Pipeline Integrity Monitoring: Developments in Non-Intrusive Flow-Through Devices

Dan Clarke MEng MA CEng MIMechE, Technical Manager
Teledyne Cormon Ltd, UK

Abstract

The requirement for real-time corrosion monitoring devices is becoming increasingly important for sub sea oil and gas pipeline systems with longer tiebacks and highly corrosive process environments now typical for new deepwater installations.

The RPCM™ is a flow-through device designed to address this requirement. It provides high resolution full circumference metal loss and temperature measurements. This paper describes the technology and key features of the RPCM™, including enhancements to the product capability allowing a wider more holistic flow assurance and integrity monitoring service, using measurement techniques such as conductivity, passive acoustics, and Venturi measurement.
1. Introduction

The requirement for accurate, reliable, real-time corrosion monitoring is becoming increasingly important in sub sea oil and gas pipelines. Two notable causes are the trend for greater use of carbon steel over corrosion resistant alloys and production from more aggressive reservoirs.

With the deployment of longer sub sea tiebacks to maximise the lifetime of existing production infrastructures, the use of carbon steel with inhibitor chemicals and corrosion monitoring systems often offers a viable solution where corrosion resistant alloys such as Duplex and Inconel would be uneconomic.

In addition, reservoirs with aggressive process conditions are becoming a viable proposition due to the depletion of more benign reserves. Such production may be highly corrosive due to the presence of carbon dioxide, hydrogen sulphide, water, organic acids and micro-organisms. High temperatures, sand production, pipeline topography, and flow regimes all can act to accelerate corrosion mechanisms.

Without control general or more likely local corrosion will eventually lead to a breach of the pipeline with far reaching consequences. The usual mitigation methods for carbon steel pipelines include the use of a corrosion allowance in the wall thickness and the injection of chemical inhibitor. The required corrosion allowance can be kept to a minimum by using an appropriate inhibitor injected in sufficient quantities. Over treating will lead to unnecessary expense; under treating will be ineffective in limiting corrosion. Typically a target corrosion rate of less than 0.1 mm per year is acceptable.

Confirming the correct chemical selection and optimising the treatment dosage require corrosion rate information from the flowing system. Intelligent pigging employing techniques such as Magnetic Flux Leakage (MFL) and Ultrasonic Test (UT) to identify defects and metal loss in the pipe wall is often used for pipeline inspection. While this may be a good method for establishing the degree of cumulative damage to the pipe over extended periods of time, it is of little use in identifying changes in the process conditions soon enough for effective inhibitor optimisation. To do this a real-time monitoring device is required.

The Cormon RPCM™ (Ring Pair Corrosion Monitor) is a flow-through sensor designed for sub sea and general pipeline applications. It provides high resolution full circumferential real-time metal loss and temperature measurement with no disruption to the flow. This paper describes the essential technology and key design features of the RPCM™, as well as enhancements to the product which extend its measurement performance and functionality. It will be seen that this device and related Cormon flow-through products can provide a comprehensive flow assurance and integrity monitoring function in addition to basic metal loss and temperature measurement.

1 RPCM™ is a registered trademark of Teledyne Cormon Ltd
2. RPCM™ System Overview

The Cormon RPCM™ has been designed for life of field operations in deepwater HTHP environments. It uses the principle of electrical resistance measurement to calculate metal loss resulting from corrosion or erosion. Enhanced resolution is achieved using the patented RPCM™ measurement technology. ‘Ring pair’ sensors exposed to the pipeline process fluids provide circumferential metal loss and temperature measurement. Sensitivities of 0.1 microns are possible depending on the precise configuration.

![Figure 1 – RPCM™ Outer Envelope](image)

The RPCM™ design can be divided into 3 key areas:

- Outer spool
- Inner spool
- Electronics
2.1 Outer Spool
The outer spool and electronics pods can be seen in Figure 1. The outer spool is constructed from two welded back-to-back forged reducers which are custom machined internally to house the inner spool assembly. The outer ends of the reducers are extended by pup pieces to facilitate weld installation to the pipeline.

A weldolet branch onto which the non-retrievable electronics pod attaches is located on the larger diameter of one of the reducers. The inner spool sensor wires are fed through the branch to the electronics via pressure retaining penetrators.

2.2 Inner Spool
The inner spool shown in Figure 2 below is housed within the outer spool. The inner spool ID is the same as the adjacent pipeline and is fully aligned, so the flow experiences no disturbance as it passes through the device.

