Ensayos No Destructivos
en la Ingeniería Civil
CAI - 10/Agosto/17

SENSORES PARA EL MONITOREO NO DESTRUCTIVO DE LA CORROSIÓN DE ARMADURAS EN ESTRUCTURAS DE HORMIGÓN

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Investigador Principal

Universidad Nacional de Gral. San Martín
Profesor Titular Degradación de Materiales

Deterioro del hormigón armado

Deterioro Físico

- Fisuración
- Congelamiento
- Fuego
- etc.

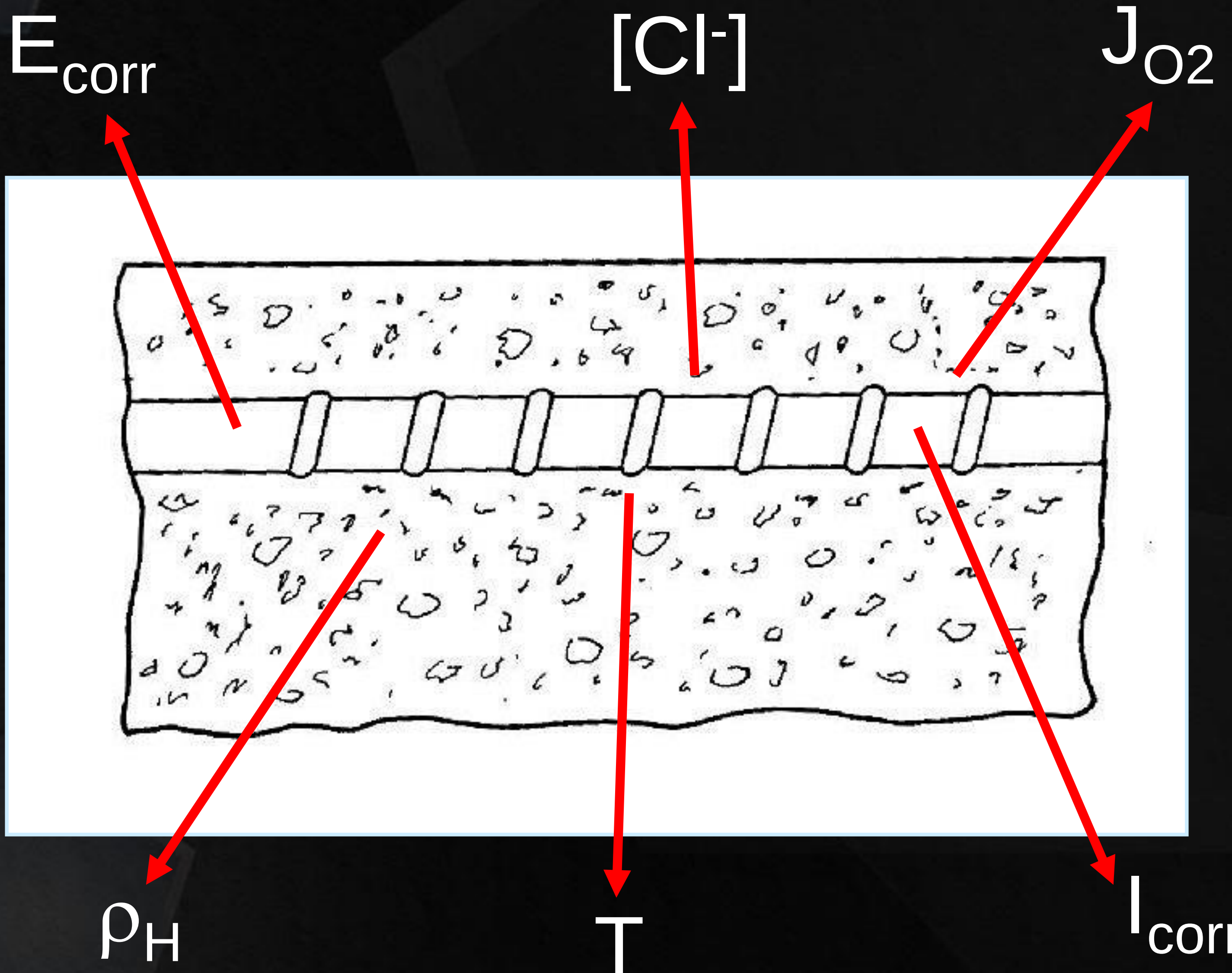
Deterioro Químico

- Ataque por sulfato
- Ataque ácido
- Agua de mar
- Reacción álcali-agregado
- Lixiviación
- etc.

Corrosión de las armaduras

→ Medición de parámetros asociados

PARÁMETROS A CONOCER



Normas + Recomendaciones

POTENCIAL DE CORROSIÓN
Norma ASTM C-876

Probabilidad de corrosión	E_{corr} ($V_{Cu/CuSO4}$)
> 95 %	< -0,350
aprox. 50%	-0,200 a -0,350
< 5 %	> -0,200

ASTM C 876, “Standard test method for half-cell potential for uncoated reinforcing steel in concrete” American Society of Testing and Materials, Philadelphia (1987).

DENSIDAD DE CORRIENTE DE CORROSIÓN

I_{corr} (µA/cm^2)	Corrosión	V_{corr} (µm/año)
< 0,1	Despreciable	< 1,2
0,1 a 0,5	Baja	1,2 a 5,8
0,5 a 1	Moderada	5,8 a 11,6
> 1	Alta	> 11,6

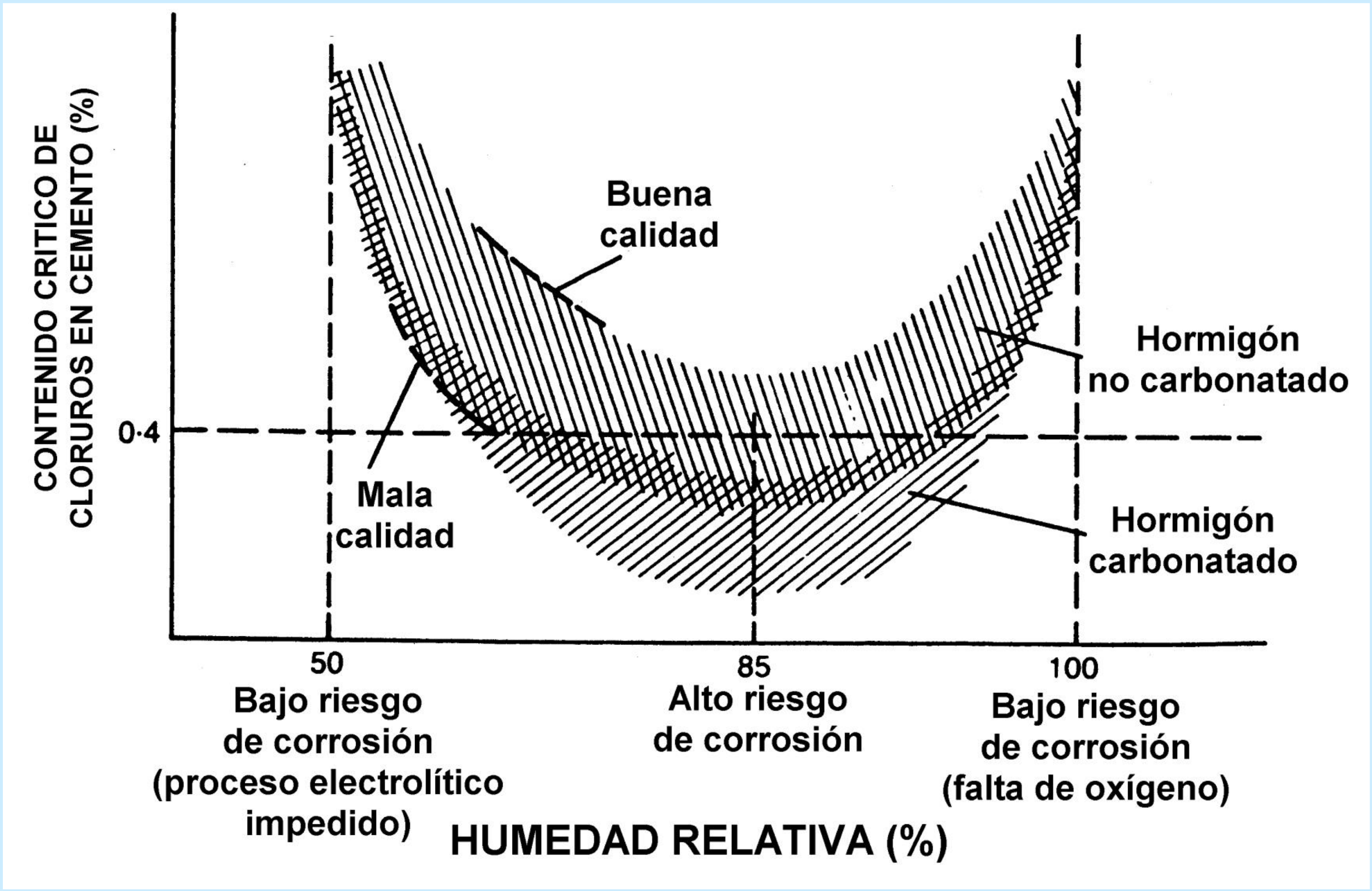
M.C. Andrade y M.C. Alonso, Construction and Building Materials, 15, 141 (2001).

