Corrosion Monitoring Manual

A comprehensive guide to corrosion monitoring in oil and gas production and transportation facilities

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Main CD Contents ☞

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Summary

Lower cost materials are the natural economic choice for oil and gas production and transportation facilities. Unfortunately these materials (e.g. carbon steel, low alloy steels) in general have a low resistance to corrosion. Therefore, the corrosion risks of these materials have to be proactively managed. To this end BPX have developed and implemented corrosion control strategies which integrate risk assessment and corrosion control with corrosion monitoring and inspection.

The application of corrosion monitoring as part of a corrosion control strategy is complex and often becomes the responsibility of engineers who are not experts in the field. This manual has been developed as an aide to those designing and operating a corrosion monitoring system. The manual focuses on techniques which are classically called corrosion monitoring techniques. The aim of the manual is not to be prescriptive or disregard conventional or other approaches/techniques but rather to put in place guidelines which will aid any operator concerned with corrosion monitoring. This document supplements the BP recommended practice on corrosion monitoring, RP6-1, by providing more in-depth information and advice based on recent operational experience. This manual addresses:

- **Choice of monitoring location/orientation.**
- **Choice of monitoring technique**.
- **Application of the various techniques.**
- **Critique of monitoring techniques.**

Other complementary methods such as inspection, intelligence pigging and downhole surveys are outside the scope of this manual and are covered by the BP recommended practice RP 32-4.

Many of the principles and concepts given here are also relevant to processing facilities such as glycol and amine gas treatment systems, although these cases are not dealt with specifically.

The main points in this Corrosion Monitoring Manual are summarised in a shorter companion document: S Webster, R C Woollam, “Corrosion Monitoring Guidelines”, Sunbury Report No. ESR.95.055, dated November 1996.

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Introduction to Corrosion Monitoring

Background

A 1988 survey revealed that BP transports 80% of its cash flow through facilities that are over 15 years old [1]. The integrity of such facilities is vital to the successful and profitable operation of the Company and the prevention of environmentally sensitive incidents. Although BP has a first class record in environmental issues, major pipeline repairs and replacements alone have cost BP around $250 million over the past 5 years. A recent survey [2] of BPX's corrosion costs in the North Sea estimated that corrosion accounts for over 10% of the lifting costs per barrel of oil.

Lower cost materials are the natural economic choice for oil and gas production and transportation facilities. Unfortunately these materials (e.g. carbon steel, low alloy steels) in general have a low resistance to corrosion. Therefore, the corrosion risks of these materials have to be managed proactively. To this end BPX have developed and implemented corrosion control strategies which integrate corrosion monitoring with risk assessment and corrosion control.

The aim of corrosion monitoring is primarily to ensure that the design life is not being adversely affected or compromised and also to maximise the safe and economic operational life of a facility by:

- **Safe operation of a process plant**

  Corrosion can compromise plant integrity. If a plant is to be operated safely, all corrosion risks must be monitored.

- **Improvement in the economic operation**

  This aims to optimise corrosion control activities (e.g. corrosion inhibitor injection rates, oxygen concentrations, flowrates, etc.) whilst minimising operational costs.

- **Improvement of maintenance/shut-down scheduling**

  This is having sufficient knowledge of the plant condition and accurate life prediction to avoid unscheduled shutdowns due to unforeseen failures. Also to ease inspection load during planned shutdowns and to optimise spares stocks.

- **Assessment of impacts of process/operational changes and upsets**

  This aims to obtain information on the relationship between corrosivity, process and operating variables such as flow rate, water cut, temperature, etc. In addition to these are the effects of corrosion control methods (corrosion inhibition, increased corrosion allowance, corrosion resistant alloys) and process changes and upsets (one-off well workovers such as acidisations well intervention, onset of water breakthrough, introduction of third party fluids).

Elements of a Corrosion Control Strategy

There are three main components in the development and implementation of the BPX corrosion control strategies.

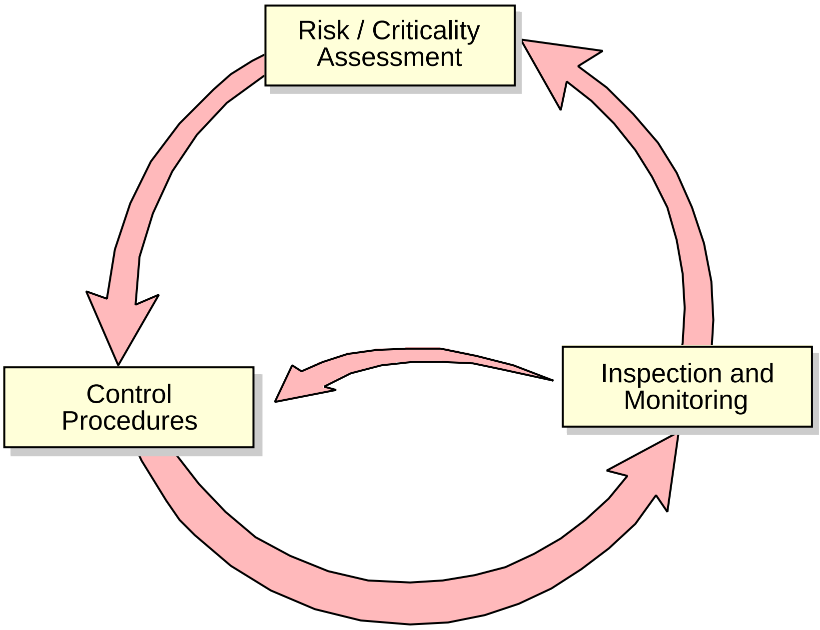


Figure 1: *A Schematic of the Inter-Relationships in a BPX Corrosion Control Strategy.*

- **Risk/criticality assessment**

  Risk assessment involves the identification of the main corrosion mechanism(s) possible for a given material/fluid combination, and the consequences of such corrosion occurring. Criticality assessment combines the **consequences** of such failure with the **probability** of it happening. The assessments can be undertaken in many ways but there should be a well-defined auditable trail (e.g. via a proprietary criticality assessment [3, 4]). Individual corrosion mechanisms depend on specific parameters that can be controlled and monitored in different ways. In most cases the probability of internal corrosion is dominated by only one or perhaps two corrosion mechanisms.

❍ Control procedures

Once the main risks have been identified and assessed, measures to mitigate the risks need to be identified, detailed and implemented. In many cases the predicted/measured rates of attack may be acceptable and it is sufficient to keep the key parameters within their design limits. In other cases additional measures will be required, e.g. material selection or chemical treatment (corrosion inhibitor, oxygen scavenger, etc.).

❍ Monitoring and inspection

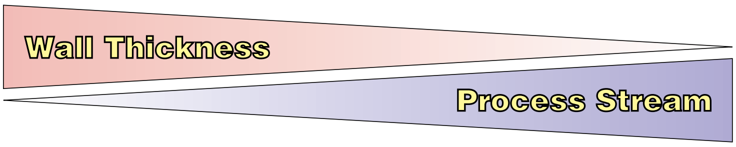
In all cases monitoring and inspection procedures will have to be put in place to confirm:

- Actual vs. predicted corrosion rates
- Process parameters within design limits
- Correct operation of control measures

Monitoring and inspection are two overlapping tasks. The first is the ongoing monitoring of the corrosion process and the measures taken to control it. The second is the provision of mechanical integrity assurance. Inspection also provides datum points against which corrosion monitoring is often related or quantified. In a corrosion control strategy these tasks aim to determine whether the expected corrosion is actually occurring, the corrosion rate, and the effectiveness of any control measures.

Figure 2 classifies currently available inspection and monitoring techniques indicating the complementary characteristics of each technique.

Figure 2: *Classification of Currently Available Inspection and Monitoring Techniques*



Large time interval between readings	Small time interval between reading
Non-destructive	Destructive (probes / consumables)
Direct measure of material loss	Indirect measure of material loss
Low sensitivity	High sensitivity
High accuracy / reliability	Lower accuracy / reliability
Lagging indicator	Leading indicator

	Visual Inspection	Radiography	Ultrasonics	Flexible UT Mats	Auto UT	Coupons	Field Signature Method (FSM)	Electrical Resistance Probes	Chemical Analysis	Linear Polarisation Resistance	Electrochemical Noise
Uniform Corrosion	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Localised Corrosion	✓	✓	✓	✗	✓	✓	✓	✗	✗	✗	✗

Notes: (a) the position of a technique in the table does **not** relate to its exact position along the arrows

(b) Flexible UT mats maximum temperature is 120°C

All of the above activities (risk assessment, corrosion control inspection and monitoring) are **interdependent**. Results from corrosion monitoring and inspection must be used to re-evaluate and modify, where necessary, the risk and criticality assessment and any control procedures.

This report focuses on the corrosion monitoring elements in a corrosion control strategy.

What are Corrosion Monitoring Methods?

When undertaking corrosion monitoring it is important not to rely on just one method. The best results are obtained by using a range of techniques. Corrosion monitoring in this context can be defined as:

> ***The use of any method that enables an operator to estimate or measure the corrosion rate occurring in service of an item of plant, or the corrosivity of a process stream.***

The main methods fall into the following four categories:

Inspection

These techniques are used to assess wall thickness changes, and detect material defects with the possibility of detecting pit growth or crack propagation.

The techniques most commonly used are: ultrasonics, magnetic flux (on-line inspection vehicle), radiography, acoustic emission, thermography, visual examination, dye penetrant and magnetic particle inspection.

On-line corrosion monitoring

These techniques are used to assess changes in corrosivity with time.

Typically the techniques are probe based and include electrical resistance methods, electrochemical methods and weight loss coupons.

Analysis of process streams

This approach is the monitoring of key process variables that affect stream corrosivity. i.e. pressure, temperature, production rates, fluid composition, production chemistry laboratory data (bio-activity, pH, oxygen content, chlorine, etc.) , corrosion product concentration (Fe or Mn concentration) and chemical treatments (dose rate and frequency). Many of these methods have fast response times ([O_2], pH, etc.) and are used to monitor process control. A good example is the use of on-line oxygen monitoring to maintain an acceptable oxygen content in a sea water injection stream to control corrosion rates. Process stream data can be used with mathematical models to predict the potential corrosion rates throughout the facility. However, the main value of process stream data is for ensuring that any control activities are working and that when corrosion has been detected effective data analysis can be undertaken to identify the cause.

Operational history assessment

This approach is the analysis of previous data as an aide to providing information about the present and predicted corrosion rates. This includes:

- Examination of production and operational records, including details of process changes (or upsets) which can give an insight to the corrosivity of the system.

- Failure analysis and inspection data can be used to predict parts of a facility most susceptible to certain modes of attack and subsequent failure.

Historically, corrosion monitoring and process data analyses were perceived as quite separate from inspection activities. Although inspection has been historically concerned with mechanical integrity, many inspection techniques can be used as corrosion monitoring tools. The complementary nature of these approaches is summarised in Figure 2.

For any corrosion monitoring/inspection programme to be fully effective it is vital that all of the above information can be accessed centrally and compared together. This can be achieved by ensuring full access to all databases which hold the relevant information and having the appropriate software to conduct the relevant correlational analysis.

The guidelines in this report focus on techniques which are classically called corrosion monitoring methods. Corrosion monitoring aspects are summarised in the current BP recommended practice RP6-1. This report supplements RP6-1 and provides a practical guide to corrosion monitoring giving full details on the design and application of a corrosion monitoring system. The aim is not to be prescriptive or disregard conventional inspection techniques but rather to put in place guidelines which will aid any operator concerned with corrosion monitoring.

The Economics of Corrosion Monitoring

In general the purpose of corrosion monitoring is to optimize corrosion mitigation/repair/replacement activities such that an optimum between corrosion control and replacement costs is achieved. It should be noted that there may be additional cost considerations related to safety, environmental and production impacts which are **NOT** considered in the following.

A given corrosion monitoring method or technique has only a limited accuracy and therefore, each corrosion rate determination has a random error associated with it. This random error can only be reduced by increasing the amount of corrosion monitoring undertaken but this will increase the overall costs of the activity. For an optimal corrosion monitoring program the benefit obtained should be greater than the cost incurred.

For corrosion inhibitor optimisation there is a trade-off between replacement costs and corrosion inhibition costs (Figure 3a). This results in an operational minimum of the sum of the corrosion inhibition costs and the pipeline equipment repair or replacement costs. In order to determine the optimum corrosion inhibitor injection rate, the corrosion rate for the system needs to be determined. The corrosion rate will determine if the corrosion inhibitor injection rate is effective, if it needs adjustment (up or down), or if some alternative means of control is required (e.g. corrosion resistant alloys, CRAs)

Figure 3a *Shows the Trade-off Between Replacement Costs and Inhibition Costs.*

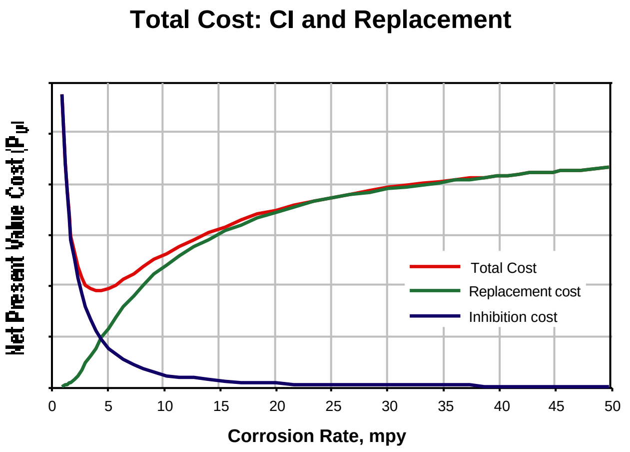


Figure 3b *Shows the Increasing Confidence and Reduction in Error, in Determining the Corrosion Rate as the Number of Corrosion Rate Measurements is Increased.*

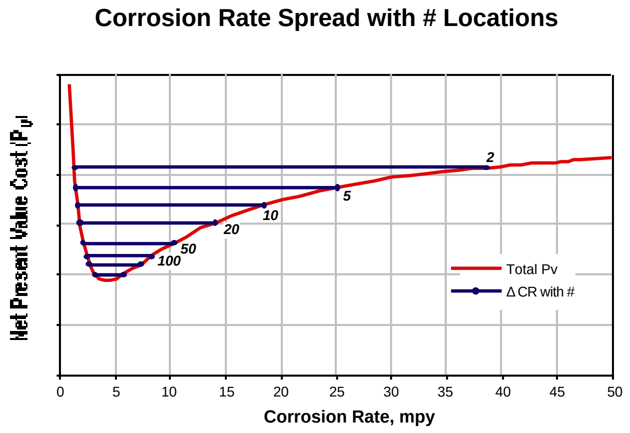


Figure 3c *The Increasing Cost of Corrosion Monitoring as the Number of Measurements Increases.*

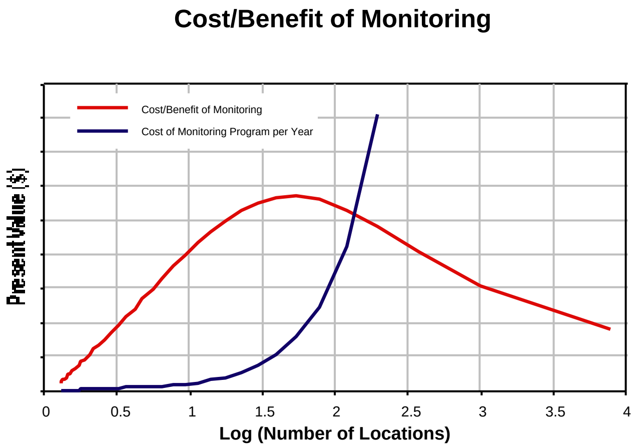


Figure 3c clearly shows the point at which no additional corrosion monitoring is warranted as the incremental savings from corrosion inhibitor optimisation are less than the cost of the monitoring program. The cross-over of the two curves indicates the level of corrosion monitoring required to optimize the overall cost structure.

This approach can be generalised to other corrosion mitigation methodologies and the monitoring of these systems. In general there is an optimum amount of corrosion monitoring in a system above which the costs of monitoring exceed any savings generated.

Costs

Table 1 gives outline costs for various corrosion monitoring techniques. This table is a guide to the relative costs of each technique (hardware) and any operational costs associated with installation and data analysis. The costs will vary depending upon asset location and number of monitoring locations. However, these figures are a guide to the costing of monitoring/inspection activities.

Table 1: *Outline Costs for Various Corrosion Monitoring Techniques based on 1995 Information (£1 = $1.6).*

Monitoring Method	*Hardware*	*Probe*	*Man-hour costs*
Weight Loss Coupons	*None*	*£300*	*Coupon insertion and retrieval. Coupon analysis*
Electrical Resistance probes	*£1500*	*£500*	*Probe insertion and retrieval. Data analysis*
Electrical Resistance Sand Monitor	*£25000*	*£1000*	*Probe insertion and retrieval. Data analysis*
FSM (Topsides)	*£30000*	-	*Data analysis*
FSM (subsea)	*£250000*	-	*Data analysis*
LPR	*£1500*	*£300*	*Probe insertion and retrieval. Data analysis*
Electrochemical Noise	*>£2500*	*£300*	*Probe insertion and retrieval. Detailed data analysis. Very time consuming*
Flexible UT Mats	*>£2500*	*£300-600*	*Data analysis*

Selection of a Corrosion Monitoring Location and Technique

Introduction

The selection of the appropriate monitoring location(s) and technique(s) is critical for successful corrosion monitoring. It cannot be stressed enough that selection of the wrong location or technique will result in a large amount of effort and expense only to generate inappropriate or even misleading information.

In many cases incorrect selection is worse than no selection as the quality of data are often **not** questioned.

Physical access is important but should **not** dictate monitoring location. However, when a monitoring point is identified the position should allow routine access for probe maintenance, retrieval etc.

> ***Incorrect selection of location or technique is worse than no selection.***

All corrosion monitoring (and inspection) locations and methods must be recorded on the relevant technical drawings. This should include process flow diagrams, process and instrumentation diagrams (P&ID's) and the isometric diagrams (PFD's). On new facilities they should be included in the Computer Aided Design (CAD) system as this aids data analysis and the development of control procedures. The records should include not only details on the system, item and location, but also the method and probe orientation.

There are no fixed rules on how to select a corrosion monitoring location or technique but the first step must be to decide the types of corrosion mechanisms to be monitored. Experience has shown that the following approaches are of value.

Approaches to Selection

- **Historical approach**

  Experience at other assets utilising similar facilities is often the best source of advice regarding the most suitable locations and/or monitoring techniques. Inspection/shutdown reports and maintenance lists can provide valuable information on which parts of a facility have experienced the most severe corrosion.

This aspect is vitally important at the ***design stage*** where operator feed back could prevent costly mistakes being re-made and minimise the cost of subsequent retro-fitting. Design contractors have limited operational experience and so it is important that BP assets support this activity by providing feedback and lessons learnt.

- **Inspection/corrosion monitoring data**

  Operating **assets** can provide valuable information by utilisation of existing inspection/corrosion monitoring data to identify the most suitable locations for future monitoring/inspection.

- **Networking**

  A wide range of disciplines need to be networked to obtain a full picture of current and potential future problems. For example production engineers can provide information on production profiles and well intervention programmes which may influence corrosion; production chemists have knowledge on fluid properties and chemical control measures which may influence corrosion; maintenance engineers can identify where most failures or replacements have been located.

