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Large-scale and long-term coupled thermo-hydro-mechanic experiments with bentonite: the FEBEX mock-up test.

Experimentación del acoplamiento termo-hidro-mecánico en bentonita a gran escala y larga duración: ensayo FEBEX en maqueta.

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Abstract

The paper summarizes the large-scale long-term experiment performed in the frame of the FEBEX and FEBEX-II projects. An almost full-scale thermo-hydro-mechanical (THM) mock-up test was designed to improve the knowledge of the coupled THM processes in the Engineering Barrier System of the Spanish reference concept for the Deep Geological Disposal in Granite. The test runs under controlled boundary conditions.

More than 500 sensors measure the most important thermo-hydro-mechanical variables within the bentonite barrier; meanwhile, data acquisition and control systems manage, supervise, record and store the data generated. The sensors were chosen to withstand mechanical stress, high temperature, humidity and salinity coming from environment.

After more than eight and a half years, the test has become a source of valuable data, both in number of involved processes and duration of the experiment, including some qualitative aspects, that indicates major implications of the thermal aspects in the transport processes.

Keywords: radioactive waste disposal, bentonite barrier, coupled processes, thermo-hydro-mechanical instrumentation.

Resumen

El artículo presenta, de manera resumida y no exhaustiva, el experimento de gran escala y larga duración realizado en el marco de los proyectos FEBEX y FEBEXII. Se diseñó un ensayo termo-hidro-mecánico en maqueta para mejorar el conocimiento de los procesos termo-hidro-mecánicos (THM) acoplados que se producen en el sistema de barreras de ingeniería prevista en el concepto de referencia para un Almacenamiento Geológico Profundo en granito. El ensayo se realiza bajo condiciones controladas.

Más de 500 sensores miden las variables termo-hidro-mecánicas más importantes en la barrera de bentonita, mientras los sistemas de adquisición y control gestionan y supervisan el ensayo y registran los datos generados. Los sensores se han elegido para soportar las duras condiciones ambientales impuestas (tensiones mecánicas, temperatura, salinidad y humedad elevadas).

Tras más de ocho años y medio, el ensayo se ha convertido en una importante fuente de datos, tanto por el número de procesos involucrados como por la duración del experimento, incluyendo algunas aspectos cualitativos que parecen indicar implicaciones importantes de los aspectos térmicos sobre los procesos de transporte.

Palabras clave: almacenamiento de residuos radiactivos, barrera de bentonita, procesos acoplados, instrumentación termo-hidro-mecánica.

1. Introduction

The knowledge and the experience acquired during the last 20 years of studies on clay materials as sealing barriers in the Spanish concept of a deep geological repository (AGP Granite reference concept; ENRESA, 1994; 1995) were integrated in a demonstration and research project to study the clay under repository conditions: The FEBEX project (ENRESA, 2000).

The FEBEX project has been developed in two phases: FEBEX I, from 1994 to 1998, and FEBEX II, from 1999 to 2004. The project consisted of three main parts: an *in situ* test under natural conditions and at full scale, in a crystalline rock formation at the Grimsel test site (Switzerland); a test on an almost full-scale *mock-up* test at Ciemat (Spain); and a series of laboratory tests aimed at providing information complementary to the two large-scale tests. All these activities served as a support for a far-reaching programme of modelling work.

The main aims were to demonstrate the technical feasibility of a repository, to know and understand the long-term behaviour of a clay barrier submitted to thermal and hydraulic gradients, and to validate and verify the near field THM models under controlled boundary conditions.

In the "mock-up" test, the heterogeneities of the natural system (granite formation) are avoided, the hydration process is controlled, and the boundary conditions are better defined than in the "in situ" test. This facilitates the verification of the predictive capacity of the numerical codes developed for analysis of the behaviour of the near-field, as only the behaviour of the clay barrier is considered. This verification by comparison only with the behaviour of the clay barrier is a necessary step prior to comparing the model results with the behaviour of the natural conditions, as in the "in situ" test. So, the *THM* behaviour of the test has been successfully modelled during the operational stage of the experiment (ENRESA, 2000; Sánchez and Gens, 2002; Sánchez, 2004), using 1-D axisymetric models and 2-D axisymetric longitudinal section models.

The components of the mock-up test are similar to those of the "in situ" test: two electric heaters, a 0.64 m-thick clay barrier, instrumentation, automatic control of heaters, and a data acquisition system for the data generated. Although the conceptualization of the two large-scale tests is very similar, there are major differences: the "mock-up" test has a clay barrier with an unlimited availability of hydration water, supplied at constant pressure, therefore, full steady state conditions, both thermal and hydraulic, were expected to be reached; secondly, the mock-up tests has a steel confining structure (instead of the heterogeneous granite mass of the "in situ" test), installed in a room with a nearly constant temperature.

The test is being performed in the facilities of CIEMAT (Madrid), in a building constructed for this purpose. The installation phase of the mock-up has been carried out between October 96' and January 97'. The clay barrier was constructed of highly-compacted bentonite blocks with 22.5 t of installed bentonite mass. A summary description of the design and installation of the physical components of the test are presented in ENRESA (2000) and Martín (2004). The operational stage – simultaneous hydration and heating– started in February 4th 1997. Since then, the test is running regulated by the heater control system (HCS), and produces information from about 500 installed sensors. The information is being stored and managed by the data acquisition system (DAS).

At the end of the operational stage, it is planned to proceed to the dismantling stage—extraction, inspection, sampling, and study of all the installed materials. The results from the dismantling stage will be used to gain insight on the final state of the instruments, the intensity of corrosion induced in the metals and, especially, the geochemical modifications produced in the bentonite.

The mock-up tests surpass the space-scale limitation of the laboratory tests, by adoption of the real dimensions of the repository, but they do not prevent the time-scale limitation. The short duration of the tests, related to the operative life of the repository, induces uncertainties to extrapolate the future behaviour of the clay barrier from the experimental transient state (ENRESA, 1997). Therefore, the qualitative analysis must allow discriminating between the possible processes that affect to the function of the EBS. The sensitivity analysis of the parameters associated with the selected processes, by previously validated numerical codes, will help in establishing priorities for the quantitative analysis.

2. Experimental set-up

2.1 Main Units

As mentioned before, the test is installed in an annex to Building 19 at the CIEMAT facilities in Madrid, Spain, constructed exclusively for this purpose. The building is air-conditioned, so that the temperature is maintained almost constant (20 ± 2 ºC).

The infrastructure of the test consists of five basic units, represented in figure 1: the confining structure with its hydration system, heating system, clay barrier, thermo-hydro-mechanical (THM) instrumentation, and systems for data acquisition (DAS) and heating control (HCS).

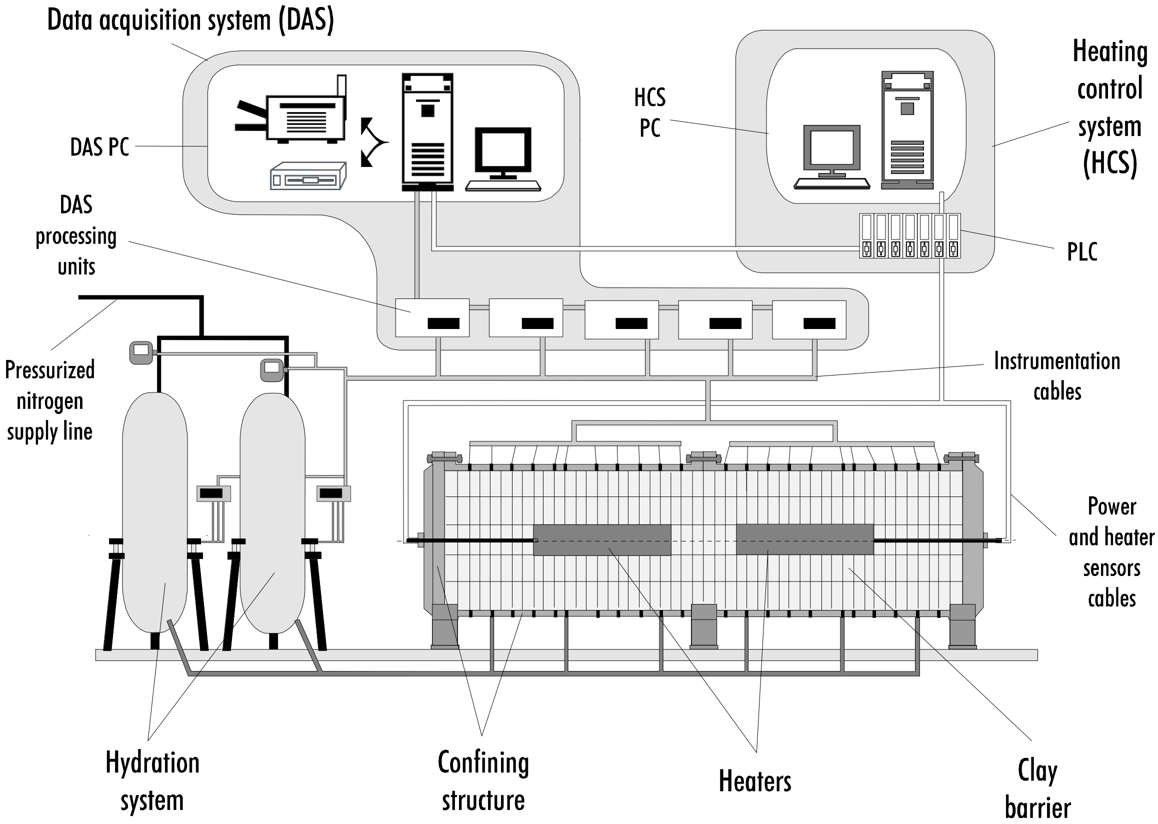

Fig. 1.- General scheme of the Mock-up experiment.
Fig. 1.- Elementos del ensayo en maqueta.