RESISTIVIDAD ELÉCTRICA

Resistividad (kΩ.cm)	Fenómeno probable
> 100	Hormigón muy seco. Las velocidades de corrosión serán muy bajas independientemente del contenido de cloruros y del nivel de carbonatación.
50 a 100	Bajas velocidades de corrosión
10 a 50	Moderada a alta velocidad de corrosión si el acero está activo en hormigones carbonatados y/o contaminados con cloruro.
< 10	La resisitividad no es un parámetro que controle la velocidad de corrosión

M.C. Andrade y M.C. Alonso, Construction and Building Materials, 15, 141 (2001).

CONCENTRACIÓN DE CLORURO



FORMAS DE MEDIR LOS PARÁMETROS RELACIONADOS CON LA CORROSIÓN DE LAS ARMADURAS

- Mediciones desde “afuera” de la estructura
- Mediciones desde “adentro” de la estructura

$\Rightarrow$ **SENSORES**

NDT JAMES INSTRUMENTS INC.
NON DESTRUCTIVE TESTING SYSTEMS

Mediciones desde “afuera” de la estructura

Gecor – 6

* E_{corr}
* V_{corr}
* Resistividad
* Temperatura

Disponible en nuestro grupo

DESARROLLO DE SENSORES DE CORROSIÓN

EVALUAR LA DURABILIDAD DE CONTENEDORES DE RESIDUOS RADIOACTIVOS DE BAJO NIVEL DE ACTIVIDAD DESDE EL PUNTO DE VISTA DE LA CORROSIÓN DE LAS ARMADURAS

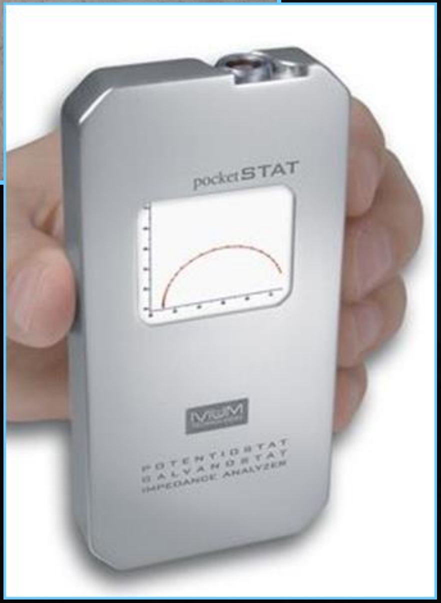
(fabricados con Hormigón Armado)

Durabilidad > 300 años

SENSOR LISTO PARA INSTALAR

Electrodos embebidos

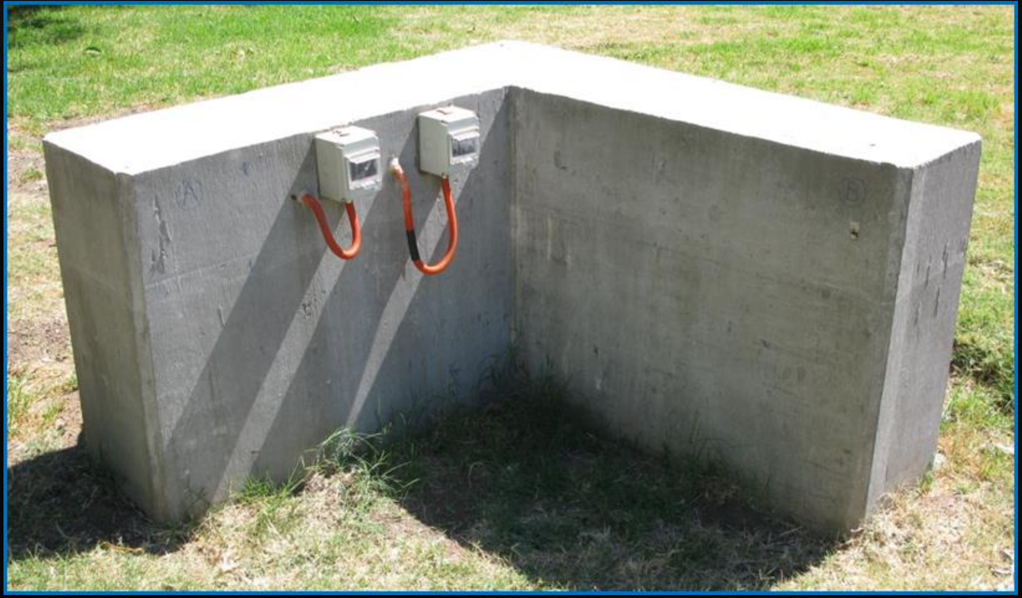
* E_{corr}
* V_{corr}
* Resistividad
* $[Cl^-]$
* O_2
* Temperatura

