



Corrosion Monitoring Systems and Sensors to Track Material Durability in Concrete Structures

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1. INTRODUCTION

Intertek has over 30 years' experience in all aspects of durability for many types of structure used in a variety of public infrastructure and industrial applications. In particular it has an in-house capability to design and supply bespoke corrosion monitoring equipment and sensors for many structures, process and exploration applications. This consulting expertise and excellence in equipment design is particularly valuable to the condition monitoring of reinforced and pre-stressed concrete structures.

Reinforced concrete structures can be under threat from a combination of insidious challenges due to environmental conditions, including temperature and humidity that lead to accelerated deterioration mechanisms like carbonation. As well as marine exposure, above and below ground structures can experience ingress from aggressive ground waters carrying chlorides and sulphates leading to unexpected deterioration that threaten the integrity of a vital structural asset; in Northern Europe / North America many highway structures are also at risk from chloride ingress due to de-icing salts. By employing corrosion monitoring technology it is possible to establish an early warning of the onset of these processes.

As a leading materials-engineering consultancy, we have provided a wide range of laboratory and site expertise valuable to plant and asset managers. This includes design advice for new structures, investigation and surveys leading to remediation systems for existing structures. Advice includes optimum concrete mix design to meet specific environmental conditions, corrosion protection for reinforcing steel, coatings / lining for concrete and design of cathodic protection systems. An important component of supporting the asset management regime is supply and tracking of appropriate corrosion monitoring on critical systems and structures. It is important that the equipment is robust and stable and to ensure the monitoring methods are accurate during the lifetime of a structure.

Our Concerto systems are in use in conditions ranging from remote locations at -40°C in northern Canada, utilising solar power and satellite communications, to indoor locations in railway tunnels and buildings, to the +80°C outdoor refinery conditions found in the Middle East.

1.1 CONCRETE DURABILITY PROJECTS

Some examples of Intertek reinforced concrete durability projects are provided below.

- Development of durability models and selection of concrete mix requirements for the Dubai Metro project, covering assessment of degradation risk for all reinforced concrete components (buried piles, diaphragm walls, cut and cover tunnels, tunnel segments, pile caps, piers, elevated deck, stations and ancillary buildings)
- Investigation into corrosion damage of berths at a number of Dubai ports followed by design of cathodic protection systems for selected berths

- Design, manufacture, installation and remote operation of corrosion monitoring systems for reinforced concrete tunnel elements in working underground rail and road tunnel networks in central London.
- Design and supply of corrosion monitoring systems for pre-stressing steel in motorway over-bridges on the UK M4 and M5 roads.
- Design, manufacture, installation and operation of monitoring system for London's Limehouse Link tunnel, to assess effect of early age cracking on risk of corrosion to reinforced concrete tunnel roof.
- Design, manufacture and supply of concrete corrosion monitoring systems for refinery structures and buildings across the Ruwais complex in Abu Dhabi.
- Design, manufacture, installation of corrosion monitoring systems for reinforced concrete nuclear storage facilities, UK and Canada.
- Design, manufacture and supply of corrosion monitoring systems for submerged tube elements of the 2nd Tyne Tunnel, UK.

As global experts in materials and corrosion our personnel have cross-industry experience and use this to transfer and adapt solutions from one sector to another. For example, as a market leader in the supply of monitoring equipment Intertek has adapted this from use in the oil and gas field to tracking concrete durability. Intertek products can calculate corrosion risk and we can offer tools that work in conjunction with corrosion management strategies. This white paper aims to highlight the typical probe types developed by us to track material durability, or solve corrosion problems.

Corrosion Monitoring Systems in Concrete

The design, installation and operation of corrosion monitoring systems for new-build or existing structures demands expertise in a wide range of materials and electrical engineering skills. Data gathering with either permanent or hand-held recording systems needs to be understood and assessed with regulated personal trained in corrosion data interpretation. Our equipment provides a range of solutions for measuring and monitoring the corrosion condition of steel reinforcement in concrete structures. We provide through-life operational support to gather and assess the outputs and to provide asset owners with an annual corrosion health report.

2. PROBE TYPES

2.1 M3 PROBE

The M3 probe (see Fig.1) is a multi-element sensor used to monitor corrosion rate and condition of reinforced concrete structures. This probe is designed to be installed *during* concrete construction and the probes are designed and manufactured to suit the particular structure.

