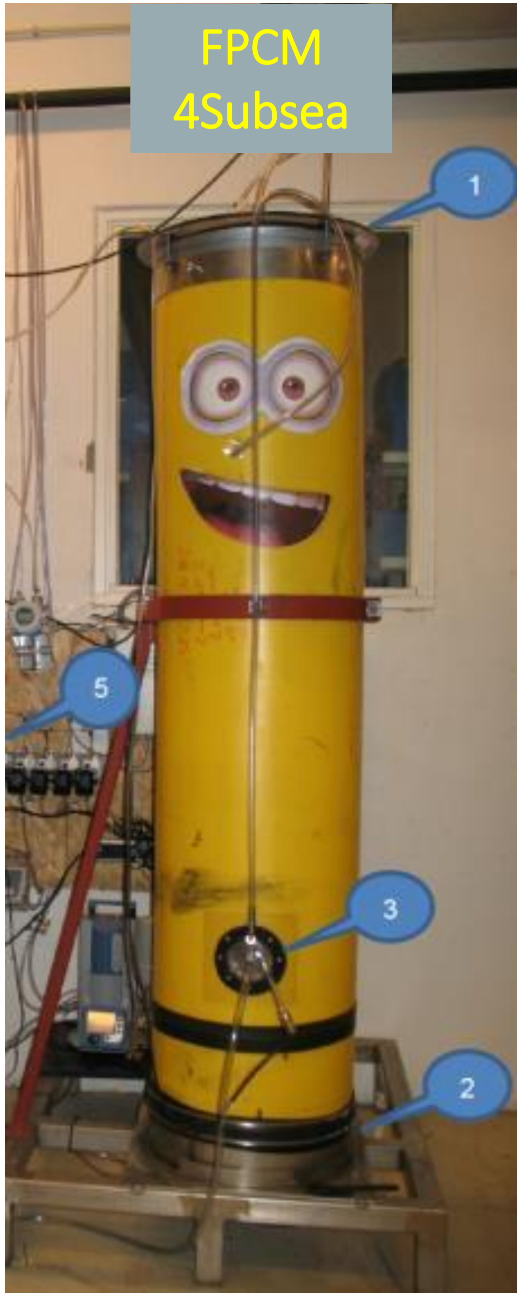
$$Fe^{2+} + CO_3^{2-} = FeCO_3(s)$$

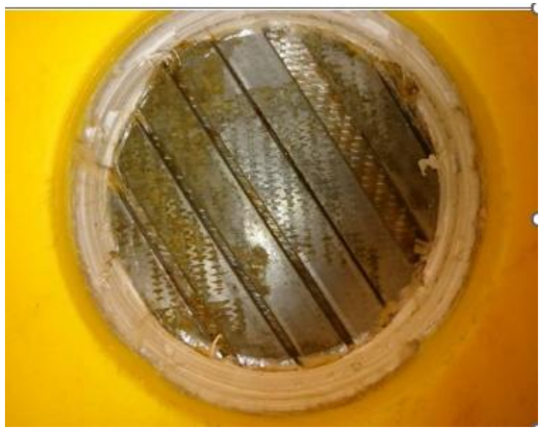
pH, SR_{FeCO3}

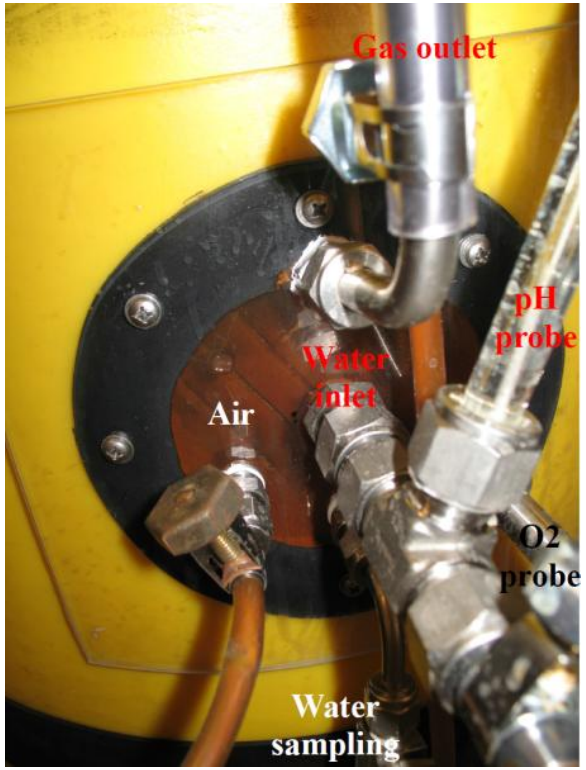




O_2 ingress- damaged outer sheath

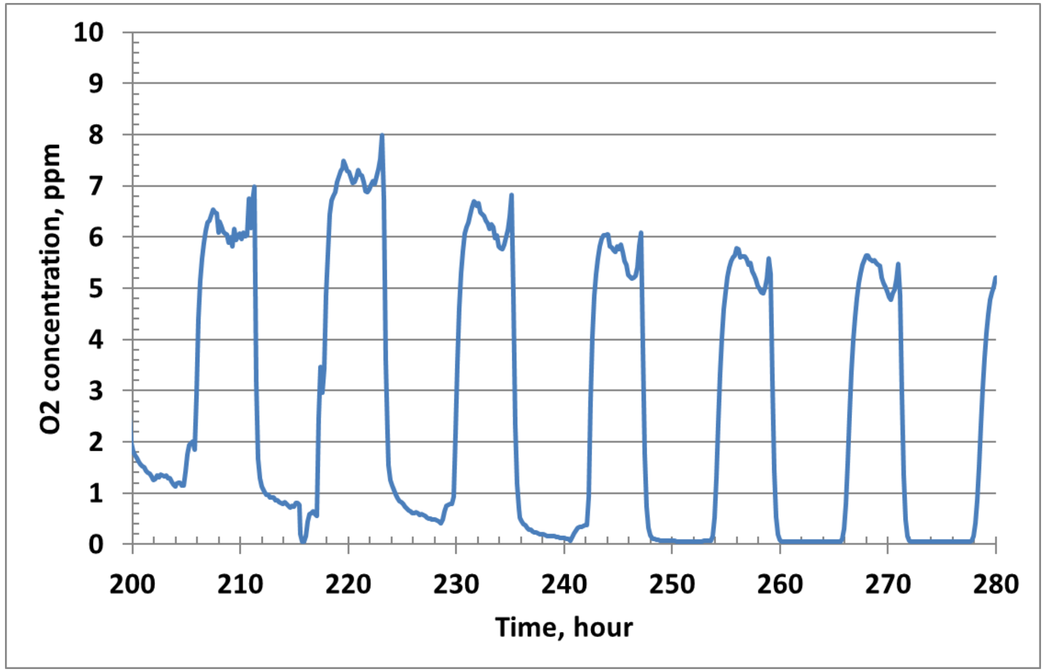