The test is functioning automatically, regulated by the heater control system (HCS), and produces information from about 500 THM sensors that is stored and managed by the data acquisition system (DAS). Besides, as critical components, some aspects of the clay barrier, and the hydration and heating systems are presented below.

Specimens of different metals were installed in the clay barrier to complement the study of the corrosion affecting the metallic components of the system (heaters and sensors). In addition, artificial chemical tracers were installed to facilitate understanding of the geochemical processes of the water/bentonite interaction and of mass transport.

2.2. Confining structure and hydration system

2.2.1. Confining structure

The structure (6.0 m inner length, 1.61 m diameter, Fig. 2) that encloses the clay barrier is a cylinder of carbon steel with an interior cladding of stainless steel. It consists of two cylindrical bodies joined by a central flange and closed by two metallic end covers, of the same materials. The design pressure is 9 MPa. The confining structure is supported by three metallic legs.

In each end cover there is an exit for the power and temperature sensor cables from the heaters. The cylindrical surface of the confining structure is drilled in 234 points: 48 for water injection and 186 for the exit of sensor cables.

CIEMAT performed the inspections and tests considered necessary to monitor and control the materials and construction techniques used. The most significant examinations were by X-rays and by penetrating liquids; the acceptance of an inspection point program (IPP) and the performance of two hydraulic tests, one structural in character and the other to detect leaks (performed with water under pressure, up to 112 bars). The materials used were received with their corresponding quality certificates.

2.2.2. Hydration system

This system supplies water for hydration of the bentonite mass, at a constant and controlled pressure. Two tanks (Fig. 1) with a total capacity of approximately 1.3 m^3, working under nitrogen pressure, supply water through a network of pipes joined to the 48 water nozzles in the confining structure. The design pressure is 3.5 MPa.

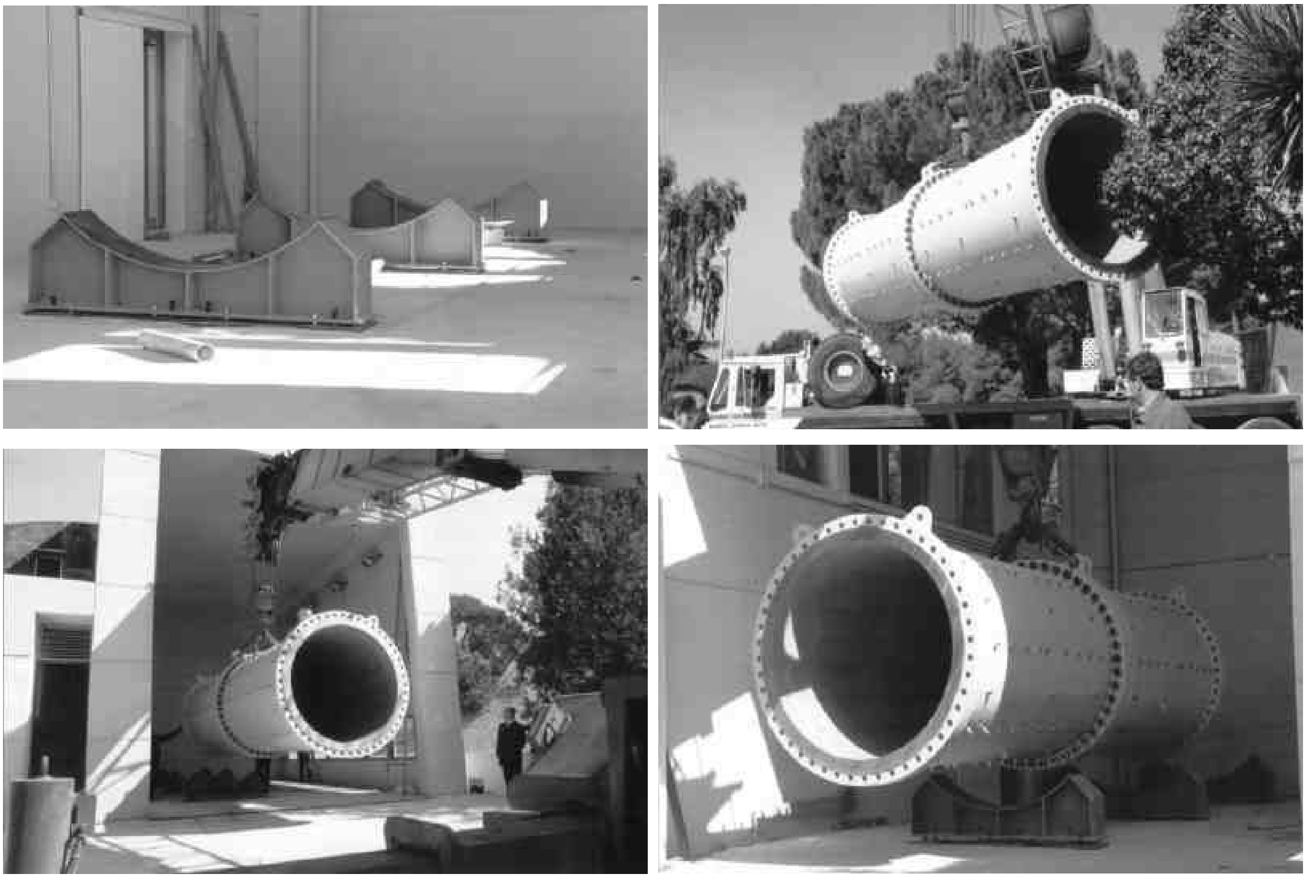

Fig. 2.- Installation of confining structure.
Fig. 2.- Instalación de la estructura confinante.

The hydration tanks have been subjected to a hydraulic test at 1.5 times the nominal design pressure (4.0 MPa) and 100% of the welds were examined. The parts of the system in contact with the water are made by stainless steel, AISI 304L. The materials were supplied with their corresponding quality certificates.

The connection between the hydration system and the confining structure is made by means of 48 injection points distributed in six sections, each section with eight injection nozzles distributed at 45º and connected to a pipe ring. To avoid clogging produced by the clay, the injection nozzles are protected by two filters of stainless steel, one stainless steel mesh disk, and one geotextile disk. The internal surface of the confining structure is covered by four layers of geotextile to facilitate the homogeneous hydration of the clay barrier. The properties of compressibility and permeability of the geotextile have been verified by laboratory tests.

Commercial (granitic-type) water hydrates the experiment, due to the ease of supplying the necessary quantity of chemically stable water over the entire test period. Furthermore, the same water was used in the laboratory tests in recent years, and its composition is known and stable. Iodine and deuterium were added to the water as tracers. The resulting water has a pH of 8.1 and an electrical conductivity of 278 μS/cm.

The injected water volume is calculated from the masses of the tanks, corrected by the nitrogen pressure. The values obtained are sent directly to the data acquisition system (DAS).

2.2.3. Installation

The two parts forming the confining structure were assembled and then transported by road to CIEMAT. The positioning of the structure on the three supporting legs was carried out before the annex building front end was completed, due to the size and difficulty in handling the confining structure (Fig. 2).