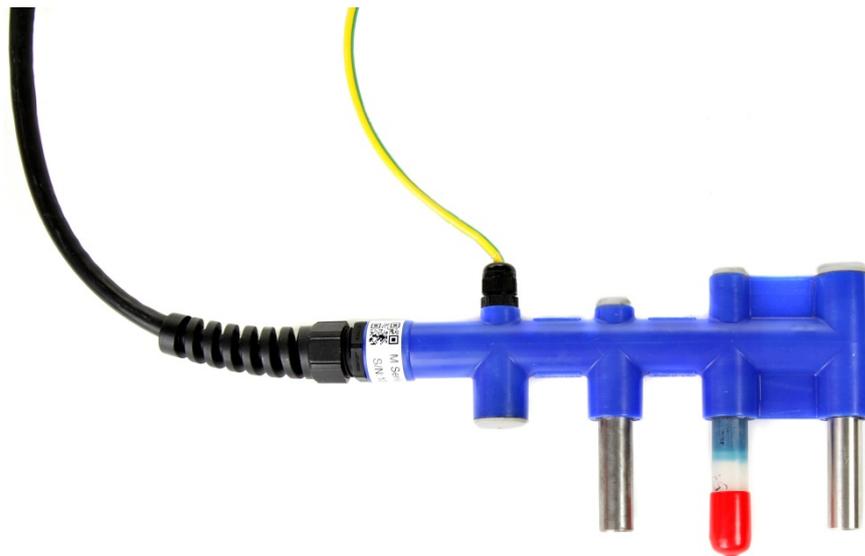


Figure 1 – M3 Probe

A standard M3 probe (as shown in Figure 1) comprises the following elements:

- Carbon steel working electrode
- Silver/silver chloride/potassium chloride (Ag/AgCl/KCl) reference electrode
- UNS S31600 (EN 1.4401) stainless steel auxiliary electrode
- Flying lead connection to main reinforcing steel with integral connection
- Thermistor temperature sensor

Alternative configurations include for example, using manganese dioxide (MnO_2/NaOH) true reference electrodes or inert pseudo reference electrodes (such as lead, UNS N10276 (EN 2.4819) or others); alternative temperature sensors (such as PT100) can also be used.

Options also exist for incorporating additional test electrodes and for smaller size units designed to focus on the requirements for any particular structure (see section 2.3).

2.2 M4 PROBE

The M4 probe (Figure 2, Figure 3) is a multi-depth or ladder-type sensor that provides early indication of corrosion events that may lead to a degradation of the integrity of the structure before it becomes a major issue, by tracking chloride penetration and carbonation before it can affect the reinforcement of the structure. This is achieved by measuring the corrosion conditions at 4 different depths; by placing it next to the steel reinforcement within the concrete, the corrosion ingress from the concrete surface, through the concrete cover, to the rebar depth can be determined. Most rebar cover depths can be catered for by easy adjustments on site as part of the installation process

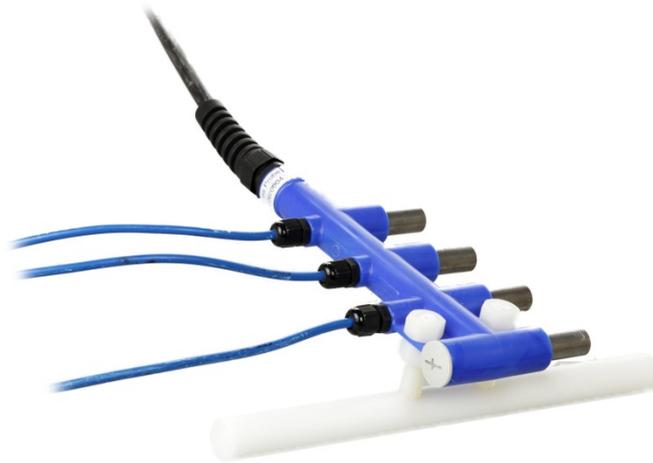


Figure 2 – M4 Probe



Figure 3 – M4 probe installed into reinforcement cage

Image shows ladder profile against rebar plane and additional reference electrode and auxiliary electrode components

The probe is also available in an M6 configuration with a 6 element ladder. The standard features the probe provides are:

- Rebar mounted with adjustable depth to suit most concrete covers from 20mm.
- 4 element ladder assembly 15mm \varnothing with 34mm exposed section giving surface area of 1780mm² per element
- Designed for use in concrete elements with up to 10m head of wet concrete during installation (e.g. columns, side walls, etc) and/ or constant submersion up to 30m of water.
- Special ratings for deeper installations (e.g. diaphragm walls, foundation piles, etc) are available on request.
- PT1000 Temperature sensor
- Alkaline resistant body to ensure long life

- 8mm Ø PtTi element bar with active length of 260mm
- MnO₂/NaOH reference electrode suited for carbonated and chloride rich concrete environments.
- High quality toughened low resistance multicore cable
- Reinforcement connection kit and mounting brackets included

The probe design allows a wide range of measurement function to be applied using the Concerto RCC instrumentation including corrosion rates, galvanic currents, potentials, temperature and resistivity on combinations of electrodes in sequence.

2.3 C2 AND C4 PROBES

The C4 probe (see Fig. 3) is a multi-element sensor used to monitor the corrosion rate and condition of existing reinforced concrete structures. It is optimised for use with tunnel elements but the C4 probe is also ideal for installation into any reinforced concrete structure. The standard measurements the C4 Probe provides cover corrosion and temperature information at two different depths making it ideal for both intrados and extrados reinforcement in a tunnel element, with respect to a reference electrode while using an integral UNS 31600 (EN 1.4401) ring as auxiliary electrode. Reference electrodes are included within the body of the probe pre-potted in mortar.