Two examples from recent BP operations are given here and highlight where inappropriate selection of the monitoring location or technique caused problems:

Corrosion monitoring in a main oil export line with water cut below 1%.

Corrosion monitoring was undertaken using an intrusive electrical resistance probe via a top of the line access fitting. Low corrosion rates were observed which appeared to be insensitive to process changes. In this case the probe response was most likely reflecting the corrosivity of the continuous hydrocarbon phase and not that of the aqueous phase which constituted the corrosion hazard. A more reliable approach may well have been to have used a flush mounted electrical resistance probe via an access fitting located at the bottom of line where water separates out.

Corrosion monitoring in a sulphide containing produced water line.

Corrosion monitoring was undertaken using a flush mounted linear polarisation resistance (LPR) probe via a bottom of line access fitting. The monitoring programme yielded an exponentially increasing corrosion rate with time. In this case the most likely explanation of the results was that the probe response reflected the shorting out of the probe elements due to the formation of a conducting sulphide film. A more reliable approach may have been to substitute the LPR probe with a flush mounted electrical resistance probe in the same location.

Selection of Location within Plant for Corrosion Monitoring

This section outlines the main points that should be considered when identifying a corrosion monitoring location. These are summarised in Figure 4.

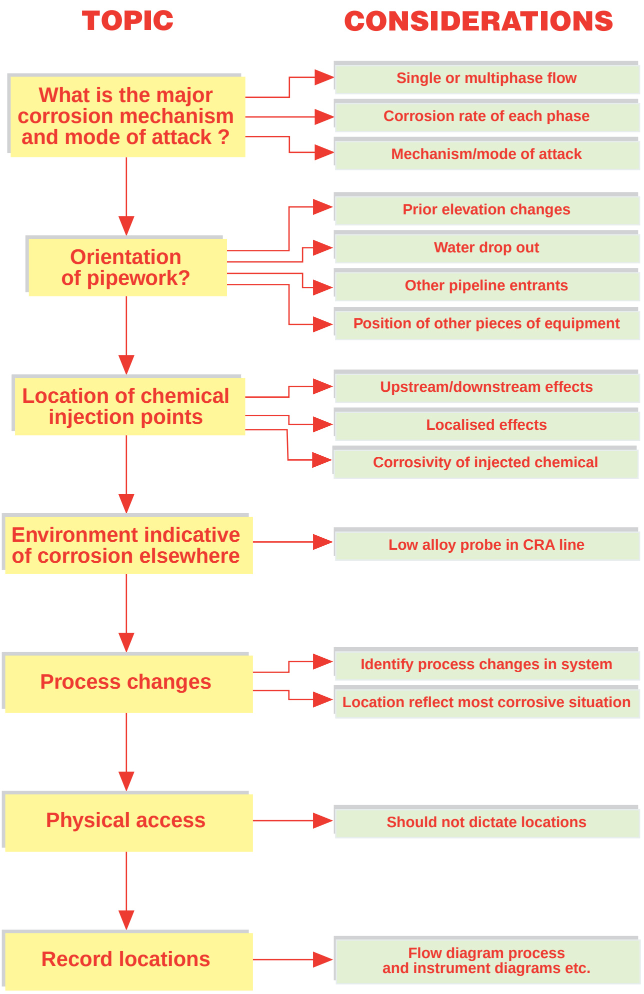


Figure 4: *A Check List for Identifying a Corrosion Monitoring Location*

Direct Monitoring

From the initial criticality assessment the predicted internal corrosion rates will have been identified. However, the following factors need to be considered when selecting the most appropriate monitoring points in a given system.

- **Location of corrosive phase**

  From the predicted corrosion rates the most likely location for corrosion to occur for a given phase must be identified. A good example is the transportation of wet gas. In this case corrosion related to water drop out will occur at the bottom of line. Corrosion at the top of line will occur as a result of water condensing from the gas phase.

- **Mode of attack**

  The anticipated corrosion mechanisms and modes of attack must be understood (general or localised attack, stress corrosion cracking, under deposit corrosion, process upset detection etc.) This will determine the siting of any monitoring points and help in selecting the most appropriate monitoring techniques at those points.

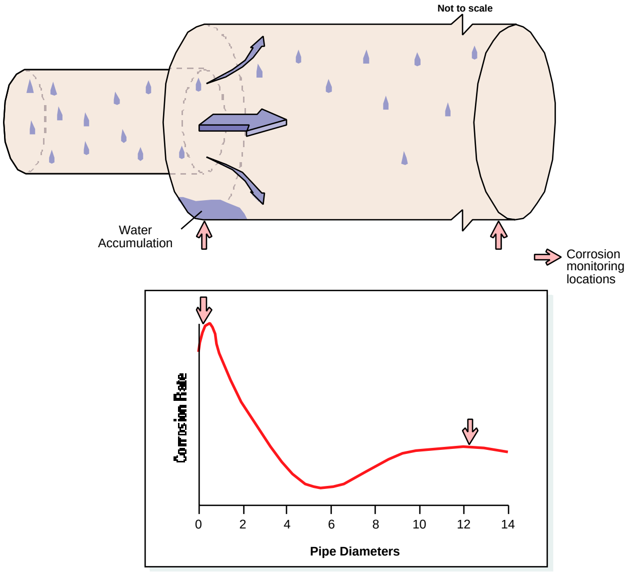
- **Flow effects**

  The flow rate and flow regime has a major impact on corrosivity and the location of the attack. The current BP corrosion monitoring recommended practise RP 6-1 [5] states that "access fittings should be located a minimum distance of 7 pipe diameters downstream of and a minimum of 3 pipe diameters upstream of any changes in flow caused by bends, reducers, valves etc". This is to ensure that the probe is sited in a region where water drop out is more likely. This location also ensures that the hydrodynamics are more uniform and so will provide a fluid corrosivity represenative of most of the pipe.

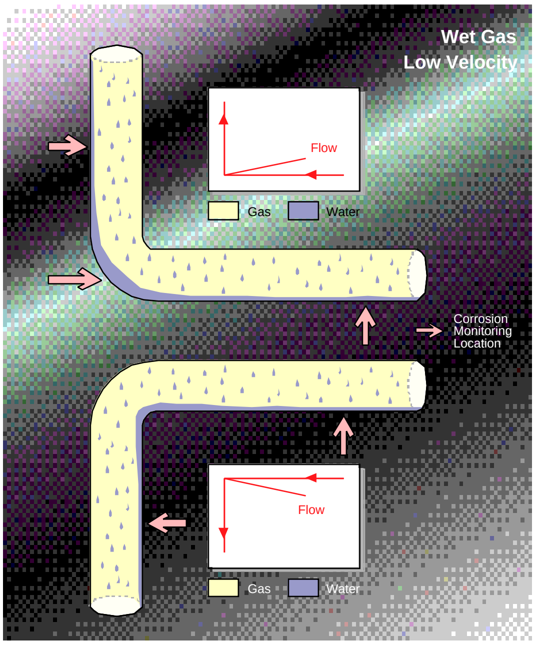
  Higher or lower corrosivities are possible in the hydrodynamically severe regions such as bends, reducers, valves, elevation changes and areas close to some major pieces of equipment (eg pumps). For example, BPX Alaska have had accelerated corrosion at road crossings (multiple elevation changes), and Magnus have had accelerated corrosion in the tortuous discharge pipework from the main-oil-line booster pumps. This acceleration can arise through enhanced water drop-out and wetting via centrifugal action (Figure 5). In

Figure 5: *Effect of Elevation Change on Water "Drop Out"*

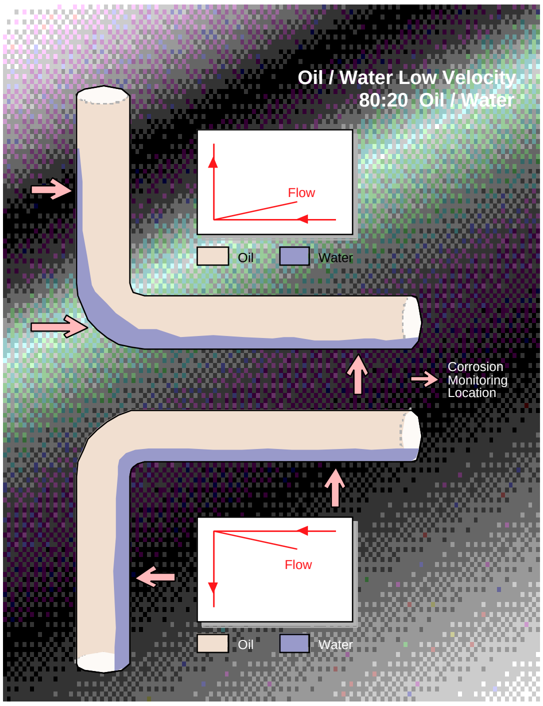
CORROSION MONITORING LOCATIONS
DOWN STREAM OF EXPANSION



CORROSION MONITORING LOCATIONS
AFTER ELEVATION CHANGE



CORROSION MONITORING LOCATIONS
AFTER ELEVATION CHANGE



contrast, in water/crude oil systems it is equally possible to have reduced corrosivity at elevation changes because the extra turbulance causes emulsification of the water.

Water hold-up and water drop-out effects are therefore of central importance in deciding the optimum corrosion monitoring location. Water hold-up, drop-out and deposit build up are all less likely in vertical sections than in horizontal. Drop-out is most likely in long horizontal pipe runs.

❍ Process stream changes

Process changes (pressure, temperature, flow rate etc.) will affect potential corrosivity due to solution chemistry changes. It is important to consider process changes in the system to ensure that the chosen monitoring location coincides with the location of highest corrosivity. The position of equipment which affects process conditions (e.g. vacuum/gas stripping towers in sea water systems, pumps, heat exchangers) should also be considered.

Third party entrants: Consideration should be given to other entrants to a pipeline system as these could influence corrosivity considerably. This may include mixing of separate well streams, through to third party entrants from other fields. Factors which are important include: water cut, flow rate, inhibition levels, water chemistry effects (pH, scaling), CO_2 and volatile fatty acid content.

Location of chemical injection points: The injection of production chemicals (corrosion inhibitors, scale inhibitors, demulsifiers, oxygen scavengers, etc.) can have a marked effect on corrosion. It is important to consider the positions of injection points when siting corrosion monitoring locations. In some cases it may be pertinent to monitor both upstream and downstream of the production chemical injection point. Scale inhibitors can be corrosive to certain steels and render corrosion inhibitors less effective if they are not fully compatible.

BPX Alaska have experienced high corrosion rates close to scale inhibitor injection points due to poor positioning of the injection quills. This aspect of localised attack is of importance to integrity inspection.

Indirect Monitoring

❍ Environment indicative of corrosion elsewhere

In areas of high corrosivity, corrosion resistant alloys (CRAs) are often specified. Locating a carbon steel coupon/probe in a CRA line can give important data regarding the potential corrosivity of the processed fluids to other carbon steel equipment located downstream or in other parts of the system. A good example is the use of CRAs in the produced water lines from a first stage separator. Small amounts of residual produced water will enter the main crude oil export line after further processing. Monitoring the corrosivity of the fluids in the CRA line will give information on the potential corrosion rates in the carbon steel export line. However, extrapolation is needed to ensure system changes are taken into account.

❍ Process stream monitoring

This approach is the monitoring of key process variables that affect corrosion rates. The measured variables - pressure, temperature, production rates, fluid composition, production chemistry data (bio-activity, pH, oxygen content, chlorine etc.), corrosion product concentration (Fe or Mn concentration) and chemical treatments (dose rate and frequency) - can be used with predictive models and current corrosion knowledge to give a reasonable estimate of potential corrosion rates.

Corrosion Monitoring Technique Selection

This section covers the selection of a corrosion monitoring technique. Details of inspection-based activities are given in the BP Standard RP 32-4 which covers:

- **Inspection scope and frequency**
- **Inspection techniques**
- **Inspection pigging technology**

The inspection or monitoring technique selected must provide information relating to the actual corrosion mechanisms. Consideration of the corrosion environment is important as this will often preclude many techniques (e.g. electrochemical methods are not suitable in low water cut or low conductivity situations). An understanding of the anticipated corrosion mechanisms (general, pitting, cracking etc.) is also important as this will give an insight into the most suitable monitoring technique(s) and eliminate many that are unsuitable (e.g. pitting most easily detected using weight loss coupons). The application of any of the techniques must be carefully considered (see Data Handling p34) because the economic benefit must outweigh the cost of the activity. A schematic for selecting a corrosion monitoring method(s) is presented in Figure 6.

There are no fixed rules on which methods are most suited for a given system (i.e. water injection system, crude oil flow lines etc.) as the conditions in each can vary. However, Table 2 gives a general guide to the possible application of the various monitoring techniques on a system by system approach.

When selecting a monitoring technique it must be realised that each technique gives only a limited amount of information. It is good practice to use a selection of techniques to give overall confidence in the results. The first choice must always be inspection-based methods as they are very reliable for integrity assurance. This can then be supported by probe-based methods. If only one probe-based method can be used then the first choice should be weight loss coupons as this technique gives both general and localised information.

The utility of inspection based methods is tempered by the fact that they are "lagging" indicators of corrosion. If inspection data says the situation is bad then it may be too late to do anything about it because the damage has already been done. Monitoring methods are "leading" indicators of corrosion. They show the fluid corrosivity at a particular moment, potentially before any significant damage has occurred. Hence, monitoring methods are always a valuable complement to inspection methods.

Design of Corrosion Monitoring Location

Access Fittings

The insertion of probes and coupons into pipework and facilities without the need for plant shutdown relies on the use of proprietary

Figure 6: *Schematic for Selecting a Corrosion Monitoring Method*

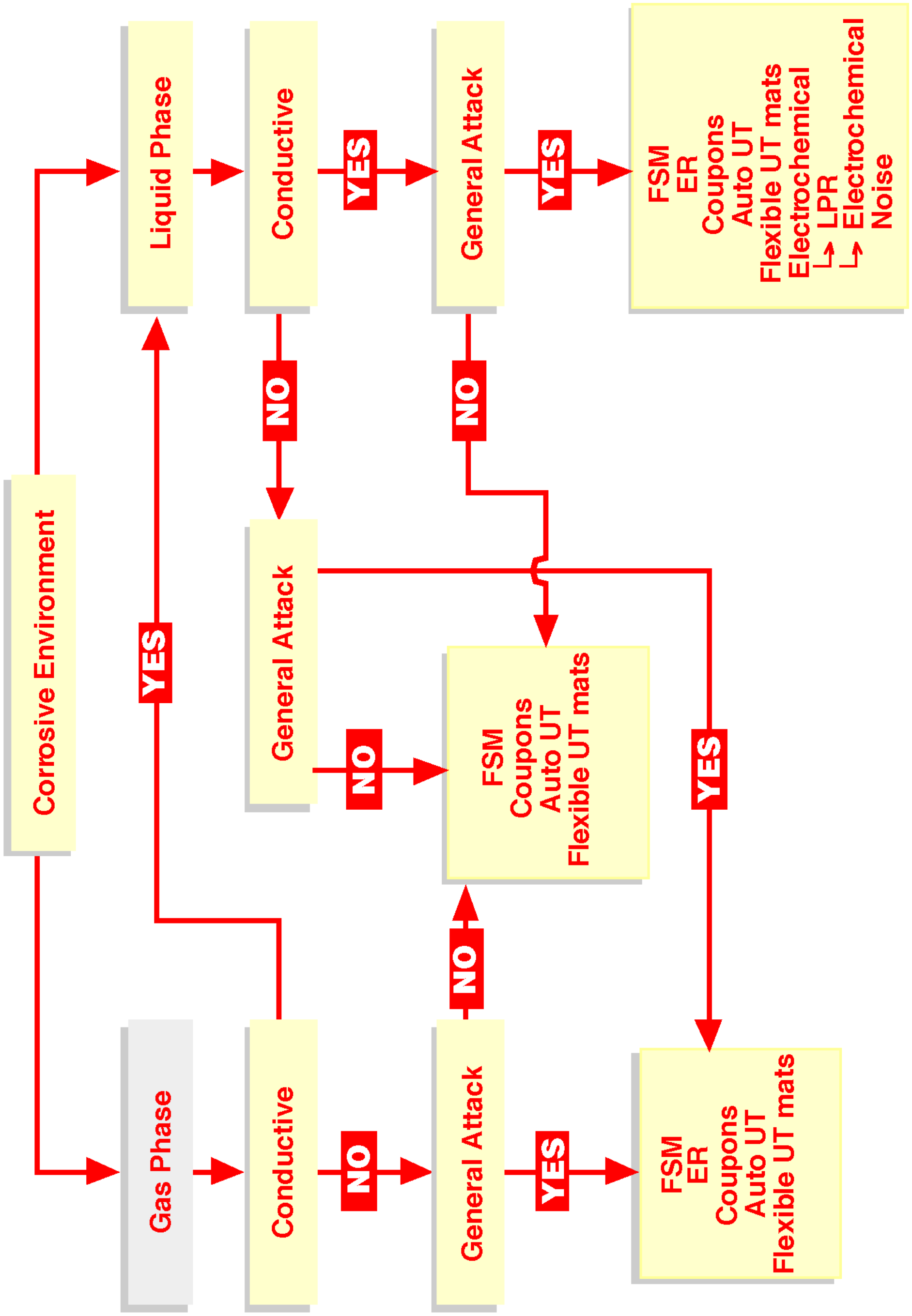


Table 2: *A General Guide to the Application of Corrosion Monitoring Techniques*

	Weight Loss Coupons / Spool Pieces	Corrosion Product Analysis	Electrical Resistance Probes	Electrochemical Probes	Galvanic Probes	Bacterial Monitoring	Suspended Solids	Dissolved Solids	Dissolved Gases	pH	Hydrogen Probes / Patch	Flexible UT mats[6]	Field Signature Method
Seawater Injection	✓	✓	✓[5]	✓[4]	✓	✓	✓	✓	O_2,Cl_2	✓	✗	✓	✓
Flow Lines (oil, water, gas)	✓	✓	✓	✓[3]	✗	✗	✓	✓	CO_2,H_2S	✓	✓	✓	✓
Aquifer Water	✓	✓	✓	[1]	✗	✓	✓	✓	CO_2,H_2S	✓	✗	✓	✓
Unstabilised Crude Oil	✓	✓	✓	✗	✗	✗	✗	✗	CO_2,H_2S	✗	✓	✓	✓
Hydrocarbon Gas	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗[7]	✓	✓	✓
Effluent Water	✓	✓	✓	✗	[2]	✓	✗	✓	O_2,H_2S	✓	✗	✓	✓
Storage Vessels with Separated Water Bottom	✓	✓	✓	✗	✗	✓	✗	✗	H_2S	✓	✗	✓	✓

[1] Depends on water quality. LPR unsuitable where there is a low ion content or a strong scaling tendency (or other form of electrode contamination is possible).

[2] May be used where oxygen content is high.

[3] Only in water cuts above ca. 10%-20%.

[4] Depends on water quality. LPR unsuitable where biofilming tendency.

[5] Intrusive probe prefered. Flush mounted unsuitable where biofilming tendency.