$$Fe_{stål} + \frac{1}{2}O_2 + H_2O \rightarrow Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2$$

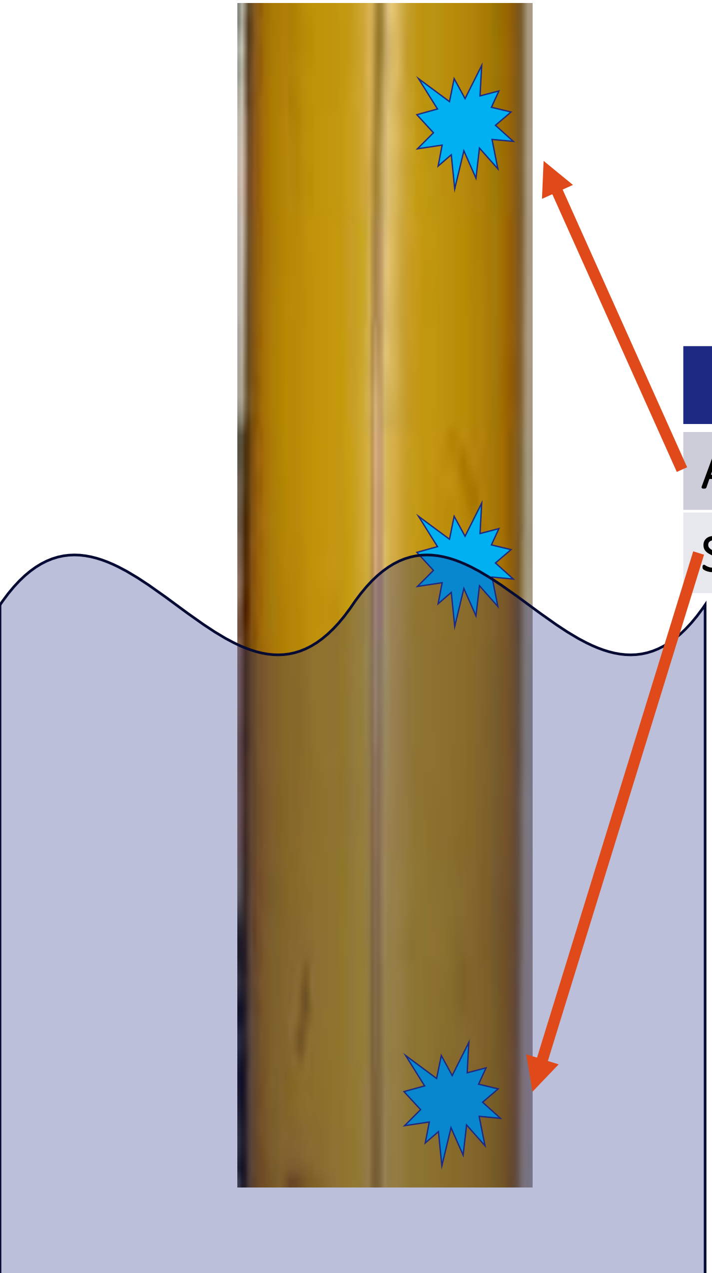
$$4Fe^{2+} + O_2 + 2H_2O \rightarrow 4Fe^{3+} + 4OH^- \rightarrow 4Fe(OH)_3$$