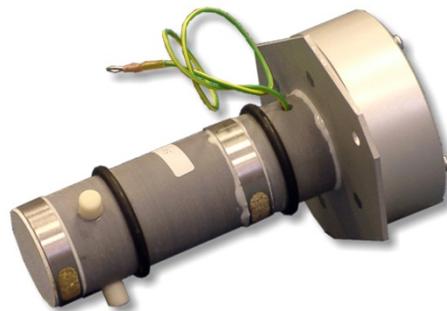


Figure 4 – C4 Probe

The length of the C4 probe is specified to match the depth of the measurement rings to the structure reinforcement design. The C2 Probe follows the same base design but with a single measurement ring. When connected to the Concerto RCC monitoring instrumentation these probes provide the following standard set of measurements for each set of electrode rings:

- Corrosion potential
- Corrosion Rate of main reinforcement using Linear Polarisation Resistance (LPR)
- Concrete resistivity
- Concrete temperature
- Optional set(s) of additional electrodes can be incorporated to add other additional measurements.

2.4 SENSE PROBE

The Sense probe (Figure 5) is a flush mounted electrode designed to detect stray voltages occurring around a structure from local sources such as pipeline cathodic protection systems and railways as well as 'internally' generated stray currents found in rail system tunnels.

It is embedded into the external soil-facing surface of a concrete structure (Figure 6) as part of its construction, with the sensing element isolated from the surrounding concrete via an HDPE shell.



Figure 5 – Sense electrode



Figure 6 – Sense electrode installed onto rebar cage

The electrode material and dimension is selectable as a function of the local environmental conditions, such as soil aggressivity and resistivity.

2.5 OTHER PROBE CONFIGURATIONS

Corrosion probes are crucial non-serviceable parts of the monitoring system and are designed and manufactured to suit the particular structure. Key

factors taken into account in the design are the reinforcement density and cover, type of form work, location of permanent monitoring equipment, access during and post construction, etc. Some structures demand assurance of durability over 100 years or more where sensor material compatibility and durability become key. We developed the M9 probe (see Fig.5) to meet this need. This provides a multi-layered configuration for use in aggressive environments or where the ability to make measurements at various cover depths yielding early warning of deterioration is crucial.

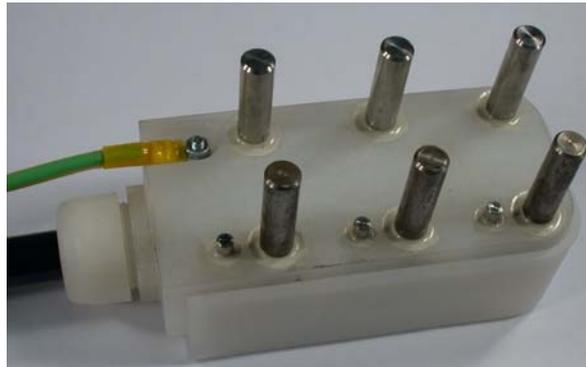


Figure 7 – M9 Probe

Because no two structures are exactly alike it is recognised that different probe designs may be required to accommodate the following factors

- particular structure geometries (such as low cover),
- location (side entry, over head, etc),
- method of installation (during construction, post-construction),
- environment (buried, submerged, atmospheric) and
- means of connection (temporary access direct to probe, temporary access remote from probe, permanent connection, etc)

Consequently whilst working to a number of base designs, we are able to tailor probe configurations for specific applications on a case-by-case basis.

3. RCC MONITORING INSTRUMENTATION

Intertek supply a range of instrumentation options to support the C and M series condition monitoring sensors for reinforced concrete ranging from portable units to web-enabled remote systems.

Common to all of these is the Concerto corrosion and condition measurement interface ensuring the same measurements are conducted in the same way regardless of the option used. At the heart of the systems is the Concerto MkII engine providing state of the art electrochemical measurement for multiple applications whether for field or laboratory use. The standard output from the systems is an open-access data structure suitable for direct import into database or spreadsheet applications. Configuration software is provided to allow users to adjust the measurement sequences for their particular application.

Concerto RCC can provide asset owners and maintainers with a continuous condition history for the steel reinforcement and concrete matrix in the face of multiple degradation threats from chloride diffusion, sulphate attack, carbonation as well as thermal and natural groundwater effects.

The measurements allow direct correlation with operational and environmental parameters enabling performance trends to be established and generating early warnings of deterioration with sufficient time to plan and execute remedial actions.

The systems are compatible with future cathodic protection application and can change roles to verify CP performance.

The Concerto RCC field systems can operate in standalone, networked and remote access configurations either as independent corrosion monitoring facilities or integrated into structure / plant DCS / SCADA / Asset Integrity systems.

In all systems the interface electronics connect directly to the probe electrodes and perform a variety of corrosion and electrical resistance measurements and convert these to digital signals. The interface is user configurable to allow flexibility of operation with a range of sensor types (including all of the C and M series sensors as well as third party systems), concrete environments and measurement requirements. In its handheld and data acquisition unit (DAU) configurations the interface is integrated with some or all of CPU, data storage, network, display and keyboard components. In the instrument cabinet configuration a number of interface cards are connected to a common CPU and data storage & communications system.