2.3. Clay barrier

The material used for the clay barrier comes from Serrata de Níjar (Almería, Spain). It is a Ca-Mg montmorillonite (92%) with low quantities of feldspars, biotite,

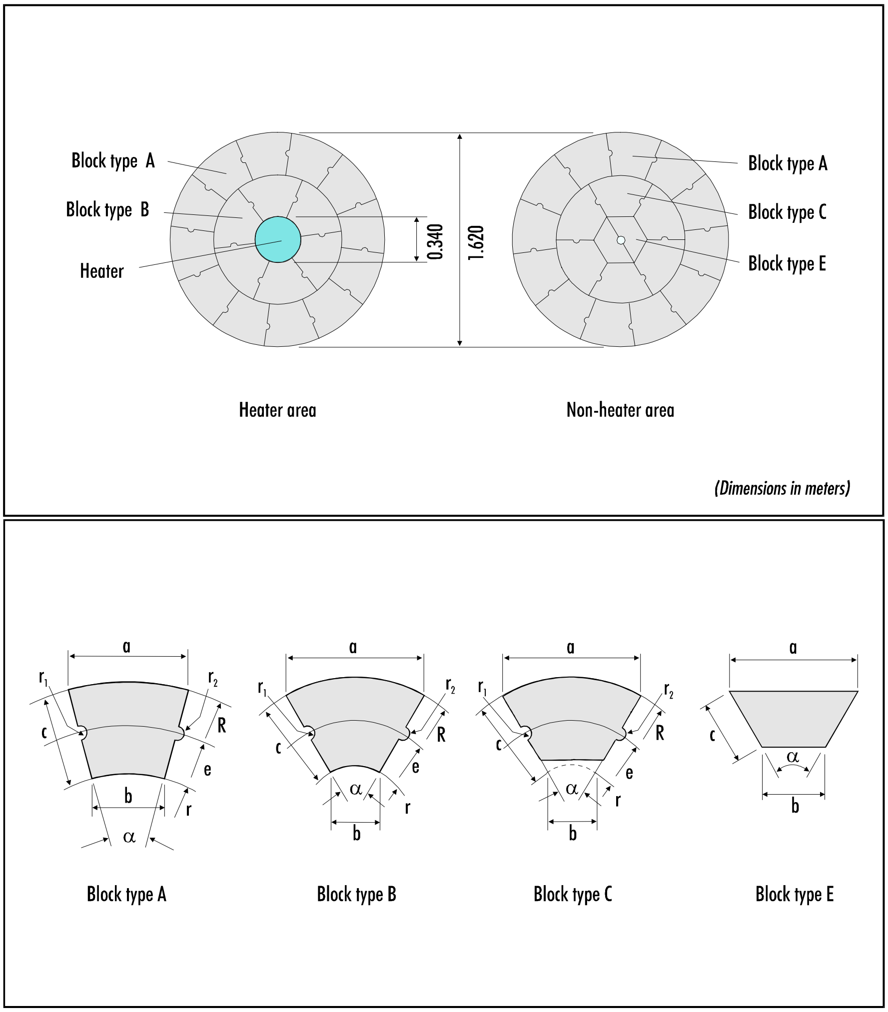

Fig. 3.- Geometry of the barrier (top) and forms of the blocks (bottom).
Fig. 3.- Geometría de la barrera (arriba) y forma de los bloques (abajo).

quartz and fragments of volcanic rocks; and presents the required properties: thermal, hydraulic, mechanical and physico-chemical (ENRESA, 2000; Villar, 2000, 2006). The same bentonite was used throughout the FEBEX project.

2.3.1. Design

The clay barrier, 6.0 m-length and 0.64 m-thick, was constructed by bentonite blocks. Figure 3 shows the geometry of the barrier in two representative sections, one corresponding to the heater area and another outside the heater area. This geometry is made with four types of blocks: A, B, C, and E, as indicated in Figure 3.

The blocks are arranged in 48 sections: 26 sections of two concentric rings around the heaters and 22 other sections of two rings and a core (ENRESA, 2000).

2.3.2. Fabrication

Moulds were designed and manufactured for fabrication of the block types A and B. Some of the B-type blocks were machined to have a plane inner face for C type blocks. Then the B mould was modified (protrusions were removed) to obtain intermediate blocks (D-type) which were then machined to obtain E-type blocks.

The blocks were compacted in a single-acting, uniaxial hydraulic press by three successive strokes of 40 MPa to 50 MPa pressure. Table 1 shows the average values of the characteristics of the different types of blocks. In total, 25870 kg of bentonite were compacted to manufacture 1012 blocks. The average weighted values of the water content and dry density are 13.6% and 1.77 g/cm^3,

	Type of block		
	A	B+C	D(E)
Weight per block (kg)	25.8	25.2	25.3 (D)
Average water content (%)	14.2	13.2	13.1
Dry density (g/cm^3)	1.77	1.76	1.82
Number of fabricated units	598	322	92
Total weight (kg)	15428	8114	2328

Table 1.- Average values of the physical properties and number of blocks fabricated.
Tabla 1.- Promedios de las propiedades físicas y número de los bloques compactados.

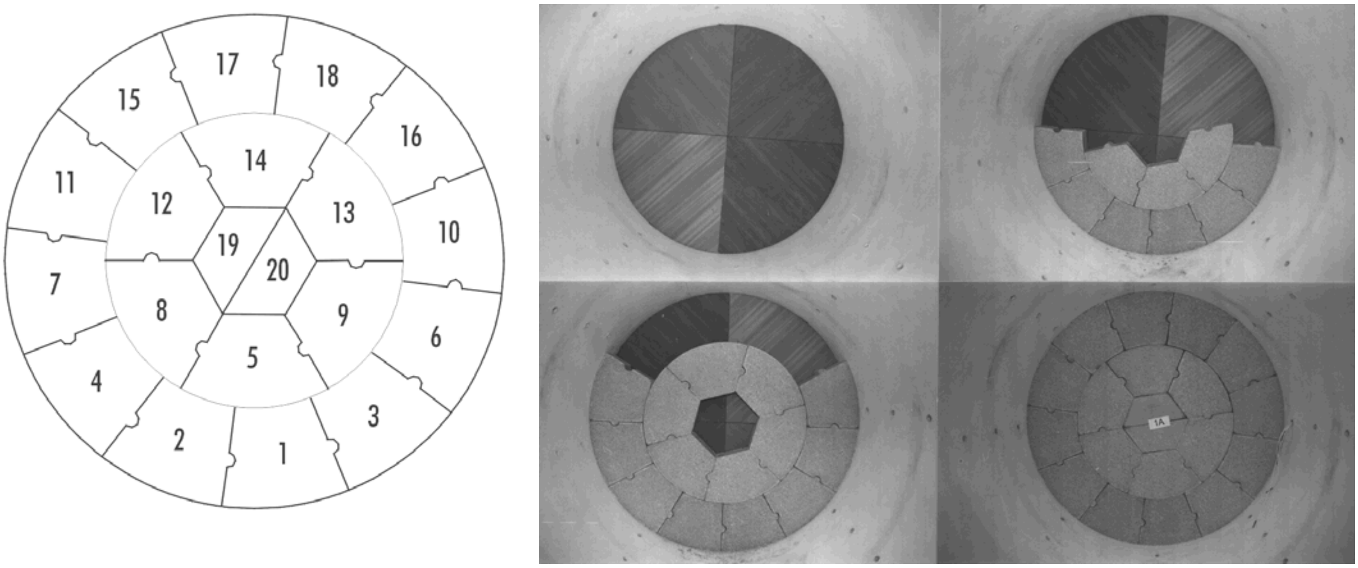

Fig. 4.- Sequence of installation of a slice of bentonite blocks.
Fig. 4.- Secuencia de instalación de una sección de bloques de bentonita.