Corroded steel $\propto$ water volume x [Δ O_2]

O_2 ingress

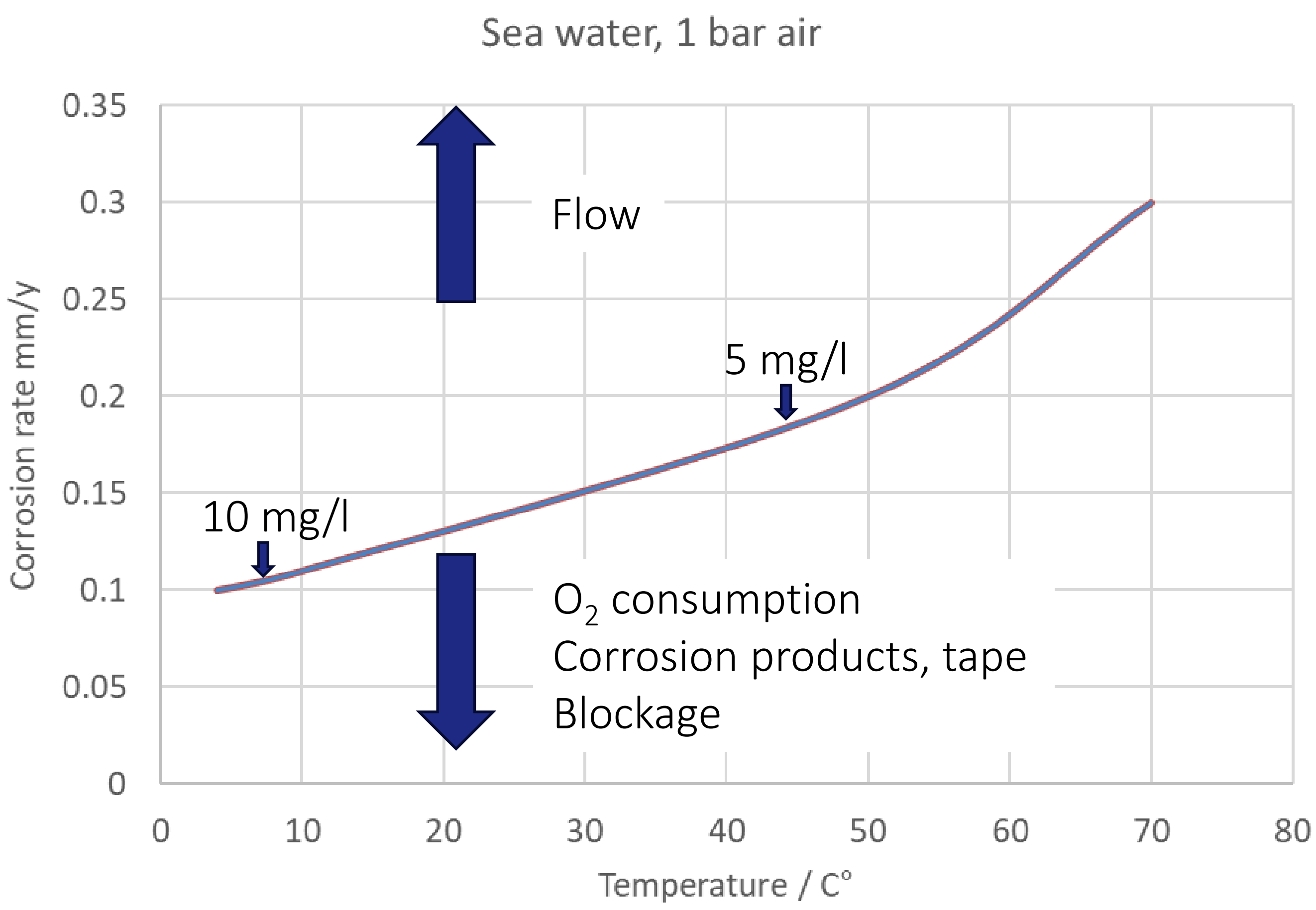
air/water pumping through vent port and damaged outer sheath