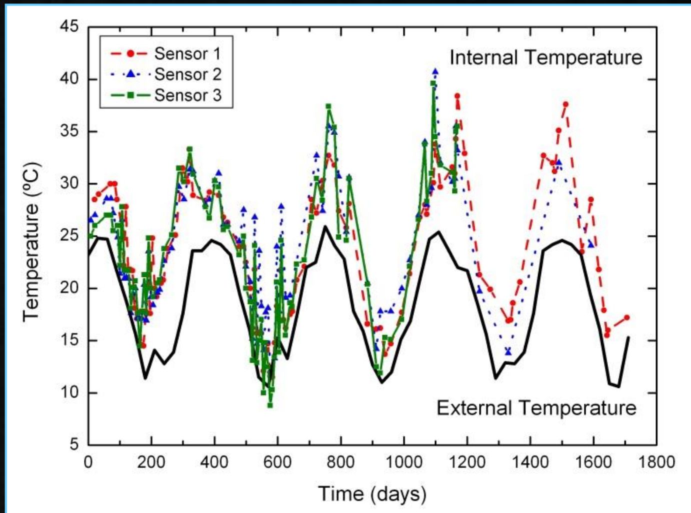


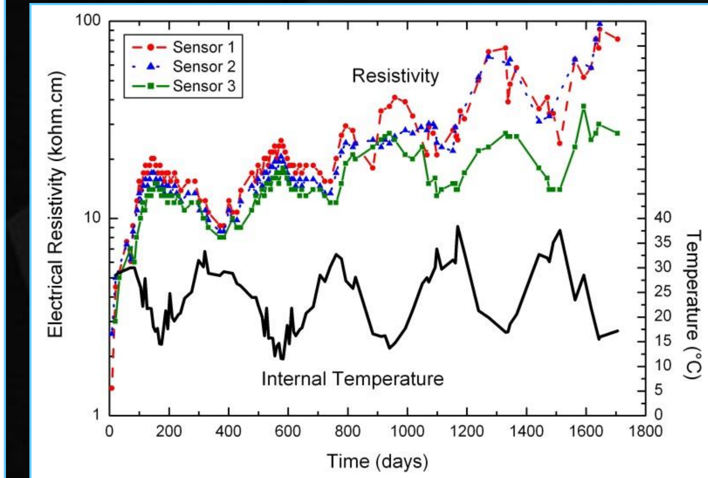
FACTIBLE DE INSTALAR EN ESTRUCTURAS NUEVAS O YA EXISTENTES

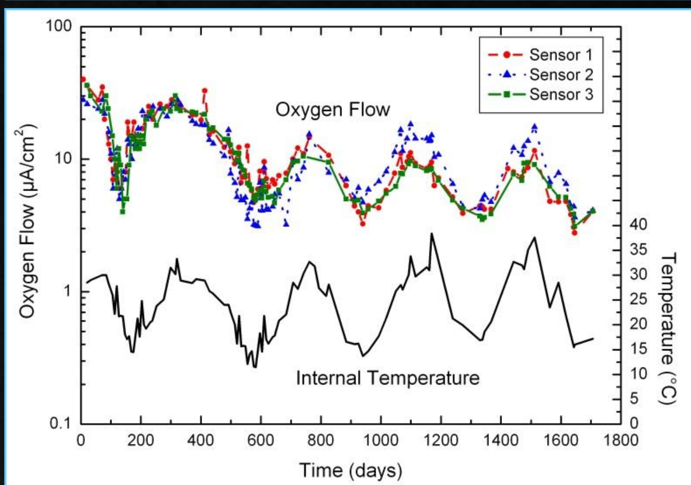
PROTOTIPO DE CONTENEDOR DE RESIDUOS RADIOACTIVOS DE BAJO NIVEL DE ACTIVIDAD

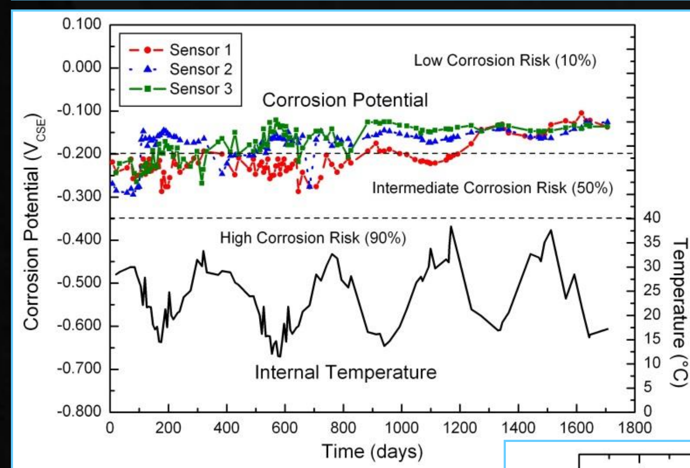
(Ho.Ao. desarrollado en el INTI)

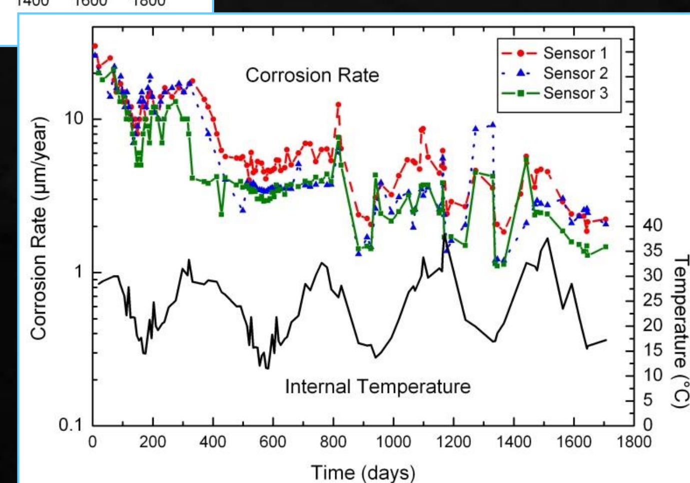



Sensor 1
Sensor 2
Sensor 3
Internal Temperature
External Temperature
Temperature (ºC)
Time (days)


Sensor 1
Sensor 2
Sensor 3
Resistivity
Internal Temperature
Electrical Resistivity (kohm.cm)
Temperature (°C)
Time (days)


Sensor 1
Sensor 2
Sensor 3
Oxygen Flow
Internal Temperature
Oxygen Flow (μA/cm²)
Temperature (°C)
Time (days)

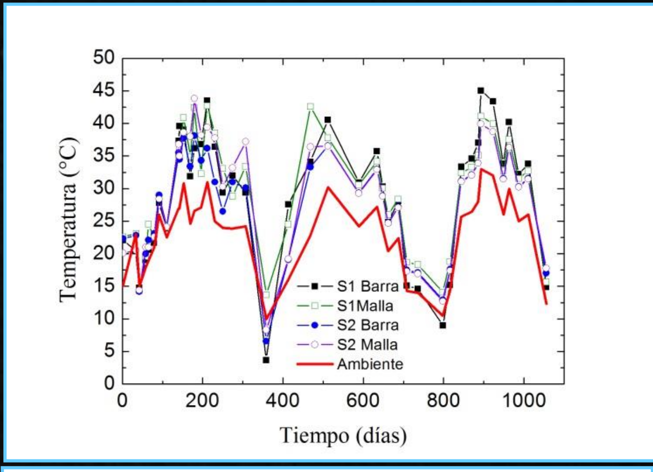

Sensor 1
Sensor 2
Sensor 3
Low Corrosion Risk (10%)
Corrosion Potential
Intermediate Corrosion Risk (50%)
High Corrosion Risk (90%)
Internal Temperature
Corrosion Potential (V_CSE)
Temperature (°C)
Time (days)

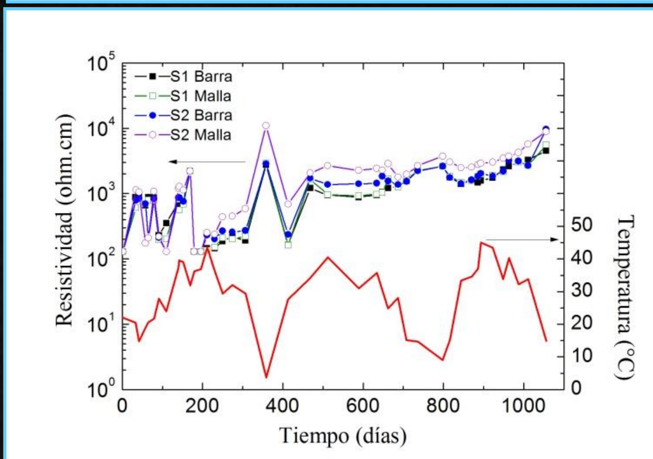

Sensor 1
Sensor 2
Sensor 3
Corrosion Rate
Internal Temperature
Corrosion Rate (μm/year)
Temperature (°C)
Time (days)

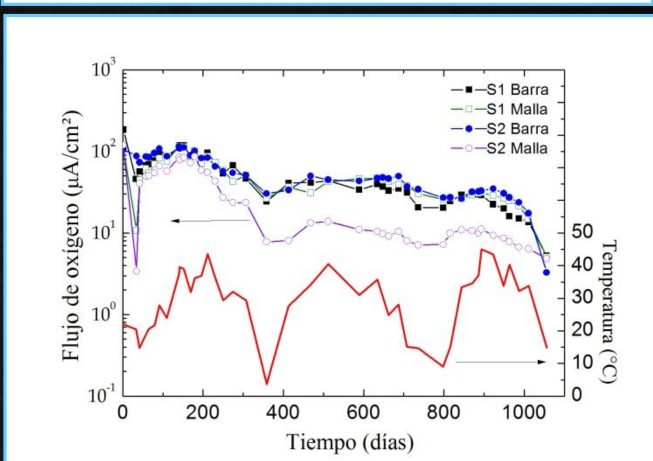
EVALUACIÓN DE NUEVOS HORMIGONES PARA LA CONSTRUCCIÓN DEL REPOSITORIO DE RESIDUOS RADIOACTIVOS