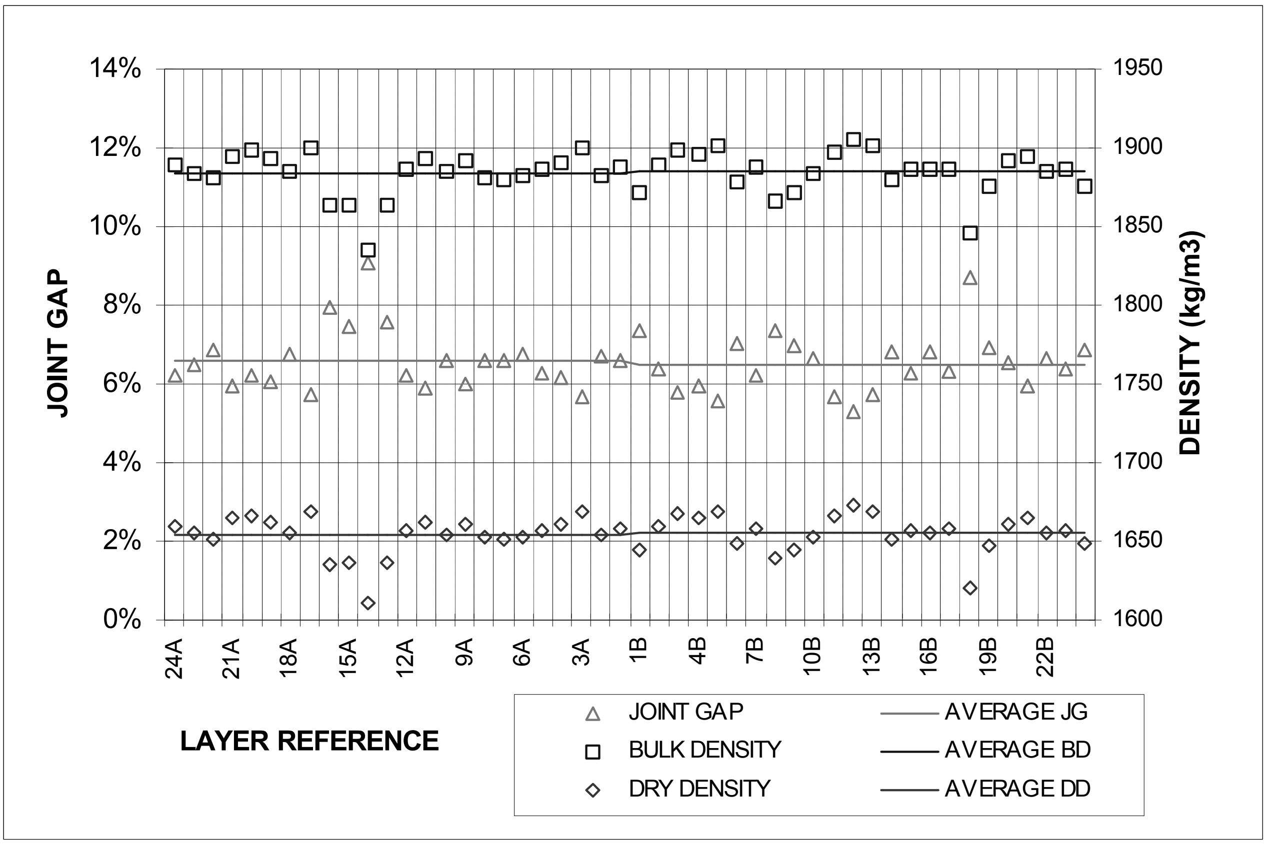

Fig. 5: Average values in the installed barrier: void ratio and density.
Fig. 5: Valores promedio en la barrera instalada: índice de vacíos y densidad.

respectively (ENRESA, 1998a; 1998b). This density is based on considering the anticipated volume of construction gaps to obtain the final dry density of the design criterion of Spanish concept (AGP Granite), 1.65 g/cm^3.

2.3.3. Instalation

The installation was carried out manually, one slice of blocks at a time. For the installation of each slice, the block positioning sequence was as indicated by the numbers in Figure 4. In agreement with this sequence, the blocks were first placed in the lower part of each ring, followed by the external ring, closure of the interior ring, completion of the external ring and finally closure of the core in the non-heater areas.

After saturation, the dry density of the barrier would decrease to the reference value in the AGP-Granite, an average value close to 1.65 g/cm^3 (target dry density of the barrier). The final distribution of the dry density agrees with the expected values (1650 Kg/m^3 in average, Fig. 5). The joint gaps in the experiment were limited to 6.6% of total volume (Fig. 5).

As shown in Figure 6, the complexity of the actual distribution of blocks could be one important factor affecting the mechanical and transport properties of the clay barrier. It could generate preferential flow paths and modify the mechanical behaviour of the barrier.

2.4. Heating system

The system consists of two cylindrical heaters and their corresponding monitoring and control systems. The heaters, 1.625 m-length and 0.17 m-diameter, are in direct contact with the bentonite, with a 0.75 m horizontal separation between them (Fig. 1). Each heater has three internal electrical heating elements (resistors) capable of individually supplying the power necessary to maintain the superficial temperature in the heater/bentonite contact around 100ºC, even during the most unfavourable conditions.

Each heater consists of a carbon steel core (reel) into which the resistors are inserted. A carbon steel casing (0.34 m in external diameter), closed with two end covers (welded at the back end and fixed by screws at the front end), protects the set (reel and resistors).

The heating elements selected are shielded resistors, THERMOCOAX ZEZ Ac 25/600-2600-600/2 CM 25 (2.5 mm diameter, resistance 2.0 Ohm/m, 220 VAC/50 Hz). The total length of the elements is 48 m (6 m of cold ends and 26 m of hot zone).The heating core is composed of Ni/Cr 80/20 and the cold zones of Cu/Zr. The core is insulated from the sheath by MgO powder, which increases the dielectric resistance, the heat transfer and the lifetime of the element. A stainless steel sheath, AISI 304L, with external connections (150 W/m, to 200 °C), protects the set.

To ensure a high probability of power being supplied throughout the entire test, each heater has three resistors, each having the capacity to supply the nominal power required. The resistors of each heater are controlled as a set.

For the insertion of the heaters, a table with rollers was constructed, allowing the heater to be aligned with its location in the clay barrier and facilitating insertion by sliding. Figure 7 shows various moments of the insertion process and the good fit between the heater and its location in the clay barrier.

The Heater Control System (HCS) consists of all the electrical and/or electronic components and computer programs for autonomous supervision of the operation of the heaters. The main element is a Programmable Logic Control (PLC) that makes the calculations, regulates the power supply by the auxiliary electronics, activates the alarms and sends the temperature and instantaneous power data as demanded by the Data Acquisition System (DAS).

3. THM instrumentation

The THM behaviour of a soil, under hydration and thermal load, is well characterized when its reaction to the stresses, suction (total water potential) and temperature changes are well known. This approach considers that the amount of water available to the THM process is better represented by the suction (water activity), than by the evolution of the saturation degree. In certain conditions (quasi-equilibrium conditions), the water activity can be assimilated to the relative humidity of equilibrium (RHE), imposed by the barrier material.

The analysis of the THM behaviour requires the measurement of the distributions of the process variables (temperature, total pressure, fluid pressure and RHE), as well as the controlled boundary conditions, both thermal (power supply and heater's temperature, outside structure temperature, and room temperature) and hydraulic (injection pressure and volume).

3.1. Technical requirements

The test design must support long-time operation with THM instrumentation placed in harsh conditions. So, the choice of sensors was based on a set of electrical, mechanical and functional characteristics to withstand mechanical stress, high temperature, humidity and salinity coming from this environment. They are passive trans-