25 C	O_2, mg/l
Air	260
Sea water	8

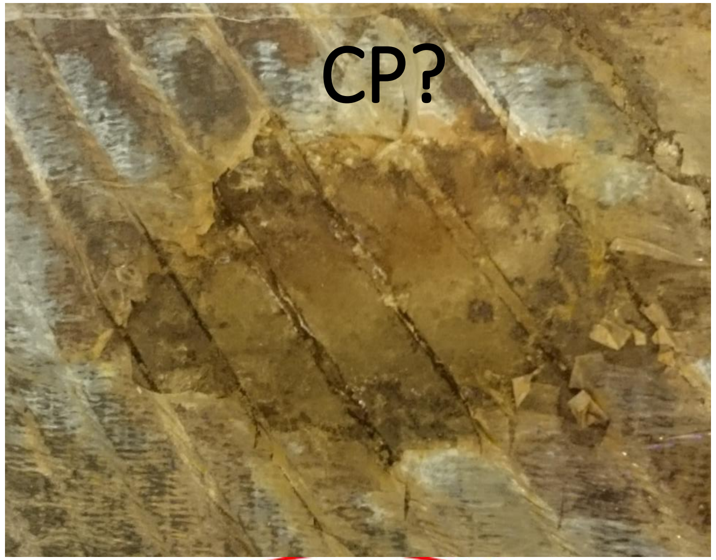
32 times more O_2 in air

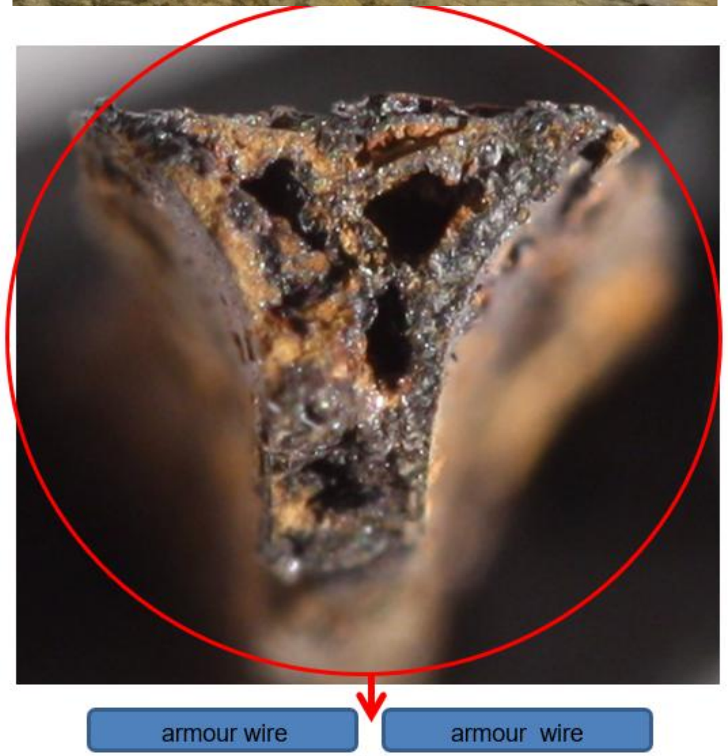
- Atmospheric pressure variation
- Tide water
- Waves
- Venting (pressure drop)
- Temperature variation
  - Shut down
- Open vent
  - Pressure variation vs dead volume vs permeation



$$Fe_{stål} + \frac{1}{2}O_2 + H_2O \rightarrow Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2$$

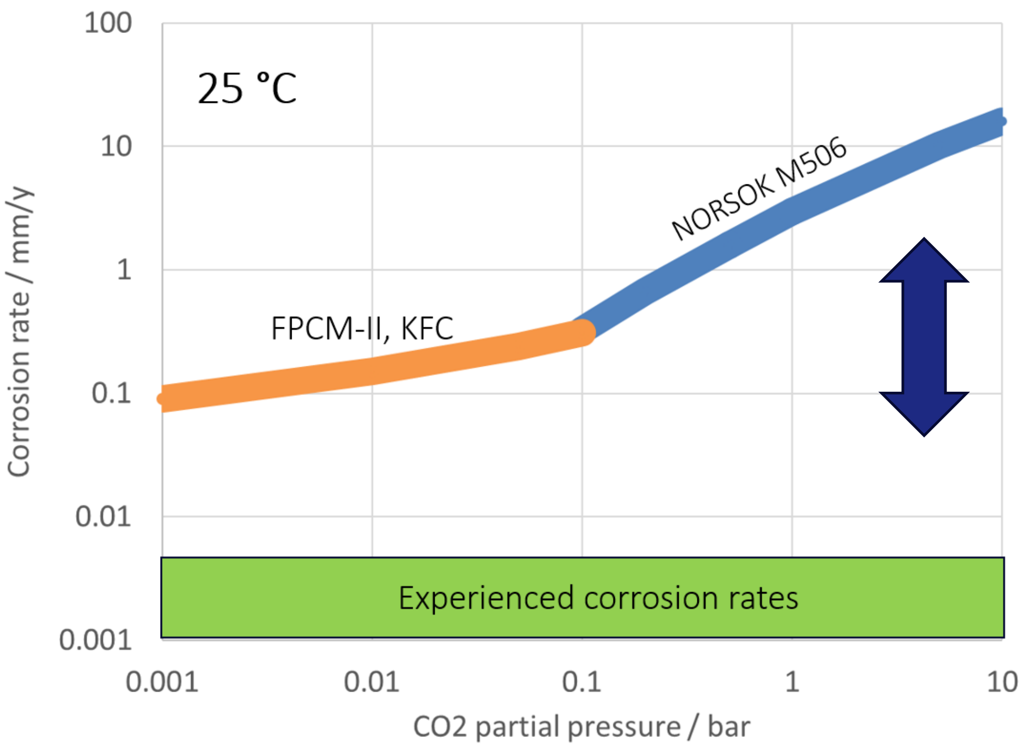
$$4Fe^{2+} + O_2 + 2H_2O \rightarrow 4Fe^{3+} + 4OH^- \rightarrow 4Fe(OH)_3$$





Low [Fe^{2+}] combined with low CO_2 (hungry water)

Temp °C ↓	*pCO_2 →*	*<0.01*	*0.01-0.1*	*0.1-0.5*	*>0.5*	*Air (amb)*
		Corrosion rate mm/y				
< 30	High Fe^{2+}	< 0.01	< 0.01	< 0.01	< 0.01	<0.15
	Low Fe^{2+}	< 0.15	< 0.4	< 1	> 1	
	Post repair	< 0.05?	< 0.05?	< 0.05?	< 0.05?	