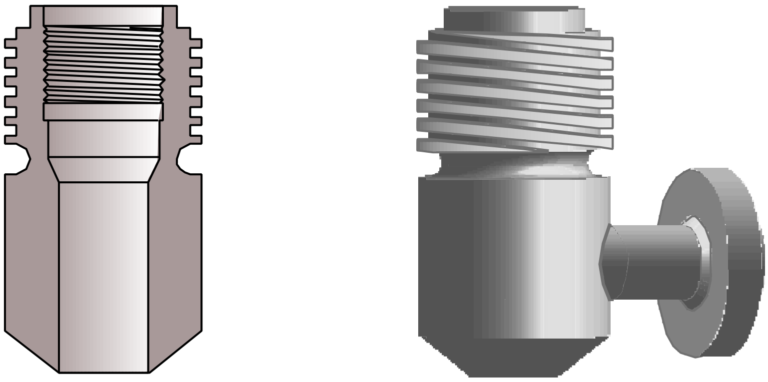
[6] Maximum temperature 120°C

[7] May be useful for condensed water in wet gas export line

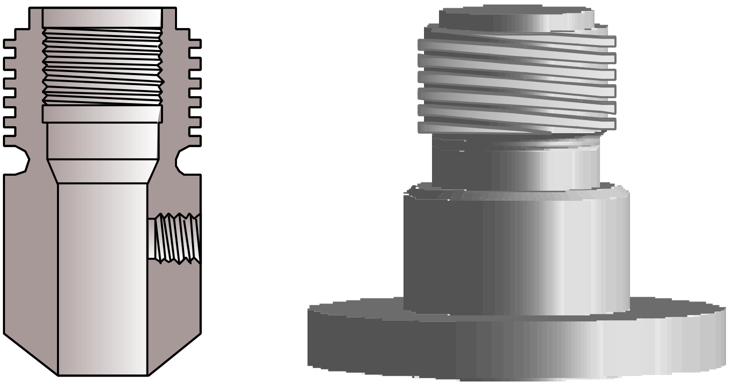
two inch access fittings. Access fittings are usually installed at the construction phase or during subsequent planned plant shut downs. Therefore, it is important that the corrosion monitoring requirements are well thought out at the design stage otherwise subsequent installation can be difficult and costly. Access fittings can be installed during plant operations using a hot tap but in many circumstances safety concerns will preclude such activity. If this is the case, there could be a long time interval before information is gained.

Access fittings are suitable for operating pressures up to 137 bar(g) (2000 psi(g)). Typical high pressure access fittings are shown in Figure 7.

Figure 7: *Typical High Pressure Access Fitting Design*



Flareweld **Flareweld Flanged Tee**



Flareweld Threaded Tee **Flange**

The BP recommended practice RP 6-1 gives a thorough overview of access fittings and retrieval tools. However, the following points should also be considered.

❍ Orientation of access fitting

RP6-1 recommends top of line access fittings. This general statement can be misleading and often the location should be at other orientations. The bottom of line location can cause problems with accumulation of debris and the possible galling of the threads. However, modern access fittings (e.g. CorrOcean hydraulic access fitting) or improved retrieval procedures can minimise these effects.

BPX Norway have developed a procedure to minimise the effect of debris build up on bottom of line location using standard access fittings [6]. This involves back pressuring the retrieval tool so that any debris is pushed back into the line. This procedure has been used on Ula since 1986 without any problems.

If corrosion is occurring at the bottom of line (e.g. wet oil, wet gas) then the access fitting should be located in this position. This will also minimise probe length and so reduce the possibility of fatigue failure and make the line easier to pig. The access orientation is less critical for a single phase water stream since all parts of the pipewall well experience the same environment.

Retaining adequate clearance for the retrieval tool is important when locating an access fitting for a corrosion probe : otherwise the fitting will be unusable. RP 6-1 gives full details on the clearance required for different retrieval tools. However, it is vital that a fitting is **not** simply located at a particular point because it happens to have a convenient space. The location must be also capable of providing useful information or else it is not worth having. Of course, retrofitting a probe at the optimum corrosion monitoring location may be impossible in a mature plant. This emphasises the importance of good early corrosion engineering design.

❍ Access fitting and sampling point design

For systems operating at pressures below 10 bar(g) (150 psig), low pressure access fittings can be used. Full details are given in RP 6-1. All probe and coupon holders used in low pressure fittings should be fitted with a blow out preventer to limit the slide out of the monitoring device during installation and retrieval. Safety clamps should also be used to secure retractable probes and coupon holders whilst on line.

For operating pressures from 10-137 bar(g) (i.e. 150-2000 psig) proprietary 2" high pressure access fittings should be used. All access fittings should be fitted with heavy duty covers to protect the fitting threads and electrical connections from damage. The cover should be fitted with bleed plugs (or possibly a pressure gauge) so that any leaks which may have occurred between the access fitting body and the monitoring device can be easily identified. The design should not allow the probe to be inserted back-to-front.

Sample points for the collection of process fluids should include two isolating valves in series, one of which should be a needle valve. Details are given in RP 42-1 [7].

❍ Material selection

Access fitting material should conform to the requirements of the piping specification. The welding of access fittings onto any equipment must comply with the requirements of the various codes. The solid and hollow plugs used in the access fitting should be manufactured from corrosion resistant material, with the choice of material depending on the service duty. Austenitic stainless steels are suitable for most carbon steel access fittings.

The risk of thread galling rules out stainless steel plugs for corrosion resistant access fittings made from materials such as 316 and duplex stainless steel. Alternative corrosion resistant plug materials have been tried including a hard stainless steel called Nitronix 60 and a ceramic coated stainless steel. Both still suffer galling problems and are not recommended. The preferred material is to use carbon steel plugs which have been phosphate coated. This approach dictates that there is regular servicing of the access fitting to monitor the condition of the carbon steel plug.

The problem of thread galling can be eliminated by converting existing threaded access fitting to hydraulic retrieval by means of a permanent adaptor. This approach has been taken by BP Norway on both the Ula and Gyda offshore production facilities. Furthermore, new projects should consider using hydraulic access fittings where access fittings are used on corrosion resistant piping materials.

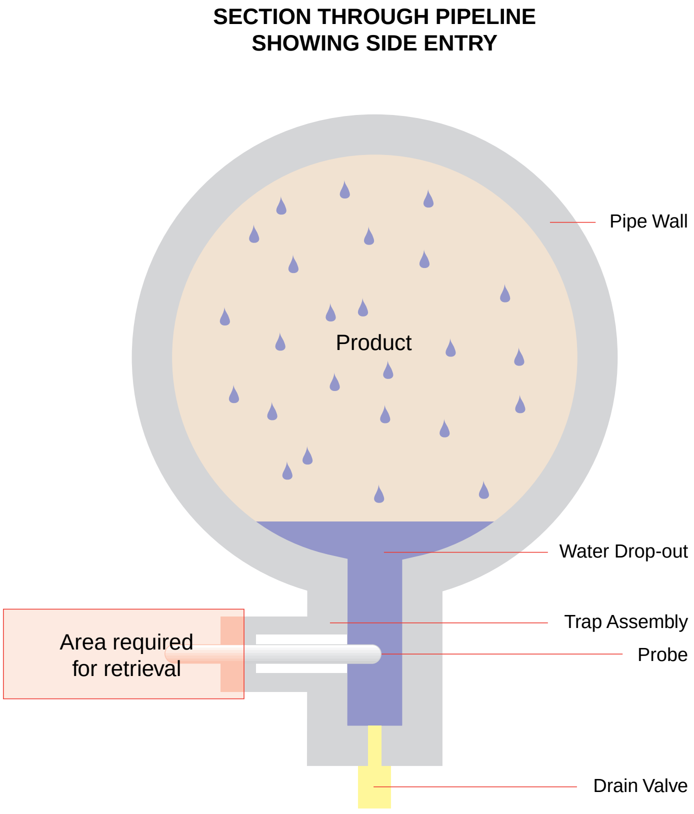
Recent experience at a refinery has highlighted the importance of material selection. A 316 stainless steel probe holder on a Crude Distillation Unit top pump-around-circuit suffered chloride stress corrosion cracking in service leading to a hydrocarbon leak and a serious "near miss". The incident report recommended that all future fittings should be constructed from Hastelloy for this application in which chloride ion concentration and low pH put conventional austenitic stainless steels at risk.

It is also important that any seals associated with the probe assembly should have satisfactory performance under the operating conditions[8].

❍ Trap-type monitoring point

In low water cut situations some operators have adopted the use of water traps. These traps act as a sink for water drop-out and allow conventional monitoring methods to be employed. This approach is shown schematically in Figure 8.

Figure 8: *Schematic of Water Trap for Corrosion Monitoring*



In this monitoring system the results reflect the inherent corrosivity of the fluid but do not allow other process conditions such as flow effects to be simulated. This is a major limitation. The trap can also promote bacterial activity which might not be typical of normal operations under flowing conditions. The design of the trap must include appropriate isolation to allow accumulated water to be drawn off. Traps can also be used to collect water samples from low water cut situations for laboratory evaluation. Traps can become a potential corrosion site by acting as a dead leg and so their use is not recommended.

Probe Configuration

Probes and coupons fall into two main categories:

- **Flush mounted**

  These are designed to be positioned so that the probe element is flush with the inside pipe wall. This approach will simulate processes which occur at the pipe wall surface. Typically this type of probe would be used to monitor corrosion in low water cut situations (e.g. wet oil), water drop out (e.g. wet gas), under deposit corrosion, and areas where water condenses. A turbulent location will help reduce fouling.

- **Intrusive**

  These probes protrude well into the process stream and are suited for measuring the overall corrosivity of a process stream rather than specific aspects like the flush mounted probe. Typically they are used to monitor process upsets in a single phase, high wall shear stresses, or “worst case” situations. They are especially well suited to clean water streams (e.g. sea water injection). In dirty systems (bugs, suspended solids etc) they are less likely than intrusive probes to become fouled, especially if they are in a turbulent location. However, they cannot be used in lines which are pigged.

There is no generalisation as to which of these probe configurations is most appropriate for corrosion monitoring. The choice will depend on the information required.

Validation of Monitoring Method Response

Before embarking upon a detailed corrosion monitoring programme it is important to ensure that the response of the monitoring method is sufficiently sensitive and reliable and responds to changes in the conditions being monitored.

This aspect is often overlooked when undertaking routine monitoring. If data validation has not been undertaken, corrosion monitoring data can actually be misleading. This can lead to complacency in corrosion control, unnecessary modification of control methods or changes to operational parameters being made. Increasing probe corrosion rate is usually a warning of increasing corrosivity but a low probe corrosion rate is **not** a guarantee that a system is under control.

> ***A lack of probe response has often been interpreted as a sign of good control rather than a sign of poor positioning/choice of the monitoring technique.***

For any monitoring programme control checks must be included to ensure the reliability of the data. These should include routine cross checks with other methods, checking of process data for major changes in operating conditions that should lead to changes in corrosivity (e.g. increase in water cut) or deliberately changing the corrosivity of the system and monitoring the probe response. When changing the corrosivity of the system the full risks of the operation must be identified, including the fact that the data being collected could have limited value.

> ***A recent corrosion survey [9] of a sea water injection system showed good oxygen and free chlorine control according to the on-line dissolved gas monitors. However, when the responses of the on-line monitors were checked against proprietary chemical kits the levels of dissolved gases were found to be an order of magnitude higher than monitored. Also the probe responses were very slow, i.e. hours, to respond to instantaneous changes in dissolved gas levels. It was found that the probes were fouled and needed more frequent maintenance.***

In the case cited above the electrochlorinator output was being adjusted based on poor quality on-line monitoring information. This resulted in an increase in hypochlorite concentration and a corresponding increase in corrosivity. In this case, process changes are now only made after confirmation of the on-line data by the manual chemical kits

Process Monitoring

Background

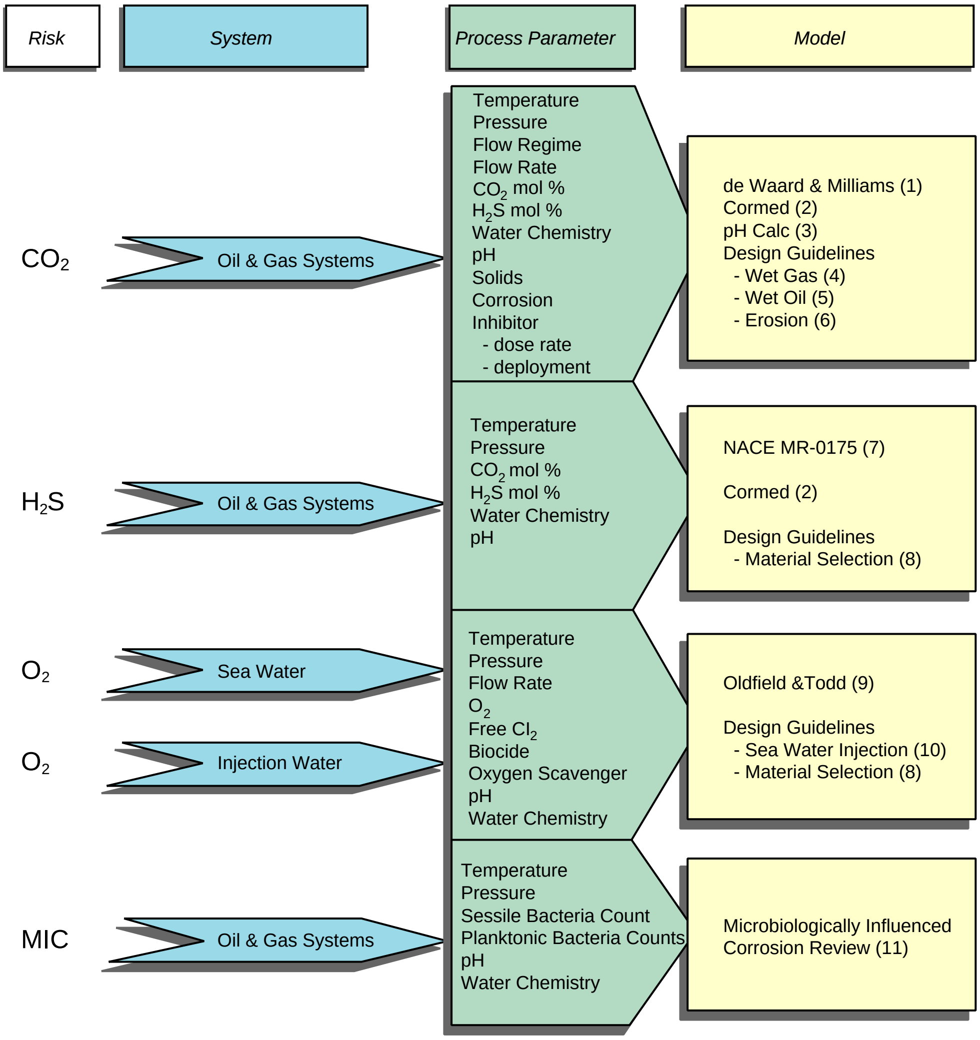
Process monitoring is a key aspect of any corrosion monitoring programme and covers a wide range of activities including but not limited to, the following:

- Measurements of standard process data (temperature, pressure, flow rates, water cuts etc.)
- Chemical analysis of the process streams (dissolved ions, bacterial levels, suspended solids, dissolved gases etc.)
- Chemical analysis of corrosion products.
- Details of production engineering activities (workovers, acidisations etc.)
- Monitoring the addition of production chemicals.

Full details of these activities are given in the Process Stream Monitoring section (p76). All of the above activities can have a major impact on corrosivity. Process monitoring is essential in predicting potential corrosivity and in the interpretation of corrosion monitoring data to validate the ongoing inspection/monitoring programme.

Process monitoring measurements can be made either on-line or by samples taken at regular intervals. Sampling must be carried out correctly and the time and place recorded so that the data can be compared to other process monitoring and on-line corrosion monitoring information. In many cases the analysis of the sample can be undertaken at the site rather than in the controlled environment of the laboratory. This route is often preferred as it minimises the effect of sample ageing. There are standard procedures available for most of the methods discussed, the details of which are outside the scope of this document and are listed below.

Figure 9: *The Use of Process Monitoring Data to Predict Corrosion*



1 C de Waard et. al., Prediction of CO_2 Corrosion of Carbon Steel, NACE 93, Paper 69 1993
2 J L Crolet, "Cormed Lotus 123 Spread Sheet for Calculating pH of Produced Waters" Elf Aquitane-SNEA (P) Copyright 1988, 1990
3 pH prediction
4 J Pattinson et. al., A Corrosion Philosophy for the Transport of Wet Hydrocarbon Gas Containing CO_2, ESR. 93. ER016
5 J Pattinson et.al., A Corrosion Philosophy for the Transport of Wet Oil and Multiphase Fluids Containing CO_2, ESR. 93.ER013
6 J Pattinson, Erosion Guidelines, ESR.94. ER070
7 NACE MR-0175
8 J Martin, Guidelines for Selecting Downhole Tubular Materials with Particular Reference to Sour Conditions, ESR. 94.ER043
9 Oldfield et.al., Corrosion of Metals in Dearated Seawater, BSE-NACE Corrosion Conference, Bahrain, Jan 19-21 81
10 J T A Smith, Minimising Corrosion of Carbon Steel in Sea Water Injection Systems - Guidelines for Water Quality, ESR. 94.005
11 I Vance, Microbiologically Influenced Corrosion (MIC) in Oil Production Operations, Topical report No 8615 1993

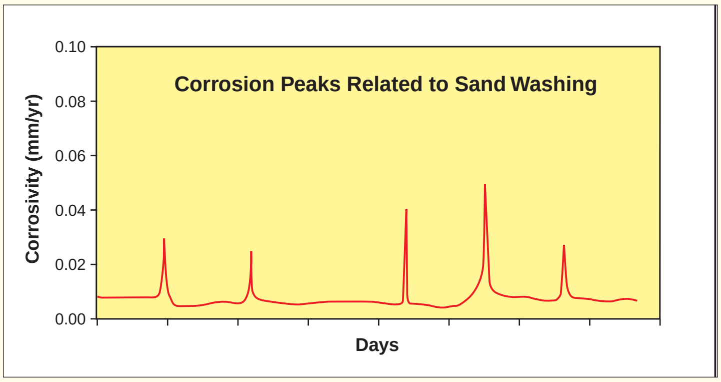
API RP 38	*Recommended Practice for Biological Analysis of Subsurface Injection Waters.*
API RP 45	*Recommended Practice for Analysis of Oilfield Waters*
NACE RP 0173	*Recommended Practice: Collection and Identification of Corrosion Products*
NACE RP 0192	*Recommended Practice : Monitoring Corrosion in Oil and Gas Production with Iron Counts*

The process data required to supplement the corrosion monitoring will depend on the application. However, consideration of the mechanism or mode of attack will help identify the most appropriate methods.

Application of Process Monitoring Data

The application of process monitoring data with inspection and corrosion data is important if the full value of the data is to be obtained and to provide the necessary assurance of plant integrity so minimising shutdowns and extending vessel inspection intervals. Typically the data will be used to assess corrosion rates indirectly (e.g. iron counts) or be used to predict potential corrosivity from a detailed knowledge of the corrosion processes. The latter approach is extremely valuable as it enables an operator to predict changes in corrosion rates and modify any monitoring/inspection activities or control procedures before significant damage has occurred. Figure 9 gives a broad summary of the use of process monitoring data.