The systems are also designed to allow incorporation of other, 3rd party, structure monitoring sensors; such as stain measurement, extension meters, accelerometers, inclinometers, etc allowing all data to be collected and held in a single system as opposed to the need to have different communications and data handling systems.

3.1 RCC FIELD INSTRUMENTATION SYSTEM

Measurement and data capture equipment can be located adjacent to each individual probe or (section 3.2) provided as instrumentation cabinets supporting multiple probes subject to a cable length limitation from cabinet to probe of normally 50 metres. Where individual probe data acquisition units are employed the systems can be more widely distributed depending upon the digital communications system employed and whether power is distributed over the data network or is available locally at each DAU. A typical layout is shown in Figure 8, with the network capability and topography a function of individual structure design and of interface interoperability requirements with other system health components.

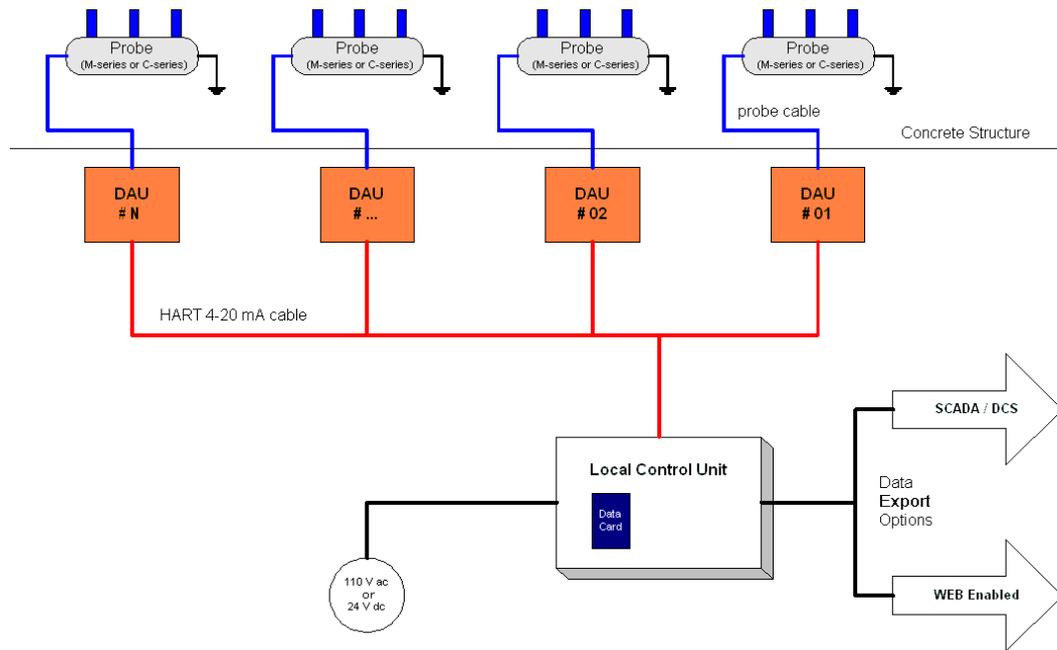


Figure 8 – Distributed data acquisition architecture

Alternate configurations, where the DAUs connect directly to a DCS or to a data logger system using 4-20mA current loops are also achievable, but with more limited measurement flexibility.

3.1.1 Standalone

Concerto RCC DL - standalone permanent field instruments for Zone 2 or safe area use supporting for example up to 6 x M3 or 2 x M9 probes, with corrosion data logging to a standard SD memory card. Larger single cabinet installations are provided through internal rack extension to support up to 16 x M9 probes. This provides unattended automated measurement and data logging. A typical layout is shown in Figure 9.

