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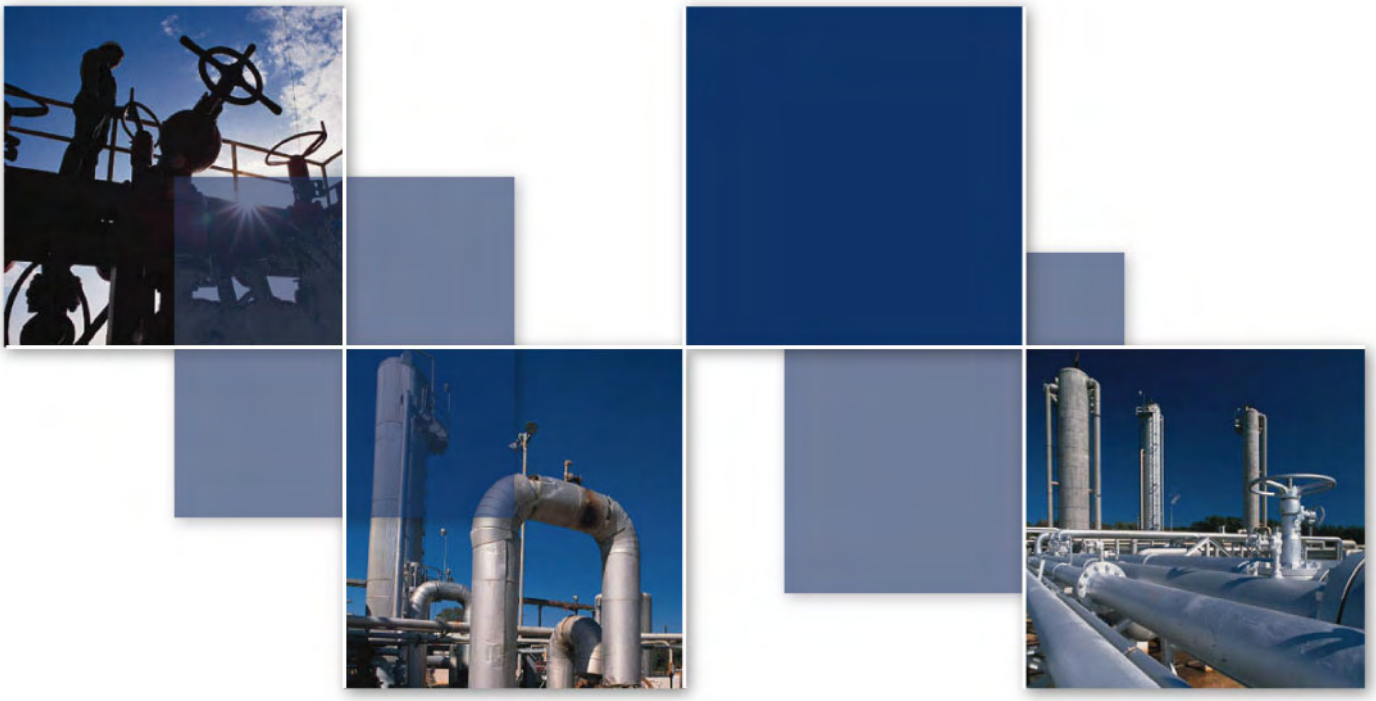

Corrosion Monitoring Systems and Sensors to Track Material Durability in Concrete Structures & Down-hole Applications

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CAPCIS Ltd

Sharjah Office	78 Carden Place	Bainbridge House	Unit 6	Libyan Office
PO Box 4660 SHARJAH United Arab Emirates 971 6 5086 186 (Direct) Fax +971 6 538 8051	ABERDEEN AB10 1UL United Kingdom t. +44(0)1224 612400 f. +44(0)1224 612401	86 – 90 London Road MANCHESTER M1 2PW United Kingdom t. +44(0)161 933 4000 f. +44(0)161 933 4001 e-mail:capcis.enquiry@intertek.com web: www.capcis.com www.intertek.com	Long Hanborough Business Park LONG HANBOROUGH OX29 8LH United Kingdom t. +44(0)1993 882445 f. +44(0)1993 882559	Fairouz Complex 4th Floor ~2 Mezran Street TRIPOLI Libya +218 21 333 0886 Extn 111 +218 21 333 6530

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1. INTRODUCTION

Intertek-CAPCIS has over 30 years experience in all aspects of durability for many types of structure used in the oil and gas industry. In particular it has an in-house capability to design and supply bespoke corrosion monitoring equipment and sensors for many 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 refinery structures.

Reinforced concrete structures in the Middle-East 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. 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, Intertek-CAPCIS has 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.

1.1 CONCRETE DURABILITY PROJECTS

Some examples of Intertek-CAPCIS reinforced concrete durability projects of particular relevance to the Middle East are provided below..

- Development of durability models and selection of concrete mix requirements for a regional rail 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 operation of corrosion monitoring systems for reinforced concrete tunnel elements in working underground rail and road tunnel networks in central London.
- Corrosion risk assessment for the Channel Tunnel project.
- Condition survey of underground wastewater treatment works
- Production of comprehensive corrosion control guidance documents for the city of Al Jubail, Saudi Arabia, work has also covered the design and

specification of cathodic protection system for seawater cooling canal, investigation of corrosion in numerous reinforced concrete structures.