The assembly consists of a series of ceramic coated rings cut from a section of actual pipe and clamped between two duplex flanges. The ceramic coating is chemically inert, abrasion resistant, and provides excellent electrical insulation properties. The CRA end flanges are located against clad sealing faces within the outer spool.
Each ring pair sensor consists of a ‘sample’ ring and a ‘reference’ ring. The two rings are identical except that the sample ring is uncoated on its inner surface allowing corrosion to take place, whilst the reference ring is fully coated.

The sensor rings may include welded joints to enable measurement of weld corrosion rates. A typical configuration includes two ring pair sensors, one general and one welded (4 rings in total). Additional ring pairs may be included for extra redundancy or for measuring corrosion for different weld types. If welded ring pairs are included, the welded pairs are placed the downstream of the non-welded pairs to prevent disruption to the boundary layer over the non-welded ring pairs.

Sample and reference rings are separated by spacers to provide robust electrical insulation between them. Wires attached to the outside of the sensor rings, and are fed through the branch to the non-retrievable electronics pod via primary and secondary sets of HTHP penetrators.

2.3 Electronics
The electronics architecture may be configured to suit specific retrievability and reliability requirements. The preferred arrangement is to house the electronics boards in two pods, one retrievable and one non-retrievable. The non-retrievable pod typically contains dual redundant CEION® measurement electronics and is connected to the retrievable electronics via external jumpers. The retrievable pod contains dual redundant electronics for performing power regulation and communications and is connected to an external electronics module via an underwater mateable connector.

The electronics uses a sequence of embedded algorithms to calculate metal loss and temperature for 8 sectors of the pipe circumference every 10 seconds. The outputs are transmitted in real engineering units to an external network using digital protocols such as CAN bus\(^2\), Modbus\(^3\) or Profibus\(^4\).

3. Metal Loss Measurement Principles

3.1 Metal Loss Resolution
Resolution is defined as the smallest change that can be detected. High resolution enables changes in corrosion rate to be identified quickly. For example if the corrosion rate is 0.1mm per year and the resolution of the instrument is 0.1mm then it will take a year to determine the corrosion rate. Furthermore the user will be oblivious to any changes in corrosion rate that may have occurred during that year as a result of process or inhibitor changes. If the resolution improves to 1 micron (or 0.001mm) then it will take just 3.5 days to identify the same corrosion rate.

\(^2\) CAN is a registered trademark of Robert Bosch, GmbH
\(^3\) Modbus is a registered trademark of Schneider Automation, Inc
\(^4\) Profibus is a registered trademark of Profibus International
Another way of looking at this is that in the event of a detrimental change to the process or an inhibitor failure, an amount of metal equivalent to the resolution will be lost from the pipe before the operator has a chance to respond. Resolution is therefore an extremely important performance metric for corrosion monitoring. High resolution is one of the unique benefits of the RPCM™ – near real time visibility of process changes.

3.2 Electrical Resistance Theory
Electrical resistance measurement is an established methodology for determining metal loss. ER devices utilise two elements: a sample and a reference. Usually (but not necessarily) these elements are identical in material and dimensions at start of life. The sample element is exposed to the process fluids and allowed to corrode but the reference is shielded from the process. As the sample element corrodes the conductive cross-sectional area is reduced thus increasing its electrical resistance with respect to the reference.

The resistance of an element is given by the formula:

\[ R = \frac{\rho \times L}{t \times b} \]  

Where:
- \( \rho \) is resistivity of the element material (\( \Omega \)m)
- \( L \) is the length of the element in the direction of current flow (m)
- \( t \) is the element thickness (m)
- \( b \) is the breadth of the element (m)

If the sample and reference elements are identical at start of life but the thickness of the sample element is reduced by corrosion then using equation (1), the ratio of the sample and reference resistances is given by:

\[ \frac{R_{\text{sample}}}{R_{\text{ref}}} = \frac{t_{\text{ref}}}{t_{\text{sample}}} \]  

Since the metal loss is the same as \( t_{\text{ref}} - t_{\text{sample}} \) then the metal loss is given by:

\[ \text{Metal Loss} = t_{\text{ref}} \times (1 - \frac{R_{\text{ref}}}{R_{\text{sample}}}) \]  

Note that this metal loss represents an average value evenly distributed across the surface. In practise corrosion is rarely uniform and will include localised features.

