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ICorr Aberdeen Branch Welcomes

Dr Muhammad Ejaz (CEng, FIMMM, MICorr)

With inputs from

Dr Ed Whyte

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PLANT INTEGRITY MANAGEMENT LTD

PIM WAS ESTABLISHED IN 2011 TO PROVIDE CONSULTANCY AND STRATEGIC MANAGEMENT SUPPORT FOR THEIR CLIENTS - HELPING THEM MANAGE THE FUNCTION AND INTEGRITY OF THEIR CRITICAL PLANT AND EQUIPMENT.

WHAT WE DO: STRATEGIC MANAGEMENT OF INTEGRITY AND THE PROVISION OF OPERATIONAL SUPPORT

WHERE WE ARE: UK, KSA, MALAYSIA

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Muhammad Ejaz

BSc, metallurgical engineering degree, Pakistan
MSc, Materials degree, South Korea
PhD, Corrosion and Protection, the University of Manchester

2010 – 2014 CAN Offshore / ENGTEQ
2014 – 2017 LR Senergy / LR
2017 – To date Plant Integrity management

CEng FIMMM, MICorr, MIEP

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Corrosion Rate Modelling and Monitoring

Introduction

CO_2 Modelling software

How to use calculated corrosion rate

Online Monitoring

What to *Expect* out of monitoring data

How to *Use* monitoring data

Introduction

PART 1 - Corrosion Modelling - complete life cycle of the plant

- **Design of new facilities**
  - Materials Selection (C-steel vs CRA)
  - Corrosion barrier (Inhibition, coating, CP etc.) requirements
- **Integrity Management**
  - React to change in process conditions
  - New facility tie-in

PART 2 - Monitoring *(Indirect estimate of corrosion through inserted probes/coupons)* observe if predicted corrosion rates are valid.

Scope and Objectives

This presentation covers

- Carbon steel - *not* Corrosion Resistant Alloys
- Linear corrosion mechanism (general corrosion) – *not* cracking

- Objective is to:
  - Provide an overview of corrosion modelling and monitoring
  - Avoid black box approach – “Computer says…..”
  - Use engineering judgment with numbers (modelling/monitoring)
  - Understand limitation of modelling / monitoring

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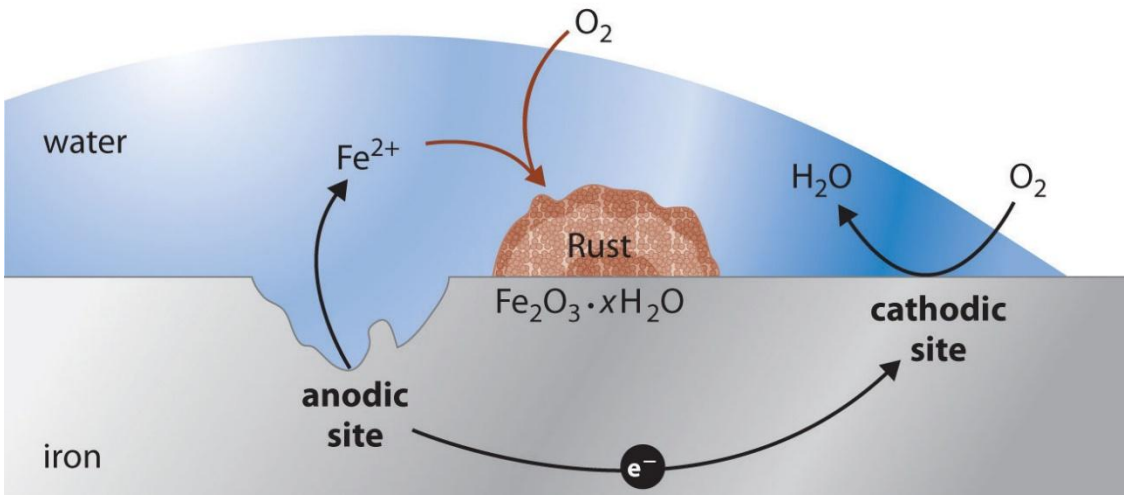
PART 1 - CORROSION RATE MODELLING

Corrosion Modelling for Oil and Gas

- **CO_2 Corrosion**
- ***O_2 Corrosion***
- ***H_2S Corrosion***



- *Anodic Reaction*

$$Fe \leftrightarrow Fe^{2+} + 2e^-$$

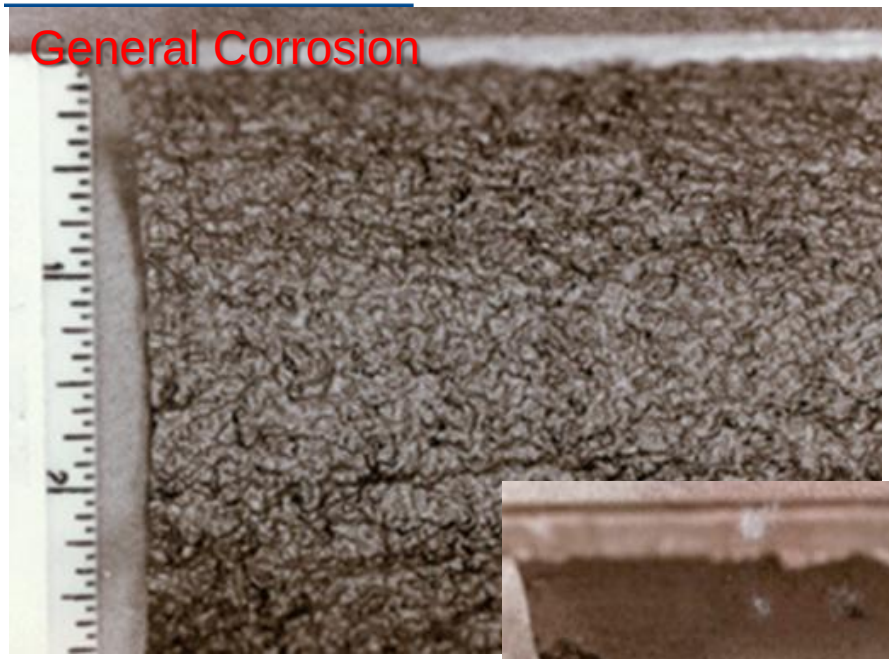
- *Cathodic Reaction(s)*

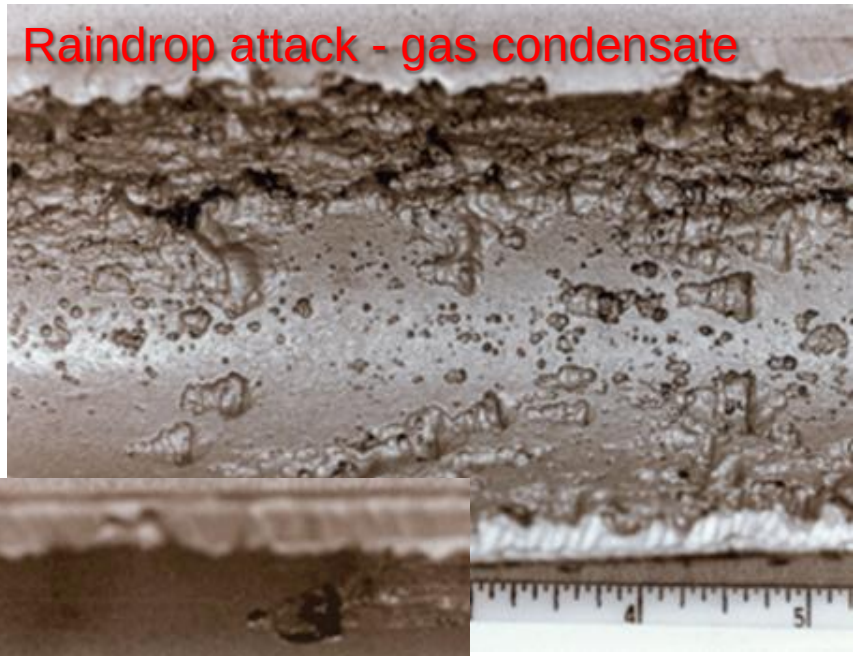
$$CO_2 + H_2O \leftrightarrow H_2CO_3 + 2e^- \leftrightarrow H_2 + CO_3^{2-} \text{ (CO_2 Corrosion)}$$

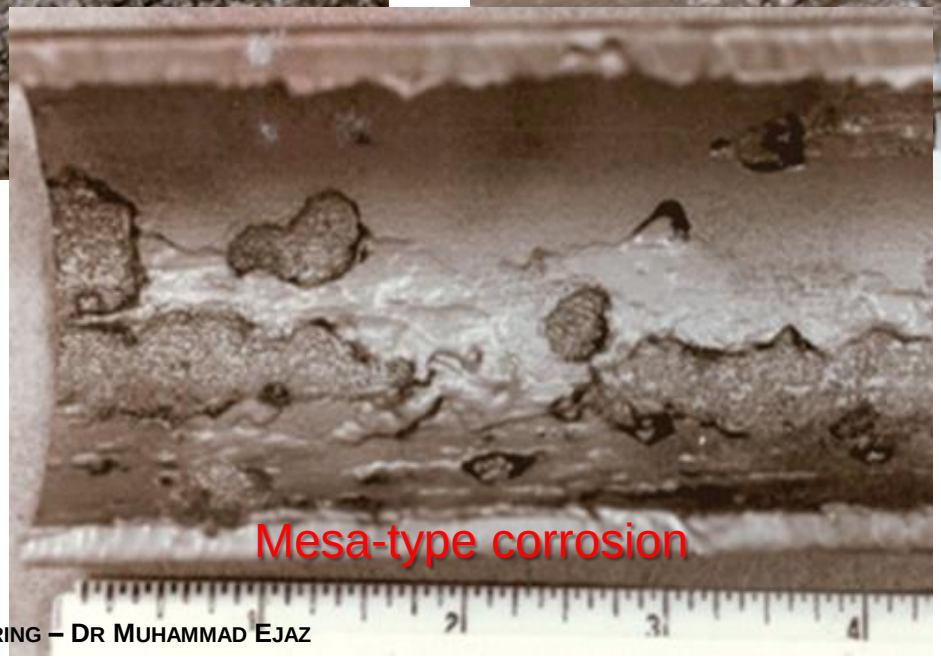
$$O_2 + 4H^+ + 4e^- \leftrightarrow 2H_2O \text{ (O_2 corrosion – Not covered here)}$$

$$H_2S \leftrightarrow 2H^+ + S^{2-} \text{ (H_2S Corrosion – Not covered here)}$$