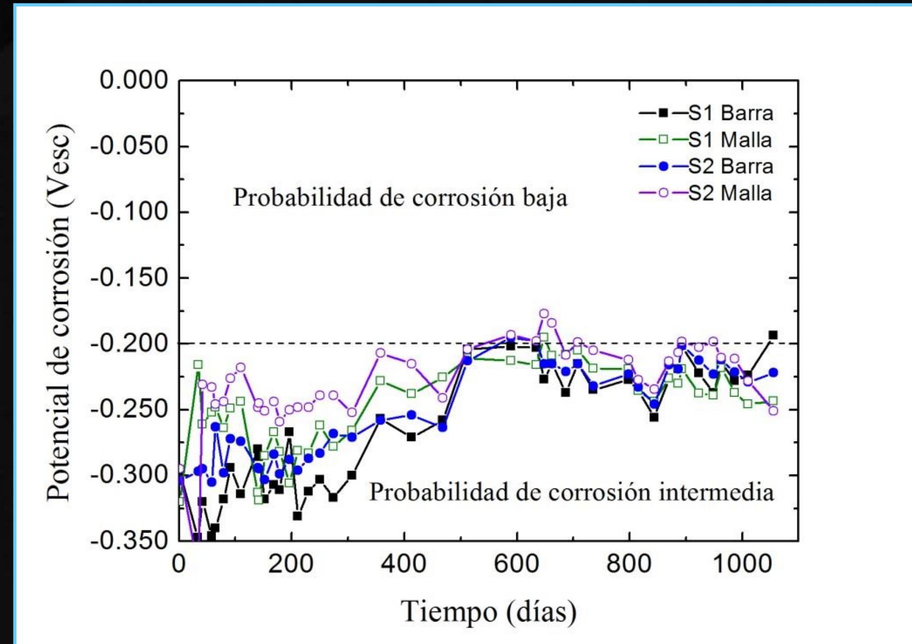
(Ho.Ao. desarrollado en el LEMIT)

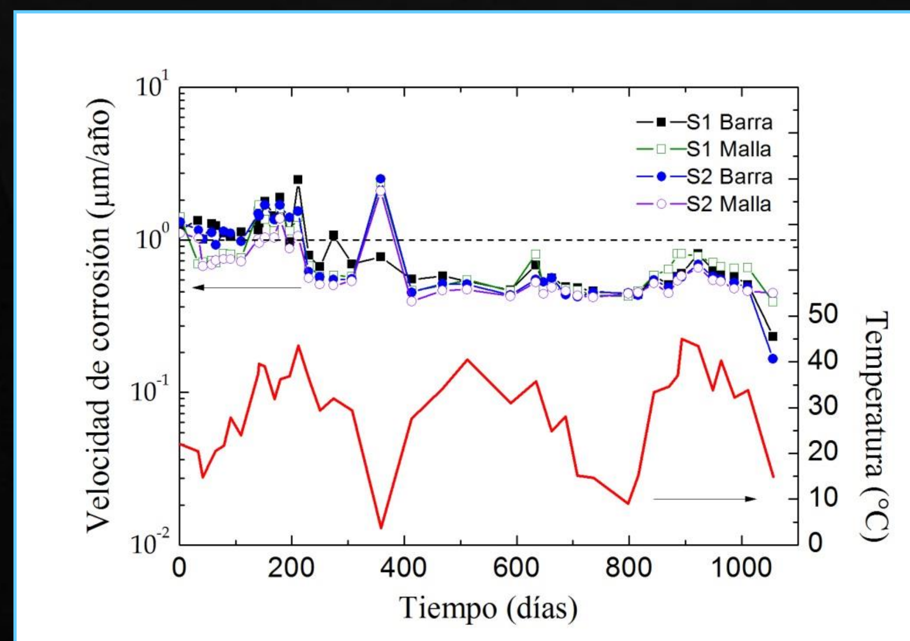
- GECOR 6
- Sensores
- Armaduras (barras y mallas), contraelectrodos de acero inoxidable y electrodos de referencia internos


Temperatura (°C)
Tiempo (días)
S1 Barra
S1Malla
S2 Barra
S2 Malla
Ambiente


Resistividad (ohm.cm)
Temperatura (°C)
Tiempo (días)
S1 Barra
S1 Malla
S2 Barra
S2 Malla

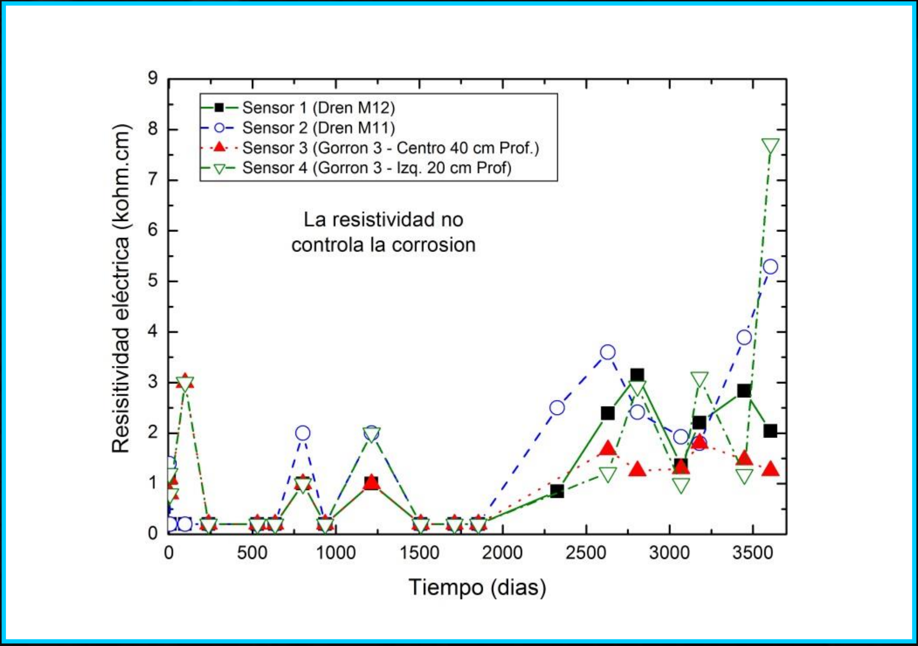

Flujo de oxígeno (μA/cm²)
Temperatura (°C)
Tiempo (días)
S1 Barra
S1 Malla
S2 Barra
S2 Malla

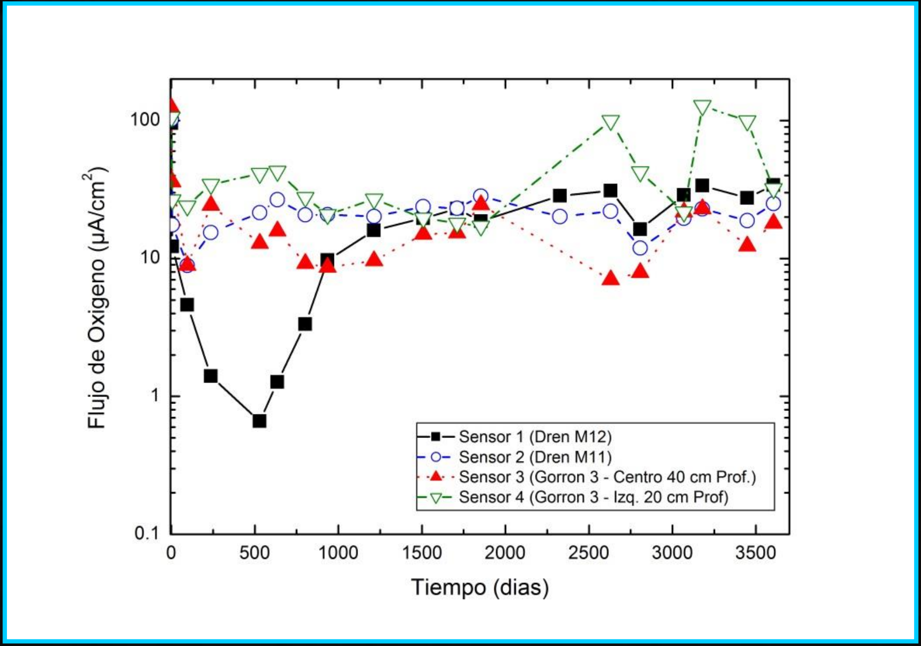

Potencial de corrosión (Vesc)
Tiempo (días)
S1 Barra
S1 Malla
S2 Barra
S2 Malla
Probabilidad de corrosión baja
Probabilidad de corrosión intermedia