In addition to metal loss measurement, the reference element can be used to measure temperature since for Ohmic conductors:

\[ R(T) = R_0(1 + \alpha(T - T_0)) \]  

Where,
R(T) is the resistance at temperature T (Ω)
R₀ is the resistance at reference temperature T₀ (Ω)
α is the temperature coefficient of resistance (K⁻¹)

α and R₀ are calibration constants that can be determined during calibration, programmed into the instrument and used to calculate temperature in real-time by re-arranging equation (4).

For more accurate temperature measurement a square term can be introduced to allow for small non-linearities in the resistance-temperature curve.

\[ R(T) = R_0(1 + \alpha(T-T_0) + \beta(T-T_0)^2) \]  (5)

Once again R₀, α and β can be determined during calibration. The temperature is then calculated by solving the quadratic equation (5) for any given resistance measurement.

### 3.3 Ceion® Enhanced ER Resolution

From equations (1) and (3) it can be seen that for high resolution, thin elements are required to enable small changes in thickness to have a relatively large (measurable) effect on resistance. Traditional ER measurements have relied on extremely thin elements to provide useful levels of resolution. The problem with using thin elements is that the life of the element is shortened.

The introduction of CEION® electronics has brought huge advances in metal loss detection resolution (of the order of x100 improvement). Using a combination of proprietary excitation, noise filtering, sampling, and DSP techniques, CEION® is able to measure exceptionally small changes in resistance allowing detection of extremely small changes in metal loss even with relatively thick elements.

In most cases the CEION® RPCM™ will provide resolution better than 500nm with the element thickness equivalent to the pipe wall thickness. For example if the corrosion rate were to rise to an unacceptable level of 1mm per year, then the rate would be detectable in just 4.5 hours.

### 3.4 RPCM™ Measurement Methodology

The RPCM™ applies CEION® ER principles using the inner spool ‘ring pair’ sensors. As described in section 2.2, each ring pair consists of a reference and a sample ring. The reference ring is protected whilst the sample is able to corrode.

The sensor rings are divided into 8 sectors. By injecting and withdrawing current at different locations in each ring and measuring the resulting potential differences across each of the sectors, the metal loss can be calculated for each sector.

In addition to the use of CEION® the RPCM™ monitoring system incorporates a number of features for optimal measurement performance.
**Temperature Compensation**

Because of the high CEION® sensitivity, the detected ‘apparent’ metal loss as a result of small changes in the process may distort the true metal loss if not adequately compensated. For example an increase of 1 degC will result in an increase in resistivity of carbon steel of approximately 0.4%. For a wall thickness of 20mm this corresponds to a reported metal loss of 80 microns!

The ring pair design virtually eliminates these effects by placing both sample and reference rings close to one another in the flow so that both rings ‘see’ the same process conditions. In addition since the rings are divided into virtual sectors, any circumferential variations are automatically compensated for. This compensation mechanism also takes care of any strain related changes to resistivity.

**Pitting Rings**

To detect the onset of pitting corrosion, additional ring pairs of smaller width (where width is the dimension parallel to the flow) may be included. In the event that a pit forms and grows on the pitting ring, the difference in metal loss seen between the pitted and the non-pitted sectors will be larger than the difference between pitted and non-pitted sectors for a general corrosion ring for the same size of pit. The result is illustrated in the plots below:

![Figure 3 – ‘General’ vs. ‘Pitting’ ring response to a pit formation](image-url)
4. Corrosion Monitoring - Implementation

4.1 Monitoring Location
The location of the RPCM™ - or for that matter any process monitoring device - is critical. The usual logic is that the device should be located where it will experience the most corrosive process conditions. Unfortunately this is not always straightforward to determine. Some of the factors to consider are as follows:

1. Electrochemical reactions are accelerated at higher temperatures (Arrhenius equation) so maximum corrosion rates generally increase toward the well end of the flowline.

2. For monitoring of inhibitor performance the device should be downstream of the injection point at a distance sufficient for adequate mixing of the chemical (usually >10D).

3. For representative levels of turbulent intensity the device should not be located immediately downstream of bends.

4. Corrosion may be problematic in areas of high velocity or high flow instability where high shear rates compromise the inhibitor persistence.

5. Corrosion may be problematic in areas of low velocity or stagnant water such as low points in the pipeline where micro-biological corrosion may occur.

6. Top-of-line corrosion is prevalent in long sections of pipe where the condensation rates are high due to high temperatures relative to pipe wall temperature, and flow is stratified so that the inhibitor is not being transported to the top-of-line. TLC can be particularly severe in cases where insulation is not applied leaving an exposed cold spot.