The Figure below is from the BP Magnus platform in the North Sea. A number of production vessels on the installation are sandwashed every day. It was assumed that all the water was routed out from the vessels via the drains. The fluid corrosivity graphs for the main-oil-line (MOL) generally showed a low value, however, high corrosion "spikes" were appearing every day. Comparing the times of these "spikes" with process conditions revealed that some of the sandwash water was in fact going down the MOL and increasing the corrosion. By doubling the corrosion inhibitor injection rate into the MOL during sandwashing, the "spikes" on the probe output disappeared and the normal low corrosion rate could be maintained.



Data Handling

The methods used to analyse corrosion monitoring data will depend on the number, location and variation in monitoring methods employed. For effective corrosion monitoring and control it is vital that all of the relevant data can be accessed easily, cross referenced and analysed. Typically in any production operation the data will be held on different databases and in a variety of formats (database or paper files). Therefore, it is essential to compile the relevant communication networks to facilitate this process. For example, BP Alaska have usefully integrated their corrosion and production databases.

BPX Alaska are now using a Corrosion Analysis Tracking System (CATS). This computer system can store multi-giga-bytes of data from literally thousands of corrosion measurements and inspections in the field. The database is helping inspectors, corrosion engineers and others to develop a systematic, comprehensive approach to locating corrosion, analysing the best treatment strategies, and monitoring corrosion chemical treatments to verify their effectiveness.

There are several proprietary database packages which can be used to do this. Typically they:

- generate monitoring and inspection reports
- generate inspection schemes, workscopes and plans
- demonstrate integrity status for certification purposes.

The main limitation with this type of package are the time taken to input data into the system and the lack of flexibility. However, such systems have the capability to become the main corrosion database for all the monitoring data. For example, CORTRAN (CORrosion TRend ANalysis) is currently used by two inspection contractors involved in the integrity management of the BP offshore assets in the UK sector of the North Sea [10].

Another albeit less efficient approach is to access all the databases and extract the relevant information needed. This is time consuming if undertaken manually and impacts on the effectiveness of any monitoring programme.

Wytch Farm has developed a user friendly front end to their distributed control system [11]. This forms the management information system which archives and displays all site data for unlimited periods of time. It also has its own programming language which allows the user to develop high level applications e.g. energy monitoring or corrosion monitoring. The system also allows manual input of data such as the addition of laboratory reports or production engineering reports.

Another proprietary data handling and analysis package available is Mentor [12]. This system was developed for condition monitoring and has now been expanded to include corrosion monitoring information. The system can interrogate data from the distributed control system as well as data input manually. The software is such that the data can easily be compared from different databases and alarm levels set to alert an operator to potential changes in corrosivity. A “Mentor” system was installed on the Magnus asset in 1995.

For effective analysis the following information is required:

1. ***Process data:*** Usually available from a central database. This information involves both on-line and off-line data. These data should be supplemented by:

   - Laboratory analysis
   - Production engineering reports detailing
     - well shut-ins
     - acid stimulations
     - wireline activities
     - sand production
     - well workovers

2. ***Corrosion monitoring data:*** Should include all the on-line data as well as the data collected manually (coupons etc.). These data should be stored in a format which enables direct comparison with the process data.

3. ***Inspection data:*** Should include the routine inspection reports and data from specialised surveys. Again the data should be in a format which is directly comparable with the process and monitoring data.

The presentation of data is very important. The type of report is dependent on the activity and the scope of the work. Recently some operators have started to use CAD drawings as an aid to presenting corrosion and integrity data. This approach is very effective in identifying areas of concern and predicting potential locations of corrosion.

Side-stream Monitoring

Side-stream monitoring is considered as a supplement to on-line corrosion monitoring. In this approach some of the process fluids are diverted from the facility into a temporary section of pipework containing the corrosion monitoring probes. The fluids then re-enter the main process stream or are collected for disposal later. This approach allows the flow rates to be modified and chemical treatments to be investigated without any major changes in production. Side-streams have been used extensively to study inhibitor performance. Although the use of side-streams appears to be useful there are several potential problems associated with their use. These are:

- The sampled fluids may not be representative of the process fluids.
- The side-stream may not simulate the correct flow regime for a given flow rate
- Side-streams tend to form well mixed fluids in low water cut situations therefore forming emulsions and preventing water separation.
- Temperature and pressure in the side-stream may not be representative of process stream.

In summary, side-streams should be used with caution and should never be used as a primary corrosion monitoring tool. Experience has shown them to be most effective on single phase systems (e.g. water injection flow lines). Any results obtained should be compared to field experience before reliance is placed on the results.

BP Alaska used a side stream device to assess the performance of biocide in the sea water injection system. Biocide was terminated, based in part on the side stream data. Corrosion rates subsequently increase by approximately two orders of magnitude. Biocide was then restarted but even after 2 years it had not reduced the corrosion rates back to their previous levels

Corrosion Monitoring: A System by System Approach

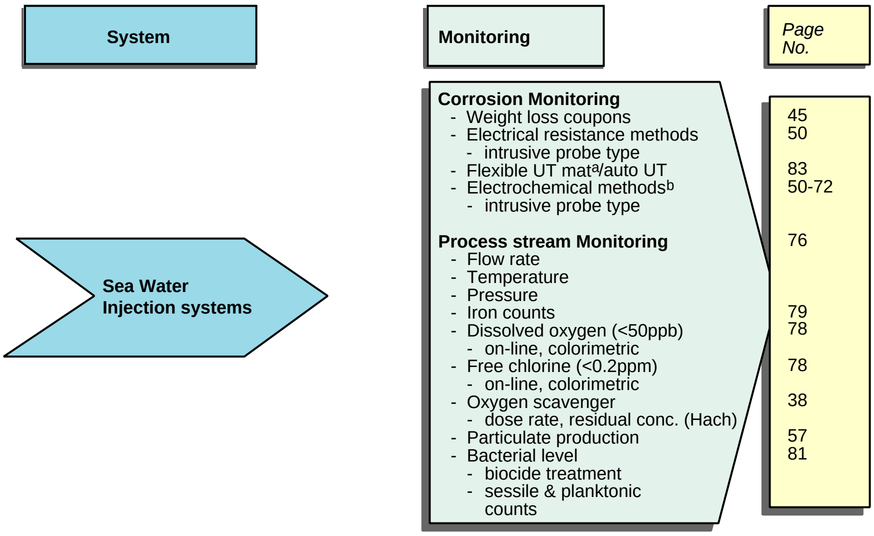
Background

This section serves to give examples of how the various monitoring techniques and approaches can be applied to given systems within an oil and gas production facility. These are only examples and in practice the monitoring system required may be quite different depending on the site specific conditions.

Sea Water Injection Systems

Corrosion monitoring in sea water injection systems is quite complex and guidelines have been issued on corrosion control methods [13, 14]. Figure 10 summarises the basic corrosion monitoring required for a sea water system and the relevant references within this manual.

Figure 10: *Corrosion Monitoring Requirements for a Sea Water Injection System*



a) Flexible UT mat: Maximum operating temperature 120°C
b) Depends on water quality. LPR unsuitable where biofilming tendency

The main corrosion mechanism is oxygen reduction. This depends on the dissolved oxygen concentration, flow rate and temperature. Microbially induced corrosion (MIC) is also possible. The activity of aerobic bacteria will be reduced by effective oxygen control. However, sulphate reducing bacteria (SRB) are anaerobic and will require an effective biociding regime. Other production chemicals added to the sea water will contribute to its overall corrosivity,

- Oxygen scavenger: This chemical (e.g. bisulphite salts) is added to remove residual oxygen but can itself be corrosive if over-dosed.

- Free residual chlorine: Sodium hypochlorite is added to control bacteria in raw sea water but a high level of free chlorine (>1ppm) can increase corrosivity. A balance of acceptable “kill rate” with acceptable corrosivity needs to be established.

- *Organic biocide treatment:* A lack of bacterial control due to infrequent or ineffective biocide treatments can lead to increases in corrosivity (MIC).

Corrosion monitoring in sea water injection systems should include:

- **Raw sea water/Upstream of deaeration towers:**

  Process monitoring: Flow rate, temperature, free residual chlorine, solids loading and bacteria concentration (sessile and planktonic) etc. are required on a regular (e.g. daily) basis.

- **Downstream of deaeration towers:**

  Process monitoring: The following parameters should be monitored: flow rate, temperature, dissolved oxygen content, free residual chlorine, residual bisulphite (if oxygen scavenger used), and bacteria concentration (sessile and planktonic). The measurements of dissolved oxygen and free residual chlorine can be made on-line. However, these measurements can be unreliable if the instruments, particularly the sensors are not well maintained and regular cross checks with other meters or proprietary kits should be made.

  Corrosion monitoring: It is recommended that in sea water systems intrusive type probes are used. The choice of techniques will depend on the system but should always include weight loss coupons (to provide valuable information on general and localised attack) which can be supported by other on-line monitoring techniques. Electrochemical methods have proved satisfactory for on-line monitoring in many systems[13]. However, if probe fouling is a problem then ER probes have proved satisfactory. The corrosion monitoring probes should be interrogated on a regular basis. On-line interrogators are preferred for this duty as they allow frequent (hourly) data collection over long periods (2-3 months). The reason for this approach is that corrosivity in sea water systems is quite often the result of short-lived transient upsets. The on-line probe data can also be supported by inspection techniques such as automated ultrasonic methods/flexible UT mats. This type of monitoring should be concentrated in areas of high turbulence (such as downstream of bends, valves or pumps) where higher corrosion rates would be most expected, and also in regions of low flow such as drains, sumps etc.

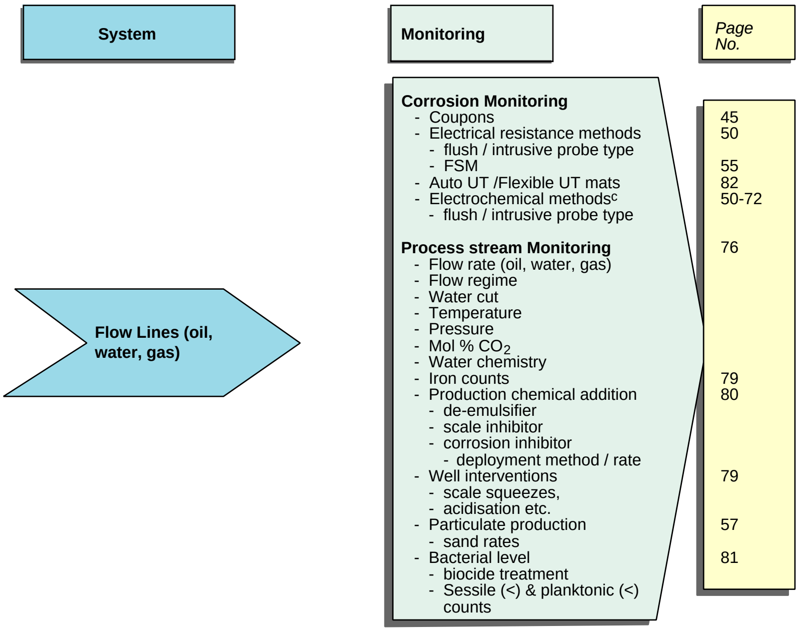
❍ Downstream of booster pumps:

Oxygen ingress is possible downstream of the booster pumps and may lead to corrosion. All of the methods described in the section above apply but in practice inspection methods should be sufficient to give confidence for integrity assurance.

Flowlines (oil, water and gas)

Flowlines in this context are pipelines carrying unprocessed fluids from the wellhead to the processing facilities. The main corrosion mechanism in these flow lines is flow-induced CO_2 corrosion. Figure 11 summarises the basic monitoring required and the relevant references within this manual.

Figure 11: *Corrosion Monitoring Requirements for Flowlines*



Monitoring	Page No.
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c) Electrochemical methods require water wetting and conductivity. Can only be used reliably in water cuts above ca. 10-20% or perhaps higher depending on the precise flow regime, e.g. stratified flow enables more reliable use of a bottom of line probe compared to turbulent flow. Each case has to be assessed individually.

The corrosion rate in a flowline will be dependent on many factors including partial pressure of CO_2, water chemistry, temperature, water cut, production rates/regimes and inhibition. The corrosion monitoring requirements in flow lines will depend on location (land or sub-sea) but should include:

Process stream monitoring: Flow rate (oil, water, gas), water cut, temperature, pressure, CO_2 concentration, H_2S concentration, water chemistry, iron counts, production chemical additives (rate and type), solids production. Flow regime predictions should be carried out using these data. Well intervention programmes should be recorded (wireline operations, acid squeezes, reservoir fracturing etc.).

Corrosion monitoring:
Subsea: The monitoring methods applicable sub-sea are very limited. At present only the FSM technique is commercially available. The FSM technique can be hard-wired back to the central facility or can be installed as a stand alone device with satellite communications. However, the cost of a sub-sea FSM is high (>£250,000). A system based on flexible UT mats is under development and may be commercially available in 1997.

Weight loss coupons, ER probes and electrochemical probes can be fitted at the top of sub-sea risers. However, these will only give information about corrosion in the riser itself. The riser conditions are not likely to be representative of those in the flowline.

Land lines: These fall into two categories, buried or raised. For buried lines the techniques for corrosion monitoring are restricted to FSM. Flexible UT mats may also be possible. However, the monitoring at the well head will be similar for both types (buried or raised). For raised lines it is recommended that a combination of flush and intrusive probes are used. (see Probe Configuration p29). The choice of probe type and location will depend on the conditions. The choice of techniques will also depend on the system but should always include weight loss coupons (to provide information on general and localised attack). These can be sited both at the wellhead and at the processing facility to give information regarding changes in potential corrosivity through the flowline. At the wellhead, intrusive coupons can be used as the fluids will be well mixed. Further down the line flush coupons may be preferred so as to reflect the corrosivity of any separated water.

The coupon data can be supported by other on-line monitoring techniques. The primary choice would be ER probes but in high water cut fluids this could be supplemented by electrochemical methods for more detailed studies. The ER probe type will depend on location (as for coupons), but a flush probe mounted in a bottom-of-line location would be preferred for corrosion monitoring in low water cut flowlines. The on-line probe data can also be supported by inspection type techniques such as automated ultrasonics. This type of monitoring should concentrate on areas of high risk i.e. where water may separate; at bends or “T’s”, elevation or direction changes where turbulence is at the highest or where erosion may be a problem. If solids (sand) production is known to occur then data on erosion can be obtained by using corrosion resistant ER probes (i.e. a probe which will not corrode but which will erode at a similar rate as the pipe material).

Oil Export Lines

Export lines fall into two categories, those carrying partially stabilised crude oil and those carrying fully stabilised crude oil. Partially stabilised crude oil is where the offshore processing only goes down to an intermediate pressure and final separation is completed onshore. As some CO_2/H_2S remains, the fluids are still corrosive and therefore careful corrosion control and monitoring are required. Most North Sea lines fall into this category. Fully stabilised crude oil is where the oil has been processed down to atmospheric pressure and possibly stored in tanks. This type of line generally has a significantly lower risk of corrosion and so less exhaustive control and monitoring are necessary.

In either case it is vital to maintain good control of export fluid quality and also to monitor any excursions in the water content. With export lines, access can be extremely restricted and so monitoring is often limited to either end of the pipeline, although the FSM method can be used to monitor subsea or buried lines. Remember that riser conditions may not be representative of the main pipeline. For export lines reliance should always be placed on internal inspection using intelligent pigs.

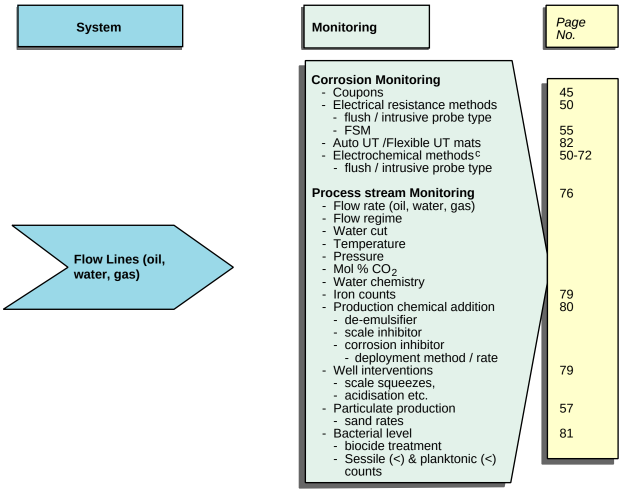


***Figure 12**: Corrosion Monitoring Requirements for Oil Export Lines.*

c) Electrochemical methods require water wetting and conductivity. Can only be used reliably in water cuts above ca. 10-20% or perhaps higher depending on the precise flow regime, e.g. stratified flow enables more reliable use of a bottom of line probe compared to turbulent flow. Each case has to be assessed individually.

The main corrosion mechanism is usually CO_2 corrosion and the same factors that apply to flowlines will apply here. The biggest difference in this case is that the water cut is usually below 2% and therefore detection can be difficult as corrosion will only occur where water separates from the crude oil and contacts the pipe wall.

> ***The old 24” Forties subsea export line suffered significant corrosion which was not detected by conventional monitoring methods although it had been operating at water cuts below 2% . While the corroded areas remained water wet, it appears that the monitoring points became oil-wet.***

Process stream monitoring: Flowrate (oil, water), water cut, temperature, pressure, CO_2 concentration, H_2S concentration water chemistry, iron counts, production chemical additives, 3rd party entrants, and solids content. Flow regime predictions should be carried out using these data.

Corrosion monitoring: It is recommended that for low water cut lines only flush mounted probes are used. The choice of technique will depend on the system but should always include weight loss coupons (to provide information on both general and localised attack). These should be situated at different parts of the system so as to reflect changes in corrosivity throughout the system. The coupon data can be supported by other on-line monitoring techniques. The primary choice would be ER probes located at the bottom of line location, preferably flush mounted. The use of electrochemical methods would only be recommended at water cuts > ca 10-20%. Hence they are inappropriate for most oil export pipelines.

Critique of Corrosion Monitoring Methods

Introduction

As stated previously there is no clear distinction between what constitutes an inspection technique and what constitutes a corrosion monitoring technique. Many of the techniques cover both aspects. A good example of this is the automated ultrasonic technique which is used in BPX Alaska both as a check of mechanical integrity and also as a corrosion monitoring tool. The critique section of these guidelines addresses the techniques which broadly fall into the corrosion monitoring category. Guidelines which focus on inspection/integrity assurance are in preparation [15].

The techniques discussed are:

- **Weight Loss**
- **Electrical Resistance**
- **Linear Polarisation Methods**
- **A C Impedance**
- **Electrochemical Noise**
- **Galvanic Probes**
- **Hydrogen Probes**
- **Ultrasonic Thickness Measurements**
- **Process Stream Analysis**
- **Radioactive Methods**

Figure 2 classifies the techniques based on their application.

Weight Loss Coupons

Background

This method involves the use of metallic coupons constructed from the material of interest to determine the average fluid corrosivity by measurement of weight loss. The coupons can also be used to assess the susceptibility to pitting, galvanic corrosion, stress corrosion cracking and crevice corrosion.