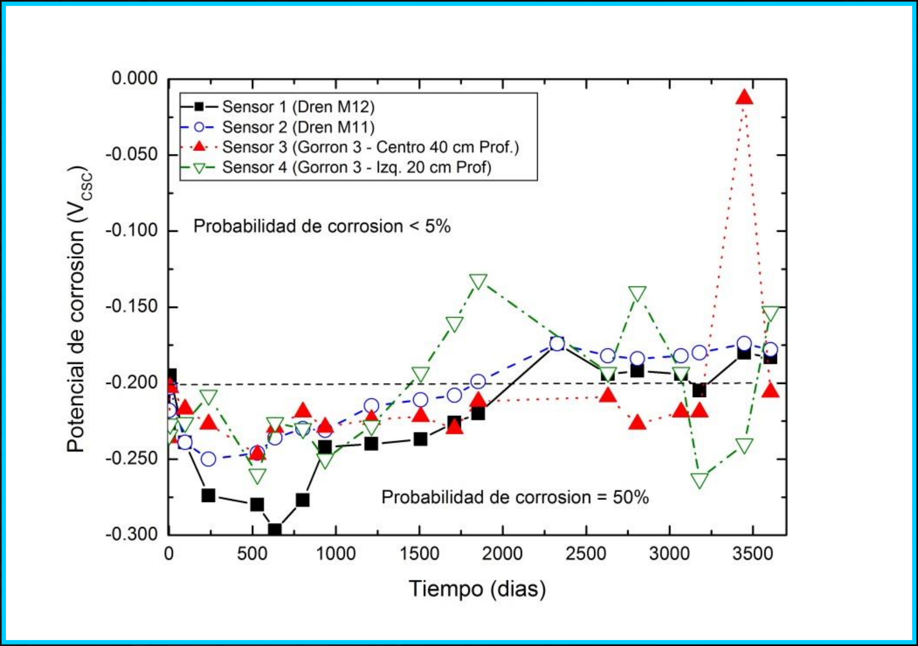

Velocidad de corrosión (μm/año)
Temperatura (°C)
Tiempo (días)
S1 Barra
S1 Malla
S2 Barra
S2 Malla

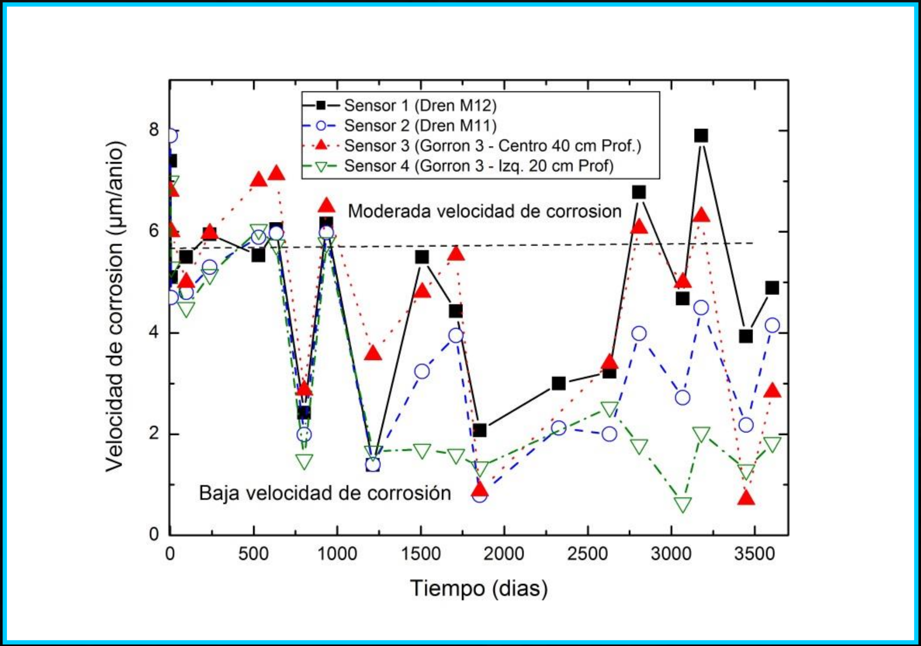
REPRESA HIDROELÉCTRICA PIEDRA DEL AGUILA

A requerimiento del Organismo Regulador de Seguridad de Presas (ORSEP)


Resisitividad eléctrica (kohm.cm)
Sensor 1 (Dren M12)
Sensor 2 (Dren M11)
Sensor 3 (Gorron 3 - Centro 40 cm Prof.)
Sensor 4 (Gorron 3 - Izq. 20 cm Prof)
La resistividad no
controla la corrosion
Tiempo (dias)


Flujo de Oxigeno (μA/cm2)
Sensor 1 (Dren M12)
Sensor 2 (Dren M11)
Sensor 3 (Gorron 3 - Centro 40 cm Prof.)
Sensor 4 (Gorron 3 - Izq. 20 cm Prof)
Tiempo (dias)


Potencial de corrosion (VCSC)
Sensor 1 (Dren M12)
Sensor 2 (Dren M11)
Sensor 3 (Gorron 3 - Centro 40 cm Prof.)
Sensor 4 (Gorron 3 - Izq. 20 cm Prof)
Probabilidad de corrosion < 5%
Probabilidad de corrosion = 50%
Tiempo (dias)


Velocidad de corrosion (μm/anio)
Sensor 1 (Dren M12)
Sensor 2 (Dren M11)
Sensor 3 (Gorron 3 - Centro 40 cm Prof.)
Sensor 4 (Gorron 3 - Izq. 20 cm Prof)
Moderada velocidad de corrosion
Baja velocidad de corrosión
Tiempo (dias)

HYDROPOWER AND DAMS (2014)

Corrosion monitoring of post-tensioned strands at the Piedra del Aguila spillway

A.L. Burkart, National Atomic Energy Commission, Argentina
G.S. Duffó, CONICET and Universidad Nacional de San Martin, Argentina
P. Castro, Hidroelectrica Piedra del Aguila SA, Argentina

The Piedra del Aguila project in Argentina is a concrete gravity dam constructed in the 1980s, on the Limay river. The dam includes a spillway channel controlled by four gates. The spillway structure includes several post-tensioned systems installed in the concrete piers. These systems do not meet the cable protection standards of modern methods, which provide two barriers against corrosion and can be monitored. In 2004, several leaks were detected that could have reached the steel tendons. Because of this, an innovative programme was developed to ascertain the integrity and remaining life of the steel strands. This paper presents a summary of the activities performed and the instrumentation installed at Piedra del Aguila to assist with the long-term monitoring of the dam.

In 2004, several leaks were detected at the lateral walls of the spillway piers of Piedra del Aguila dam in southern Argentina. Most of these leaks were located at pier number 3, near to the trunnion and below the level of the strands, coinciding with carbonation surface marks. Concern arose about the integrity of the system supporting the gates on the top of the spillway, which comprised a set of post tensioned tendons embedded in the concrete piers. It was thought that they could have been dampened by the leaking water, so the onset of steel corrosion was quite likely.

As a result, there was a need to establish whether or not the steel strands were being corroded. In case corrosion was detected, an estimate of the amount of damage (by measuring the corrosion rate of the steel) was required to assess the remaining cross section of the tendons and the impact on the integrity and safety of the support system, for the spillway gates.

In agreement with the regulatory authorities of Argentina, ORSEP (Organismo Regulador de Seguridad de Presas), a permanent safety evaluation programme to evaluate and monitor the tendon corrosion, was implemented by the operator. It consisted of three activities, which would allow for a complete assessment of the significance of the problem. The activities were:

• In-situ water sampling in several locations at the dam. The samples were chosen to represent the variety of water compositions encountered and were analysed for composition and the overall corrosion risk in accordance with DIN 50 929 Part 3 Standard. Also, a metallurgical examination of the steel strands was performed.
• Laboratory tests, carried out to simulate potential corrosion rates using actual water samples collected.
• The installation of sensors for continuous monitoring of several parameters related to the corrosion susceptibility of the grouted steel.