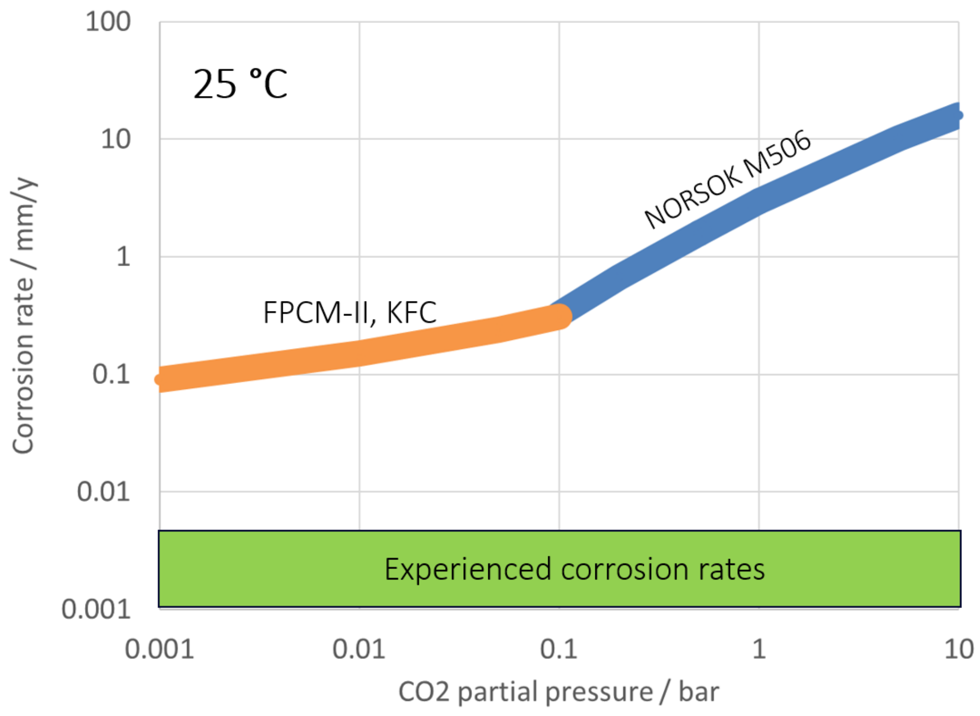


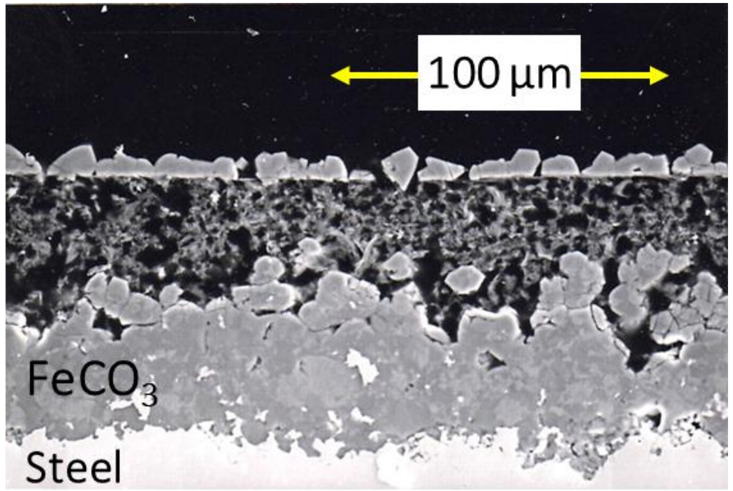
1. Backflow of condensed water from the vent system
2. Consumption of Fe^{2+}