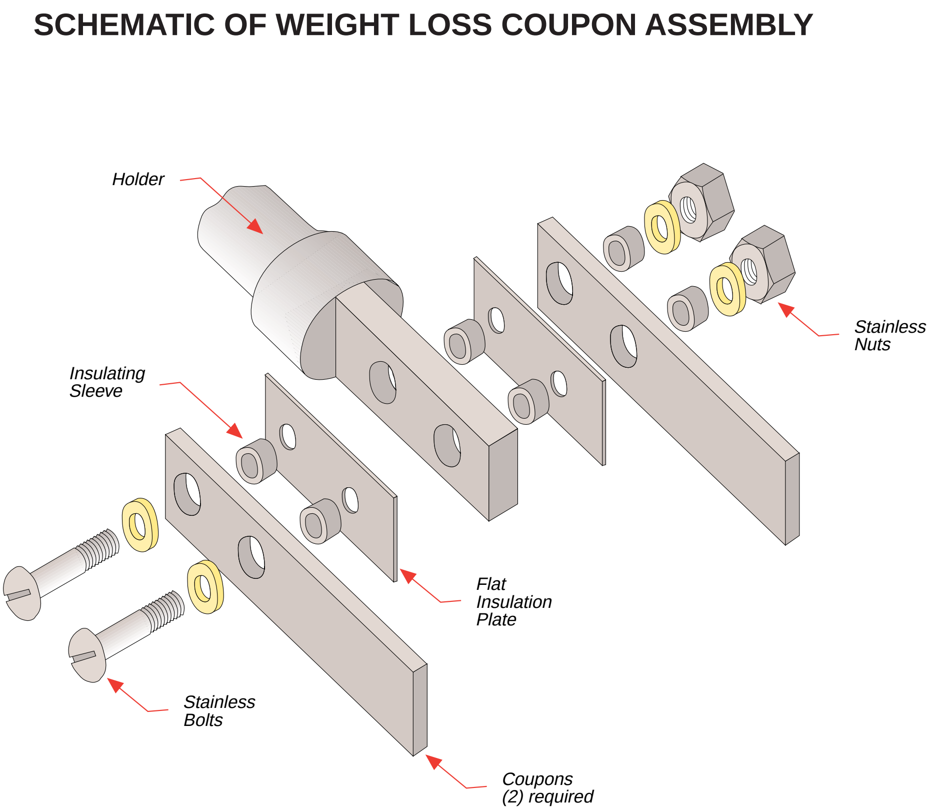
In this technique a pre-weighed sample of known area is exposed to the process stream for a known period of time. At the end of the exposure period the coupon is recovered, inspected, cleaned and reweighed. From the weight loss the corrosion rate can be estimated. Examination of the coupon can reveal details about localised corrosion. There are several industry accepted standards for this type of measurement which give full details of coupon preparation, cleaning and inspection and also cover the reporting of information.

ASTM	***G4-84*** *Conducting Corrosion Coupon Tests in Plant Equipment.*
ASTM	***G46-76*** *Practice for Examination and Evaluation of Pitting Corrosion.*
ASTM	***G1-81*** *Practice for Preparing of Metallographic Specimens.*
ASTM	***G31-72*** *Laboratory Immersion Corrosion Testing of Metals*
NACE	***RP 0775-91*** *Preparation and Installation of Corrosion Coupons and Interpretation of Test Data in Oil Field Operations*

Equipment

The equipment for undertaking corrosion coupon measurements is commercially available [16, 17, 18]. The coupons are inserted into the process fluid via a high pressure 2 inch access fitting using a retrieval tool. There are two types of coupon design: disc (flush) or strip (intrusive). Details of the intrusive probe type are shown in Figure 13.

Figure 13: *Intrusive Weight Loss Coupon Design*



The choice of coupon type will depend on the corrosion mechanism being monitored. Commercial coupons are supplied pre-weighed, marked with a serial number for future reference, and packed in vapour phase inhibited envelopes. To remove the vapour phase inhibitor the coupons are solvent cleaned prior to insertion in the line. Specialised coupons and their subsequent analysis are required for monitoring preferential weld corrosion, galvanic type corrosion or stress corrosion cracking. The ASTM standard G4-84 covers most applications.

Reporting of Data

- **Weight loss:**

The corrosion rate of the corroded specimens should be determined. This is achieved by measuring the change in weight with time and converting into a penetration rate.

$$\text{corrosion rate (mpy)} = (3.45 * 10^6 * W)/(A * T * D)$$

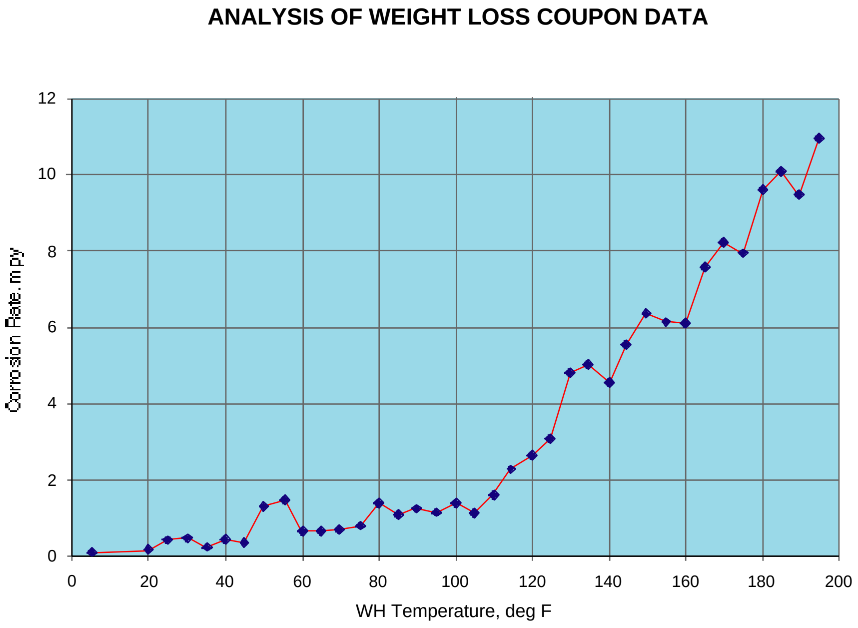
where:

mpy=penetration rate in thousandths of an inch per year
W= weight loss (g)
D= density (g/cm^3) (carbon steel = 7.86g/cm^3, 316L = 7.98g/cm^3)
A= total area of specimen exposed to the fluids (cm^2)
T= time of exposure (hours)

This approach assumes that no localised corrosion takes place. If the specimens have undergone localised corrosion this must be noted along with the general corrosion rate data.

Figure 14 presents typical weight loss data from BPX Alaska. The graph summarises weight loss data from many wellhead coupons. The data have been presented as corrosion rate versus temperature indicating an increasing corrosion rate with increasing temperature.

Figure 14: *Typical Weight Loss Data from BPX Alaska Indicating Increasing Corrosion Rate with Temperature.*



- **Visual examination:**

  After weighing, the specimens should be examined for localised attack (pitting). The measurement of pits is quite difficult and should be undertaken with the aid of an optical microscope. If pitting is observed then the number, size and shape should be reported. The pit depth should be reported in mm for the test period and not extrapolated into mpy because the rate of initiation and propagation is random.

General Comments

- The coupon should be made from the material of interest. Ideally coupons should be made from actual samples of the material of construction. This is often not practical but effort should be put into ensuring the composition and metallurgical condition are similar.
- Duplicate coupons should be used to ensure reproducibility.
- The orientation of the coupon is important. The orientation should reflect the hydrodynamics of the equipment of interest.
- Analysis of the coupon should include full examination of the coupon on retrieval from the line before cleaning. This can be

visual in nature but should cover film appearance, coverage etc. The subsequent cleaning of the coupons to remove any corrosion product prior to weight loss determination may require the use of inhibited acids. ASTM G31 gives full details of the methods required.

- The coupon should be exposed for sufficient time to give a sensible weight loss. The use of predictive corrosion models can be used to determine minimum exposure times.
- Weight loss coupons can be used to provide a source of bacterial material for determining the possibility of microbially induced corrosion (MIC).
- Chemical analysis of the corrosion product can provide valuable information regarding the corrosion mechanism. This approach can be used to detect MIC, where high levels of sulphur in the corrosion product, but not the process stream, can be indicative of MIC.

Weight Loss Coupons: Advantages and Disadvantages

Advantages	Disadvantages
❍ Cheap, easily applied	❍ Corrosion rates averaged over exposure time
❍ Coupons made of similar material to pipe	❍ Corrosion rate calculation assumes generalised attack
❍ Visual examination identifies mode of attack (localised nature)	❍ Data generation rate slow (long exposure times)
❍ Samples available for scale/ deposit analysis	❍ Requires insertion and retrieval under pressure which can have safety implications
❍ Source of microbial data	

Related Techniques

- **Spool pieces:**

In some cases spool pieces (short length of flanged pipework) have been used to obtain a direct assessment of the corrosivity of a process stream. These spool pieces can either be fabricated from similar material to the adjacent pipework or from a different material which is under evaluation. In the latter case consideration must be given to galvanic effects on both the spool piece or adjacent pipework. The standard methods used for coupon measurements should be applied to spool pieces.

Electrical Resistance Methods

Background

This approach is similar to the weight loss coupon except that the metal wastage is monitored by measuring the change in electrical resistance rather than weight loss.

The electrical resistance of a section of a conductive material can be expressed as:

$$R = \rho L/A$$

where: R = resistance (ohms)
ρ = resistivity (ohm cm)
L = length (cm)
A = cross sectional area (cm^2)

For a given alloy at a constant temperature the resistance increases as cross sectional area decreases. Assuming regular material loss (general corrosion), the change in electrical resistance can be used to determine metal loss and equated to corrosion rate. Compensation for temperature variation is made by the use of an internal reference element whose electrical resistance increases with temperature in proportion to the test element thus cancelling temperature effects. In situations where temperature fluctuations occur, data interpretation can be difficult owing to the time it takes for the reference element to equilibrate.

The advantage of the electrical resistance method over the weight loss coupon is that by taking successive readings, metal loss and hence corrosion rate can be measured with time. Figure 15 shows schematically a typical ER probe output presented as metal loss against time. The conversion to corrosion rate is the slope of the line (Figure 15). A typical response from an ER probe in a well flowline in Alaska is also shown in Figure 16.

Figure 15: *Schematic of an ER Probe Output Indicating Conversion to Corrosion Rate.*

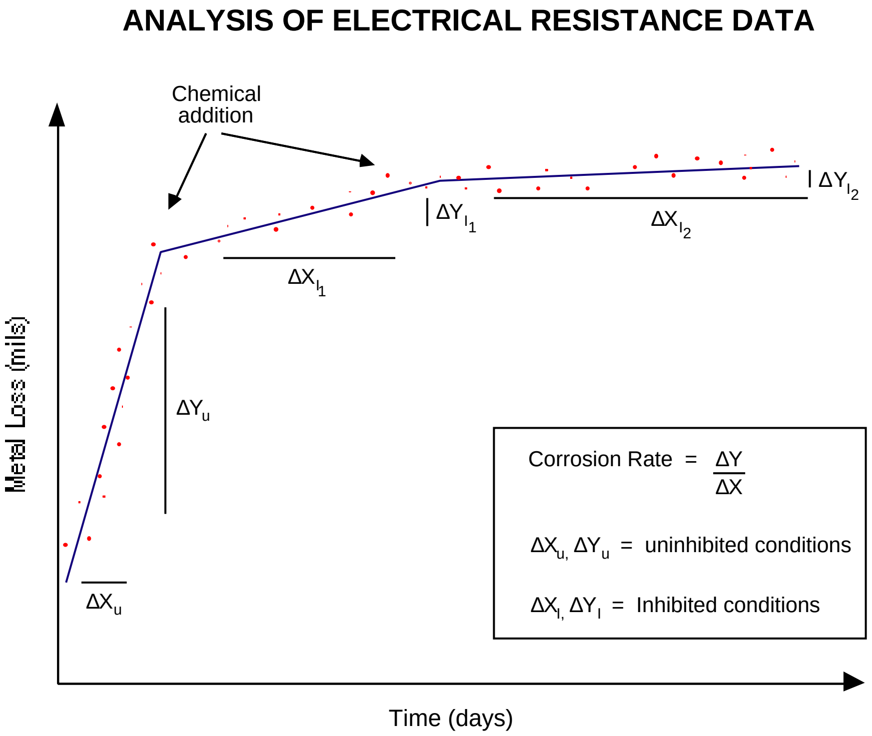
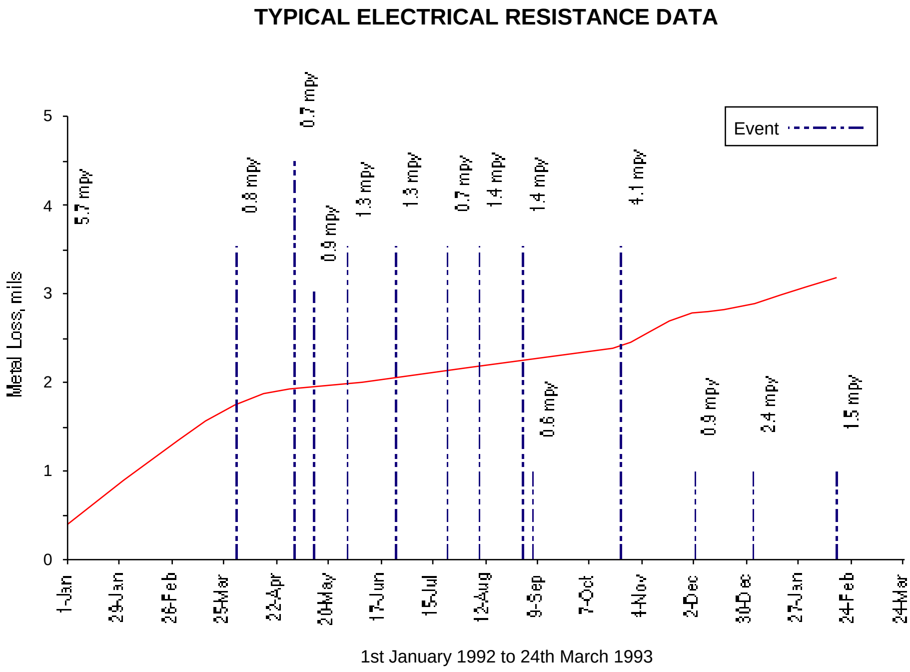


Figure 16: *A Typical ER Probe Response for a Well Flowline at Prudhoe Bay.*



Typically ER data is presented as corrosion rate against time. This approach is useful in determining actual penetration rates but quite often presentation of the raw data is sufficient to show relative corrosion trends and changes in corrosion risk.

Equipment

The equipment consists of a probe and a measuring device. Typical

Figure 17a: *Typical ER Probe Designs*

electrical resistance probe designs are shown in Figure 17a.
The measuring device passes a known current through the test sample and internal reference using a Wheatstone Bridge arrangement. The difference in resistance between the two elements is measured. This is then converted into a metal loss and subsequently a corrosion rate. The measuring equipment can either be a portable device which is used to monitor several probes manually or a hard-wired system where a dedicated data logger is installed with each probe. Hardwiring minimises signal noise associated with probe connection and recent reports from Alaska indicate an order of magnitude improvement in the quality of the data obtained. The dedicated type of data logger is preferred as it allows repetitive measurements to be taken. Commercial data loggers allow measurements to be made as frequently as every 5 minutes. However, a more typical time interval would be 15-60 minutes. The high frequency data collection rate minimises signal noise associated with any thermal oscillation of the probe. This type of data logger can also be hardwired back to a control room for subsequent data analysis or can be interrogated manually over an extended period (1-3 months).

The most sensitive probes will respond to ca 1 mpy corrosion rate after ca 1 day. However, for many applications probe life must be considered as well as sensitivity. A sensitive probe will have a short lifetime because it requires a thin sensing element (Figure 17b).

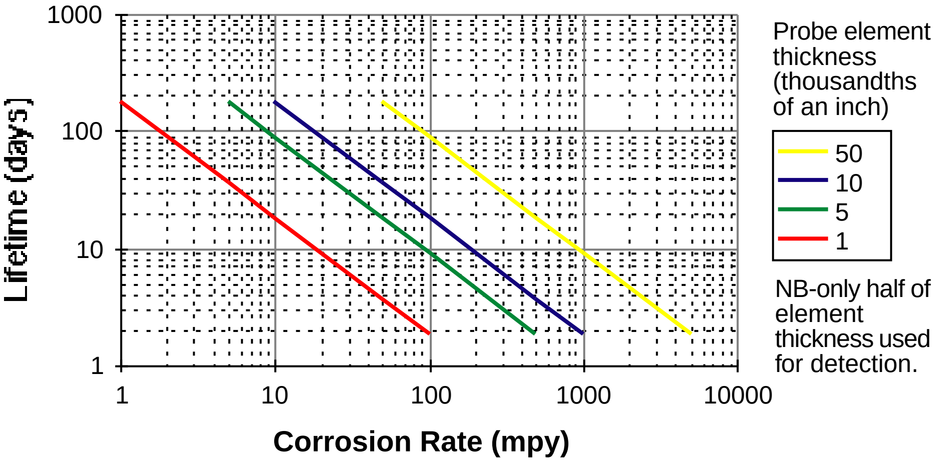


Figure 17b: *Illustrative Sensitivity Lifetime Chart for ER probes (see manufacturers' literature for precise details)*

General Comments

- Continuous logging of data gives at least an order of magnitude increase in the quality of the data obtained. This is because the signal noise associated with probe connection and thermal oscillation are reduced.
- The probe monitors material loss directly and so does not require a continuous conductive path. Therefore the ER technique can be used to monitor corrosion in areas where water wetting is not continuous or under deposits where conductivity may be limited.
- Electrical resistance probes are not just limited to monitoring corrosion but can be used to monitor any material loss such as caused by erosion or cavitation etc.

Electrical Resistance Methods: Advantages and Disadvantages

Advantages	Disadvantages
❍ Direct measurement of material loss	❍ Sensitive to thermal changes.
❍ Will work in most environments:- Does not require continuous (spatial or time) aqueous phase	❍ Corrosion rate calculated as uniform corrosion no information on localised attack
❍ Quicker response than weight loss coupons	❍ Trade off between sensitivity and probe life
❍ Data interpretation straight forward	❍ Manual readings subject to signal noise (probe connections)
❍ Continuously logged probes give high quality data (logging rate as low as 5 min.)	❍ Adversely affected by conductive surface films e.g. FeS in sour conditions
❍ Sensitive to erosion as well as corrosion. Non-corroding elements can be used as pure erosion monitor	❍ Crevice corrosion can occur on poorly constructed flush mounted probes
❍ Meter output is in cumulative material loss. Slope needed to calculate corrosion rate.	❍ Requires insertion and retrieval under pressure which can have safety implications

Downhole Corrosion Monitoring System

Rohrback Cosasco Systems are developing a downhole corrosion monitor based on their established ER technology[19]. The system comprises a probe and measuring system located in a 1.25” diameter tube which is approximately 14” long. The instrument is designed to be inserted and removed from a production string by conventional wireline operations. The system will log data continuously whilst downhole and can then be interrogated on retrieval. At present the system is under development and is undergoing limited field evaluation.