CO_2 Corrosion







Types of Predictive Models

- **Mechanistic**

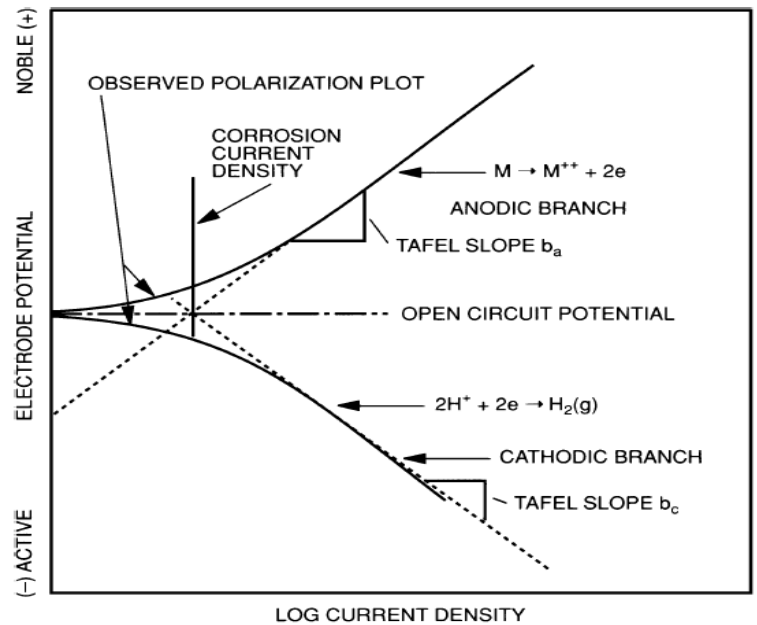
  - Formulated from quantitative knowledge of reaction *thermodynamic* and *kinetics*

- **Empirical**

  - Formulated from array of *experimental measurements*

- **Semi-empirical**

  - *Mix of Above*



Pioneering Work

De Waard and Milliams (Carbonic Acid Corrosion of Steel,1975)

$$\log V_{corr} = 5.8 - (1710 / (273 + T)) + 0.67 \log (P_{CO_2})$$

where

V_{corr} is corrosion rate
T is Temperature, and
P_{CO_2} is partial pressure of CO_2

(cathode reaction: H_2CO_3 reduction)

Partial pressure of a gas

- Partial pressure quantifies gas dissolved in water at equilibrium

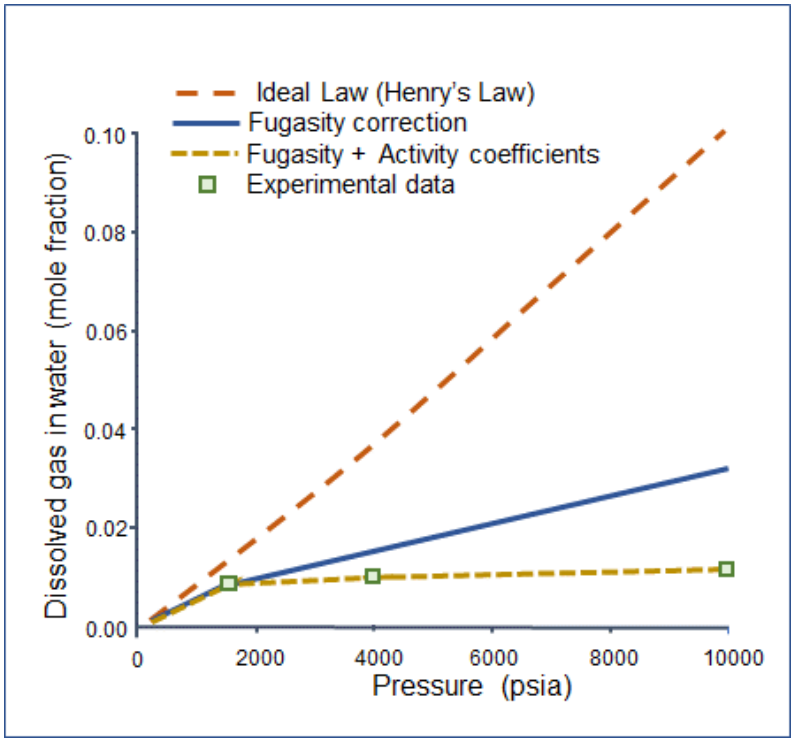
  - *Total pressure * Mole fraction in gas*

For example:
For 0.1% CO_2 in gas at pressure of 10 bara

$$P_{CO_2} = 10 * 0.1 = 1 \text{ bara}$$

- Ideal gas – Henry's law

- Fugacity correction

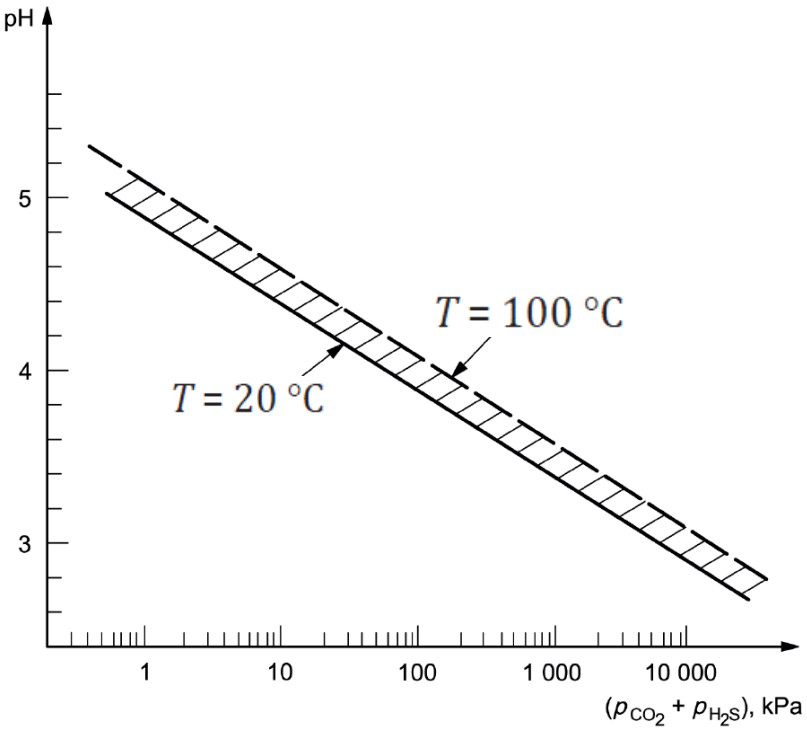


Effect of acid gases on pH

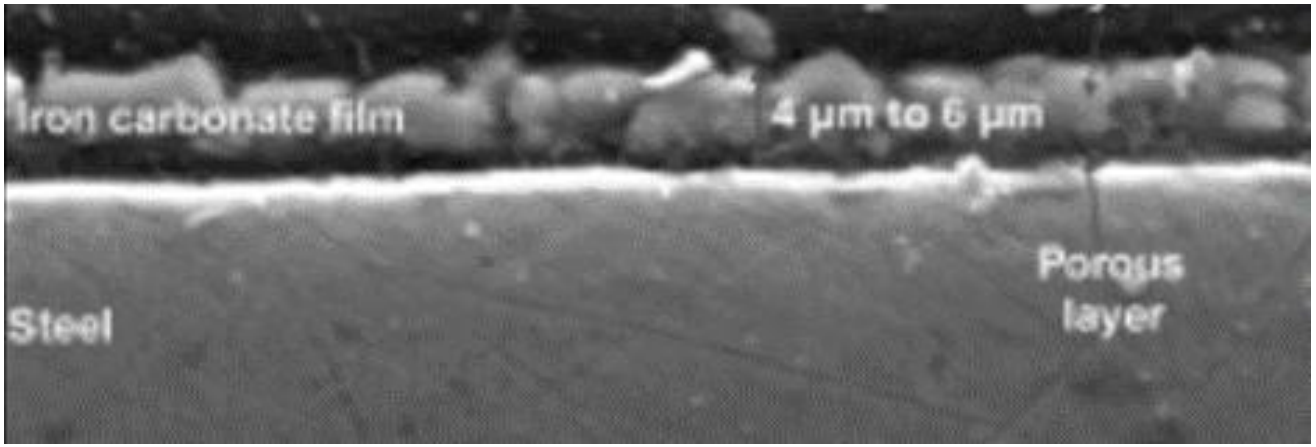
- pH is function of
  - Partial pressure of acid gases
  - Temperature
  - Organic acid (Acetates)
  - Formation water chemistry

e.g., bicarbonate ion (HCO_3^-)