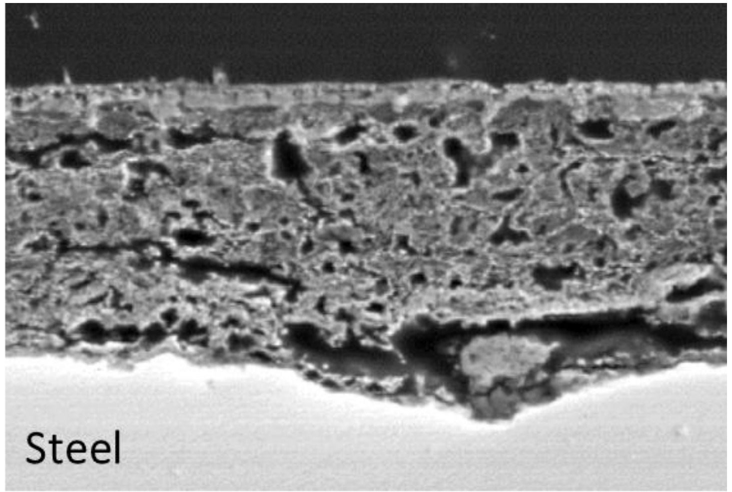
CO_2 combined with O_2

$$Fe + 2H_2CO_3 \rightarrow Fe^{2+} + 2HCO_3^- + H_2$$

$$4Fe^{2+} + O_2 + 2H_2O \rightarrow 4Fe^{3+} + 4OH^- \rightarrow 4Fe(OH)_3$$





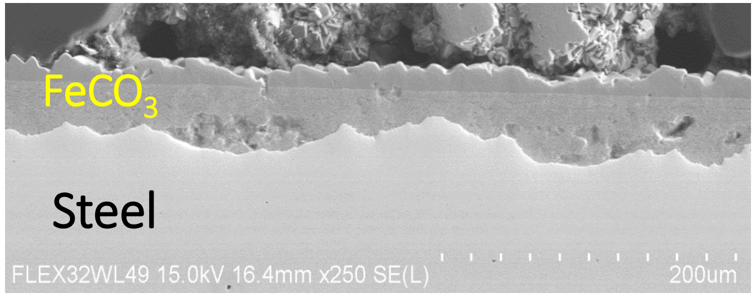


Post repair ?

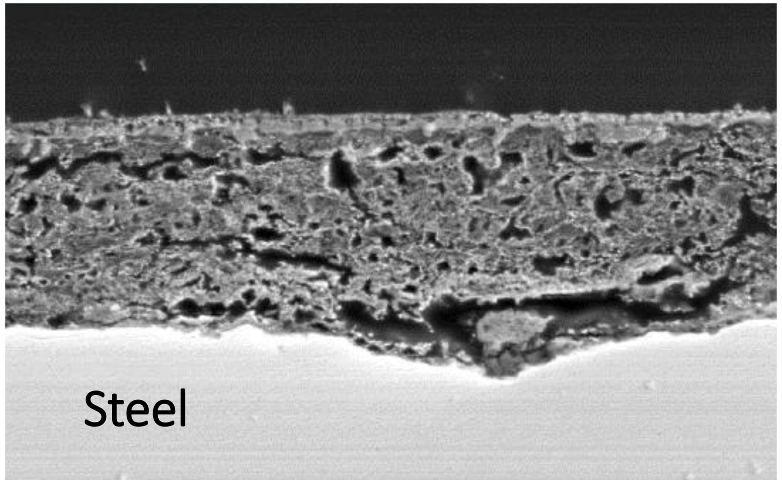
Temp °C ↓	*pCO_2 →*	*<0.01*	*0.01-0.1*	*0.1-0.5*	*>0.5*	*Air (amb)*
		Corrosion rate mm/y				
< 30	High Fe^{2+}	< 0.01	< 0.01	< 0.01	< 0.01	<0.15
	Low Fe^{2+}	< 0.15	< 0.4	< 1	> 1	
	Post repair	< 0.05?	< 0.05?	< 0.05?	< 0.05?	

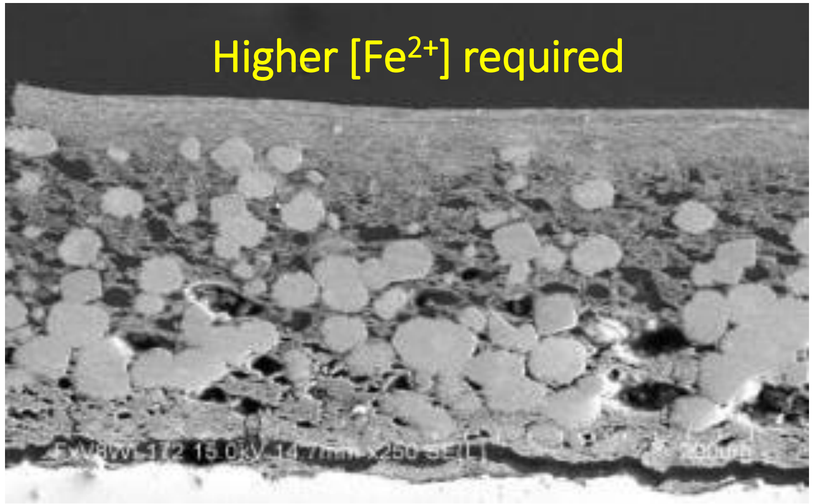
The required $[Fe^{2+}]$ to achieve and maintain protection is «history» dependent