- Investigation of corrosion damage to reinforced concrete sub-structure at an Abu Dhabi port and subsequent design and specification of cathodic protection system as part of overall repair and rehabilitation programme.

As global experts in materials and corrosion our personnel have developed methods and equipment commonly used in solving numerous oil and gas industry corrosion problems. 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-CAPCIS 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 Intertek-CAPCIS to track material durability, or solve corrosion problems.

1.2 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 with regulated personal trained in corrosion data interpretation. Intertek-CAPCIS equipment provides a range of solutions for measuring and monitoring the corrosion condition of steel reinforcement in concrete structures.

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.

A standard M3 probe comprises the following elements:

Figure 1 M3 Probe

- Carbon steel working electrode
- Silver/silver chloride/potassium chloride (Ag/AgCl/KCl) reference electrode
- AISI316 Stainless Steel auxiliary electrode
- Flying lead connection to main reinforcing steel with integral connection.
- Thermistor temperature sensor

2.2 C4 PROBE

The C4 probe (see Fig. 2) is a multi-element sensor used to monitor the corrosion rate and condition of reinforced concrete. 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 for intrados and extrados reinforcement with respect to a reference electrode while using an integral AISI 316 ring as auxiliary electrode.

When connected to the Rate of Corrosion in Concrete (RCC) Concerto monitoring instrumentation these probes provide the following standard set of measurements:

- Corrosion Potential
- Corrosion Rate (using Linear Polarisation Resistance)
- Concrete resistivity
- Concrete temperature
- Optional set(s) of electrodes can be incorporated to add other additional measurements.
- Concrete humidity is also possible with C4 probes

Figure 2 C4 Probe

2.3 M9 PROBE

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 many decades. Consequently Intertek-CAPCIS has developed the M9 probe (see Fig.3). This is a variation of the standard M3 probe that is multilayered for use in aggressive environments or where the ability to make measurements at various cover depths yielding early warning of deterioration is crucial, such as in nuclear waste storage plants.

Figure 3 M9 Probe

3. RATE OF CORROSION IN CONCRETE (RCC) MONITORING INSTRUMENTATION.

Intertek-CAPCIS 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 HTP 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.

When applied using DL or NT configurations 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.

3.1 RCC-DL DATA LOGGING SYSTEM

The RCC-DL permanent data logging system (see Fig. 4) is used to provide corrosion monitoring data for critical concrete structures in safe and hazardous area locations where portable units cannot be used and remote communications are not required or possible. While the RCC-DL system is designed to operate with the M3 and M9 probes, other systems and probe types may be used.

Figure 4 Concerto RCC- NT Networked Monitoring Unit

3.1.1 Standalone

Concerto RCC DL - standalone permanent field instruments for Zone 2 or safe area use supporting 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.

3.1.2 Handheld Units

Spot measurement on an ad-hoc or periodic inspection can be recorded using Concerto RCC HH - battery operated hand held unit for use in Zone 2, safe area or laboratory environments.

3.2 RCC-NT NETWORKED MONITORING SYSTEM

The RCC-NT networked monitoring system is used to provide corrosion monitoring data for large/complex civil structures. The units can be adapted for any structure type including bridges, tunnels, ports, harbours, high-rise buildings and industrial complexes.

RCC-NT units can be deployed as a temporary or permanent installation. The unit records data at predefined intervals that can then be stored locally on a flashcard for collection when required or data can be available over a secure website connection.

The RCC-NT comprises a number of permanent corrosion rate meters connected together and controlled by a local network control unit. The system is optimised to operate with the C4 probes but can operate in conjunction other systems and probe types. When connected to C4 probes the RCC-NT provides a standard set of measurements. However the system is flexible and is designed to allow for the incorporation of data from other physical sensors.

The measurement by LPR, polarisation voltage and time, are configured in firmware and can be tailored to specific applications. Resistivity is measured using a single frequency square wave, the amplitude and frequency is also configurable in firmware.

3.2.1 Remote Supply Network

The remote supply network is made up of individual nodes daisy chained together. The network cable supplies power and communications from a local Network Control Unit based in the instrumentation room or other secure location of the installation. For systems that have power restrictions the individual nodes can be put into a sleep mode and turned on only when a measurement is required. This system is very adaptable and in some applications more than forty (40) nodes can be placed on one chain.

As well as connecting to corrosion probes the Concerto RCC-NT can also incorporate other monitoring units supplied by third parties (e.g. movement sensors, inclinometers, accelerometers, crack width gauges, etc) to provide a comprehensive structural integrity monitoring system. The physical location of the individual monitoring pods is dependent on the local environment and access availability.

The RCC-NT networked system is CE marked and fully conforms to the EU Low Voltage Directive and EMC regulations. Various options are available for the instrumentation and Intertek-CAPCIS are able to advise on requirements and provide suitable systems on a case-by-case basis.