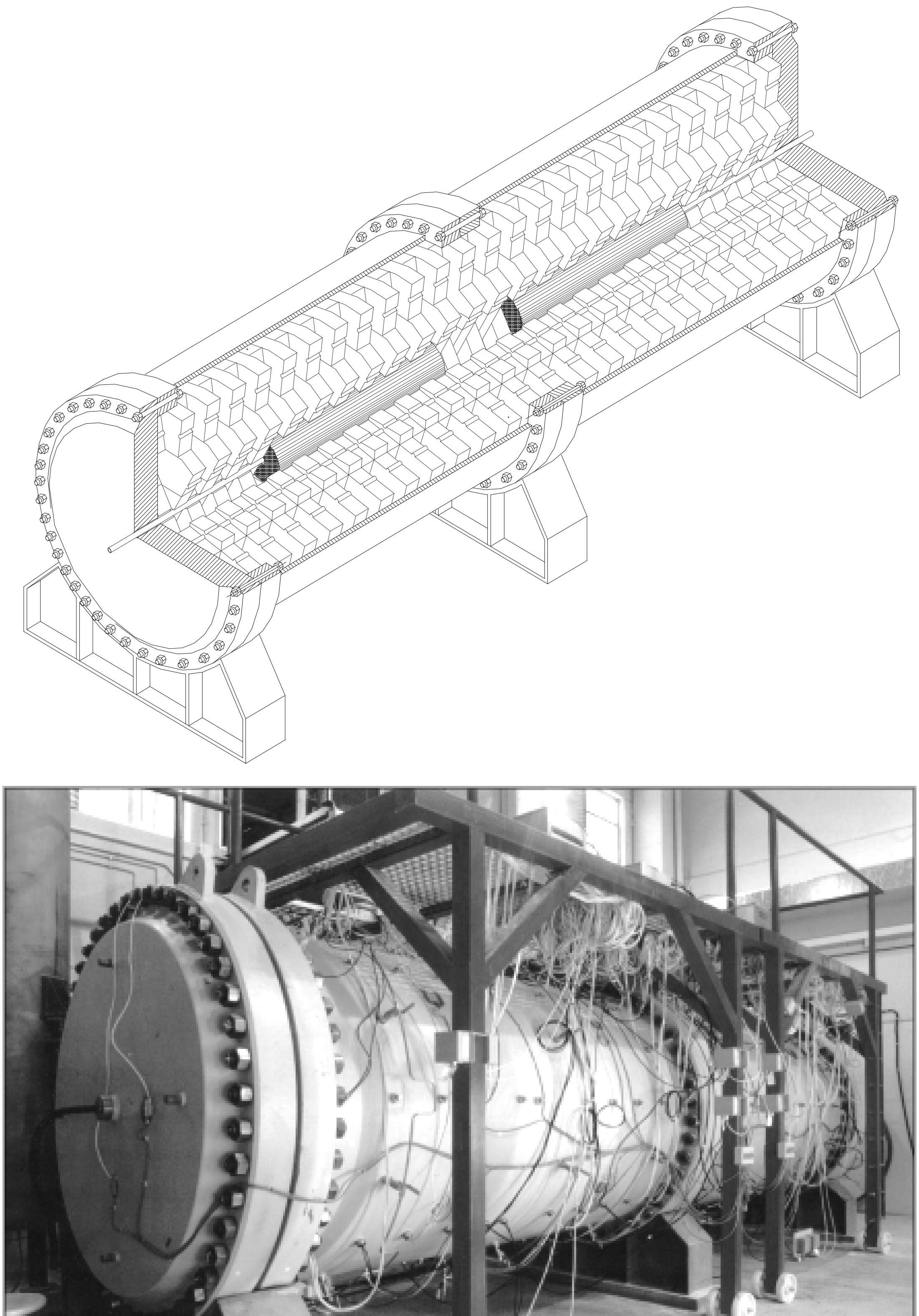

Fig. 6.- Mock-up experiment: internal distribution (blocks and heaters, top) and external view (bottom).
Fig. 6.- Experimento en maqueta: distribución interna (bloques y calentadores, arriba) y vista externa (abajo).

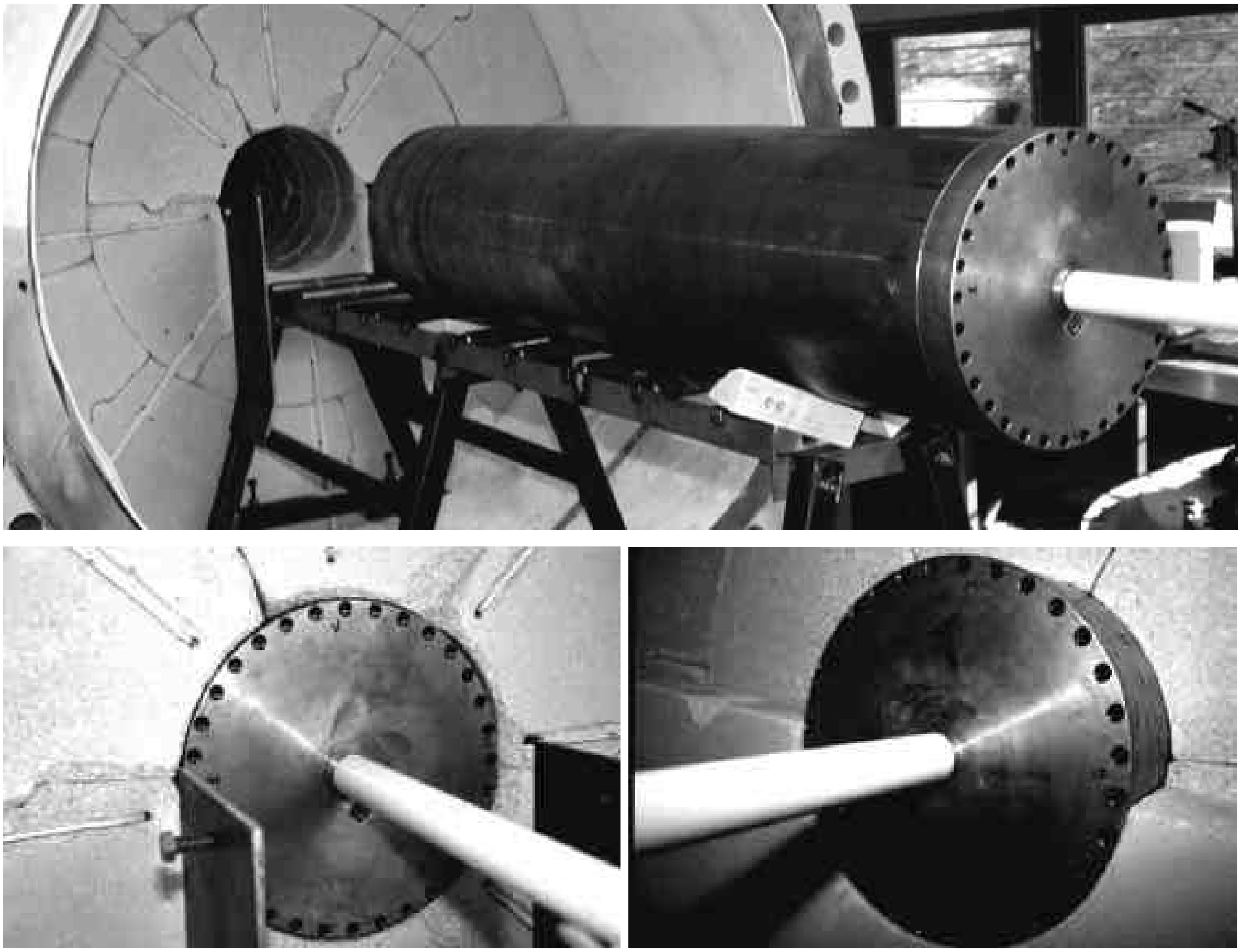

Fig. 7.- Heater insertion: table with rollers (top), Heater A (bottom left) and Heater B (bottom right).
Fig. 7.- Inserción de los calentadores: mesa de rodillos (arriba), calentador A (abajo izquierda) y calentador B (abajo derecha).

ducers, without active electronics inside, with enough accuracy and long-term stability, both thermal and mechanical. They produce a minimal interference with the THM processes that we try to measure (small volume, integrated measures, wide range). They are completely made of corrosion resistant materials.

Thin-film thermo-resistances Pt100 measure temperatures, while sensors based on thin-film semiconductor-diffused strain gages measure stresses and pressures. The transducers built using this thin-film technique have proven to be rugged and stable.

Because of the long-term operation, our choice, in 1995, was to use small temperature and RH transmitters, based on thin polymer-film capacitance sensors, instead of the traditional methods. The simultaneous measurement of temperature and RHE at the same location let us determinate the water potential (suction), one major problem in soil mechanics (Fredlund and Rahardjo, 1988).

3.2. Characteristics of the sensors

The specific characteristics of the sensors installed within the bentonite are the followings:

Temperature: 328 thermo-resistances Pt100 1/3 DIN, from Heraus, measurement at four wires with a limited current flow to avoid overheating the sensor. Some sensors within the bentonite are installed in a sheath of Inconel and connected by silicone cables, other sensors in the heaters are installed in special screws sealed with epoxy and connected by Teflon cables.

Total pressure: 50 soil load cells Kulite 0234, measurement by semiconductor strain gages, 5.0 MPa SG range, 200 % overpressure, range compensated for temperatures -20 ºC/100 ºC. They are made of AISI 316L steel with Teflon cable and high-pressure cable gland.

Fluid pressure: 20 pressure sensors Kulite HKM375, measurement by semiconductor strain gages, 3.5 MPa

Measured parameter	Sensor type	Installation		
		Bentonite	Structure	External
Temperature	RTD Pt100	328	20	
Room temperature	RTD Pt100			1
Injection pressure				
manometer	DIGIBAR II			1
water pressure	DRUCK 1400PTX		2	
Total pressure	KULITE BG0234			
radial		14		
tangential		14		
axial		22		
Fluid pressure	KULITE KHM375	20		
RH + temperature	VAISALA HMP233	40		
Extensiometric gauges	HBM		19	
Values from the PLC				
temperature	RTD Pt100			18
average temperature	calculation			2
power supplied	calculation			2
Voltage CC to the sensors				2
TOTAL NUMBER		**438**	**41**	**26**

Table 2.- Mock-up test: installed sensors and associated parameters.
Tabla 2.- Ensayo en maqueta: sensores instalados y parámetros asociados.

SG range, 200% overpressure, range-compensated for temperatures -20 ºC/100 ºC. They are made of AISI 316L steel with Teflon cable and high-pressure cable gland. The outer protection is made of AISI 316L with filter.

Relative humidity: temperature and RH transmitter, Vaisala HPM233, with capacitive sensor HUMICAP (0 to 100% RH range) and temperature sensor Pt100 1/3 (to 120ºC). They are made of ABS plastic with AISI 316L filter and Teflon cable. The outer protection is made of AISI 316L steel and epoxy.