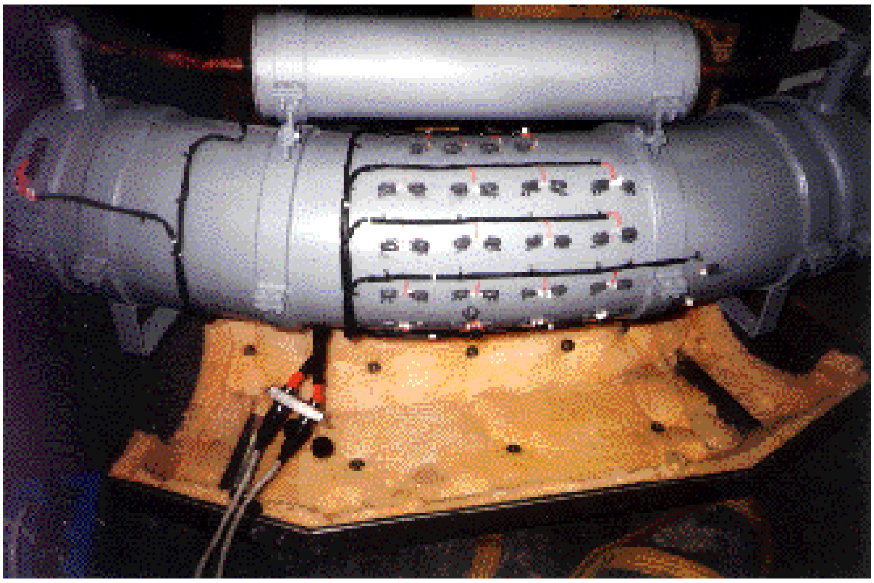
Weld Corrosion Sensor

Cormon Corrosion Monitoring Systems [16] in conjunction with a major North Sea operator are developing a weld corrosion sensor based on ER technology. The element of the probe is manufactured from the field weldment of interest. The hardware is designed such that the weldment is galvanically coupled to the pipe wall except when a resistance measurement is being made. This approach ensures that a favourable area ratio is simulated. At present there are no published results on this approach but in principle this should be an appropriate method of monitoring galvanic type corrosion.

Field Signature Method (FSM)

The field signature method (FSM) is a novel monitoring system developed by CorrOcean [20] and is a variation of the ER method. In contrast to traditional ER measurements the FSM is non-intrusive and uses the pipe wall as the active electrode area (Figure 17c). An electric current is fed into the pipe wall through two contact pins. These pins can be either welded or clamped onto the outer pipe wall. The voltage drop between the pins is then measured. The voltage drop will increase as the pipe wall thins (general corrosion). By undertaking successive measurements a rate of wall loss is obtained which can be converted into a corrosion rate. In the FSM technique an array of studs (24 to 64) are used so that a large area (0.1 to 1.1m^2) of pipe can be monitored. The sensitivity of the device is 1/1000 of the original wall thickness. This equates to detection of corrosion rates in excess of 200mpy within 1 day for a typical export pipeline (20mm pipe wall thickness). The sensitivity is comparable to auto UT measurements. The advantage over traditional methods is that non-uniform corrosion can be monitored, but the detection limit is dependant on pin number and density.

Figure 17c: *Field Signature Method Location*



Field Signature Method (FSM): Advantages and Disadvantages

Advantages	Disadvantages
❍ Monitors in-situ pipework (Non-intrusive)	❍ Initial installation costs high
❍ No access fitting required	❍ Sensitivity limited to 1/1000th of original pipe wall thickness
❍ No limitation on geometry	❍ UT map required to establish initial wall thickness
❍ Large area of pipe covered	
❍ Flexible design: can be used to monitor unique locations	
❍ Subsea version available	

"Micro-Corr" Probes

The Cortest "micro-corr" probe is a new development which was launched at the 1996 NACE Corrosion Exhibition in Denver. If the claims for the new probe are borne out then it could be a significant advance. It is similar in form to an ER probe but instead of measuring the metal loss in the foil or wire by electrical resistance, it uses magnetic inductance (ie the "Hall effect"). This gives several claimed advantages...

1. more accurate determination of metal loss, ie a higher signal/noise ratio, such that accurate corrosion rates can be obtain in minutes, the same as for LPR probes (LPR probes require a conducting media whereas micro-corr probes do not - analogous with ER probes).

2. measurement not affected by conductive surface flim (eg FeS) (can interfere with ER probe)

3. measurement not affected by temperature variations (can have a major impact on short-term ER response)

In summary the probe is claimed to..."combine the speed of LPR with the universal applicablity of ER"[21]. The probe will suit standard ER access fittings and will cost ca 20% more than ER equipment. Cortest already have a European patent and are waiting for one in the US. The probe is currently on trial with various operators.

Sand/Erosion Monitoring:

Erosion can be caused by operating under high velocity conditions or when sand (solids) are present. Detection of sand is important not only from an operational standpoint (filling of vessels) but also to determine the possibility and/or degree of erosion. At present there are three sand monitors available commercially. The Fluenta [22] and Stresswave [23] systems monitor the acoustic noise associated with particle impact which is then converted into a sand production rate. The CorrOcean [20] device is an indirect method based on the ER principle and measures material loss which is then converted into a sand production rate.

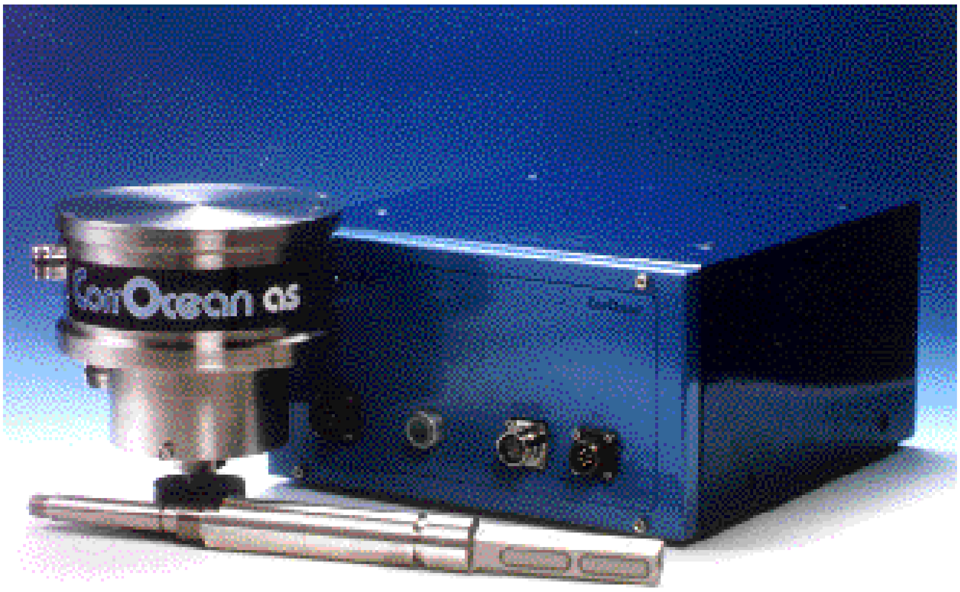


Figure 17d: *CorrOcean Sand Monitor*

The CorrOcean method is based on an intrusive electrical resistance probe. The sensing elements are made from Monel which is corrosion resistant but is claimed to have similar erosion properties to carbon steel. These elements are mounted on a ceramic substrate and vary from 20 to over 500 microns in thickness. The thickness of the elements used will depend on the sensitivity and probe lifetime required. The method allows the erosion rate to be determined and uses experimentally determined calibration factors to convert these data into sand production rates. The probe is inserted into the line using standard 2” access fittings.

Although quantitative information on sand production rates is important, often all that is required is an erosion monitor or a sand alarm (sand or no sand). In these cases all that may be required is a device which can rapidly detect material loss (erosion), such as a traditional ER probe constructed from an appropriate corrosion resistant material. Consideration should be given to probe sensitivity. The CorrOcean probe is up to an order of magnitude more sensitive than the traditional ER probes. However, for many applications probe life must also be considered as well as sensitivity. A sensitive probe will have a short lifetime.

Erosion-corrosion occurs in environments which have the potential to be both erosive and corrosive. Erosion-corrosion can be independent (total wastage is the sum of the wastage from both mechanisms) or synergistic (total wastage is greater than the sum of the wastage from both mechanisms). ER technology can be used to investigate these effects. Comparison of material loss from a carbon steel electrode compared with a corrosion resistant material undergoing erosion will give information on any synergy between erosion and corrosion. Cormon Corrosion Monitoring Systems [16] market a band probe which is designed for application in severe environments. This can have two elements, one made from carbon steel the other from a corrosion resistant material, allowing erosion/corrosion information to be obtained from a single probe.

❍ Comments on Sand/Erosion Monitoring

- ER technology for sand/erosion monitoring has been used in the field by BP Colombia.
- The use of ER technology looks promising in the assessment of erosion/corrosion where information on sand rate and material loss is required
- The ER approach measures the effect caused by the sand rather than the quantity of sand itself.
- The ER based sand/erosion technology is available for subsea applications.

ER Based Sand/Erosion Monitors: Advantages and Disadvantages

Advantages	Disadvantages
❍ Relatively simple to operate and collect data	❍ Sensitive to scale and wax formation, which may influence erosion rates.
❍ Immune to external acoustic noise	❍ Sand impact must cause erosion in order to allow the sand rate to be measured
❍ Measures material loss (erosion) rather than sand rate	❍ Relatively high cost of probe replacement compared to standard ER probes.
❍ Data interpretation straight forward	❍ Sensitive to particle size and flowrate (A 10% error in flow rate will lead to a 25% error in sand rate)
❍ Can give information relating to erosion/corrosion mechanisms	❍ Best results in small diameter high velocity lines

❍ Subsea version available	❍ Requires insertion and retrieval under pressure which can have safety implications

Linear Polarisation Resistance Method (LPR)

Background

For several decades this method has been a standard electrochemical approach for monitoring uniform corrosion. The basic principles of the method were developed by Stern and Geary in 1957 [24].

The measurement involves polarising the metal of interest and measuring the resulting current. At small voltage perturbations (up to ±25mV) the current is linearly related to the voltage giving a constant called the polarisation resistance (R_p). This is analogous to Ohm's Law:

$$R_p = \Delta E / \Delta i$$

where: R_p = polarisation resistance (ohms)
ΔE = potential difference (V)
Δi = change in current (A)

The polarisation resistance can be converted into a corrosion rate by the Stern-Geary equation,

$$i_{corr} = B / R_p A$$

where: i_{corr} = corrosion current (A cm^{-2})
B = Stern-Geary constant (typically 0.027V for carbon steel, other values available from literature [25])
A = electrode area (cm^{2}).

$$\text{corrosion rate (mpy)} = \left[\frac{1.29 \times 10^5\, M}{zD}\right] \left[\frac{B}{R_p A}\right]$$

where: corrosion rate is in thousandths of an inch per year (mpy)
M = atomic mass (g) (55.9g for iron)
z = electron loss per atom (2 for Fe^{2+})
D = density (g/cm^3) ($7.86 g/cm^3$ for iron)

The advantage of the LPR technique over both coupons and electrical resistance probes is that it gives an instantaneous measure of corrosivity.

Equipment

The technique requires both a probe and a monitoring device. The probe can be either flush mounted or intrusive and have either 2 or 3 electrodes constructed from the material of interest. Typical three electrode probes are shown in Figure 18.

Figure 18: Typical Three Electrode LPR Probes

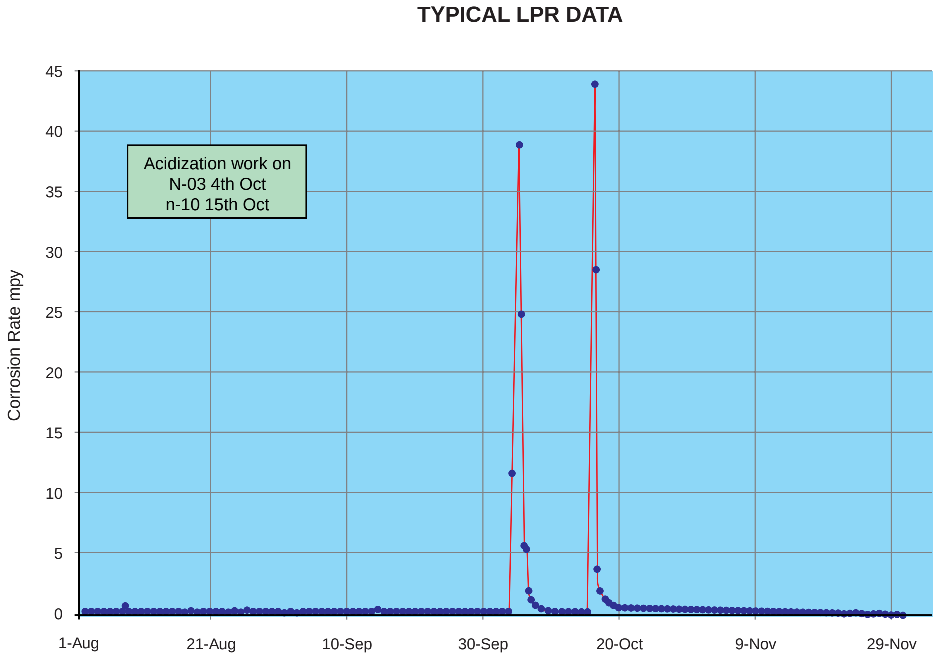
The instrument allows a fixed potential to be applied to the test electrode and the current measured. Typically the result is displayed as a corrosion rate with the instrument using an assumed Stern-Geary constant to convert the polarisation resistance into a penetration rate. Modern instruments allow the operator to define the applied potential, the time over which the current is measured and the assumed Stern Geary constant. Typical values are given in Table 3

Table 3: *Typical Instrument Settings for LPR Measurements*

LPR parameter	Typical Value
Polarisation potential	+/- 25mV
Time potential applied	20 sec
Stern Geary constant (for CO_2 corrosion of carbon steel)	0.027V

The instrument can either be a hand held device or a dedicated data logger for each probe. The installation is similar to that required for ER measurements. The advantages of the dedicated logger are that repetitive measurements can be undertaken and stored for future analysis; this allows upset conditions to be more easily identified. A typical LPR output from an Alaskan flowline is shown in Figure 19. The figure indicates the rapid response of the technique to changing operational conditions.

Figure 19: *Typical LPR Probe Response Indicating Response to Operational Changes.*



General Comments

- The LPR technique provides a rapid measure of fluid corrosivity. Therefore, the technique is extremely sensitive to changes in environment. However, it must be noted that this does not necessarily translate into wall thickness loss. The technique can be used for process control such as oxygen control in a sea water system.

- The technique measures the total resistance of the system. This includes not only the polarisation resistance (R_p), but resistances associated with the measurement leads and corrosive fluid (solution resistance). In some situations (wet gas lines) the solution resistance is significant and needs to be corrected for. Modern instruments often have the capacity to automatically compensate for solution resistance. If not, the solution resistance must be determined and corrected for in order to obtain a sensible corrosion rate estimate. AC impedance can be used to determine solution resistance.

- The conversion of the polarisation resistance to corrosion rate requires a value for the Stern-Geary constant. This value can be obtained from standard tables[26]. However, this can lead to errors in the quantification of the measurement. LPR data should be used to indicate corrosion trends rather than absolute penetration rates.

- The technique requires the probe to be continuously water wet. Lack of water wetting is not the same as low conductivity and cannot be compensated for. In most oilfield applications water cuts in excess of ca 10-20% are required.

- Electrode connector configurations used by different probe manufacturers are **not** standard. Therefore, the compatibility of the meter with the probe should be established. Furthermore, connector design is common to **both** electrical resistance and LPR probes, so it is essential to identify the probe type if the two techniques are used in the same facility.

- A given meter will assume a surface area when calculating the corrosion rate. The surface area of the probe should be established to ensure it is similar to that used in the corrosion rate calculation and if not a correction should be made.

- Flush mounted probes can often short circuit under conditions where conductive deposits can form (sulphide containing environment). This can often lead to an over estimation of potential corrosivity.

Linear Polarisation Resistance Technique: Advantages and Disadvantages

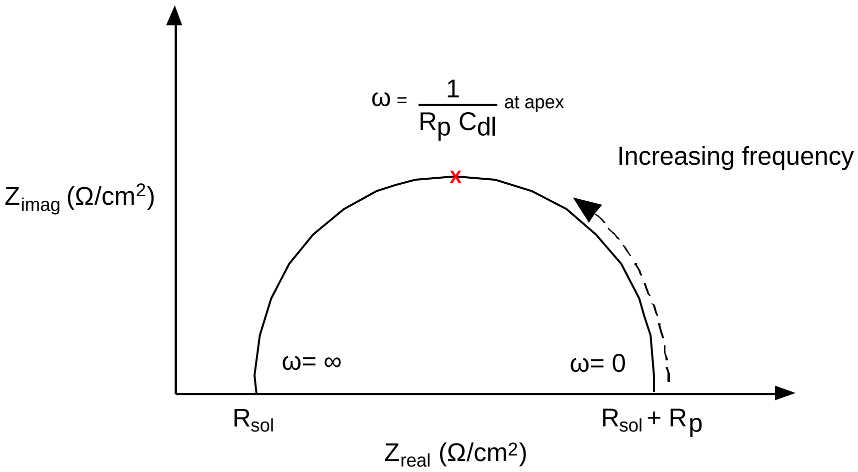
Advantages	Disadvantages
❍ Rapid measurement of corrosivity	❍ General corrosion rates indicative of trend rather than absolute.
❍ Sensitive to any process changes, flow, pressure, temperature etc	❍ Need continuous water phase (both spatially and time)
.	❍ Probes are susceptible to fouling either by deposits or partial wetting by hydrocarbon phase.
	❍ No localised corrosion information

AC Impedance

Background

AC impedance has been used in the laboratory for corrosion studies for over a decade. A comprehensive review of the theory and application is given in a review by Dawson et.al [26]. The technique uses identical probes to those in the LPR technique. However, the instrumentation is quite different. In the AC impedance technique the applied voltage is not DC as in the LPR technique but is an AC signal covering the range from 100kHz to 1mHz. The current response of the cell is monitored and, using simple AC theory, the impedance of the cell is calculated. The data can then be presented in several formats, the most common being the complex plane plot (or "Nyquist" plot). A schematic presentation of a typical AC plot is given in Figure 20.

Figure 20: Analysis of AC Impedance Data



Where :

R_{sol} = solution resistance (ohms)

R_p = polarisation resistance (ohms)

ω = $2\pi f$ (s^{-1}) = frequency in radians per s

f = frequency in Hz

C_{dl} = double layer capacitance (farads)

AC impedance allows the solution resistance (R_{sol}) to be de-coupled from the polarisation resistance (R_p) and, in addition, the double layer capacitance (C_{dl}) of the corrosion reaction can be obtained (see Figure 20).

Once a value for the polarisation resistance has been obtained then an estimate of corrosivity can be made in much the same way as the LPR technique (see p60-64). The interpretation of the AC response is often difficult in any but the most simple case and therefore, although it is possible to obtain detailed mechanistic information, in reality the technique is often only used to correct for solution resistance.

Equipment

As stated previously the probe used for AC impedance measurements is identical to that used for LPR monitoring. The instrumentation can be either portable or permanently installed. Modern equipment allows full computer control of the output signals and data analysis. The more expensive equipment has built-in frequency response analysis allowing more rapid data analysis. However, this technique requires trained personnel for its routine operation and data interpretation.

General Comments

- Provides a fairly rapid estimation of corrosivity, which is corrected for solution resistance effects. The technique should be used to indicate corrosion trends rather than absolute values.
- The technique, like all other electrochemical techniques, requires the probe to be continuously water wet. Lack of water wetting cannot be compensated for and should not be confused with conductivity. In most oilfield applications water cuts in excess of 10-20% are required.
- Data interpretation can be difficult and so the technique should not be used for routine corrosion monitoring. The technique may have limited application in troubleshooting studies.