Flow modelling software like Olga® and corrosion prediction models such as TOPOCORP may be used to determine optimum placement of the monitoring device, although some compromise is necessary as this location is likely to change with time. Once installed, modelling and monitoring results should be compared at the same location and combined to predict corrosion rates in other parts of the pipeline.

4.2 Corrosion Alarms
Due to the sensitivity of rate of change functions it is advisable to base alarms on time averaged rates of metal loss. It may also be helpful to use time-based triggers and to define at least 2 levels of alarm to indicate the level of risk and or severity.

5 Olga is a registered trademark with the SPT group
Example 1
Alarm 1 is triggered once the corrosion rate exceeds the maximum limit for more than 1 day. The timer resets if the corrosion rate falls below the acceptable limit. Alarm 2 is triggered once it has exceeded the maximum for 2 days.

Example 2
Alarm 1 is triggered when
\[ \int (dX/dt) \, dt \geq 1 \text{ day} \times dX/dt_{\text{max}} \]

Alarm 2 is triggered when
\[ \int (dX/dt) \, dt \geq 2 \text{ days} \times dX/dt_{\text{max}} \]

dX / dt is metal loss rate. dX / dt_max is the maximum allowable metal loss rate. The integral resets to zero if the corrosion rate falls below dX/dt_max.

5. Flow Assurance and Integrity Monitoring

The RPCM™ inner spool provides an excellent platform for the addition of further sensors. By modifying the profile of the inner spool to incorporate convergent-divergent sections, there are a number of possible interdependent measurements that become possible in addition to metal loss and temperature. To minimise losses the nozzle entry and exit angles (particularly the latter) must be gradual to prevent separation of the boundary layer after the throat.

Flow Rate
By measuring the change in pressure from the convergent entry to the nozzle throat (as per a Venturi meter), single phase flow rates can be estimated using incompressible flow theory (Bernoulli).

\[ Q = C_d \times A_2 \times \left( \frac{1}{1-\beta^4} \right)^{1/2} \times \left( \frac{2 \times \Delta p}{\rho_1} \right)^{1/2} \]  

(6)

Where,
Q is volumetric flow
C_d is the discharge coefficient
A_2 is the throat area
\( \beta \) is the ratio of pipe to throat diameters
\( \Delta p \) is the pressure difference
\( \rho_1 \) is upstream density
The measurement accuracy is compromised for certain flow regimes such as stratified flow and slugging, although for annular wet gas flows the discharge coefficient may be corrected to compensate for the over-reading effect.

Discrepancies between top-of-line and bottom-of-line delta P readings will provide an indication of flow stratification. Periodic delta P fluctuations will highlight unstable flow regimes such as slugging.

**Sand Erosion**

Fitting a metal loss ring sensor in the convergent section of the Venturi, where it is exposed to particle strikes, allows either erosion (for a CRA ring) or erosion-corrosion (for a carbon steel ring) to be measured. An acoustic sensor can be coupled to the ring to detect particle impacts.

Combining metal loss rate data for a CRA ring with acoustic spectral energy data provides an estimate of sand mass flow rate. For a more refined estimate the sensor can be calibrated using a combination of flow-loop testing and multiphase CFD modelling. A package such as Ansys CFX\(^6\) provides the necessary particle tracking and erosion modelling capability to do this.

**Conductivity**

Integration of flush electrodes into the divergent section enables circumferential measurement of conductivity allowing detection of scaling, water cut, and hydrate or wax deposition. Each of these phenomena will impact corrosivity and should therefore be correlated against sector metal loss rates.

Conductivity data should also be considered in conjunction with delta P measurements since wax or scale deposits will reduce the Venturi throat area thus increasing delta P due to higher throat velocities. Detection of increased water film thickness may also link to higher delta P measurements.

By considering a real-time dataset which includes all of the above measurements in addition to metal loss and temperature, a coherent understanding of the process conditions and risks can be achieved, allowing operators to make informed decisions to protect the integrity of their assets whilst maintaining optimum production rates.

6. **Conclusion**

The challenges of subsea monitoring require fast responding real-time systems to facilitate rapid informed decision-making. The CEION® RPCM™ measurement

\(^6\) CFX is a registered trademark of Ansys, Inc
performance enables fast detection of corrosion rates. It may be configured to include a range of additional sensors providing valuable process information. Suitable rate calculation algorithms and alarming functions should be used to maximise the usefulness of the data.