  - Formation water >~ 4.5
  - Condensed water >= 3.5



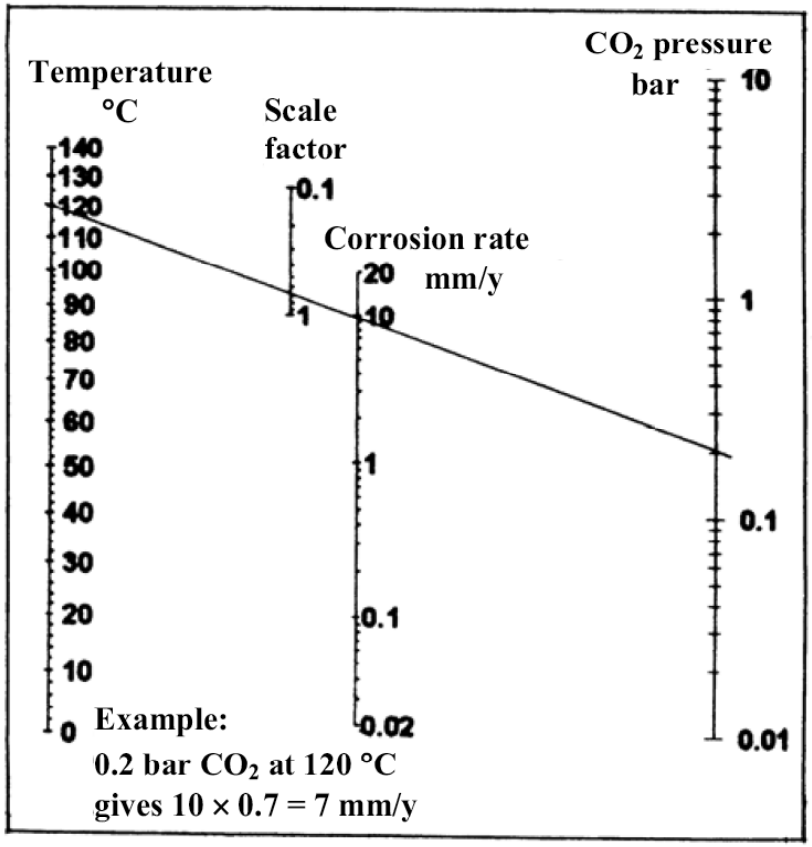
Temperature – scale formation



- About 60 - 70°C carbonate scale start forming on carbon steel surface

$$Fe + H_2O + CO_2 \leftrightarrow FeCO_3 \text{ (Siderite)} + H_2$$

De Waard & Milliams Nomogram



P_{CO2} (bar)	Temp (°C)	CR_{free} (mm/year)	Scale factor	CR_{scale} (mm/year)
1	20	1	-	1
1	40	2	-	2
1	60	5	-	5
1	80	9	-	9
1	100	16	0.5	8
1	120	30	0.2	6

$$CR_{scale} = CR_{free} \times SF$$

Development of Predictive Model Software

- pH
- Scale
- Steel composition
- Glycol %
- Inhibition
- CP
- Organic acids

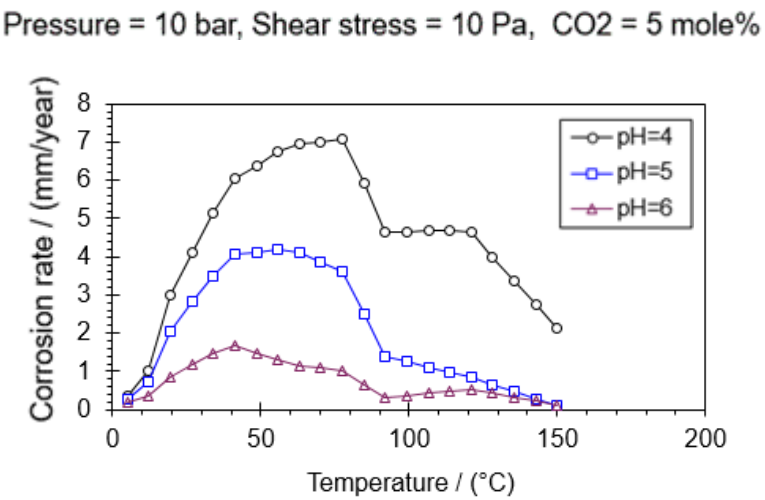
- de Waard et al (Shell)
- NORSOK model (Statoil, Saga, Hydro)
- HYDROCOR (Shell)
- Cassandra (BP)
- CORMED (Elf)
- LIPUCOR (Total)
- CORPLUS (Total)
- KSC Model (IFE)
- ECE model (Intetech)
- SweetCor (Shell)
- OLI model (OLI Systems)
- PREDICT (InterCorr)
- Tulsa model (University of Tulsa)
- Jepson model (University of Ohio)
- MULTICORP (University of Ohio)
- Corpos (CorrOcean)
- ULL model (University of Louisiana at Lafayette)
- DREAM (Oklahoma State University)

NORSOK M-506 (2005)

- Input

Temperature	40	°C
Pressure	10	bar
Mole percent CO2 in gas	5	mole%
Shear stress	10	Pa
pH	5	
Glycol concentration	0	%
Inhibitor efficiency	0	%

- Output



- Limitations

The model is valid for temperature 5 - 150 °C, pH 3.5 - 6.5, CO_2 partial pressure 0.1 - 10 bar and shear stress 1 - 150 Pa.
The model is not applicable when the H_2S partial pressure is higher than 0.5 bar, or when the ratio between the partial pressure of CO_2 and H_2S is less than 20.
The model can lead to underprediction of the corrosion rate when the total content of organic acids exceeds 100 ppm and the CO2 partial pressure is less than 0.5 bar.

Using Predictive model out put

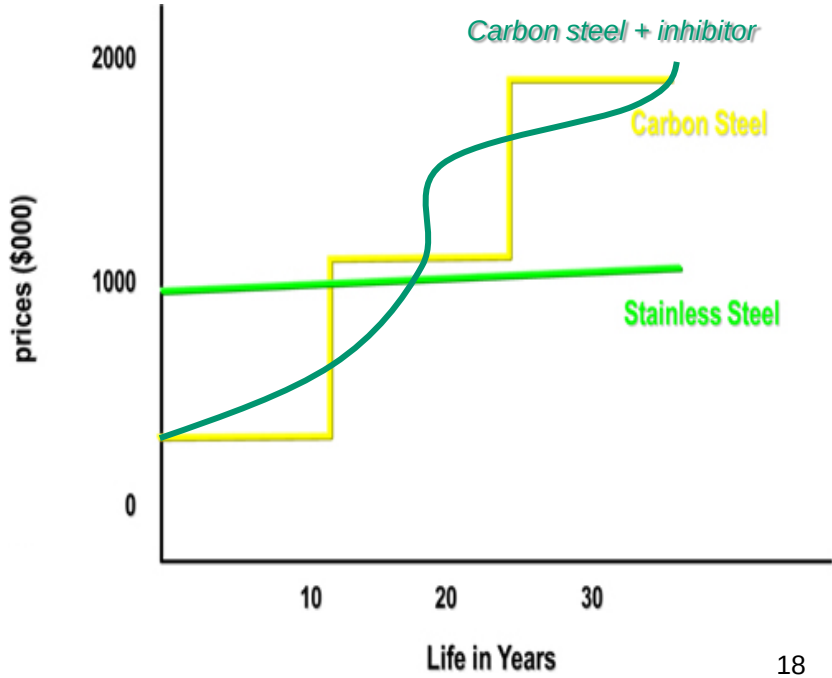
Corrosion allowance (mm)

- Calculated corrosion rate x design life

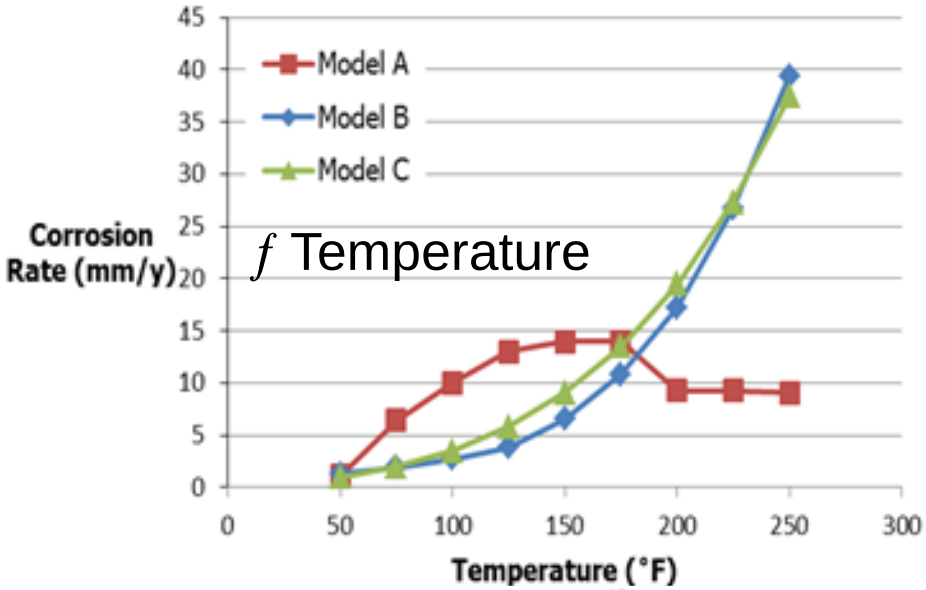
  If corrosion allowance is more than 10 mm for carbon steel – consider using corrosion resistant alloys (NORSOK M-001)