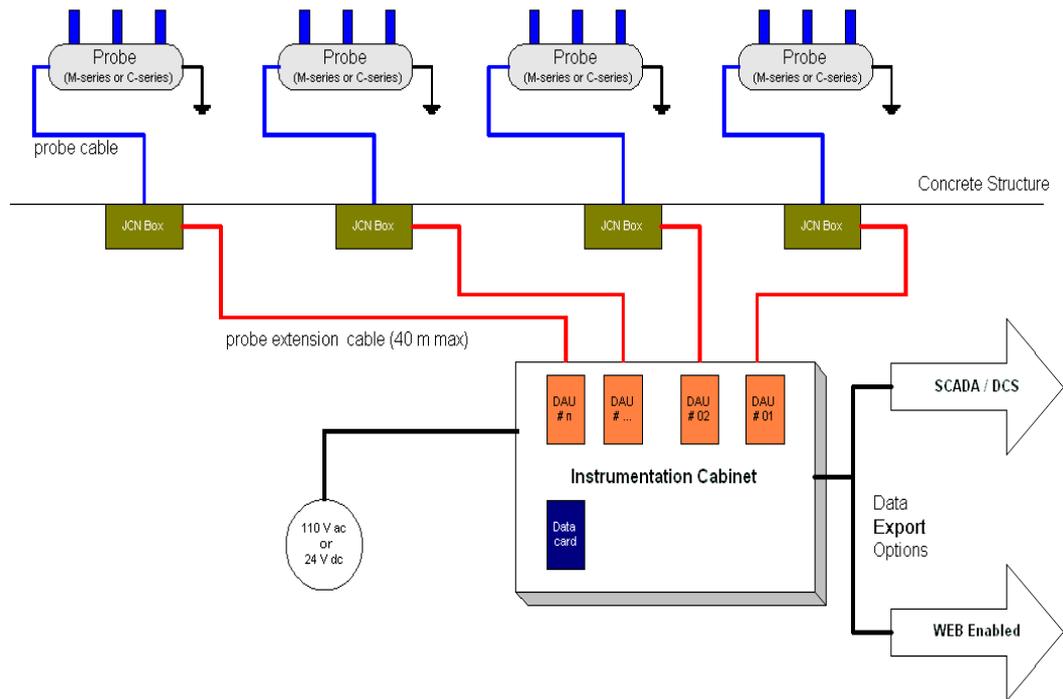


Figure 9 – RCC DL configuration

3.1.2 Handheld units

For occasional or immediate remote access to corrosion probes the multi purpose light weight Concerto handheld corrosion monitor (See Figure 10) is used for precision readings in the field or to analyse the results from a desk top computer. With its internal rechargeable battery it is compatible with Intertek corrosion probes and can be programmed to take a single LPR measurement or an automated preset sequence of measurements. Readings may be viewed directly by LCD display or downloading to a PC via its integrated USB port.



Figure 10 - Concerto MK2 Handheld Corrosion Monitoring Tool

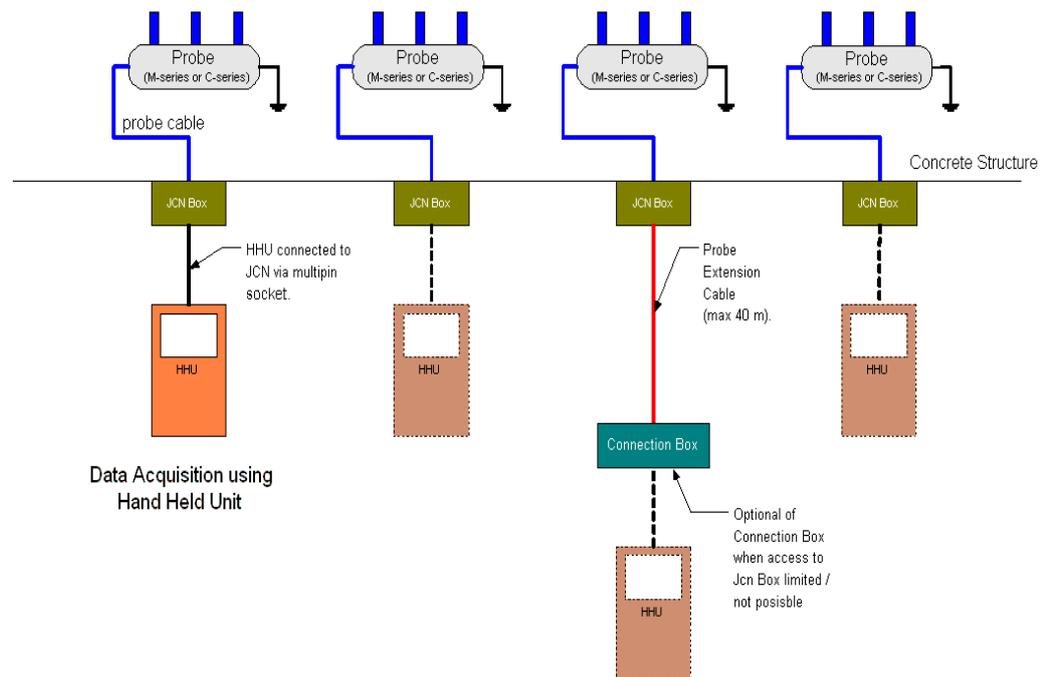


Figure 11 – Handheld system architecture

4. ECN CAPABILITY

If required the instruments can provide real time continuous monitoring of the level of corrosion activity using electrochemical noise (ECN) monitoring techniques. It can detect localised corrosion using a non-disruptive measurement technique that can interface directly to any DCS system. It uses a series of algorithms designed to convert electrochemical current and potential noise readings into a relative indication of corrosion activity / instability and localised pitting corrosion activity. This can be used to generate an alarm to notify of enhanced activity if required.

It is possible to combine linear polarisation resistance with an electrochemical noise instrument using the same probe. No additional software or hardware is needed for data handling.

Data can be stored on a SD memory card that can then be retrieved for detailed analysis and auditing. By using a modular design the system is expandable. The equipment is extremely robust and has been successfully used in a range of harsh operating environments including severe weather and temperatures from -40°C to $+50^{\circ}\text{C}$ including nuclear waste tanks, petrochemical plants, offshore oil & gas platforms and remote gas pipelines. This equipment is hazardous area Zone 2 approved and is therefore available for all Infrastructure and Oil & Gas applications. We also provide data analysis services and support for the equipment when requested (see section 6).