This work programme began in 2005 and is still running, managed by the Auscultation and Maintenance Division (A&MD) of Piedra del Aguila Company and carried out by the Corrosion Department of the National Atomic Energy Commission of Argentina (CNEA). Only a few references were found in literature concerning this type of task [Herweynen and Hughes, 2002[1]; Powers, 1999[2]; Powers *et al.*, 2001[3]].

1. Features of the Piedra del Aguila dam

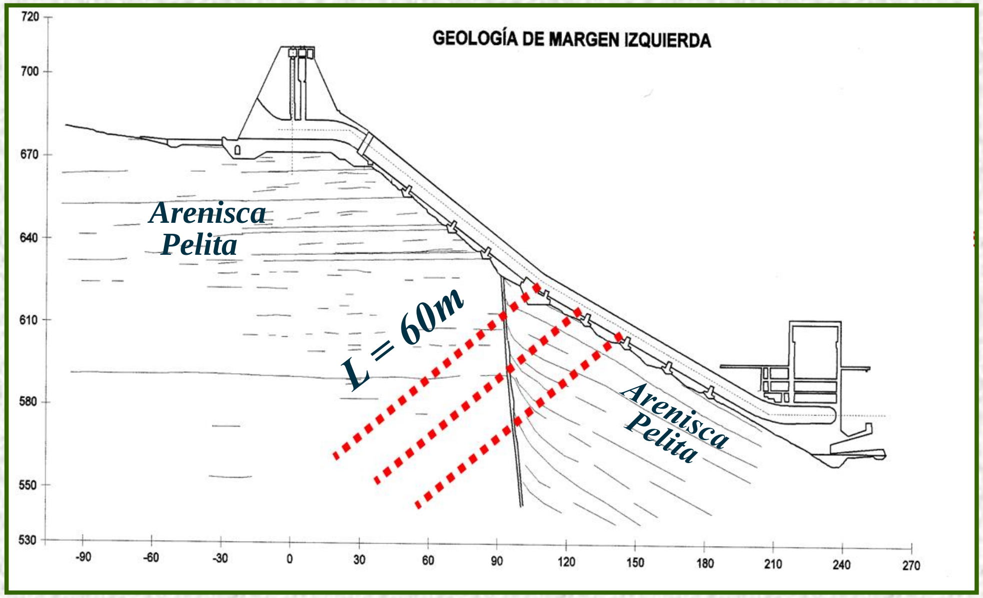
The Piedra del Aguila project is a 1400 MW hydropower plant located in the province of Neuquén in the northern part of Argentinean Patagonia. As with the other four dams built along the Limay river by the state enterprise Hidronor, it was constructed in the 1980s. The Hidroeléctrica Piedra del Aguila SA Company (HPDASA) is currently the operator. As HPDASA started operating the utility in 1993 an Auscultation and Maintenance Division (A&MD) was created to work on the safety requirements imposed on the dam by ORSEP.

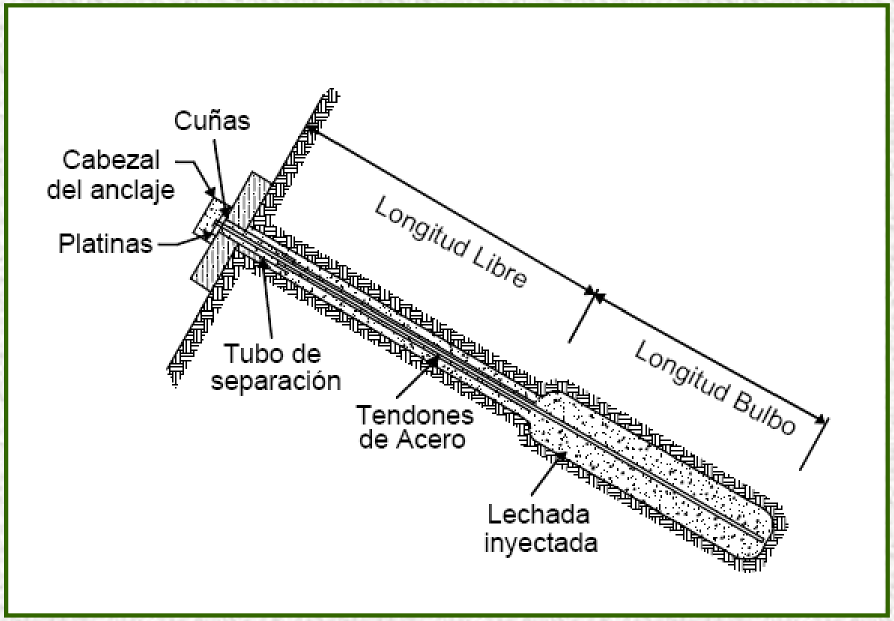
(a) General view of the Piedra del Aguila dam.

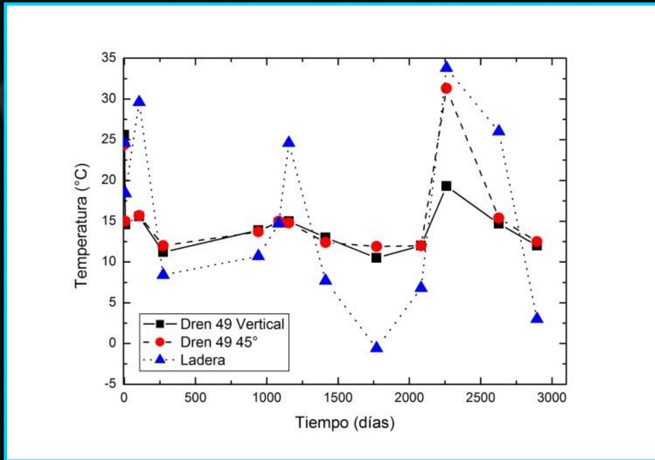
(b) View of the spillway and floodgates.