CO_2 - exposure



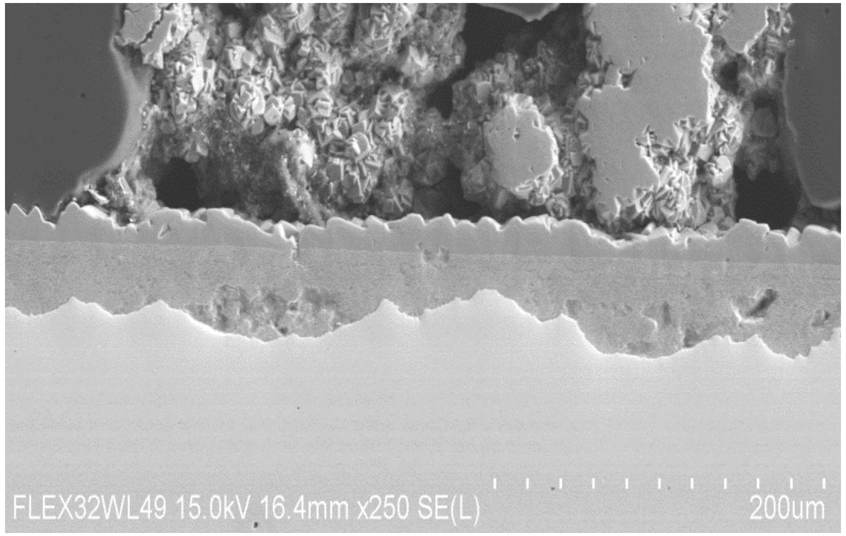
CO_2 exposure - failure/flooding – O_2 exposure – repair - CO_2 exposure

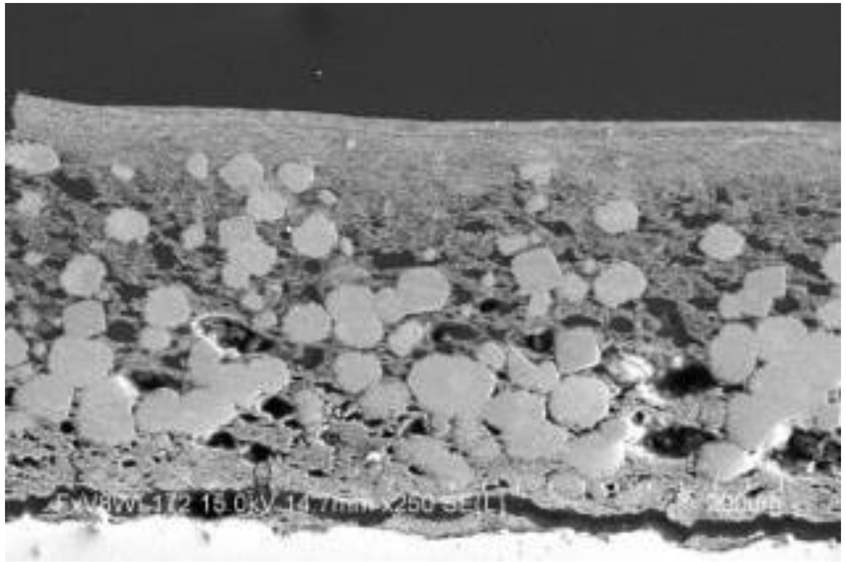


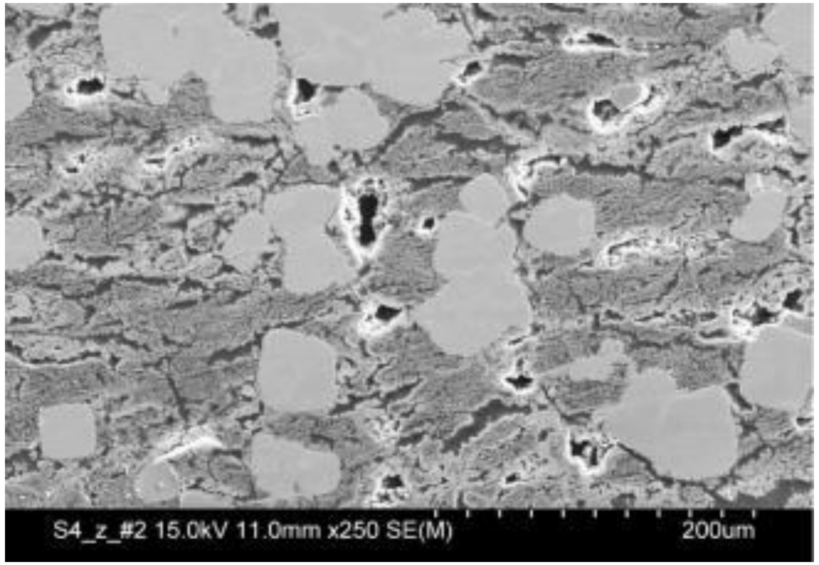


Experiments

Field case







Arne Dugstad, Simona Palencsar, Tonje Berntsen, Linda Børvik"Corrosion of Steel Armour Wires in Flexible Pipes – History Effects", Oilfield Corrosion 2018, SPE-190907-MS

A. Dugstad, S. Palencsár, G. Svenningsen, J. Muren, M. Eriksen, J. Melville, K. Sanghavi, *The combined effect of O_2 and CO_2 on corrosion of flexible armour wires,* CORROSION/2020, paper no. 14790 (NACE International, 2020)

H_2S consumption

- FeS precipitates much faster than $FeCO_3$ for a given supersaturation.
- Essentially instantaneous reaction: SR_{FeS} about 1 (?)