Table 2 summaries the number and type of sensors, the parameters measured, and the area in which they are located. More than 500 sensors or instruments were installed, with 481 signals automatically registered in the experiment. The signals correspond to the sensors installed inside the confining structure, within the bentonite or incorporated to the heater, as well as the external sensors and instruments; among which those signals given by the sensors installed outside the barrier, either on the external surface of the structure (like the extensometric gauges and some temperature sensors) or within the heating and hydration systems (water pressure and mass, and heater temperature).

3.3. Installation of the sensors

For each sensor, the location was machined into the bentonite, after completion of the corresponding slice of blocks, keeping the orifice to a minimum (Fig. 8). All the space surrounding the sensor was filled with bentonite powder and the cables were guided in the channels machined into the surface of the blocks. The cables were placed so as to avoid sharp curves or sharp edges and were not tightened, in order to reduce problems from movements due to the swelling of the bentonite. Each set of cables goes out of the confining structure through hermetic seals.

3.3.1. Sensors distribution

The sensors within the bentonite barrier were grouped in 25 instrumentation levels, distributed in the two zones in which the installation of the experiment was divided: zone A and zone B (Fig. 9). The intermediate vertical plane between the zones defines the instrumentation level named AB. Each lateral zone has 12 instrumentation levels, named Ann or Bnn, nn being the ordinal of installation (related to the distance of each level to the AB level).

Nine temperature sensors on the surface of each heater are distributed in three sections, transverse to the heater axis. The control level is placed in the section in the middle of the heater and provides the average temperature value in order to calculate the power supplied to the heater.

Temperature sensors associated with extensiometric gauges were installed on the surface of the structure, some time after the beginning of the test.

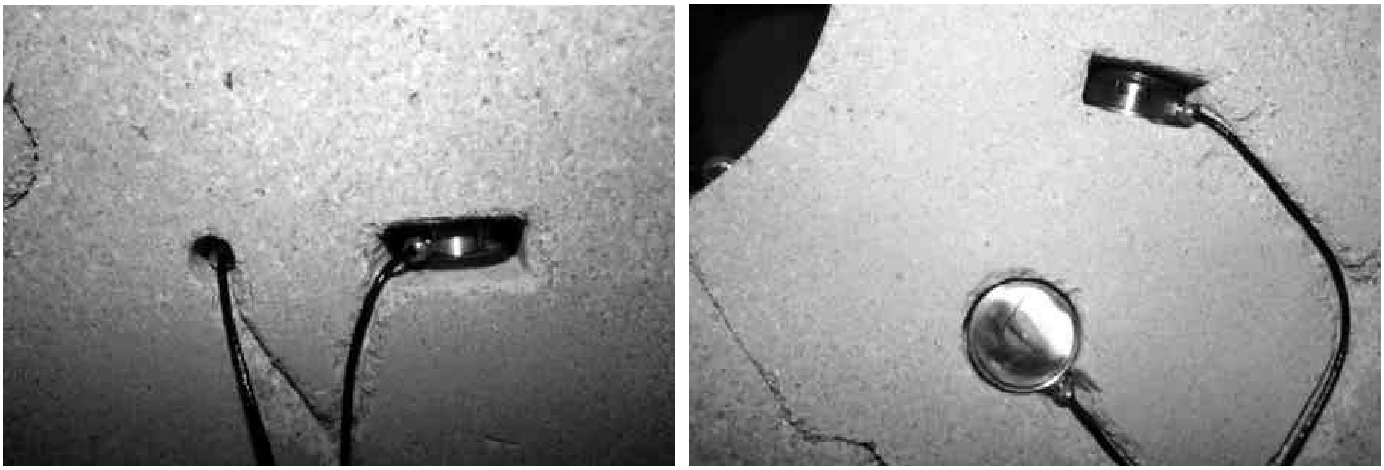

Fig. 8.- Installation detail of pressure sensors.
Fig. 8.- Detalle de la instalación de los sensores de presión.

Four groups of signals were defined: those coming from the bentonite barrier, the heaters, the surface structure, and the external sensors and instruments.

3.3.2. Codification of the sensors

A cylindrical co-ordinate system has been chosen to identify the sensors in the experiment by an alphanumerical code that describes the position of the sensor, both in the experiment and in the instrumentation level. In this co-ordinate system (R, angle and Z), the point of origin O has been taken as the intersection of the central vertical plane AB with the longitudinal axis of the confining structure (axis Z). In accordance with the rules of this co-ordinate system, values of R increase from axis Z, values of the angle increase from the reference radius (upper vertical radius of each section) and Z increases from the point of origin O to Zone B (Fig. 10).

The entire sensor coding follows these general rules with a few exceptions. A distinction has been made between four main groups of sensors: in the clay barrier, in

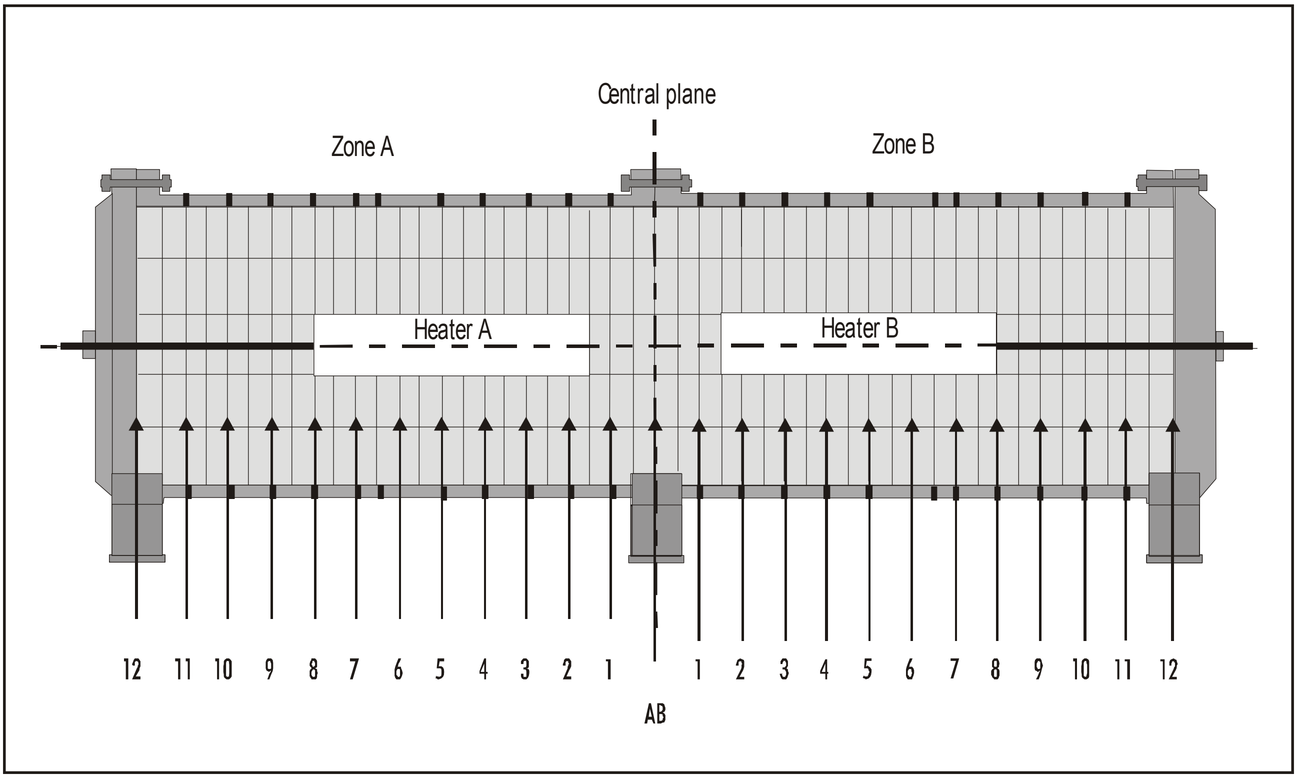

Fig. 9.- Distribution of instrumented sections.
Fig. 9.- Distribución de las secciones de instrumentación.

the heaters, on the surface of the confining structure, and outside the confining structure.

4. Data acquisition system

The Data Acquisition System (DAS) includes all the electrical/electronic components, as well as the software necessary to autonomously supervise, register and store on a hard disk the set of data obtained from the test. It provides conversion of the analogue signals from the transducers into numerical data and performs data analysis, display and storage over the long time period (years) that data are being acquired.

4.1. Hardware

Five HELIOS I processing stations (from FLUKE, a master unit and four slaves), connected one to the next by means of a high velocity RS-422 serial link, compose the acquisition units. Each processing unit has its analogue/digital converter and controls the nearest signals. A PC is connected simultaneously, by independent RS-232C serial links, with the main processing unit of the DAS and with the PLC of the HCS. It functions independently, although periodically it is connected to a local network to allow for maintenance and file transfer operations. Finally, an uninterrupted power system (UPS) is used to guarantee the stability of the power supply and to secure the data against supply surges or failures.