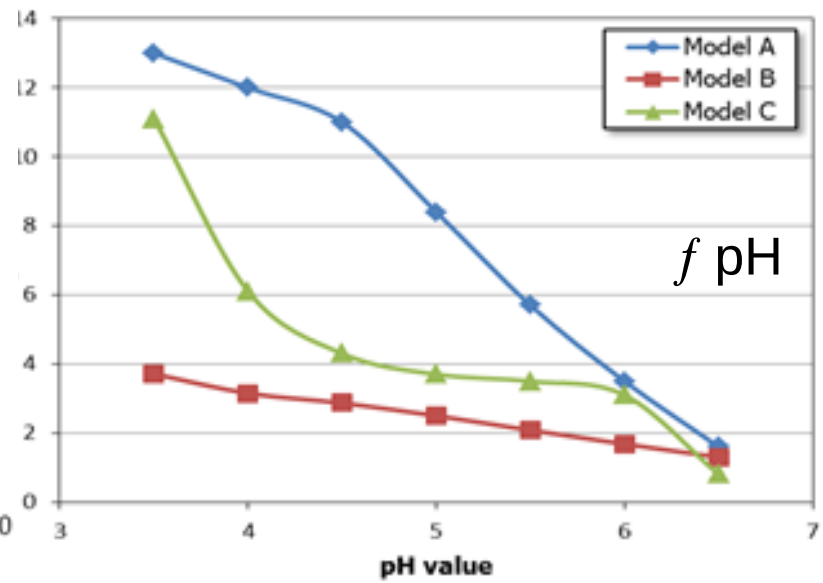
- Complete life cycle cost analysis with carbon steel + inhibition

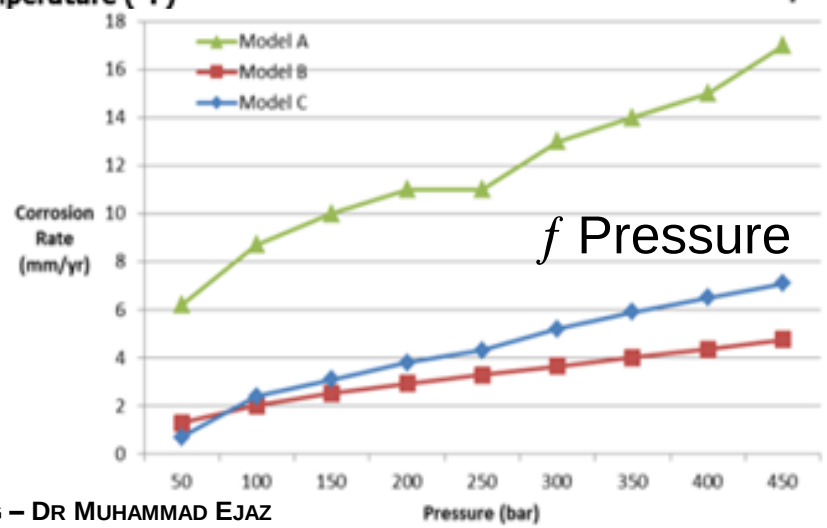
- Be aware of different corrosion rates (outputs) from different models



Comparison of Predictive models







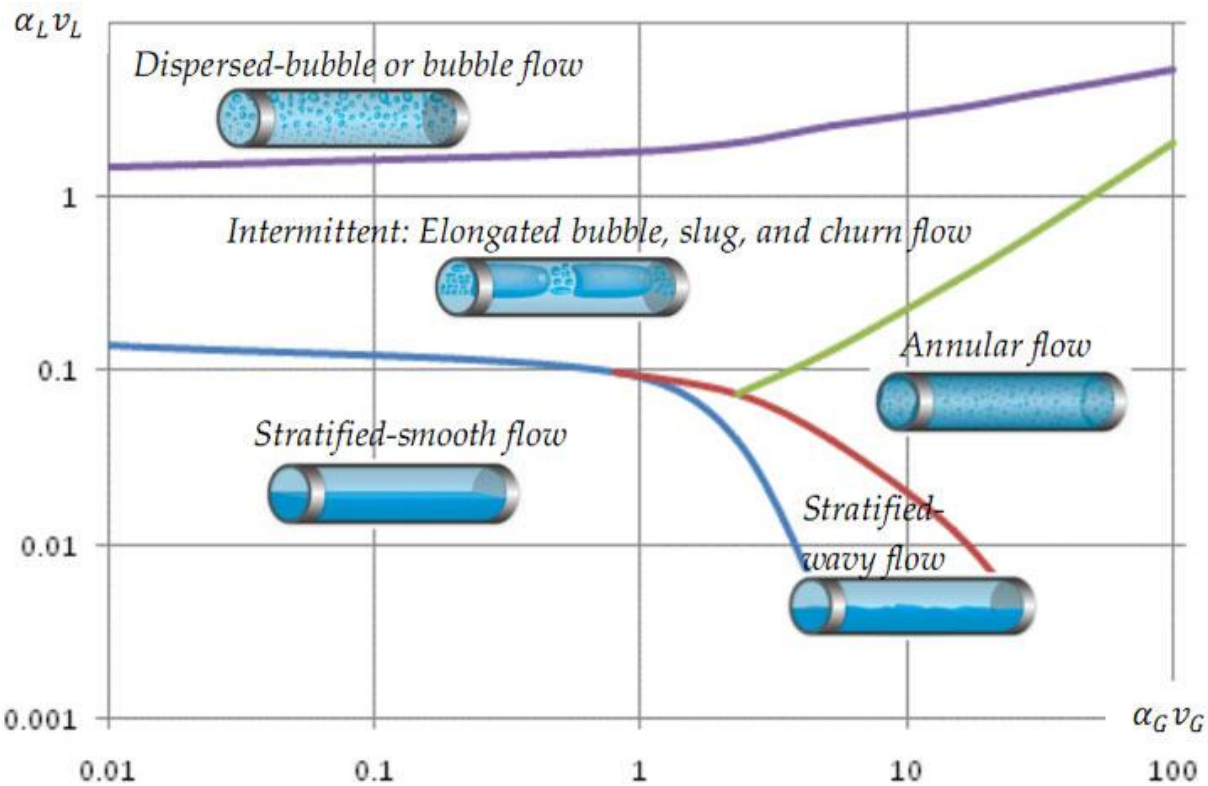
INSTITUTE OF CORROSION

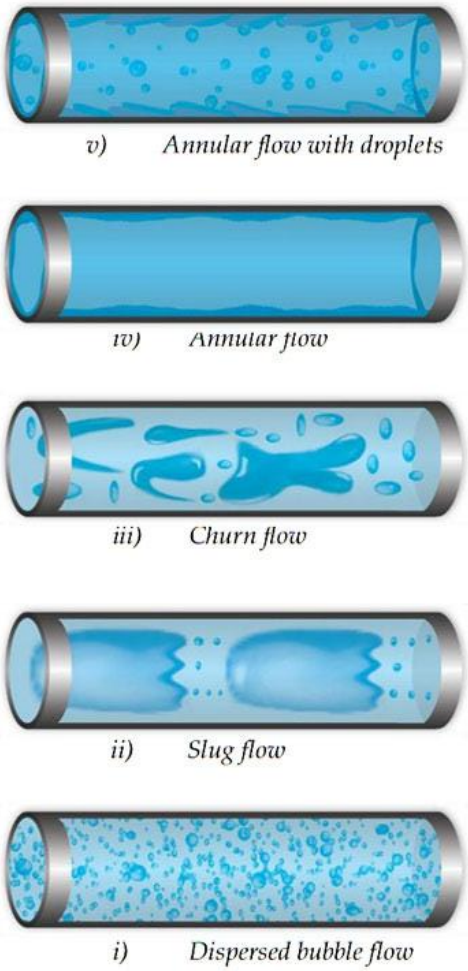
Example:

Cassandra				Norsok		ECE
Inhibited Rate mm/yr				Uninhibited	Inhibited	Inhibited
Basic		Flow-sensitive		mm/yr	mm/yr	mm/yr
BP93	DW93	BP95	DW95	M-506		
4.3	6.2	5.0	5.3		4.8	5.9
Required corrosion allowance						