4. CONCERTO MK II

The Concerto MK II (see Fig. 5) provides real time continuous monitoring of the level of corrosion activity using Electrochemical Noise (EN) Monitoring techniques which can be used in Infrastructure and Oil & Gas applications. It can detect localised corrosion in a variety of metallic materials using a non-disruptive measurement technique that can interface directly to any DCS system and a series or algorithms designed to convert electrochemical current and potential noise readings into a relative indication of activity / instability and localised pitting corrosion activity. This can generate an alarm to notify of enhanced activity.

Figure 5 Concerto MK II

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

Data can be stored on a compact flash memory 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^{o}C to +50^{o}C including nuclear waste tanks, petrochemical plants, offshore oil & gas platforms and remote gas pipelines. Intertek-CAPCIS can also provide data analysis services and support for the equipment when requested.

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.

6. WIRELINE DEPLOYED CORROSION MONITORING TOOLS

One important example of the use of EN and LPR monitoring system in the Middle East relates to Downhole wireline corrosion monitoring at oil wells (see Fig. 6). While significant efforts are made to prevent or inhibit expensive corrosion processes because the rate and type of corrosion is not uniform throughout the depth and life of a well, these strategies may not be optimum. Therefore a Downhole corrosion monitoring system offers material advantages to the operator.

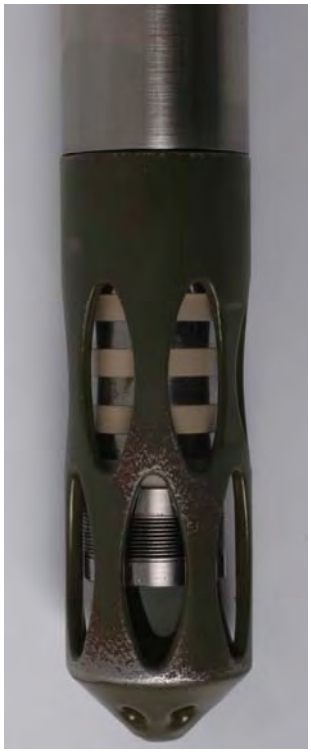

Figure 6 Downhole (Wireline) Corrosion Monitoring Tool

The application of Intertek-CAPCIS electrochemical noise techniques to an assortment of wellbore monitoring systems provides the opportunity to effectively monitor the corrosion activity of the entire wellbore, throughout its lifetime. This system was first used by Saudi Aramco. The system is a wireline deployed logging tool and is rated to cover most of Saudi Aramco wells (water and oil) except gas wells, which operate at higher temperatures (> 150°C).

The Intertek-CAPCIS downhole corrosion monitoring tool provides the relative corrosion severity, temperature and pressure against depth, as well as distinguishing between localised and general corrosion. This particular downhole tool also generates a general corrosion rate at specified depths.

The tool acquires and presents real time data identifying:

- Regions or specific depths most susceptible to corrosion
- The relationship between corrosion and the process parameters
- The appropriateness of selected Downhole materials
- The accuracy of corrosion and flow simulations and predictions
- Localised and general corrosion and provides a general corrosion rate.

This therefore indicates:

- The effectiveness of inhibitor treatments
- The appropriateness of selected Downhole materials
- The accuracy of corrosion simulations and predictions.

7. DATA ACQUISITION & PRESENTATION

The electrochemical noise and linear polarization techniques that the Intertek-CAPCIS corrosion monitoring systems utilize are particularly useful. For example when recording data from the Downhole environment they enable:

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

The measurements taken are processed producing a relative indication of the surface activity and pitting corrosion activity. This Downhole corrosion monitoring tool presents this data at the surface as a record against depth while the data is stored on a USB flash stick or transferred to a PC, via cellular or satellite modem.

7.1 DATA INTERPRETATION AND SUPPORT SERVICES

The Intertek-CAPCIS data management system is designed to highlight significant corrosion events. However, the experience of the corrosion engineer is often valuable and Intertek-CAPCIS provides expert services to support and manage an evaluation program in the field.

8. CORROSION MONITORING CASE STUDY

Careful choice and application of corrosion sensors and monitoring systems is essential for cost effective structural monitoring. Intertek-CAPCIS is able to advise on monitoring requirements and provide suitable systems on a case-by-case basis. An example of the application of this was a sub-contract supply for a petrochemical recycling extension at Ruwais which installed Intertek-CAPCIS corrosion monitoring systems at critical concrete structures.

8.1 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-CAPCIS 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.

8.2 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.

8.3 CORROSION MONITORING SYSTEM COMPONENTS

The corrosion monitoring system used standard M3 probes and RCC instrumentation (see Fig. 7): 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 7 Rate of Corrosion in Concrete (RCC) Monitoring Instrumentation

8.4 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.

8.5 PROBE REQUIREMENTS

M3 probes were installed 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 8 Modified M3 probes ready for casting into a reinforced concrete structure.

Fig. 8 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.

8.6 CONCLUSION

Carefully chosen and applied corrosion monitoring systems and sensors are an essential part of tracking material durability and reliability in reinforced concrete structures and Downhole well applications. Intertek-CAPCIS 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.