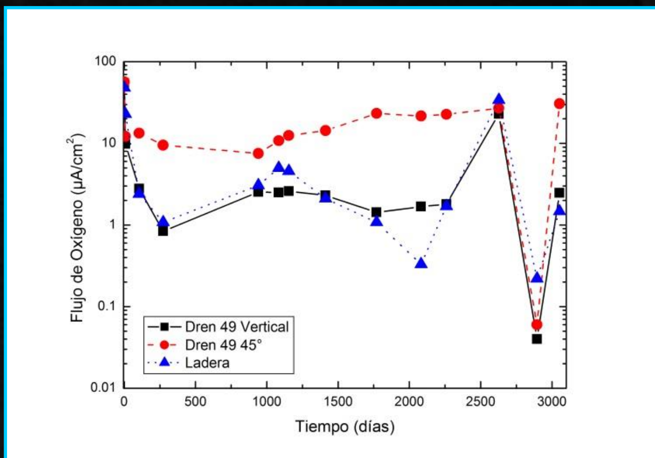
REPRESA HIDROELÉCTRICA AES-ALICURA

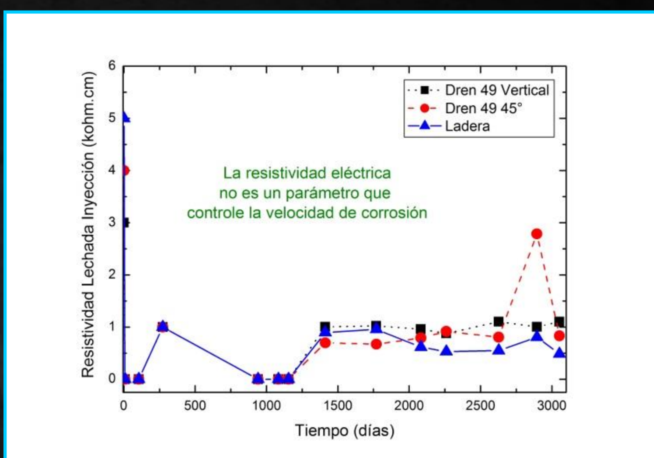
SISTEMA DE ANCLAJE

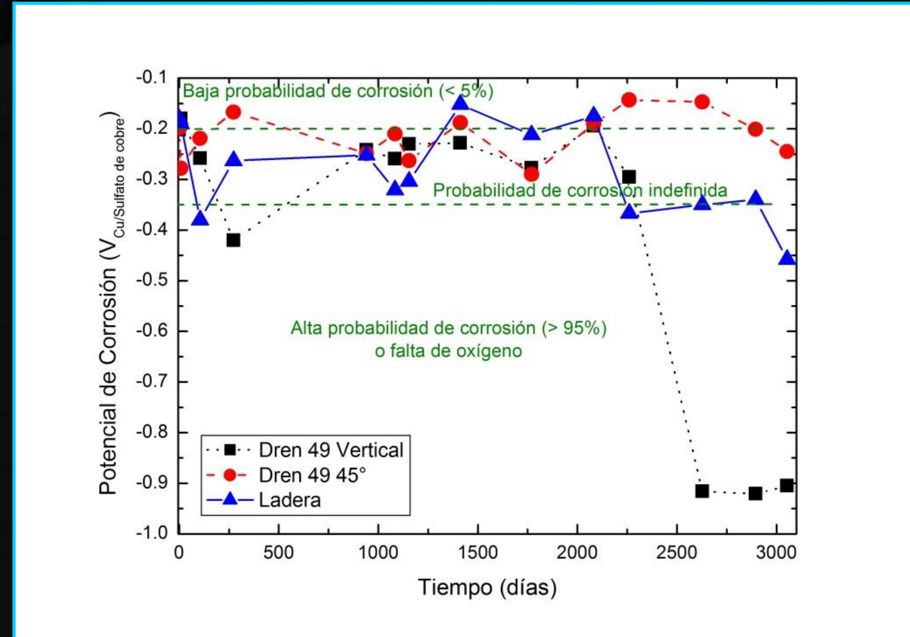


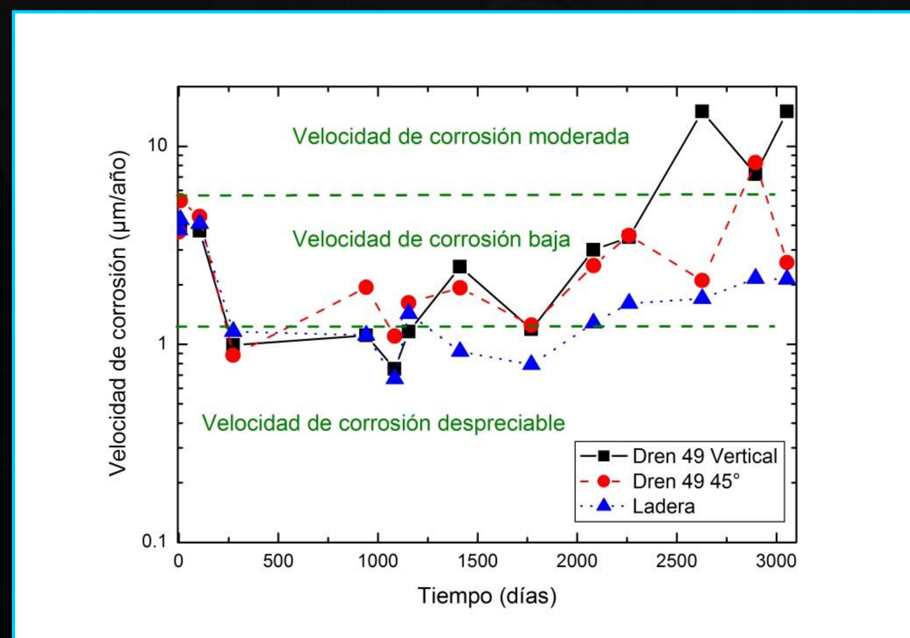



Temperatura (°C)
Tiempo (días)
Dren 49 Vertical
Dren 49 45°
Ladera


Flujo de Oxigeno (μA/cm²)
Tiempo (días)
Dren 49 Vertical
Dren 49 45°
Ladera


Resistividad Lechada Inyección (kohm.cm)
Tiempo (días)
Dren 49 Vertical
Dren 49 45°
Ladera
La resistividad eléctrica
no es un parámetro que
controle la velocidad de corrosión


Potencial de Corrosión (V Cu/Sulfato de cobre)
Tiempo (días)
Baja probabilidad de corrosión (< 5%)
Probabilidad de corrosión indefinida
Alta probabilidad de corrosión (> 95%)
o falta de oxígeno
Dren 49 Vertical
Dren 49 45°
Ladera


Velocidad de corrosión (μm/año)
Tiempo (días)
Velocidad de corrosión moderada
Velocidad de corrosión baja
Velocidad de corrosión despreciable
Dren 49 Vertical
Dren 49 45°
Ladera

REPRESA HIDROELÉCTRICA CABRA CORRAL

PROTOTIPO DEL SUPERCONTENEDOR DE RESIDUOS RADIOACTIVOS

BÉLGICA (SCK) - PROYECTO EUROPEO DE COOPERACIÓN (ESV EURIDICE GIE)

Laboratorio Magnel
Universidad de Gent

CORROSION ENGINEERING SCIENCE AND TECHNOLOGY (2014)

Preliminary results of corrosion monitoring studies of carbon steel overpack exposed to supercontainer concrete buffer

B. Kursten*[1], F. Druyts[1], L. Areias[2], Y. van Ingelgem[3], D. De Wilde[3], G. Nieubourg[3], G. S. Duffó[4] and C. Bataillon[5]

The supercontainer (SC) is the reference concept for the postconditioning of vitrified high level radioactive waste and spent fuel in Belgium. It is designed with a concrete buffer completely surrounding a carbon steel overpack. A half-scale (HST-2) experiment was set up to measure the instantaneous uniform corrosion rate, representative of the initial oxic phase, *in situ*. The test set-up has the same diameter as a full size SC, but it is limited in height to approximately half of a real SC. The corrosion rate of carbon steel is measured in four ways: weight loss measurements (carbon steel coupons), corrosion sensor based on linear polarisation resistance, corrosion sensor based on multisine electrochemical impedance spectroscopy and corrosion sensor based on single sine electrochemical impedance spectroscopy coupled to a unique analytical method. This paper presents the preliminary results of the corrosion rates measured with these independent methods.

Keywords: Uniform, Corrosion, Passive, Concrete, Steel, LPR, EIS, Disposal

This paper is part of a special issue on 'Long-Term Prediction of Corrosion Damage in Nuclear Waste Systems'

Introduction

The supercontainer (SC) is the Belgian reference concept proposed by ONDRAF/NIRAS for the packaging of vitrified high level radioactive waste (VHLW) and spent fuel (SF).[1,2] It consists essentially of a prefabricated massive cylindrical concrete block (ordinary Portland cement), named 'the buffer', into which a watertight cylindrical carbon steel container, the so called overpack, holding either VHLW waste canisters or SF assemblies, will be inserted. There is also an alternative design option in which the concrete block will be fitted into an outer stainless steel container, termed the 'envelope'.

The reference material to construct the overpack is currently the P355 QL2 grade carbon steel. The long term safety function of the overpack is to contain the radionuclides during the thermal phase, which will last several thousands of years. The concrete buffer has a thickness of 54–70 cm (depending on the waste to be placed in the SC) and completely surrounds the overpack. One of the main long term functions of the concrete buffer is to provide a highly alkaline chemical environment, in which a thin but tightly adhering oxide film is formed on the surface of the carbon steel overpack that protects the underlying metal and is believed to result in very low and almost negligible uniform corrosion rates (passive dissolution). Apart from creating a favourable environment around the overpack, the concrete buffer also provides the required radiological shielding.

Half-scale prototype test

As part of the present experimental programme to verify the feasibility of constructing the SC, a second half-scale experiment (HST-2) was performed in 2013. The test set-up has the same diameter as a full size SC (~2·1 m), but it is limited in height (~3·5 m) to approximately half that of a real SC. Figure 1 shows the general set-up of the half-scale test.