AC Impedance : Advantages and Disadvantages

Advantages	Disadvantages
❍ Determination of solution resistance	❍ General corrosion rates indicative of trend rather than absolute. Little advantage over LPR.
❍ Solution resistance compensation. Some application in low salinity brines (wet gas).	❍ Need continuous water phase. Does not work with intermittent oil wetting of probes.
❍ Rapid measurement of corrosivity	❍ Equipment very expensive and data interpretation can be difficult
❍ Sensitive to any process changes, flow, pressure, temperature etc.	❍ No localised corrosion information

Electrochemical Noise

Background

The electrochemical noise (EN) technique is a relatively new technique for corrosion monitoring [27]. The technique differs from most electrochemical techniques in that an external signal is not applied to the corrosion probe but rather the inherent potential and/or current fluctuations are monitored with time. These oscillations in potential (electrochemical potential noise, EPN) and current (electrochemical current noise, ECN) are a result of the random nature of corrosion. Data analysis methods have focused on both statistical and spectral methods. The trend for corrosion monitoring applications is moving towards data analysis based on simple statistical manipulation of the data. CML [28] have shown that the ratio of the standard deviation of the voltage noise (V_n) and the current noise (I_n) for digital systems allows a noise resistance (R_n) to be estimated.

$$R_n = V_n / I_n$$

Where: R_n = Noise resistance
V_n = Standard deviation of 1024 potential noise datum points
I_n = Standard deviation of 1024 current noise datum points

The noise resistance (R_n) is equivalent to the polarisation resistance (R_p) obtained from the LPR technique and can also be used in the Stern-Geary equation to determine corrosion rates.

With the EN method the data sampling rate and data collection time is very important. Typically a data collection rate of 1 Hz is used and the data collected for a period of 15 minutes to obtain a reliable estimate of corrosivity. The data sampling rate may need to be increased if the process perturbation is on an equivalent or faster time scale (multiphase flow). Comparing the EN technique with the LPR technique, EN has the advantage in that no external signal is applied but the measurement time is significantly longer and the data analysis more complex. Some commercial suppliers of EN systems [29] claim that simple statistical data can give qualitative results regarding the localised nature of the corrosion process. The ratio of the amplitude of the current noise to the mean value of the current noise has been shown to give an indication as to the type of corrosion mechanism occurring. Work undertaken at BP Sunbury [30] has shown that the basic concept is correct for austenitic stainless steels (316 etc.). However, caution must be applied in using this approach to other materials (carbon steel and CRAs) and systems which are not fully characterised.

Another approach is to monitor the raw potential and current data along with other process parameters. This approach would be carried out in order to identify process operational changes which occur at short time intervals, but contribute significantly to the overall material loss. The limitation of this approach is that it only gives qualitative data. However, it does allow short lived transient upsets to be identified and rectified. An example of this approach has been the detection of oxygen transients in re-injected produced water lines at Wytch Farm[31].

Figure 21 shows a raw data response for the addition of corrosion inhibitor to a multiphase flow line.

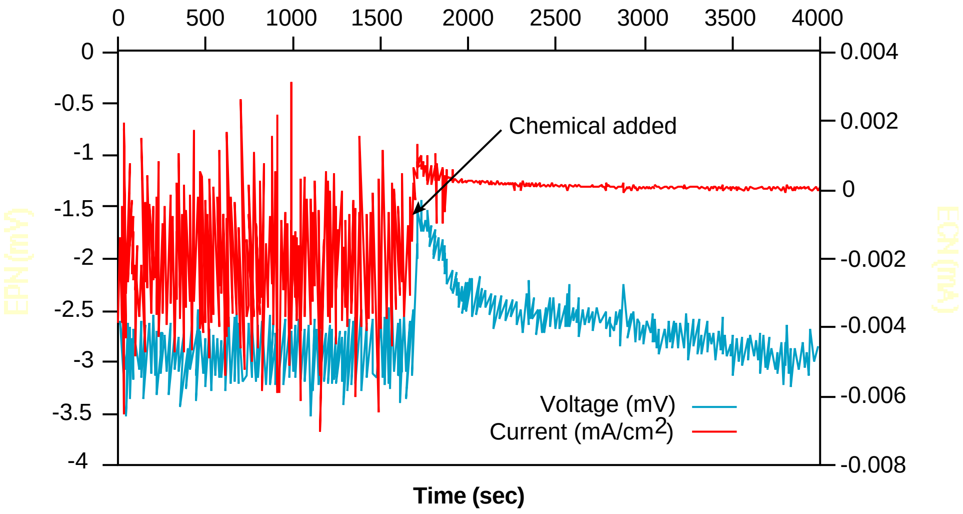


Figure 21:
Electrochemical Noise Response to Corrosion Inhibitor Addition in a Multiphase Flowline.

Equipment

The equipment required includes a probe and monitoring system. The probe is a traditional LPR probe and so the technique suffers all of the drawbacks associated with this approach. The hardware consists of a fully computer-controlled zero resistance ammeter (ZRA) and voltmeter. This allows the electrochemical current and noise signal to be collected simultaneously and stored for future analysis. It should be noted that the system should allow flexibility in data collection rates depending on the process being monitored. Typically the range 10 to 0.01 Hz is sufficient. Although the technique is relatively new several manufacturers now offer complete corrosion monitoring systems based on this technique.

General comments

- The technique gives a rapid response to changing operating conditions. The output is only qualitative and quantifiable results can only be obtained by statistical analysis of relatively large data sets. Analysis time is in the order of minutes. The data analysis and conversion to corrosion rate is based on the determination of a polarisation resistance and so suffers the same limitations as the LPR technique.
- Claims have been made on its applicability to determine localised corrosion rates but this is still at the laboratory stage of development.
- The technique should be seen only as a useful supplement to other more traditional monitoring methods.
- The main benefit of the technique is that the response of the probe can be related back to operational data on a similar time frame. This allows corrosivity changes to be related directly back to precise operational activities.
- The technique requires the probe to be continuously water wet. Lack of water wetting is not the same as low conductivity and cannot be compensated for. In most oilfield applications water cuts in excess of 10-20% are required.
- Flush mounted probes can often short circuit under conditions where conductive deposits can form (sulphide containing environment). This aspect can often lead to an over-estimation of potential corrosivity.

Electrochemical Noise Technique: Advantages and Disadvantages

Advantages	Disadvantages
❍ Rapid response to process upsets. Useful in correlating process to corrosion response, e.g. “troubleshooting”.	❍ General corrosion rates indicative of trend rather than absolute rates for the pipewall
❍ Useful in some mechanistic studies: inhibitor film persistency	❍ Need continuous water phase both spatially and in time
❍ Sensitive to any process changes, flow, pressure, temperature etc	❍ Probes are susceptible to fouling either by deposits or partial wetting by hydrocarbon phase.

- Standard LPR probe used

- No localised corrosion information
- Data interpretation difficult. Large amounts of data collected with long term data more easily obtained from ER etc.

Galvanic Corrosion Monitors

Background

Galvanic corrosion monitors are based on the zero resistance ammeter (ZRA) technique and monitor the current flowing between two dissimilar metal electrodes. The materials of interest are coupled together through the ZRA. The electrodes adopt a common potential and the galvanic current flowing is measured by the ZRA. The magnitude of the current and its direction of flow gives an indication of corrosivity and which material is anodic or cathodic. The output signal is dependent on the electrode materials, the area ratio between the anode and cathode, and the potential corrosivity of the fluids. The latter property has been used to monitor dissolved oxygen in sea water for many years e.g. carbon steel and admiralty brass when coupled together give a galvanic current which is proportional to the dissolved oxygen content.

Equipment

The equipment for galvanic monitoring consists of a probe and a relevant monitoring instrument. The probe is usually based on a standard LPR design or can be a multi-element probe constructed from the relevant materials. The instrumentation is available commercially [16, 17] and is based on the use of a ZRA and voltmeter. The equipment can be hand held or hardwired for on-line monitoring. The latter is preferred for ease of data handling and interpretation.

General Comments

- The technique gives a rapid response to changing operating conditions but the output is only qualitative. The magnitude of the output signal is related to the electrode area as well as corrosivity. Although the output signal is proportional to the corrosion current, it is not equal to it, as part of the corrosion current is always distributed between localised areas on each electrode. Care must be taken when using galvanic monitors to monitor dissolved gases such as oxygen since the measurement will be related to the relative areas of the anode and cathode electrodes.

- The main benefit of the technique is that the response of the probe can be related back to operational data on a similar timeframe. This allows corrosivity changes to be related directly back to precise operational activities.
- The technique requires the probe to be continuously water wet. Lack of water wetting is not the same as low conductivity and cannot be compensated for. In most oilfield applications water cuts in excess of ca 10-20% are required.
- Flush mounted probes can often short circuit under conditions where conductive deposits can form (sulphide containing environment). This aspect can often lead to errors in monitoring the galvanic effect.
- Fouling of the probe is very common in sea water systems and can lead to a lack of sensitivity. The output of the probe should always be checked against other monitoring methods.
- The galvanic type of approach has been used to study preferential weld corrosion. In this case the technique is only valid if the corrosion mechanism is galvanic. Recent studies have shown that in production systems preferential weld attack is related to a corrosion resistance effect rather than a galvanic mechanism.
- With all galvanic corrosion monitoring it is important that the probe material reflects the application of interest. Great care must be given to ensuring that the alloy composition and micro-structure of the probes is representative of actual system materials.

A major Norwegian operator undertook an extensive preferential weld corrosion monitoring programme. It was only after the trials had finished that it was found that probe elements had been incorrectly mounted in the probe. Data which were thought to relate to the heat affected zone were in fact relating to the weld root itself.

This problem highlights the need for good quality control in the preparation of such sophisticated probes.

Galvanic Corrosion Monitoring Technique: Advantages and Disadvantages

Advantages	**Disadvantages**
❍ Rapid response to process upsets. Useful in correlating process upsets to corrosion response. ("Troubleshooting")	❍ General indication of corrosivity. Rates indicative of trends rather than absolute.
❍ Sensitive to any process changes, flow, pressure, temperature etc.	❍ Need continuous water phase
❍ Standard LPR probe used or more sophisticated multi-element probe	❍ Probes are susceptible to fouling either by deposits or partial wetting by hydrocarbon phase.
	❍ No localised corrosion information
	❍ Only valid for monitoring true galvanic corrosion effects.

Other Related Techniques

At present Cormon Corrosion Monitoring Systems [34] are developing a galvanic corrosion monitor based on the ER technique. In this new method the active element is constructed from the material of interest (i.e. weld root) and connected to the pipewall to simulate any galvanic effect. The galvanic couple is disconnected each time the ER probe is interrogated. This provides a more accurate measurement of the corrosion rate than is possible by using the galvanic current alone. However, it does have the limitations of any ER based technique.

Hydrogen Probes

Background

Corrosion reactions occurring at low pH or where proton reduction is a significant cathodic process generate molecular hydrogen as a cathodic reaction. The reaction is fairly complex...

$$
\begin{array}{rcl}
H^{+}{}_{sol} & \rightarrow & H^{+}{}_{ads} \\
H^{+}{}_{ads} + e^{-} & \rightarrow & H^{o}{}_{ads} \\
H^{o}{}_{ads} + H^{o}{}_{ads} & \rightarrow & H_2 \uparrow \\
\text{and } H^{o}{}_{ads} & \rightarrow & \text{diffusion through metal}
\end{array}
$$

Hydrogen ions are formed in solution and will adsorb onto the metal surface (H^{+}_{ads}) where they can be reduced to form atomic hydrogen (H^{O}_{ads}). Atomic hydrogen atoms then combine to form molecular hydrogen (H_2). A proportion of the atomic hydrogen atoms do not combine on the active corroding surface but diffuse through the metal until they reach a defect or the outer surface of the metal where they combine to form molecular hydrogen. In certain steels this can lead to blistering and hydrogen induced cracking (HIC) and, with high strength steels, hydrogen embrittlement. H_2S, HCN and HF are known to retard the recombination of atomic hydrogen at the corroding surface. For a given corrosion rate there will be an increase in the flux of atomic hydrogen atoms through the micro structure of the steel in the presence of these gases.

Hydrogen monitoring measures the flux of hydrogen passing through the steel and correlates this with general corrosivity and the possibility of hydrogen-related damage. The methods presently used to monitor this effect comprise probes inserted directly into the process stream or patch detectors welded onto the outside of the pipe wall.

Equipment

❍ Hydrogen probe

The hydrogen probe was developed to monitor hydrogen flux in sour oil and gas production equipment. The probe can be inserted into a line through a standard 2” access fitting. The probe is thin walled and collects the molecular hydrogen (H_2) resulting from the combination of atomic hydrogen diffusing through the steel in an artificial cavity within the probe. The increase in pressure associated with this molecular hydrogen is detected by a gauge or with a pressure transducer. The introduction of the pressure transducer allows the system to be monitored continuously. The rate of pressure build up can be related to the potential for hydrogen damage occurring in the vessel or pipework. A typical hydrogen probe is shown in Figure 22.

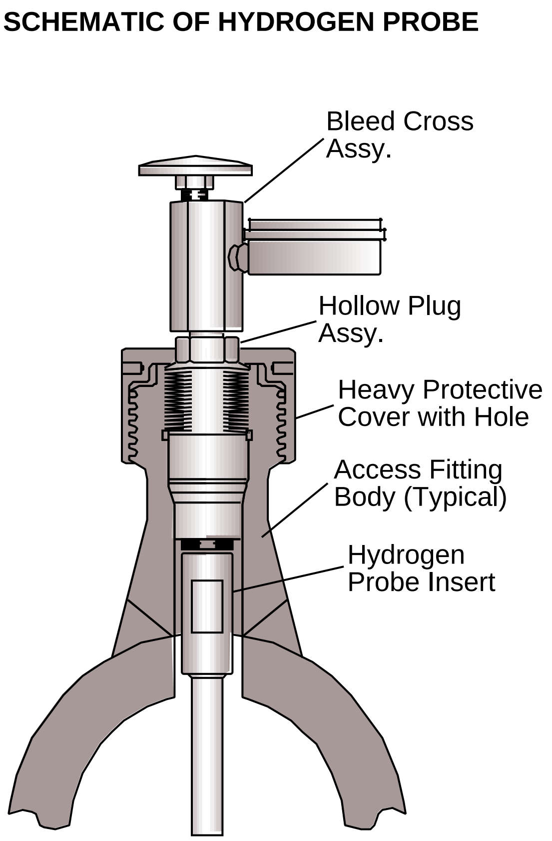

SCHEMATIC OF HYDROGEN PROBE

Figure 22: *Schematic of a Typical Hydrogen Probe*

❍ Patch probe

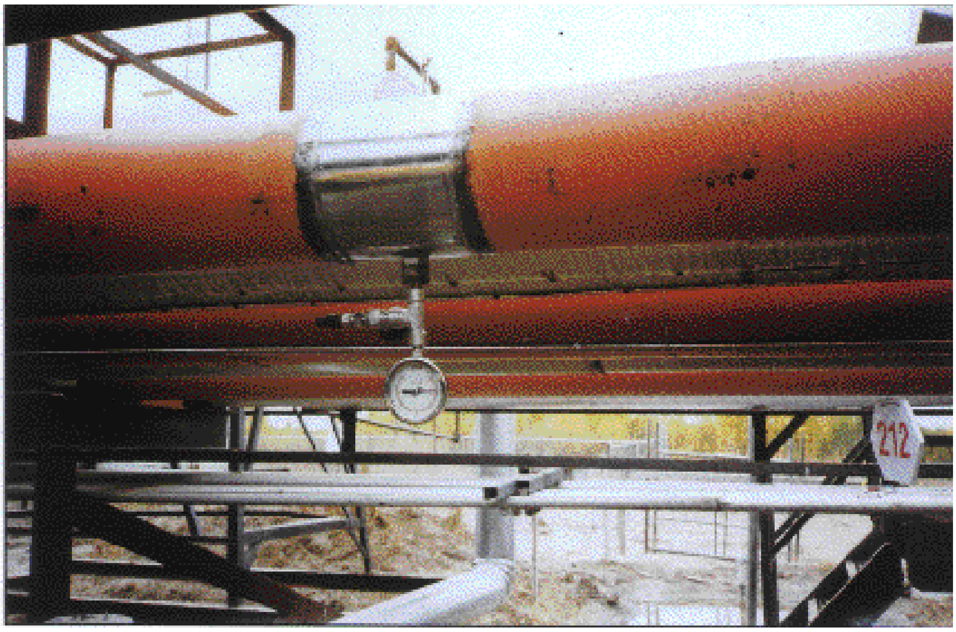
There are several designs of patch probe but they all are based on the same principle. The traditional patch probe involves the attachment of a contoured carbon steel patch to the outside of the pipework. The atomic hydrogen diffusing through the steel is collected in the cavity underneath the patch and measured by the build-up of pressure. The advantage over the hydrogen probe is that it measures the direct flux through the pipework. Patch probes can be quite slow to respond and it may be necessary to stress-relieve after welding the patch in place which is difficult on large vessels.

Other types of patch probe involve attaching a small electrochemical cell to the outside of the vessel or pipework. One electrode, usually a palladium foil, is attached to the pipework which is used to oxidise the atomic hydrogen as it diffuses into the electrochemical cell. The current flowing is proportional to the hydrogen flux. This method is quite sensitive but is difficult to use and needs a skilled operator, regular maintenance and is not suitable for routine use.

- **Beta-Foil**

The Beta-Foil is a variation on the traditional patch probe [32]. In this case a thin foil is glued onto the outer pipewall and a vacuum drawn between the foil and pipework (Figure 23).

Figure 23: *Typical Beta Foil Installation*



As the atomic hydrogen diffuses into the vacuum, and recombines to form molecular hydrogen, the pressure increases. The increase in pressure can be measured via a vacuum gauge or a pressure transducer. No welding is involved in this system and so it can be retrofitted to any pipework or vessel without the need for stress relieving. However, it can sometimes be difficult ensuring a gas-tight seal around the foil and in the link to the gauge.

General Comments

- Hydrogen probes or patches are ideal for estimating the flux of hydrogen through a steel structure. This information is important with respect to establishing whether a material may be susceptible to cracking or blistering. As the hydrogen flux passing through a metal is only a fraction of the hydrogen produced at the cathode, it can only be used as a qualitative corrosion monitoring method. In addition there are many reactions which can affect the diffusion of hydrogen without affecting corrosivity. Also some corrosion inhibitors work by retarding the recombination of atomic hydrogen at the surface. This can lead to an increase in hydrogen flux combined with a real decrease in corrosivity.

- Careful consideration of the corrosion mechanism is needed before deploying this monitoring method.
- The hydrogen monitoring system cannot be used when the cathodic reaction does not involve hydrogen reduction (i.e. sea water systems, alkaline systems). The technique is not applicable to nickel or copper based alloys where atomic hydrogen is insoluble in the metal structure or with titanium, which forms stable hydrides and limits the diffusion of hydrogen.
- Care must be taken to ensure gas seals are maintained in these pressure type systems.