4.2. Software

Monitoring and control are performed by a generic commercial client-server system SCADA (Supervision, Control, And Data Acquisition) called FIX DMACS by INTELLUTION, Inc. (USA). In addition, the FIX DMACS also performs the test supervision and display, and the process data storage and report generation. There have been specific protocols developed for communication between the PC, the principal station of the DAS, and the PLC of the HCS.

5. Other elements

The test includes two types of elements associated to the installation of the instrumentation, but that will not supply information until the dismantling phase (profiles of concentration and distribution). These elements are related to the pore-water chemistry under experimental conditions: corrosion behaviour and tracer behaviour (tracer stability, tracer speciation in the pore-waters and precipitation reactions). Information on the specimens and tracers used, placement form, location, etc. is given in ENRESA (2000).

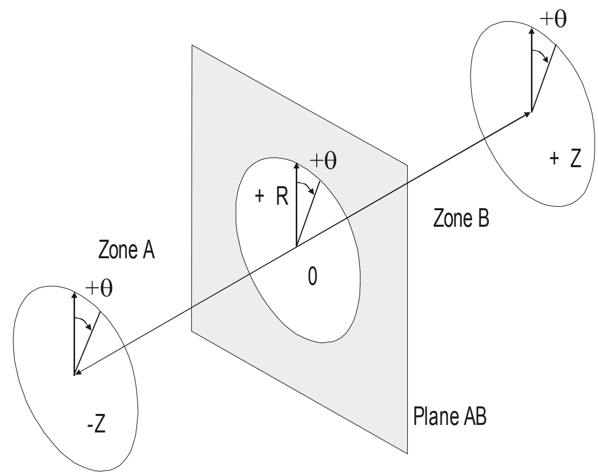

Fig. 10.- “Mock-up” test coordinate system.
Fig. 10.- Sistema de coordenadas del ensayo.

5.1. Corrosion behaviour

Metallic specimens —carbon steel, stainless steel, titanium, copper, and welds of the same materials— were placed in the clay barrier (Fig. 11) to analyse their possible corrosion under conditions that may be considered close to those expected in a repository. The specimens prepared by INASMET (San Sebastian, Spain) were mounted on a Teflon rack.

5.2. Tracer migration

Both conservative and non-conservative tracers were used to analyse their migration in the clay. The selection was done as function of their stability under the physico-chemical conditions during the experiment time, their different detection limits and solubility, and the composition of the clay. The tracers (deuterium, iodide, boron-10, rhenium, selenium, europium, uranium, thorium, neodymium and caesium) were installed in different ways (Fig. 12): dissolved in the saturation water; placed in clay plugs; placed in a solid form within porous metal capsules; and covering the bricks with a special impregnated filter paper.

6. Operation

The operational stage of the “mock-up” test (heating and hydration) started on February 4, 1997, which represents “day 0” on the time scale. Three days before, a volume of 634 litters of water injected at high flow (3.5 l/min.) to flood completely the voids and made possible the closure of the gaps, by the swelling of the bentonite, between blocks and along cables. The early reaction caused in RH or fluid pressure sensors and pressure cells was irrelevant.

The heating and hydration of the clay barrier are the basic operations of the test. Consequently, precautions were taken to ensure correct operation of the heating system throughout the scheduled test period, with redundancy in the heating elements, the establishment of regulation and control processes, allowing for the immediate detection of failures, the maintenance of a stable thermal level surrounding the heaters, the availability of the historic record of the thermal and power regimes of the heaters and regulation of the temperature in the test room, to obtain stable initial and boundary conditions.

The power supplied to maintain the temperature at 100 ºC at the heater-clay interface increased slowly from 450 to 550 W/heater. Important changes in the external temperature produced only small increases in heating power during this phase. Finally, since last two years, the heater is operated at constant power supply (700 W/heater) with a temperature close to the target.

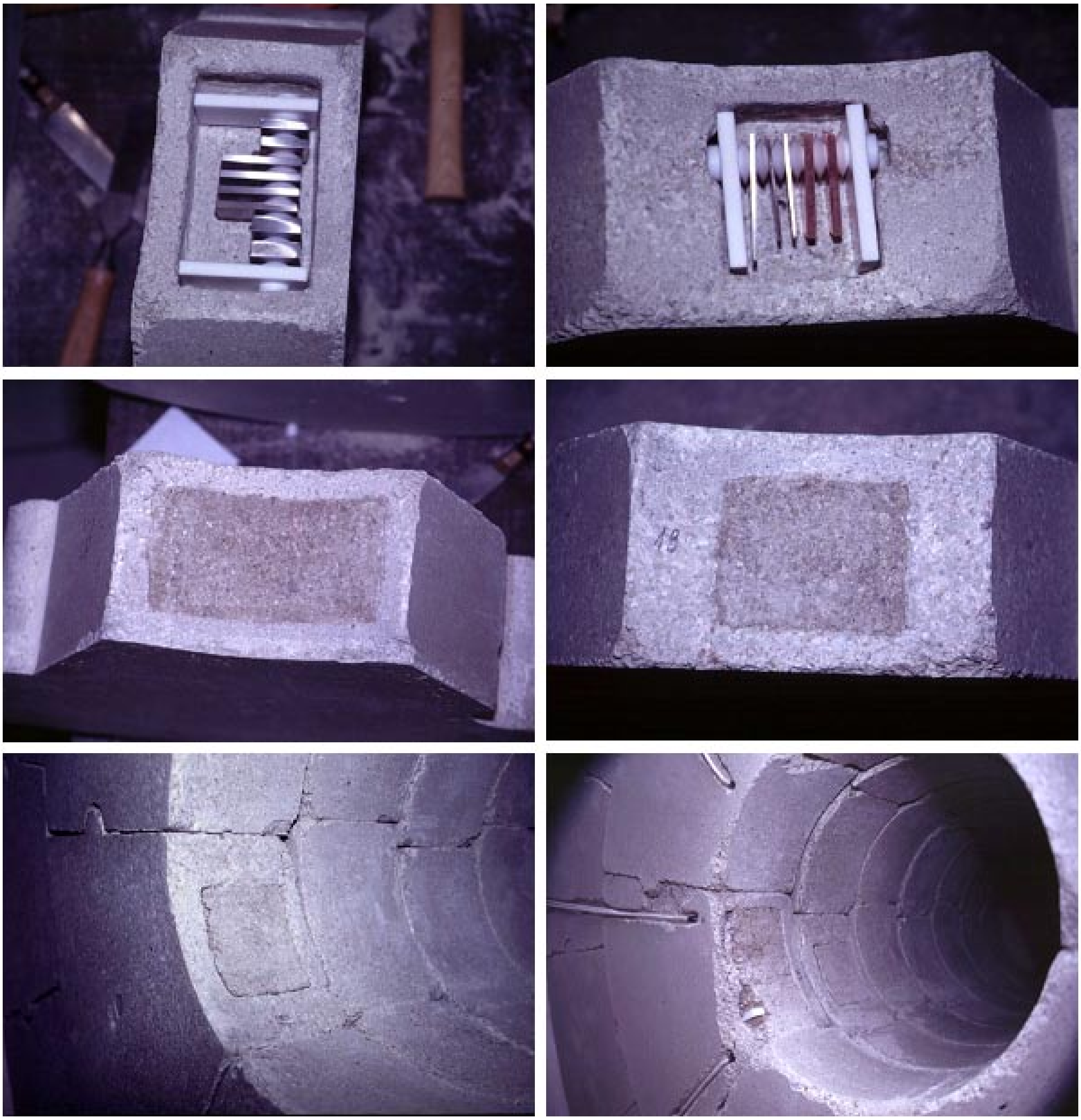

Fig. 11.- Installation of corrosion specimens.
Fig. 11.- Instalación de las probetas de corrosión.