5. OVERALL SYSTEM CONTROL

Variants on all these systems can be provided to suit plant or customer requirements and meet a range of field environments configured in firmware and tailored to specific applications. Local control units provide dc power, network communication, control of the individual monitoring units with local data

storage and remote communications. The control unit may be configured to operate in a remote condition, with communications via a modem (posting data automatically or on demand) or may be incorporated into a plant / facility network for direct communication and remote access control. This provides the ability for complete automation through to online asset condition database systems in a wide range of challenging environments. The systems are also designed to allow incorporation of other, 3rd party, structure monitoring sensors; such as stain measurement, extension meters, accelerometers, inclinometers, etc allowing all data to be collected and held in a single system as opposed to the need to have different communications and data handling systems.

6. DATA INTERPRETATION AND SUPPORT SERVICES

The electrochemical noise and linear polarization techniques that our corrosion monitoring systems utilize are particularly useful. For example they enable:

- The differentiation of localised and general corrosion
- Monitoring to be performed passively
- Real time data acquisition

The measurements taken are processed to produce a relative indication of the corrosion activity. Data can be stored on a USB flash stick or transferred to a PC, via cellular or satellite modem.

Our data management system is designed to highlight significant corrosion events in the field. However, the experience of the corrosion engineer in interpretation of these events is essential and valuable; and we provide expert services to support and manage asset evaluation programs using corrosion monitoring. Intertek is well qualified to provide a data interpretation capability and complement any range of inspection activities with the required engineering skills necessary to provide reliable routine assessment of health of a structure at any point of its life.

Data Tree Explorer

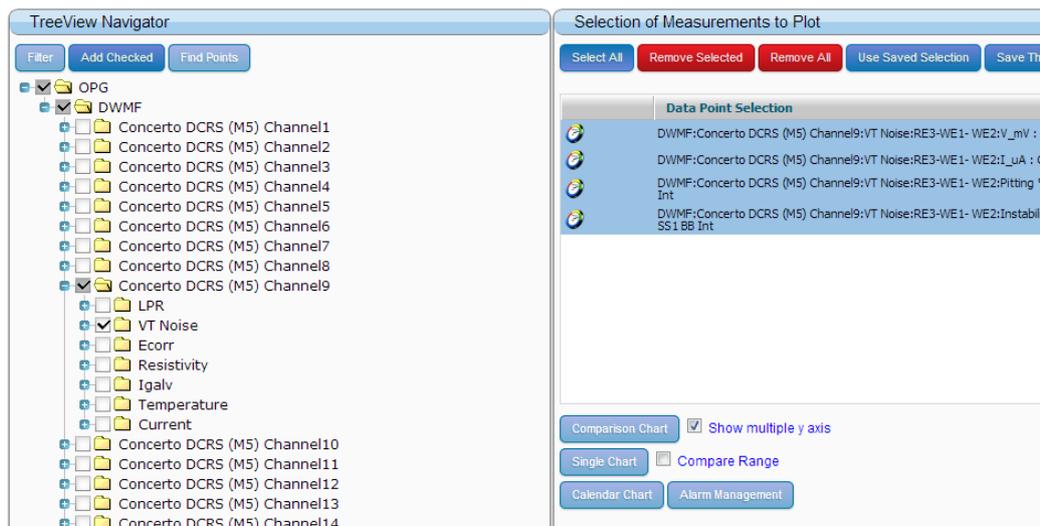


Figure 12 – Data management explorer view

7. CORROSION MONITORING REINFORCED CONCRETE CASE STUDIES

Careful choice and application of corrosion sensors and monitoring systems is essential for cost effective structural monitoring. We advise on monitoring requirements and provide suitable systems on a case-by-case basis. Examples of the application of this are a sub-contract supply for a petrochemical recycling extension at Ruwais, which installed corrosion monitoring systems at critical concrete structures, and work for London Underground, which required the design, manufacture, installation and operation of probes in Jubilee Line Extension tunnels.

7.1 CASE STUDY – NEW CONSTRUCTION; CRITICAL CONCRETE STRUCTURES RUWAIS

7.1.1 Allocation of probes

A challenge for each structure is to specify the number and location of measurements probes and data loggers. In this case the design was developed through the application of a set of criteria relating to the structural components and environmental threats facing each individual structure

The corrosion monitoring system installed in 2004 was supplied to provide the owner with confirmation of the corrosion integrity of the monitored structure and gives advanced information necessary to plan corrective actions. The key advantage is that any disruption to production can be accurately planned and unplanned shutdowns avoided.

Intertek systems are installed for seven identified structures categorised as 'critical' – i.e. where a failure of the structure would cause a plant shutdown. These include reactors, bund walls, amine surge tanks and substations.

7.1.2 Risk Categories

Two corrosion risks categories were addressed:

Primary Risk: degradation of reinforced concrete foundations, due to the ingress of saline ground water and transport via capillary rise and evaporation, leading to build up of chlorides eventually leading to corrosion of the steel reinforcement.

Secondary Risk: degradation of above-ground concrete, due to accumulation of air blown chloride rich dust depositing on concrete surfaces, with chloride ingress occurring during periods of heavy dew point.