Corrosion Inhibitor		95%								Pipe	OD		219.1	mm		196.5	mm ID
Design Life		15	years								WT		11.3	mm			
8" Production										Cassandra					Norsok		ECE
Year		Temperature	Pressure	Average Mol% CO_2	Mol% H_2S	Oil Flowrate	Water Flowrate	Gas Flowrate	pH	Inhibited Rate mm/yr					Uninhibited	Inhibited	Inhibited
		°C	bara			m3opd	m3wpd	sm3/d		Basic		Flow-sensitive			mm/yr	mm/yr	mm/yr
									PHACT	BP93	DW93	BP95	DW95		M-506		
1	1	67	73	6.50	0	2584	79	113267	4.4	0.8	1.2	0.9	1.0		20	1.1	0.1
1	11	67	73	0.89	0	2584	79	113267	5.3	0.2	0.3	0.2	0.2		2.7	0.2	0.01
2	1	67	73	6.50	0	3483	228	339802	4.4	0.8	1.2	1.2	1.4		23	1.2	0.3
2	11	67	73	0.89	0	3483	228	339802	5.3	0.2	0.3	0.3	0.3		3	0.2	0.1
3	1	67	73	6.50	0	1048	1984	339802	4.4	0.8	1.2	1.2	1.3		22	1.2	1.8
3	11	67	73	0.89	0	1048	1984	339802	5.3	0.2	0.3	0.3	0.3		3	0.2	0.4
4	1	67	73	6.50	0	911	2411	339802	4.4	0.8	1.2	1.2	1.3		23	1.2	1.8
4	11	67	73	0.89	0	911	2411	339803	5.3	0.2	0.3	0.3	0.3		3	0.2	0.4
5	1	67	73	6.50	0	804	2443	339802	4.4	0.8	1.2	1.2	1.3		23	1.2	1.8
5	11	67	73	0.89	0	804	2443	339803	5.3	0.2	0.3	0.3	0.3		3	0.2	0.4
6	1	67	73	6.50	0	578	2926	311485	4.4	0.8	1.2	1.2	1.3		23	1.2	1.8
6	11	67	73	0.89	0	578	2926	311486	5.3	0.2	0.3	0.3	0.3		3	0.2	0.4
7	1	67	73	6.50	0	470	3070	311485	4.4	0.8	1.2	1.2	1.3		23	1.2	1.8
7	11	67	73	0.89	0	470	3070	311486	5.3	0.2	0.3	0.3	0.3		3	0.2	0.4
8	1	67	73	6.50	0	340	3186	283169	4.4	0.8	1.2	1.2	1.3		22	1.2	1.7
8	11	67	73	0.89	0	340	3186	283170	5.3	0.2	0.3	0.3	0.3		3	0.2	0.3
9	1	67	73	6.50	0	291	3236	254852	4.4	0.8	1.2	1.1	1.2		22	1.2	1.7
9	11	67	73	0.89	0	291	3236	254853	5.3	0.2	0.3	0.3	0.3		3	0.2	0.3
10	1	67	73	6.50	0	240	3313	169901	4.4	0.8	1.2	1.0	1.1		21	1.1	1.6
10	11	67	73	0.89	0	240	3313	169902	5.3	0.2	0.3	0.2	0.3		2.9	0.2	0.3
11	1	67	73	6.50	0	196	3294	198218	4.4	0.8	1.2	1.1	1.2		22	1.2	1.6
11	11	67	73	0.89	0	196	3294	198219	5.3	0.2	0.3	0.2	0.3		2.9	0.2	0.3
12	1	67	73	6.50	0	164	3382	198218	4.4	0.8	1.2	1.1	1.2		22	1.2	1.6
12	11	67	73	0.89	0	164	3382	198219	5.3	0.2	0.3	0.3	0.3		2.9	0.2	0.3
13	1	67	73	6.50	0	154	3404	198218	4.4	0.8	1.2	1.1	1.2		22	1.2	1.6
13	11	67	73	0.89	0	154	3404	198219	5.3	0.2	0.3	0.3	0.3		2.9	0.2	0.3
14	1	67	73	6.50	0	135	3442	198218	4.4	0.8	1.2	1.1	1.2		22	1.2	1.6
14	11	67	73	0.89	0	135	3442	198219	5.3	0.2	0.3	0.3	0.3		2.9	0.2	0.3
15	1	67	73	6.50	0	121	3472	198218	4.4	0.8	1.2	1.1	1.2		22	1.2	1.6
15	11	67	73	0.89	0	121	3473	198219	5.3	0.2	0.3	0.3	0.3		2.9	0.2	0.3
										4.3	6.2	5.0	5.3			4.8	5.9
										Required corrosion allowance							

Flow regimes in horizontal pipe





Example of steady-state flow regime map for a horizontal pipe. Superficial liquid velocity V_L *vs* superficial gas velocity V_G.

Exploiting Output – Inhibition categorisation

Category	*Maximum Required Availability*	*Maximum Expected Uninhibited Corrosion Rate (mm/yr)*	*Comment*	*Possible Category Name*
1	0%	0.4	Benign fluids where corrosion inhibitor usage is not anticipated (dry gas, stabilised oil). Predicted metal loss can be accommodated by corrosion allowance alone.	Benign
2	50%	0.7	Corrosion inhibitor will probably be required but at the expected corrosion rates there will be time to review the need for inhibition based on inspection data.	Low
3	90%	3	Corrosion inhibitor will be required for the majority of the field life but the facilities need not be available from day 1.	Medium
4	95%	6	Inhibition is relied on heavily and will be required for the lifetime of the operation. Inhibitor must be available from day 1 to ensure success of the inhibition programme.	High
5	>95%	>6	Carbon steel and inhibition is unlikely to provide integrity for the full field life. Select corrosion resistant materials or plan for repairs & replacements.	Unacceptable

B. Hedges, D. Paisley and R. Woollam, "The corrosion inhibitor availability model," in Corrosion 2000.

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PART 2 - CORROSION MONITORING

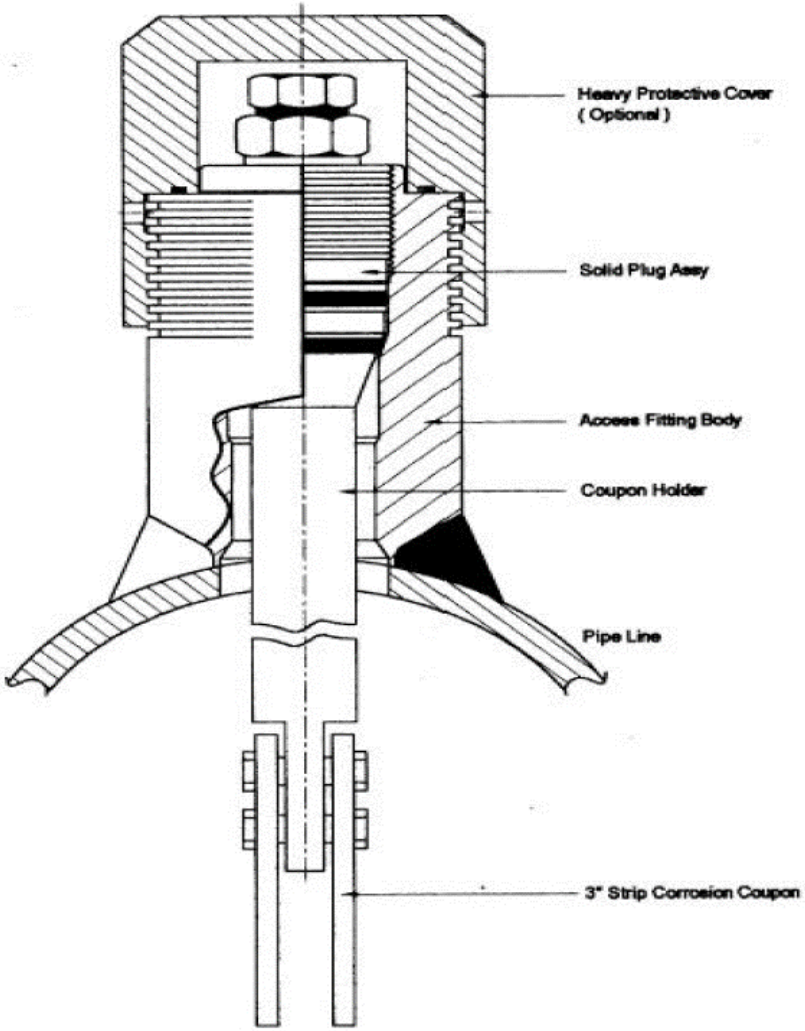
Online Corrosion monitoring

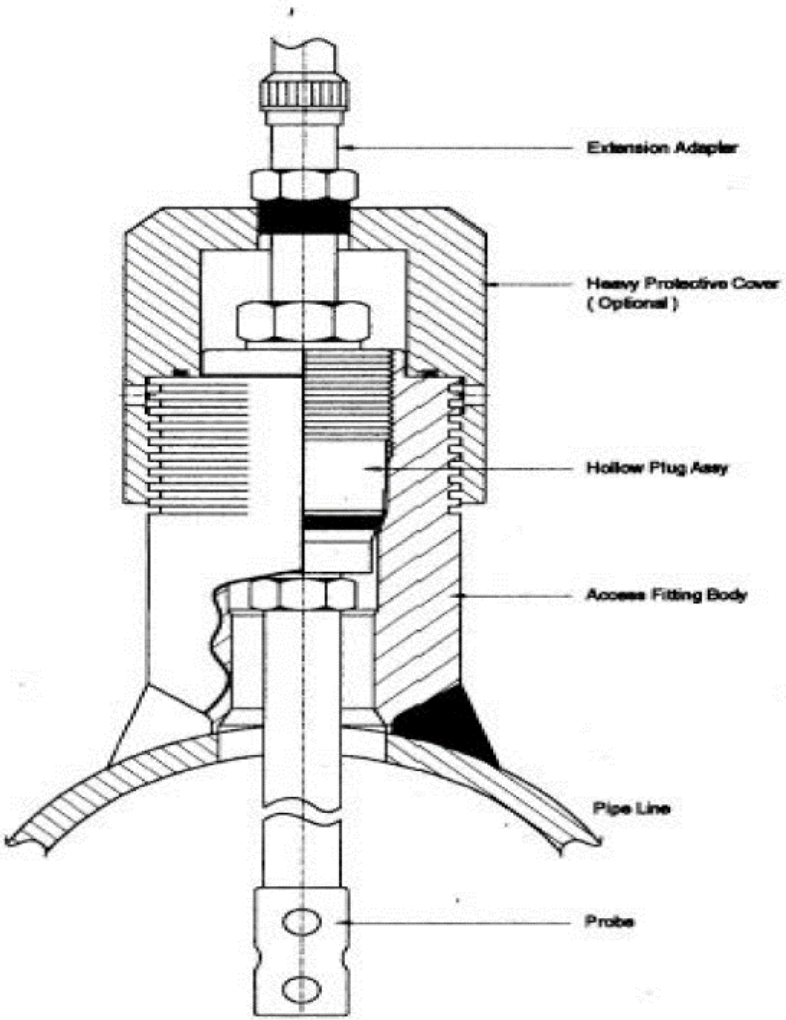
- Corrosion Coupons
- Electrical Resistance
- Linear Polarisation Resistance
- Galvanic Current
- Electrochemical Noise
- Hydrogen Permeation
- Field Signature Method
- Ring Pair Corrosion Monitoring
- Iron Counts/Chemical Analysis models