Hydrogen Probes: Advantages and Disadvantages

Advantages	**Disadvantages**
❍ Direct measure of hydrogen liberated by corrosion process	❍ Only a general indication of corrosivity.
❍ Does not have to be intrusive and can be retro-fitted	❍ Sensitive to environment changes which affect the hydrogen combination process (H_2S)
❍ No need of a continuous water . phase. Will work wherever corrosion occurs	❍ no localised corrosion information
	❍ Detailed understanding of corrosion mechanism required before application

Process Stream Monitoring

Process Data

It is important to record standard process data on a regular basis. This should include temperature, pressure, flowrates (oil, gas, water), water cut etc. Ideally these should be recorded on a central database for easy access.

Water Analysis

Water sampling involves the collection of water samples for chemical analysis. The analysis traditionally concentrates on inorganic salts such as: Ca^{2+}, Ba^{2+}, Sr^{2+}, Na^+, K^+, Mg^{2+}, SO_4^{2-}, Cl^-, HCO_3^-. The analysis should also measure the level of organic acids (acetic acid, propionic acid, butyric acid etc.) in solution. The concentration of bicarbonate and organic acids have a major impact on CO_2 corrosion rates and mechanisms [33]. Furthermore, the concentration of organic acids needs to be known in order to correct the determination of bicarbonate via titration[34]. Analysis information should be taken on an annual basis or more regularly if the water chemistry is likely to change with time.

A knowledge of the water chemistry coupled with CO_2 partial pressure can be used to predict in-situ pH [35] and potential corrosivity [36]. This approach can also be used to predict potential problems associated with the commingling of process streams.

Basic Sediment and Water (BS&W)

It is important to quantify the free water and suspended solids present in export fluids. This type of standard analysis should be carried out routinely at a frequency appropriate to the specific system and will give a good indication on process control.

Gas Analysis

Analysis for gases such as CO_2 and H_2S is important as these gases have a major impact on corrosivity in oil and gas production systems. CO_2 corrosion is caused by the CO_2 gas dissolving in an aqueous phase to form carbonic acid and not as a direct reaction with gaseous CO_2. The corrosion rate prediction models [33] are based on partial pressure of CO_2 in the gas phase rather than the CO_2 activity in the aqueous phase. In order to predict potential corrosivity it is important to know the concentration of CO_2 and the system pressure at the last point the aqueous phase was in contact with the produced gas. A knowledge of the H_2S partial pressure in conjunction with pH and temperature can be used to estimate operational limits for corrosion resistant alloys [36].

On-line Process Monitoring

On-line process monitoring is often preferred to manual methods as it reduces manpower costs and the measurements can be made more frequently and recorded centrally. In a modern production facility many process parameters can be monitored on-line. The section below gives examples of the important on-line monitors with respect to corrosion monitoring.

pH Probes

These can operate in low pressure aqueous process streams where control of the pH is required. On-line monitoring is often preferred over laboratory analysis as the pH of the sample can change considerably on removal from the system. It is recommended that the pH electrode should be easily isolated from the process stream for routine maintenance. This is often achieved by the use of a sidestream. The distance from the fluid take-off should be as short as possible to minimise pressure drop and any change in pH. pH probes suffer from fouling and require frequent cleaning and calibration.

Measurement of Dissolved Gases

The measurement of dissolved gases can be undertaken on-line or by the use of proprietary kits. On-line monitoring is usually used in sea water systems to monitor dissolved oxygen and free residual chlorine concentrations.

The on-line oxygen monitor is an electrochemical-based probe which uses an oxygen-permeable membrane. The oxygen is reduced in the internal electrochemical cell and the current flowing gives an indication of the concentration of dissolved oxygen in the process fluids. Dissolved oxygen probes should not normally be inserted directly into the process stream but fitted into a small flow chamber connected to a sidestream or process off-take. The on-line monitors need routine maintenance and their accuracy checked by other methods e.g. proprietary dissolved oxygen kits. Oxygen monitors can often become fouled or the membrane can be affected by chemicals such as during biocide treatments.

On-line oxygen monitors can be affected by other dissolved gases such as CO_2 or H_2S. Modifications can be made to desensitise the probe response to these gases.

Proprietary kits may be used for the rapid on-site determination of oxygen, CO_2, free chlorine or H_2S in aqueous process streams. These kits are designed to withdraw a small fluid test sample from the flowstream and give a colour change, as a result of a chemical reaction with an in-situ reagent, which is proportional to the particular dissolved gas concentration. Care must be taken to ensure that the fluid sampled is representative of the process fluids. This type of measurement is very reliable in giving relative changes in dissolved gas concentrations. Proprietary kits should be used regularly as a quality control check for all on line monitors.

Other chemical tests can be undertaken to monitor chemicals present in the aqueous stream (e.g. residual sulphite levels) but these are slightly more complicated and require appropriate training/expertise.

Measurement of Dissolved Iron (Iron Counts)

The measurement of dissolved iron in a process stream can be used as a qualitative indicator of corrosivity. This approach is covered in the following recommended practice:

NACE RP 0192:	*Monitoring Corrosion in Oil and Gas Production with Iron Counts*

Many factors can affect the concentration of dissolved iron found in the process fluids and this undermines its reliability as a corrosion monitoring method. For example, precipitation of iron is affected by changes in the production profile through a facility (temperature, pH, [H_2S] etc.). Despite these limitations the iron count approach is valuable in giving a general indication of corrosivity and changes in corrosion trends. When estimating corrosivity changes based on iron counts, consideration must be given to production rates as this will affect the iron concentration. Typically iron counts are presented as iron production rates rather than iron concentration as this will take into account production rate variations. An increase in iron production rate is a warning of an increase in corrosion rate. However a low iron production rate is not a guarantee that a system is under control since pitting corrosion can be occurring which yields only minimal iron mass compared with general attack.

Uniform corrosion will produce other ions as well as iron. Some operators monitor manganese as this element is found in most downhole oilfield steels. The ratio of the manganese:iron concentrations can give an indication of the amount of iron originating from the steel, i.e. corrosion as compared with that being produced from the reservoir fluids. Changes in the ratio between iron and manganese can be indicative of changes in corrosion rate.

Process upsets and shutdowns can lead to short term increases in iron concentrations. Acidisation can result in short term increases in iron concentrations due to the dissolution of protective scales. Significant increases in iron concentrations after a process upset may indicate that more effective control measures are needed during such periods.

Corrosivity Measurements of Fluid Samples

Fluids samples (brine or oil) can be collected from a production system for laboratory corrosion assessment. The corrosivity assessment can be undertaken under controlled laboratory conditions using standard protocols and conditions [37]. This indirect method gives an indication of potential corrosivity and corrosion trends rather than quantifiable corrosion rates.

A representative brine sample can be collected from the field and stored in a sealed plastic bottle for future laboratory evaluation. On reaching the laboratory the sample should be filtered to remove any solid particles and separated from any residual oil. The brine sample is then reconditioned and tested under simulated field conditions to determine its potential corrosivity.

Oil samples are more difficult to evaluate. A new method has been developed at BP Sunbury [38]. An oil sample is mixed with a standard simulated brine solution at two different water cuts (20% and 80%) under simulated field conditions. This allows any residual inhibitor in the oil to partition between the oil and brine phase. The corrosivity of the brine can then be measured. From this result one may be able to extrapolate backwards to make estimates of the corrosivity of the brine which was in the pipeline.

Chemical Deployment Rates

It is important to record chemical treatment type and frequency. Chemical deployment rates should be recorded on a regular basis. The actual dose rate recorded should be a measure of the concentration in the line rather than a volume injected. This aspect is very important as dose rates are often not adjusted after production rate changes.

> ***A recent survey of a North Sea asset indicated that the actual corrosion inhibitor dose rate had been 20-30% below the recommended dose rate for over 12 months due to poor pump calibration and changes in production rate.***

The recording of dose rate can be supplemented by measuring residual inhibitor concentrations in the aqueous stream. This approach assumes that an inhibitor has only one active component or that all of the components distribute between the oil and water phase in the same ratio. This approach is used by some inhibitor vendors to ensure adequate inhibitor concentration in the aqueous stream. Experience has shown that caution should be applied when using this method because interference with other production chemicals can occur. It is recommended that the residual technique is supplemented by the corrosivity approach described above because chemical compatibility may affect inhibitor performance. A more comprehensive review of inhibitor deployment is given in a companion Corrosion Inhibitor Guidelines document [39].

Bacteria

There are several mechanisms by which microbially induced corrosion (MIC) can occur and therefore there is not one single method for diagnosing MIC. The evidence for MIC falls into three categories:

- The nature of a corrosion product
- The morphology of corrosion damage
- The presence of micro-organisms

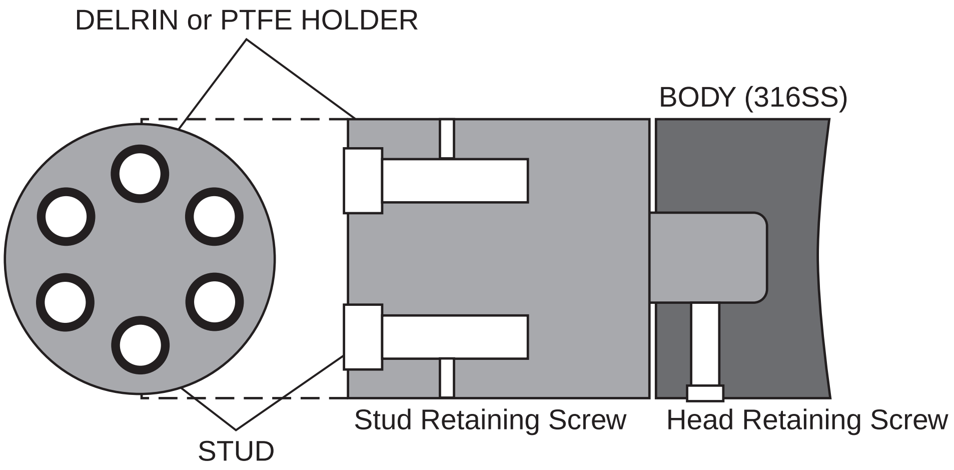
In order to detect and quantify the propensity for microbial corrosion it is necessary to quantify both the mobile (planktonic) bacteria and surface-adhering (sessile) bacteria. The API standard and NACE review covering this area are:

API RP 38	*Recommended Practice for Biological Analysis of Subsurface Oilfield waters*
NACE/ICorr	*Review of Current Practices for Monitoring Bacterial Growth in Oilfield Systems Document 001/87 dated 1987*

The planktonic bacteria may be assessed by removing a liquid sample from the process stream into a standard serial dilution test kit at the well/sample site.

The enumeration of the sessile population development should be assessed by use of a bio-probe exposed to the process stream through a standard 2" access fitting. A standard bio-probe is shown in figure 24.

Figure 24: *A Schematic of a Typical Bio-Probe*



A bio-probe is installed in the flowstream and typically carries 6 removable studs on which the bio-films are allowed to develop. Sequential removal of one or more of the studs from the bio-probe enables the growth of sessile populations to be quantified over time and may provide additional information on the morphology of the corrosion attack. Typical exposure times for bio-probes are 2-4 weeks.

MIC is a problem in oil production systems [40] in areas of low flow such as dead legs, traps or sample points. In water injection systems it is often a serious problem leading to the build up of sludge and/or biofilm with a corresponding increase in corrosion risk. Sea water systems are routinely treated with biocide to control bacteria growth. In these systems routine bacteriological analysis is important.

A recent trial at Prudhoe Bay investigated the effect of biocide treatment on sea water quality. The work indicated a significant increase in biological activity and corrosivity when the biocide treatment was stopped for a prolonged period or the frequency substantially reduced.

Ultrasonic Thickness Measurement

Background

Ultrasonic inspection is one of the most important non-destructive testing (NDT) methods used for detecting and measuring general material loss, preferential weld attack and cracking due to internal corrosion or erosion. Ultrasonic techniques used under controlled conditions are capable of very accurate estimates of wall thickness but for reasons such as calibration, surface condition or positioning of the probe, the accuracy produced in the field can be considerably less than ideal. The measurement time is relatively short and the probes can be scanned manually or automatically. For corrosion monitoring the use of automatic scanning or scanning frame systems is preferred. The advantage of this type of approach is that wall thickness contour maps of areas up to $0.5m^2$ can be obtained. The sensitivity of automated UT is typically <1/200th of the original wall thickness but this can vary considerably with the application. At low wall thicknesses (<3mm) on corroded surfaces UT can be inaccurate. Comparison of the maps from successive inspections allows an estimate of corrosion rate to be determined. The main problem with this approach is determining the relative position on the UT map of the corrosion attack from inspection to inspection.

Methods Gaining Acceptance for Corrosion Monitoring

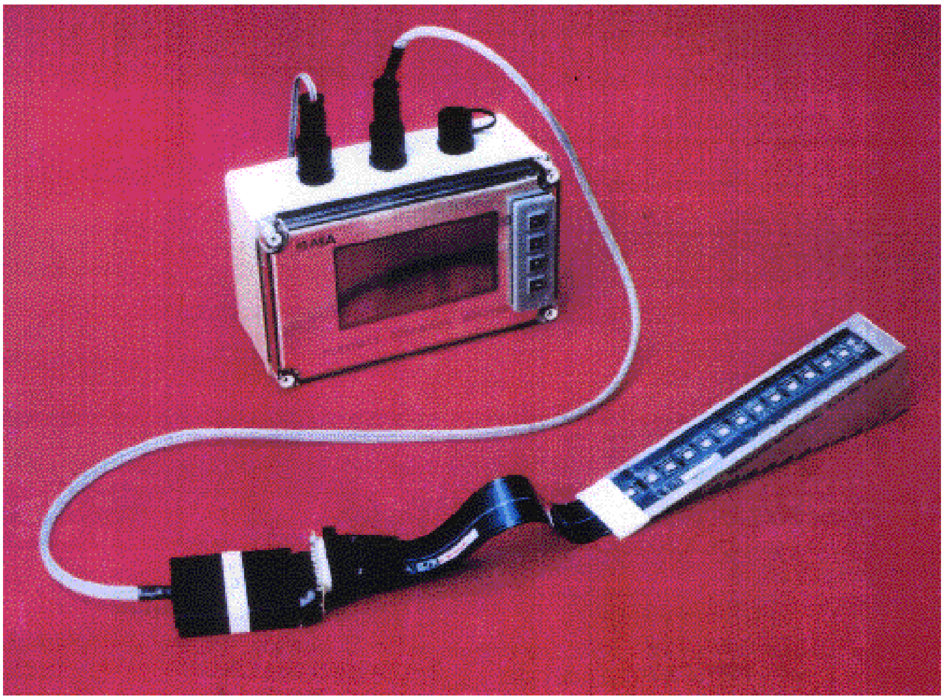
Position sensitive scanning: Conventional ultrasonic thickness gauge measurements provide no accurate information on location. This leads to problems with reproducibility of location for each inspection. There are a growing number of position-sensitive methods to accurately locate the probe and provide stored digital mapping of areas being inspected. These are:

Automatic Scanning: In this approach the probe is scanned over the area of interest using a scanning device or frame. Measurements are made relative to a reference point, stored and analysed using a computer to produce a detailed thickness map (C scan).

Manual scanning: In this system the probe is moved manually to required locations and the probe position is recorded using mechanical or optical methods. As with automatic scanning the data are recorded digitally and can be used to give detailed contour maps (C-scan)

Flexible Ultrasonic Transducer Mat (e.g.Fleximat): A typical flexible UT mat is shown in Figure 25.

Figure 25: Flexible UT Mat



The device was developed for permanent installation on areas of pipework and vessels. The transducer material is polyvinylidene fluoride (PVDF) which is mounted on a flexible printed circuit board. The mat has up to 12 sensors and can operate at temperatures up to 120°C. The mat can be interrogated with a data logger allowing repetitive measurements of exactly the same area to be made. The advantage of this technique is that it can be installed in areas of restricted access and then monitored from a more convenient position. The mat can also be installed under lagging which reduces the need to remove the lagging for routine inspection.

Rabco[41] are now marketing a system comprising flexible UT mats and pipeline data transmission. This enables the integrity of remote or buried flowlines to be monitored continuously. The first application of this technology by BPX will be at Cusiana in Colombia.

Radioactive Methods

Background

There are two main radioactive methods used in corrosion monitoring:

- **Thin Layer Activation (TLA):** The surface of a metal is bombarded with high energy charged particles in an ion beam which causes a small fraction of the atoms of the metal to become radioactive isotopes. The depth of activation is precisely determined by the beam energy and the particle mass. The radioactive elements emit gamma rays which can be detected externally and enable material loss to be calculated.

- **Neutron Activation:** This method is similar to the TLA technique but in this case the whole specimen is irradiated by neutrons prior to exposure to the corrosive medium. The irradiation is carried out in a nuclear reactor which is available at a limited number of centres. This limits the size of the test piece which can be used. The emitted radiation (gamma rays) is used to monitor material thickness or mass which radiates less energy as it corrodes.

General Comments

- For both techniques either a spool piece or a piece of plant can be irradiated and monitored. This allows a direct measurement of actual plant material loss to be made. The limitation is on the size of equipment which will fit into the reactor etc.
- The technique relies on complete dissolution of metal ions into the process stream. If the corrosion mechanism includes the formation of corrosion product on the surface of the metal then data interpretation is difficult because the technique can not distinguish between radioactive atoms in the metal or in the corrosion product.
- The level of radioactivity is very low and should not present any health hazard
- The sensitivity of the method is very high. In the laboratory detection limits as low as 1/1000th of an inch have been reported for TLA and slightly lower for neutron activation. The lifetime of the activation is anticipated to be in excess of 20 years.
- Consideration has been given to using this approach to sub-sea applications where the measurement can be monitored remotely or with a ROV.

Radioactive methods: Advantages and Disadvantages

Advantages	Disadvantages
❍ Direct measurement of material loss.	❍ Need specialist centre to activate specimens. Size limitations.
❍ Can use "real" pipework/ plant.	❍ Corrosion rate calculated as uniform corrosion. No information on localised attack.
❍ Data interpretation fairly straight forward.	❍ Film formation makes data interpretation difficult.
❍ May be suitable for sub-sea applications.	
❍ Sensitive to erosion as well as corrosion.	

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Appendix 1: Monitoring Technique Definitions

Abbreviation	***Technique***	***Required Water Cut***	***Definition***
LPR	Linear polarisation resistance	greater than ca 10-20%	Indirect measurement of corrosivity using electrochemical method. Probe inserted into line through access fitting.
ER	Electrical resistance	not a requirement	Direct measure of material loss from a probe by monitoring changes in resistance of probe element. Probe inserted into line through access fitting.
FSM	Field Signature Method	not a requirement	Commercial system which monitors changes in pipe wall thickness using the same principle as the ER probe but applied to a full pipe. No probe required. Uses a spool piece or external installation.
UT	Ultrasonic thickness measurement	not a requirement	Monitors thickness of pipe wall using an ultrasonic source.
FM	Flexible UT mats	not a requirement	Ultrasonic device which measures changes in pipe wall thickness. The device is fixed permanently to be area being monitored.
WL	Weight loss coupon	not a requirement	Direct measure of material loss by measuring changes in weight of a corrosion coupon. Coupons inserted into line through access fitting.
EN	Electrochemical noise	greater than ca 10-20%	Indirect measurement of corrosivity using a complex electrochemical technique. Data analysis very difficult, time consuming and uncertain.

Appendix 2: Conversion of Units

kilometre = 0.621 mile
foot = 0.305 metre
bar = 14.5 psi

pound = 0.454 kilogram
mil per year (mpy) = 0.0254 mm per year
dollar = 0.625 pound sterling (Q2 1996)

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