Consequences:

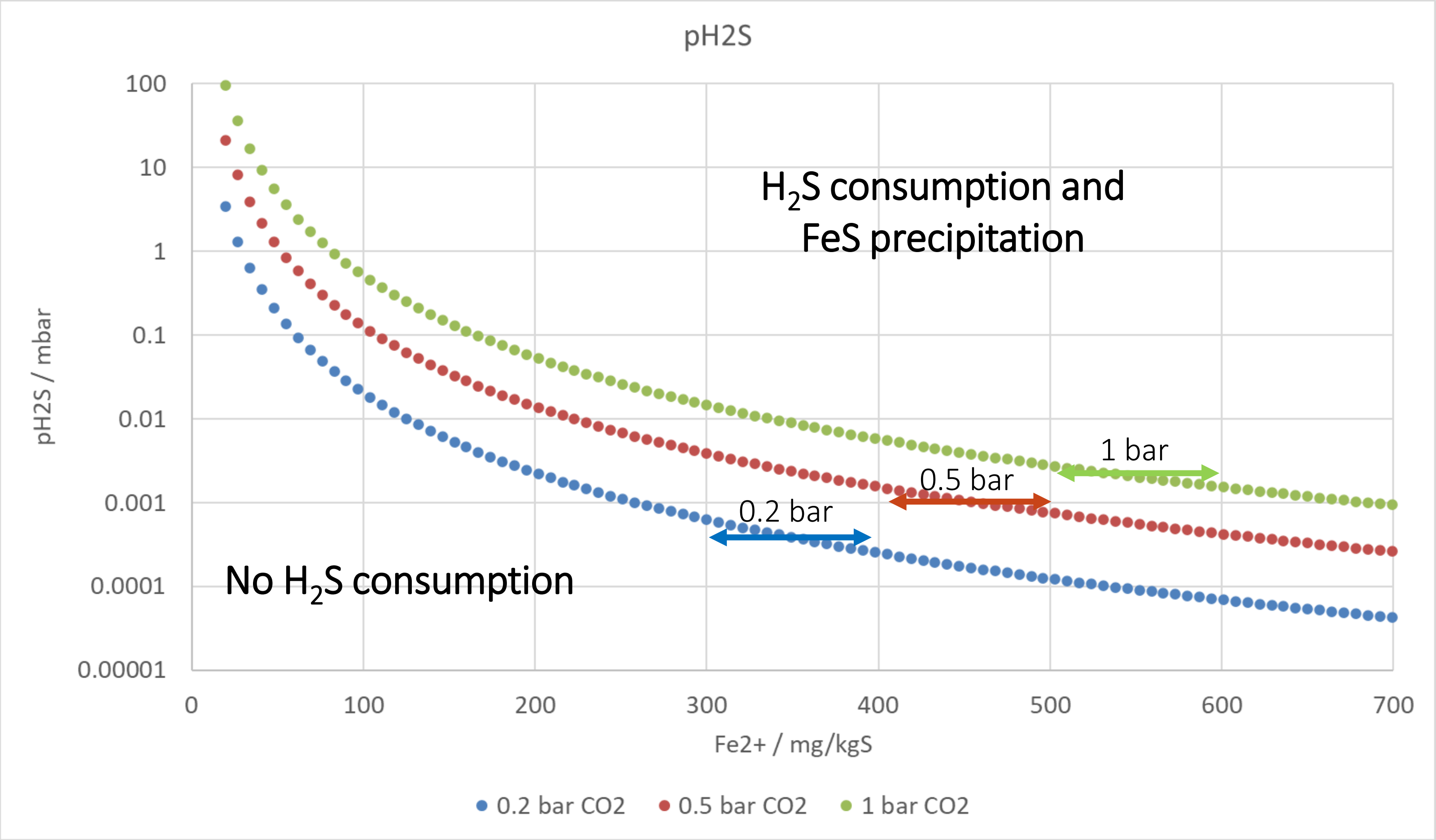
- Precipitation of FeS consumes the added H_2S
- Direct relationship between Fe^{2+} and H_2S concentration

$$Fe^{2+} + 2HS^{-} = FeS(s) + H_2S \qquad SR = \frac{C_{Fe^{2+}} \cdot (C_{HS^{-}})^2}{K_{sp}}$$

Not possible to have CO_2 controlled corrosion rate and high H_2S content at the same time!

pH_2S assuming equilibrium ($SR_{FeS} = 1$)

Temp, pCO2, type of water, Fe^{2+} precipitated, Fe^{2+} produced



Summary

- Most flexibles perform as expected, i.e. corrosion rates < 0.01 mm/y, no cracking
- Air ingress, damaged outer sheath and sea water flooding are challenging
  - Oxygen ingress destabilize protective $FeCO_3$ films and gives higher corrosion rates and pitting
- What is the corrosion rate after repair (history effect)?
- H_2S consumption expected. Very fast precipitation of FeS
- CO_2 consumption reduces the potential corrosion rate
- CO_2SCC cracking (a new failure mode Brazil 2016) and Fatigue
  - **Residual stress**, surface history/microstructure, steel type and annulus chemistry important
- The annulus chemistry is complex, like a clockwork depending on a large number of time dependent parameters

Issues for new IFE JIP KFC-II

Sea water ingress

O_2 ingress

Pressure

Temp

O_2