Why Monitoring

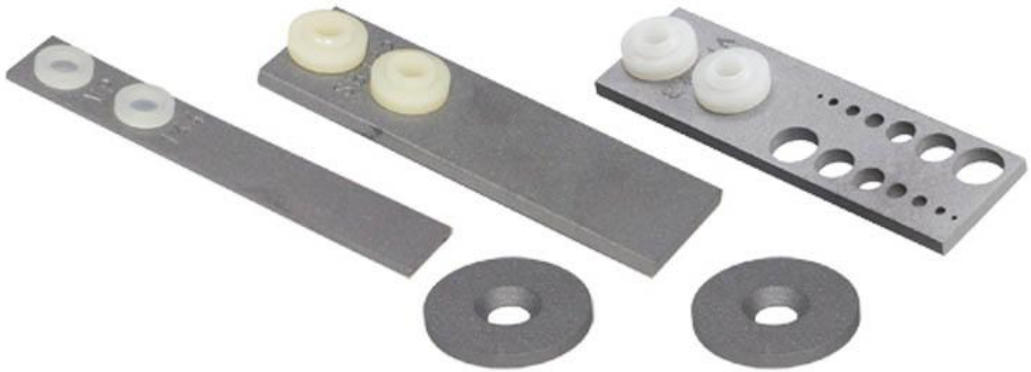
- Identify rate and type of corrosion at given location (e.g. general corrosion, localized corrosion)
- Provide assurance of chemical performance (e.g. injection rates)
- Provides an early indication of potential threat allowing proactive resolution and reduce risk of hydrocarbon release.
- Used as input into RBI assessment (IoW)
- Increase confidence in plant integrity.

Corrosion Coupon and Corrosion Probe (Typical Assembly)





Corrosion Coupons

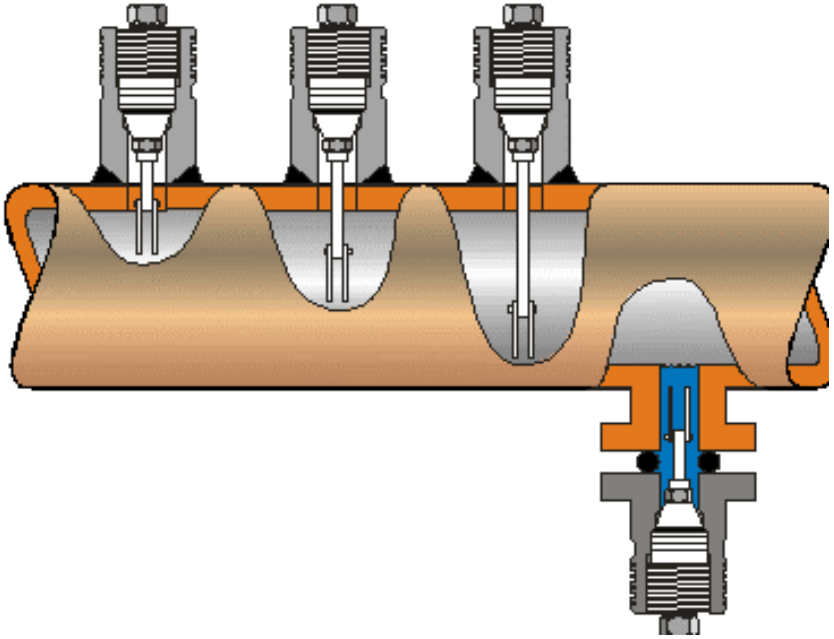


- Weight loss - average corrosion rate

$$\frac{(Initial\ wieght\ - Final\ wieght) * Unit\ factor}{Area\ *\ Density\ * Exposure\ period}$$

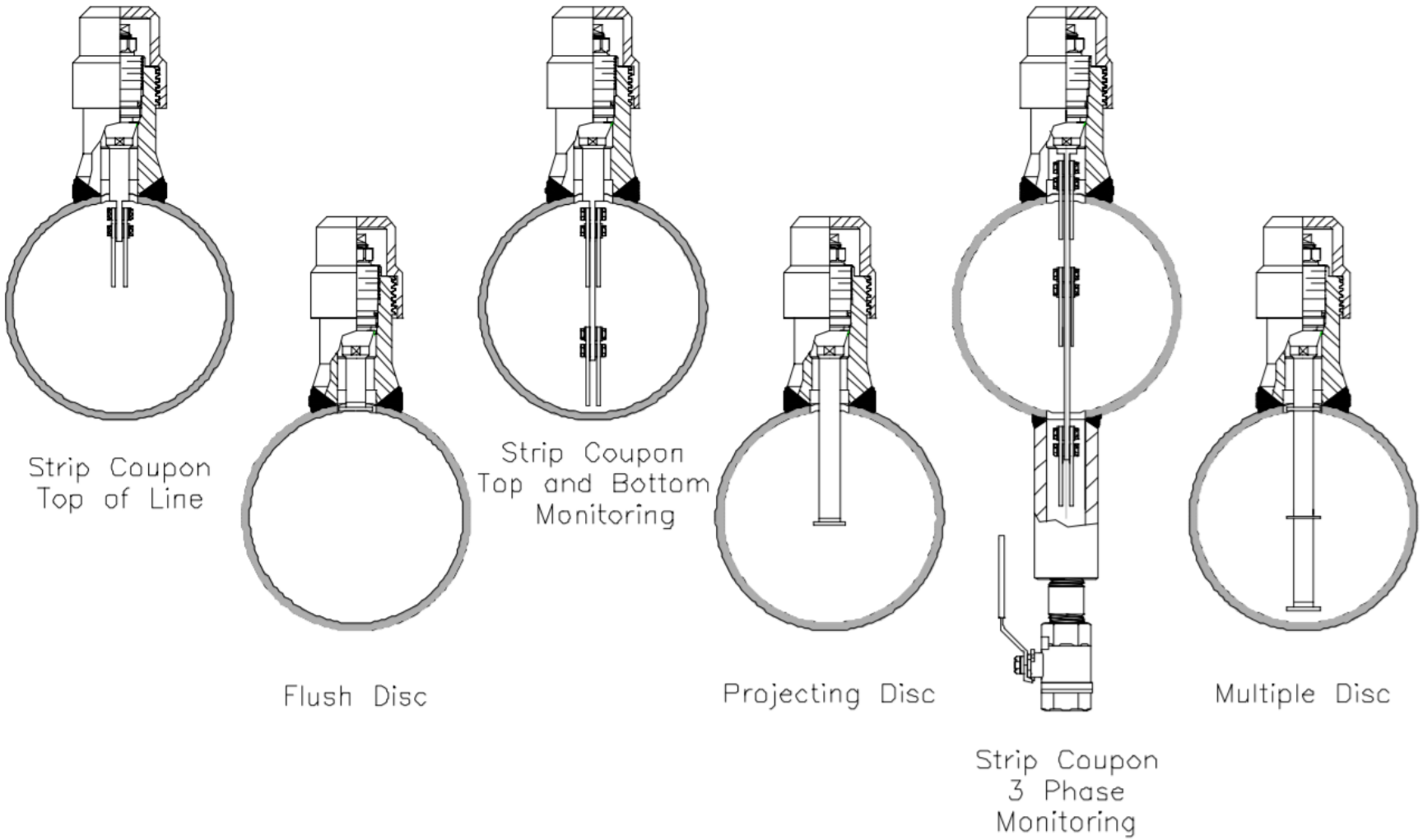
- Visual Inspection – Localised corrosion
- Microbial Sampling (Swab)