Measurement of the effects of these risks is achieved by discrete probes installed at critical locations across the structure. The number of probes required to provide a determination of the risks were determined from a number of guidelines:

For a monitoring system to provide reliable information on the overall structure performance, the number of probes should relate to a minimum of 5% to 10% of the overall structure area, covering variances in construction, exposure conditions, etc with a minimum of two probes per critical structure. The location of individual probes within a structure should provide both a uniform distribution of probes around the structure, whilst ensuring that key areas, identified as positions that are most at risk of attack, are included.

Where possible probes should be connected to data loggers and the location of these is selected to minimise the total probe cable length if wireless connections are impractical.

7.1.3 Corrosion Monitoring System Components

The corrosion monitoring system used standard M3 probes and RCC instrumentation (see Figure 13). The instrumentation provides a single-box system to automatically measure and store probe parameters at user-configured intervals. The monitoring instrumentation is permanently powered from single-phase supply.

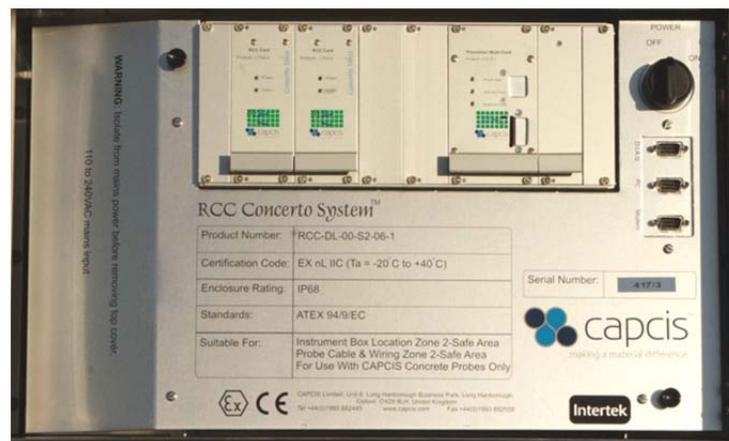


Figure 13 – RCC Monitoring instrumentation

7.1.4 Design Assumptions

In any one structure there are many variables. To avoid an excess number of probes being required it is assumed that the structure is built in accordance with the project standards and that quality control procedures are rigidly applied. It is assumed that there are no significant construction differences between, for example, two adjacent columns or beams such that monitoring the condition on one element will provide a reasonable estimate of the condition of other element.

7.1.5 Probe Requirements

M3 probes were installed at a range of different cover thicknesses to the reinforcement in locations considered to be at the highest risk of chloride ingress and hence corrosion of the reinforcing steel.



**Figure 14 - Modified M3 probes
(Fixed prior to placement of concrete)**

Figure 14 shows an image of a modified M3 probe ready for casting into a reinforced concrete structure. Degradation was considered to be expected to occur first at locations that are south facing and exposed to highest temperature cycle and also highest risk of saline water rise due to evaporation. Also support columns adjacent to areas where there is an increased risk of saturation from roof water run off.

7.2 CASE STUDY – EXISTING STRUCTURE; JUBILEE LINE EXTENSION, LONDON UNDERGROUND

7.2.1 Introduction

Intertek's scope for the Jubilee line extension to the London Underground was to provide a retrofit on-line corrosion monitoring for pre-cast reinforced concrete tunnel elements. The Jubilee Line Extension runs through some challenging and potentially aggressive ground conditions, with the risk of chloride ingress to the external surface and hence attack at the extra-dos reinforcement. Conditions vary both along the tunnel route and radially around the tunnel. Access is restricted to engineering hours (i.e. periods of tunnel position typically between 01:00 and 04:30 hrs) and all equipment had to be installed so as not to impact on (or be affected by) the tube trains, from both a mechanical and electromagnetic interference aspects.

For condition monitoring systems to be of value there must be confidence in the quality of the data collected. In this work we have employed proven corrosion techniques, including monitoring corrosion potentials and corrosion rates, for the tunnel works. Other techniques, where additional research or validation is required were investigated in a parallel laboratory program, intended to confirm the sensitivity of the system to the anticipated degradation process. Where material parameters are being inferred from direct measurement of other parameters such as resistivity, temperature and moisture content, the interrelationships are clearly defined. In addition the monitoring techniques and locations of measurement were selected such that the range of environments and conditions 'seen' by the tunnel were covered from a limited number of measurement nodes.

Concrete cores retained from the installation of the probes were analysed for chloride, sulfate and carbonation concentrations and concrete quality to assess the condition of the structure to provide a benchmark for future changes.

7.2.2 Design of Condition Monitoring Probes

The design objective for the probe to minimise the number of intrusions into the structure whilst measuring conditions on both faces of the segment led directly to the developed solution of using a single multi-component package to measure at different points in the rebar cage.

This project used C4 probes (as shown in Figure 4, section 2.2)

The reference electrodes are embedded in a grout filled cavity within the probe which is in direct electrolytic contact with the grout used to install the probe and hence the segment reinforcement. The reference electrodes are used to measure the corrosion potential of the reinforcement within the concrete, which will vary depending on the aggressiveness of the environment and the condition of the reinforcement.