The outer mould consists of two cylindrical steel segments held together and to a steel base plate by means of bolts. A steel inner mould is inserted to create an inner cavity for later installation of the heater. The space between the outer and inner mould is filled with a non-reinforced, self-compacting concrete (i.e. the buffer). After removal of the inner mould, a carbon steel container with a diameter of 508 mm and a thickness of 15·06 mm, simulating the overpack, is inserted in the remaining cavity. Inside the overpack are four heating elements to simulate the heat generated by the

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[2]EIG EURIDICE, c/o SCK-CEN, Boeretang 200, Mol 2400, Belgium
[3]Vrije Universiteit Brussel, VUB, SURF, Pleinlaan 2, Brussel 1050, Belgium
[4]Comisión Nacional de Energía Atómica, CNEA-CONICET-UNSAM, Corrosion Department, Av. Gral. Paz 1499, (1650KNA) Buenos Aires, Argentina
[5]CEA, DEN, DPC, SCCME, Laboratoire d'Etude de la Corrosion Aqueuse, Gif-sur-Yvette F-91191, France

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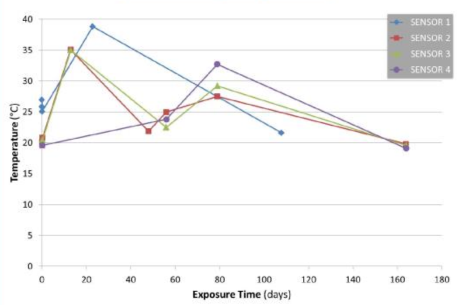
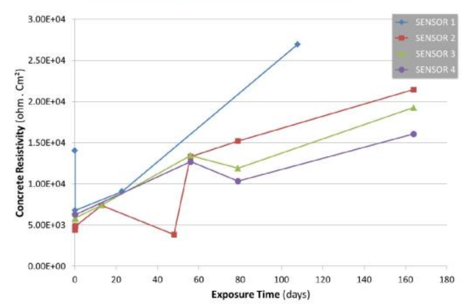
EXPERIMENTAL RESULTS

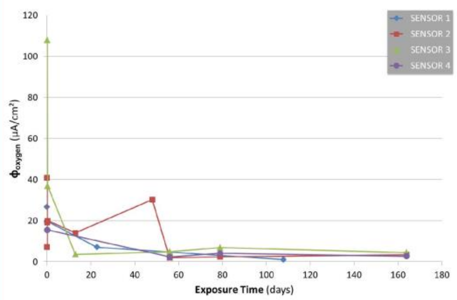
Evolution of temperature



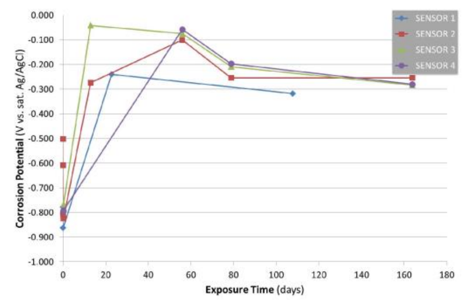
Evolution of concrete resistivity



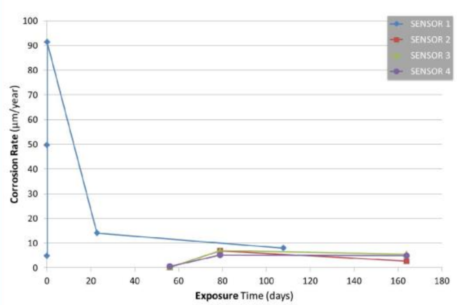
Evolution of oxygen flow



Evolution of corrosion potential



Evolution of corrosion rate



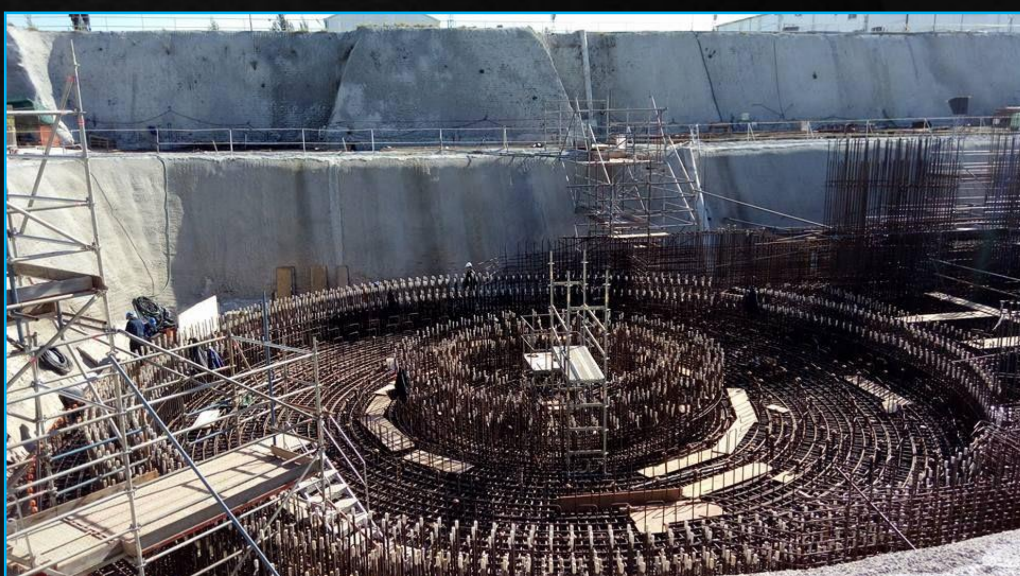
- Sensor 1 is installed on top; sensors 2, 3 and 4 are installed radially at mid-height
- Temperature increase
  - ➡ onset of heating
- Concrete electrical resistivity increases
  - ➡ hydration of concrete
- Oxygen flow decreases
- Ennoblement of corrosion potential
  - ➡ Formation of passive film
- Decrease of corrosion rate after initial increase

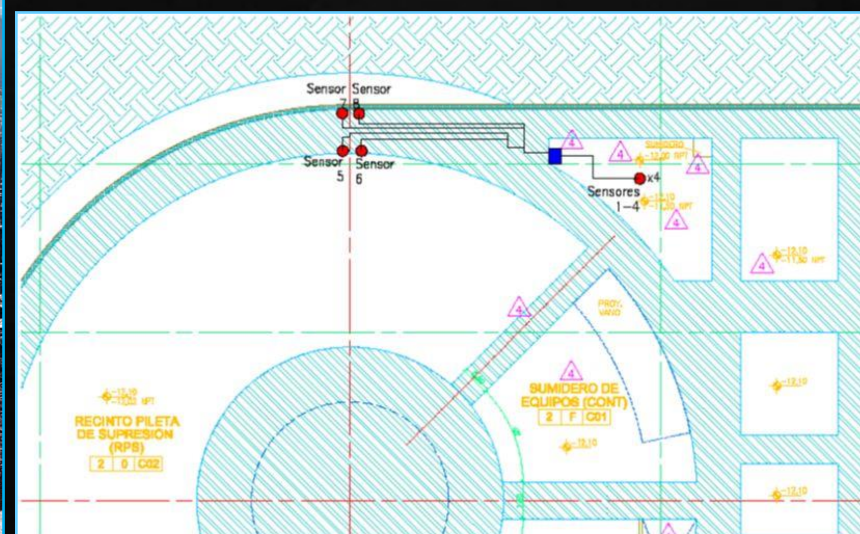
SILO DE ALMACENAMIENTO EN SECO DE ELEMENTOS COMBUSTIBLES NUCLEARES GASTADOS

Central Nuclear Atucha I

REACTOR CAREM 25

El Proyecto Carem 25 tiene por objeto la construcción y puesta en marcha de un prototipo de reactor nuclear de baja potencia, diseñado íntegramente en el país





REACTOR CAREM 25

Sensores

CONCLUSIÓN

- La utilización de sensores en la determinación de parámetros relacionados con la corrosión de armaduras es una de las herramientas más promisorias para establecer la vida útil de una estructura de hormigón armado

- Más de 10 años de experiencia en el empleo de sensores en diferentes áreas (nuclear, hidroeléctrica, convencional, etc.)

MUCHAS GRACIAS POR SU ATENCIÓN

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