Mounting / Location

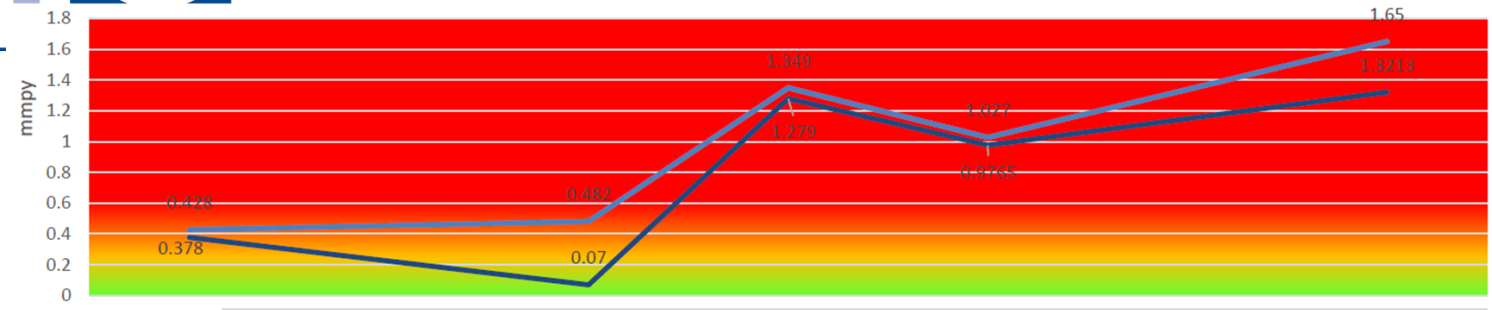


- Electrically isolated to avoid galvanic interaction
- Strip coupons usually mounted in pairs from top / side / bottom of pipe
- Flush Disc normally mounted in top/bottom of pipe

Mounting/Location Examples



Methodology - Coupons



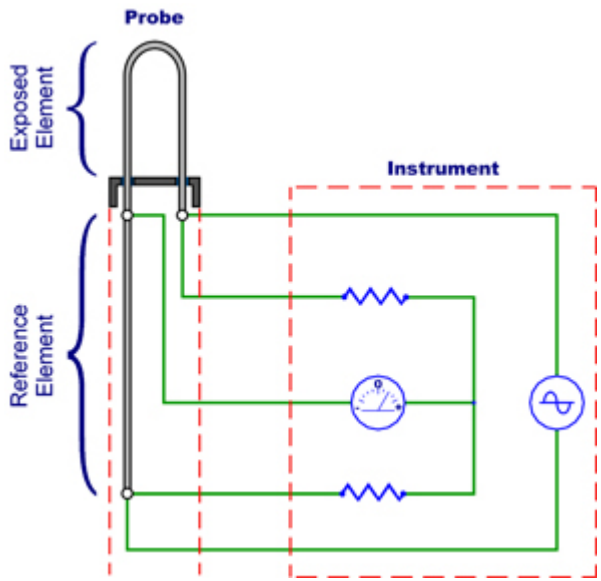
	Aug-10	Aug-12	Aug-13	Aug-14	Aug-16
CC27041 Coupon 1	0.428	0.482	1.349	1.027	1.65
CC27041 Coupon 2	0.378	0.07	1.279	0.9765	1.3213

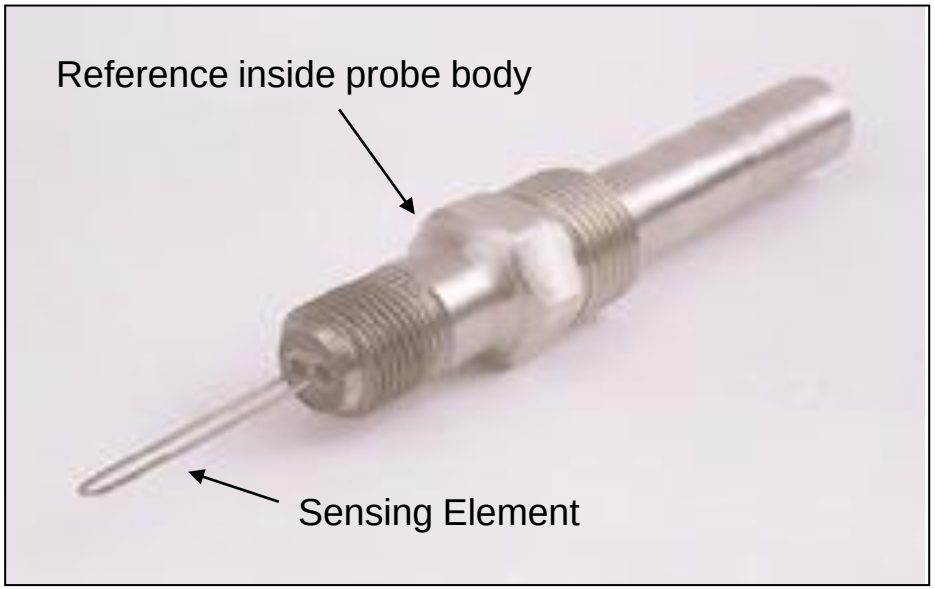
- Select appropriate material / dimensions / surface finish
- Weigh coupon
- Insert into equipment
- Retrieve after a period (e.g. 6 months) - Swab for microbial analyses
- Clean/reweigh
- Calc. CR

Coupons – Pros-Cons

Corrosion Coupons	
Advantages	Disadvantages
Simple and cheap	In very low corrosion rate conditions - insensitive - long exposure periods are required
Can be used in any environment	Can provide relatively long term data
Provide a visual indication of corrosion type as well as rate	Require laboratory stage (cleaning and weighing) before data are available
Can provide pitting rate data	Time averaging – will not tell you about corrosion rates at any specific time

Electrical Resistance (ER) Probe





- Corrosion cause reduction in cross section

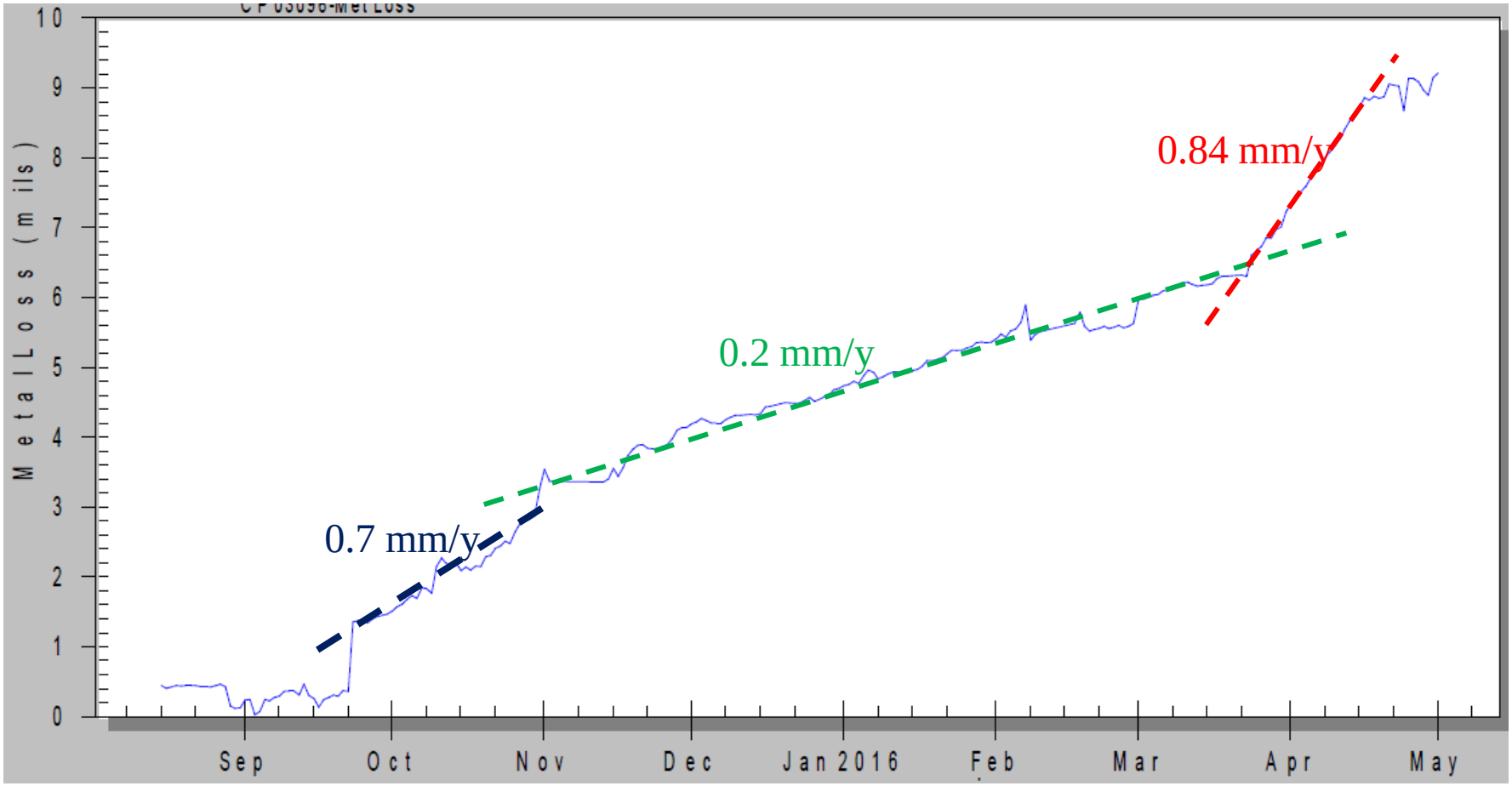
  Δ(x-sectional area) $\rightarrow$ ΔER is measured $\rightarrow$ $\propto$ corrosion rate