The overall length of the probe varied depending on the precast concrete segment thickness, which for this work ranged between 150 to 210 mm. The probes were installed into a hole cored into the concrete of 75 mm diameter, so that the 2 reference elements are nominally inline with the intra-dos and extra-dos reinforcement as shown in Figure 15 (intra-dos and extra-dos refers to the inner and outer layers of reinforcement within the precast concrete segment respectively, as viewed from within the tunnel). The probes were grouted in place using concrete of the same specification as the original concrete used in manufacturing the segments.

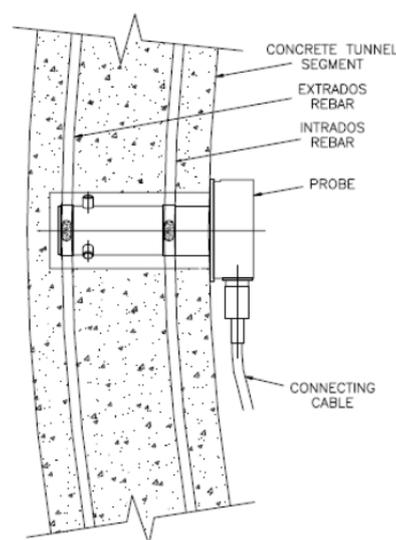


Figure 15 – Schematic of installed C4 probe in tunnel segment

The flying lead from the probe was connected to the reinforcing steel in the concrete segment, achieved by coring a nominally 75 mm diameter hole to expose the reinforcement and drilling a small diameter hole into the steel to take a self tapping screw connector. A chase in the concrete between the two-cored holes (for probe and rebar connection) was made to pass the connecting cable. The access and chase were repaired using the same repair mortar. The coring and probe installation was carried out under separate possessions to

workaround the time constraints and to minimise the amount of equipment and materials that had to be hand carried to and from the site.

7.2.3 Design of Networked Measurement Systems

Figure 16 represents a schematic diagram of the networked condition monitoring system.

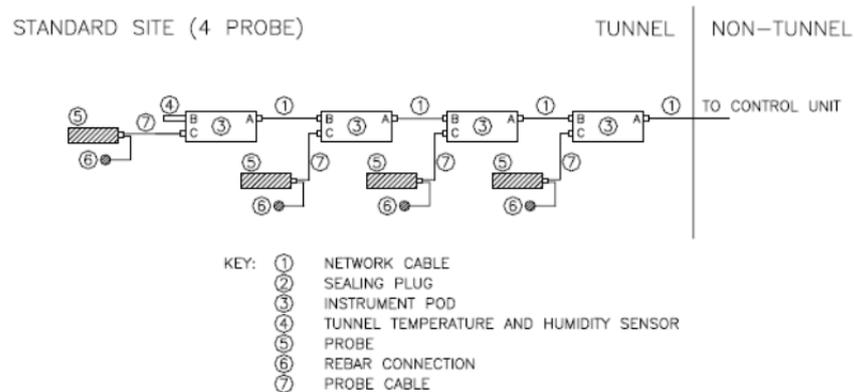


Figure 16 – Schematic configuration of tunnel monitoring system

The main elements of the system are:

- **Control Units** – comprising a network controller module, power module and telecommunications modem. It operates from single-phase AC power and is connected to a standard telephone line for remote access/control. The Control Unit operates all the Monitoring Units.
- **Monitoring Units** (or instrumentation pods) - comprising the measurement electronics, a galvanic isolation barrier and a network interface barrier. It is connected to the sensing probe via a screened multiway cable fitted with a plug/socket. Each pod is connected to other pods and Control Unit via a screened network cable in a “daisy chain” arrangement.
- **Measurement Probes** – as described above (section 7.2.2).

A complete monitoring system is situated at each site, with 4 measurement probes mounted at predefined locations within the tunnel wall. As shown in Figure 16 each system functions as a small local area network with its own local control box acting as a stand-alone network and linked with 4 monitoring units and an additional monitor for tunnel humidity and temperature at each site.

Figure 17 shows two instrument units associated with two probes installed in the tunnel wall at knee level position. The Probes are grouted into the tunnel wall and further secured using fixing bolts. The instrument units are placed in the allowed service zone in the tunnel and fixed to the cable support brackets on the tunnel wall. All network cables are placed on the existing cable racks labelled and secured with halogen free cable ties. The data from the system is collected automatically by the control unit and transferred to a central server for access via the internet.



Figure 17 – Instrument pods and installed C4 probes

Further details of the overall system are given in paper 03437, *The development of concrete and corrosion condition sensors for railway tunnels*, presented at NACE CORROSION'2003, San Diego, CA March 2003.

8 CONCLUSION

Carefully chosen and applied corrosion monitoring systems and sensors are an essential part of tracking material durability and reliability in reinforced concrete structures. Intertek offers a wide choice of highly flexible instrumentation and condition monitoring probes capable of meeting the needs of industry and infrastructure applications where accuracy, durability and reliability are essential. This equipment can be used as part of a corrosion management in an asset management strategy supported by expert consultancy in all aspects of the system installation with training and data interpretation.