- Reference element eliminates temperature effects

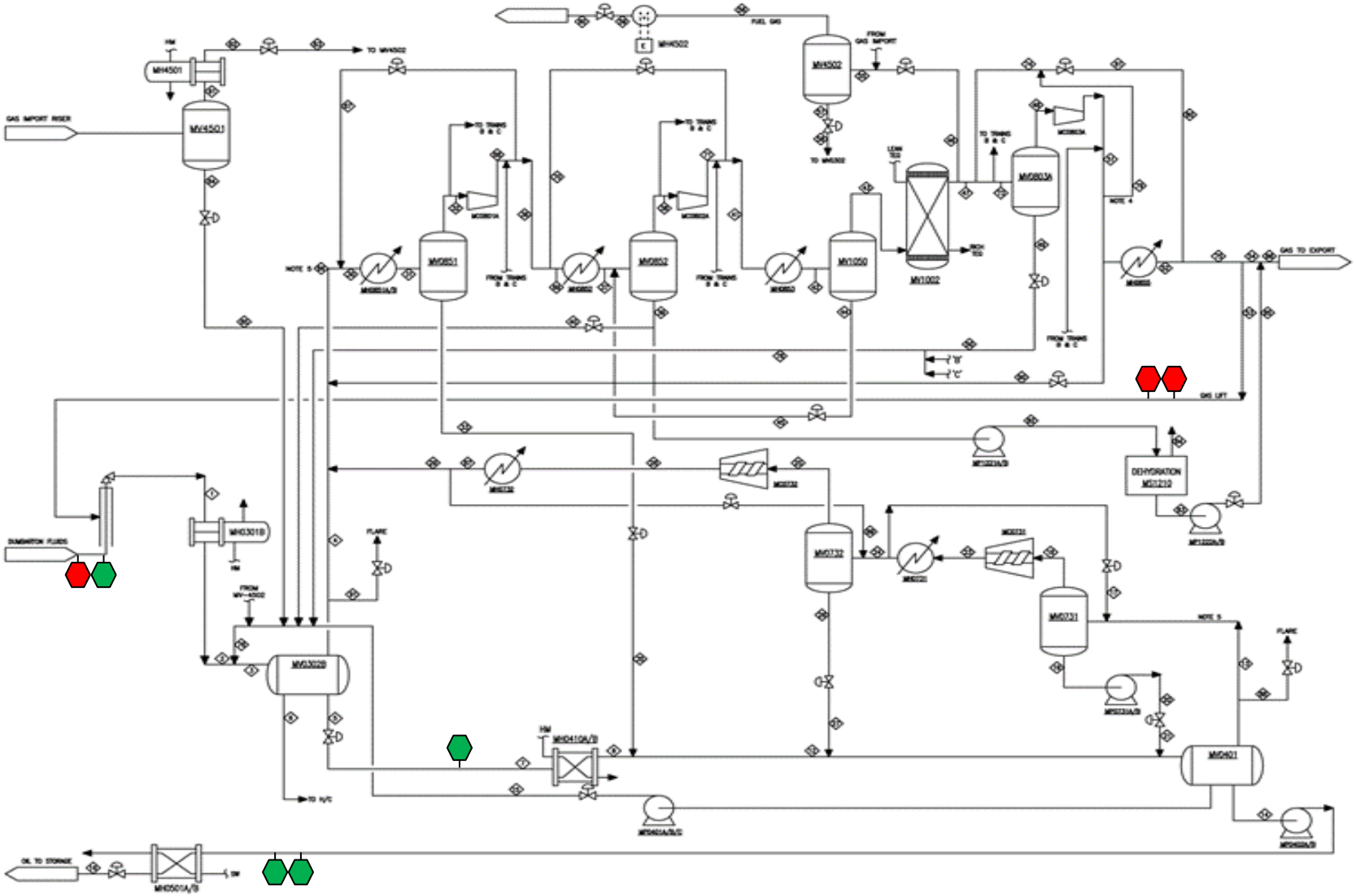
ER probe – Pros-Cons

ER probes	
Advantages	Disadvantages
Can be used in any environment (conducting and non-conducting)	Will not give reliable data in pitting or localised corrosion conditions
Different types of probe elements available to cover different requirements, i.e. high sensitivity, long life, flush or protruding shapes	Probes can be either sensitive with a short life, or insensitive with a long life, but not both
Can give data “on-line” either: Intermittently (single readings taken daily/weekly/monthly Continuously (readings taken at regular intervals, typically 1 hourly)	Response time for reliable result dependent on corrosion rate: 1 - 10 hrs at 5 mm/yr 10 - 100 hrs at 0.5 mm/yr 100 - 1,000 hrs at 0.05 mm/yr
Sensitivity down to several nm possible with latest technology	Average rates only between data sampling intervals

Typical ER probe data



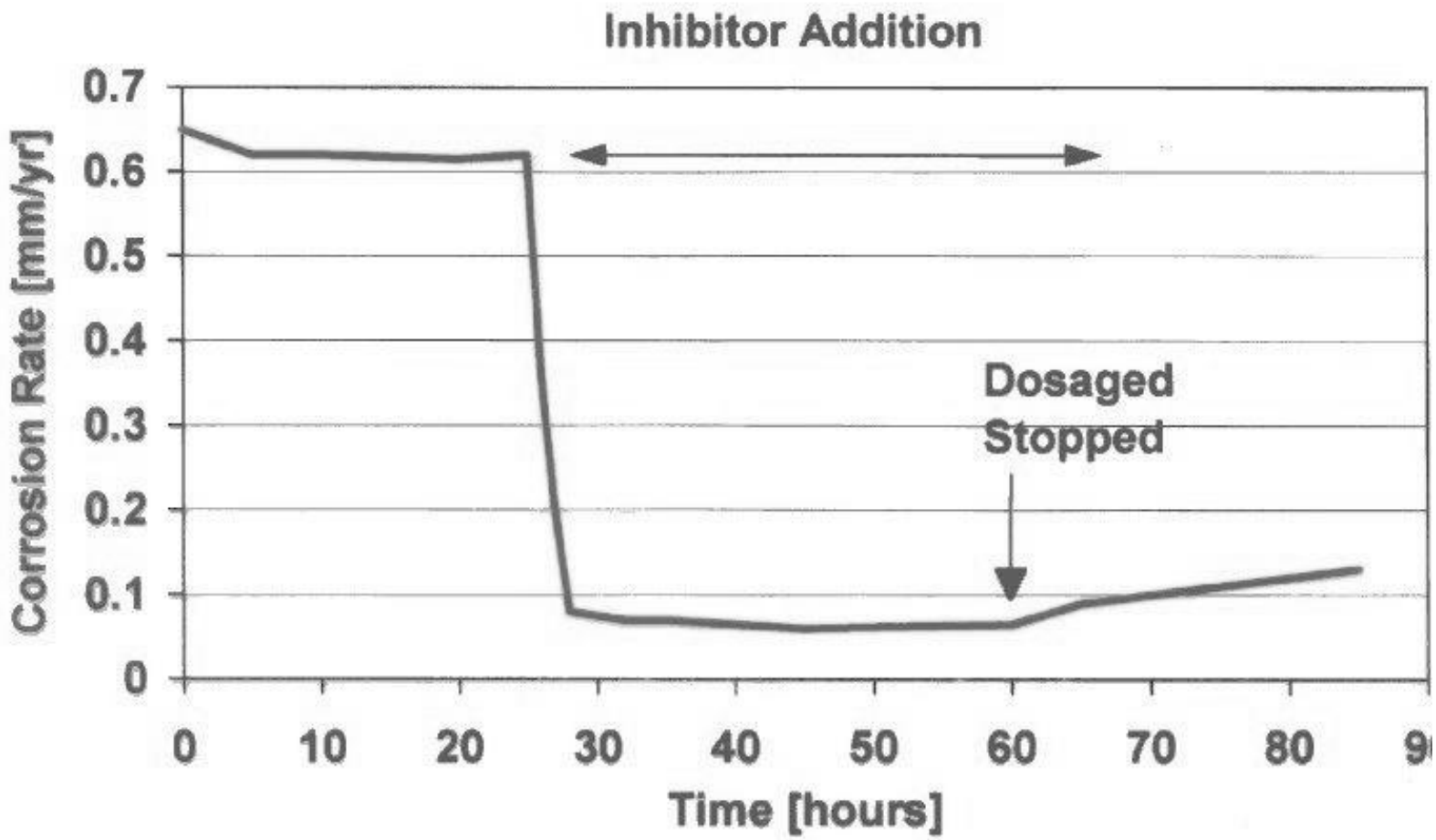
Reporting Monitoring Data



Linear polarisation resistance (LPR) Probe

- Based on standard LPR technique
- Corrosion rate is $\propto 1/R_{electrode}$
- I*nstantaneous* corrosion rate (~ 1 min for a measurement)

LPR Probe Measurement



LPR Probe – Pros-Cons

LPR probes	
Advantages	Disadvantages
Gives relatively instantaneous corrosion rate	Can only be used in conductive media (mainly aqueous)
	If electrodes become fouled - can give erroneous results
	Generally gives little information on localised corrosion

Summary

Various Corrosion prediction models and monitoring options are available

- *Use corrosion prediction model with <u>care</u> and engineering judgment should always be applied.*
- *Always challenge and sense check the out put - Don't always believe what "Computer says……..".*
- *Understand the limitation of predictive models.*
- *Correlate predictive and monitored rates with in-service inspection data for integrity management decisions.*
- *Corrosion monitoring is 'part of' not the whole story.*

INSTITUTE OF CORROSION

Aberdeen Branch

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ANY QUESTIONS?