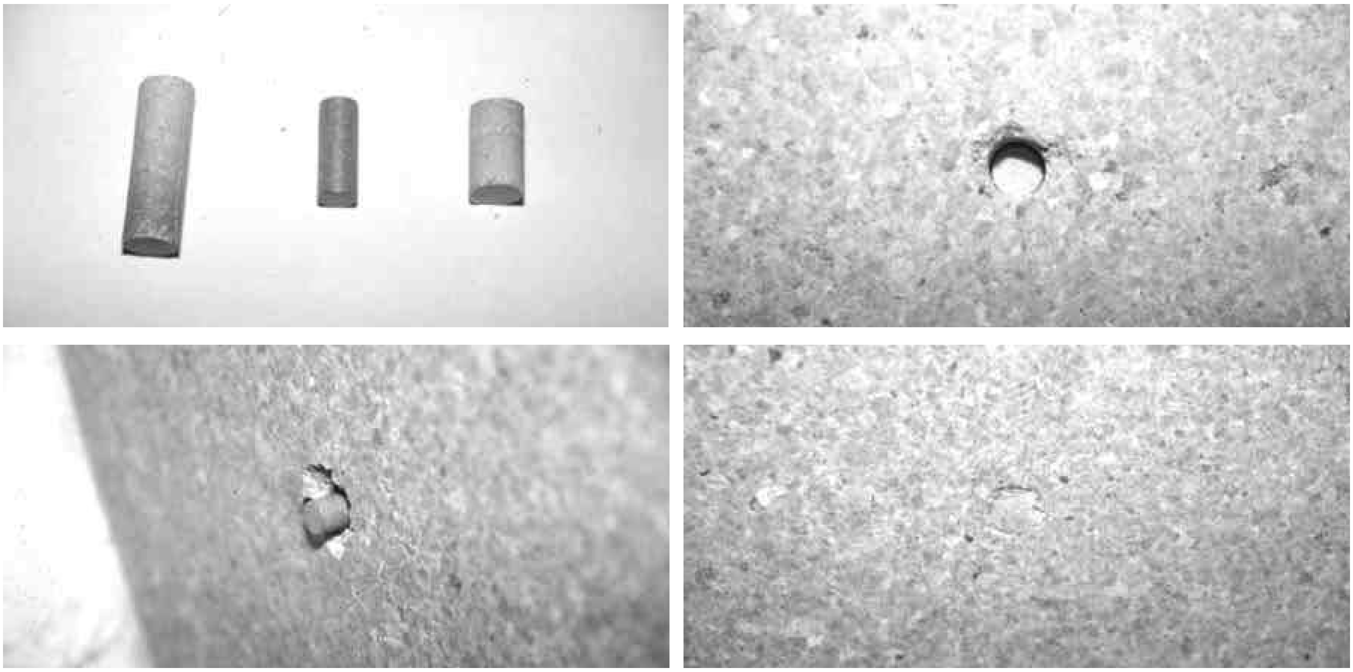

Fig. 12.- Method of installation of tracers in capsules.
Fig. 12.- Métodos de instalación de trazadores en cápsulas.

Because of the observed changes in the value of nitrogen pressure, due to external temperature variations, which controls the injection of water it was decided setting the pressure by a pressure-controller. The nominal value of pressure injection is 0.53 MPa.

6.1. THM behaviour

The readings from the sensors within the bentonite, reported in Martín and Barcala (2004; 2006), are plotted by groups of measured parameters (temperature, RH, total pressure and fluid pressure), to facilitate comparison between the sensors of the same kind at different sections.

6.1.1. Temperature

After the first two weeks, the test continued in a quasi-stationary temperature state. The slight temperature waves were caused by external variations due to the difficulty of conditioning the test room. These fluctuations are evident in the sensors placed in the outer radii, as expected.

The data show good homogeneity throughout the test. The initial variations observed between sensors placed on the same radial distance are less than 2 ºC.

The average measurements from section A5 are shown in figure 13 as an example of temperature data. It shows the temperature peak produced during an overheating incident that increased the temperature in the contact bentonite-heater to values close to 200 ºC (Martín and Barcala, 2001; 2004; 2005). This incident has not produced permanent variations in the THM behaviour of the test.

6.1.2. Relative Humidity

The RH sensors allow the monitoring of the hydration drying-wetting process. The accuracy of values from these sensors are considered good because similar sensors, recovered from the in-situ test (ENRESA, 2000), accomplish the manufacturer's specifications after operation during more than five years within the bentonite barrier. A representative evolution of the RH measurements is presented in figure 14, for section A4.

Depending on the location of the RH measurement (distance to the hydration surface and thermal gradient imposed on the sensor) different behaviours can be observed. Values measured close to the heater surface show clearly the effects of evaporation (drying) and condensation (wetting) in different zones of the barrier. Values measured close to the hydration surface suggest that bentonite in this external zone is fully saturated.

In sensors located close to the heater the following phases can be distinguished: (i) a sharp increasing RH value appears related to the vapour phase generated by the initial heating; (ii) continuous heat transfer from the heaters produces the drying of the clay that causes decreasing RH; (iii) after some time, hydration reaches the dried zone and overcomes the drying process, increasing the RH values.

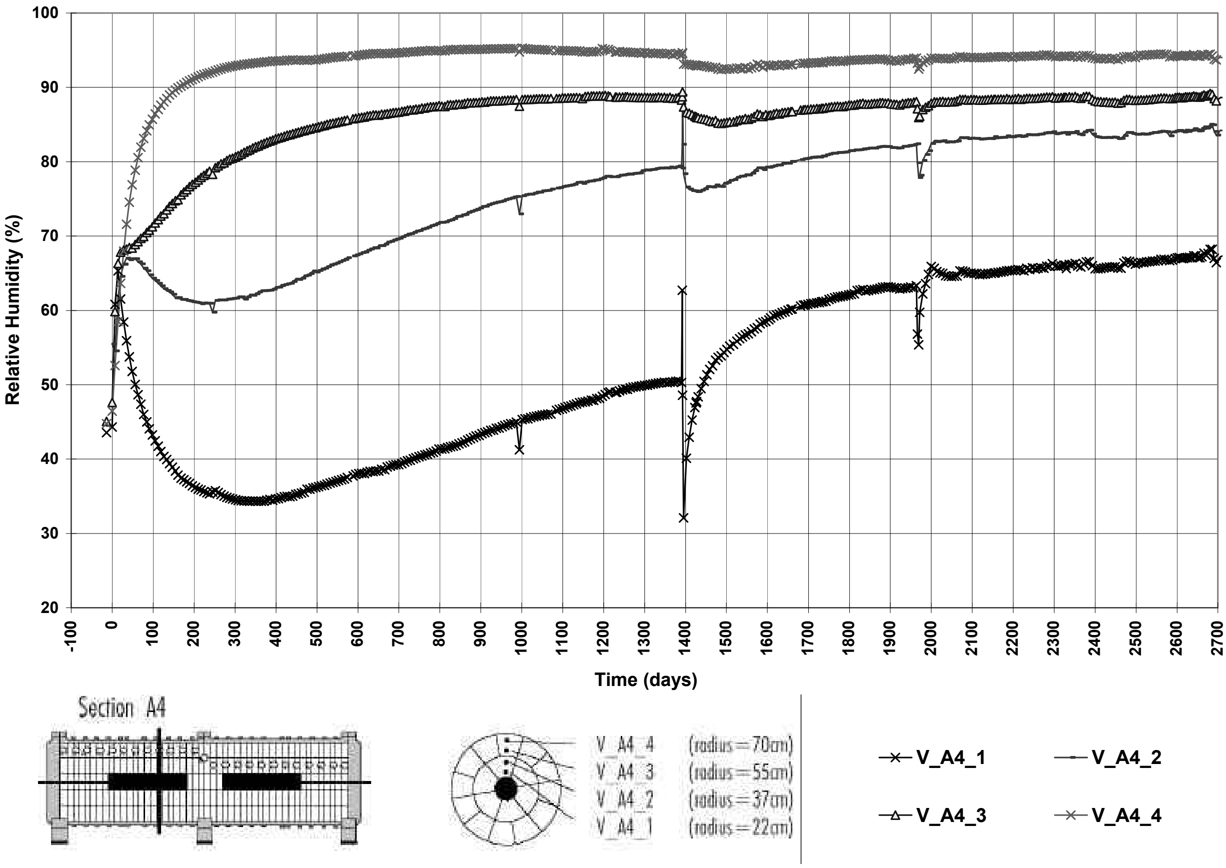

Fig. 14.- Evolution of relative humidity in section A4.
Fig. 14.- Evolución de La humedad relative en la sección A4.

This transient indicates the redistribution of water, which is a process with slower dynamics than the thermal transfer. So, 360 days are needed to reach the minimum value of RH and 1080 days to recover the initial values in the level closer to the heater; however, level 2 achieves a relative minimum at 270 days but without retrieving the original value, indicating in this way the adsorption of water through the vapour phase that came from heater.

The synchronous evolution of the different RH sensors (Fig. 15) indicates that their behaviour is a real process and not an artefact in the RHE (relative humidity of equilibrium) evolution of the material. The variations observed between sensors placed at the same radial distance are not significant. This evolution is shown as a decrease of magnitude in the more saturated zones of the external ring in the barrier. From above, the water inflow is radial and homogeneous, only modified by the intrinsic THM behaviour of the barrier. This was a specification of the design.

6.1.3. Total pressure

Under hydration, the bentonite develops a mechanical pressure by swelling recorded by the total pressure sensors located at selected radial distances (35.0 cm and 66.5 cm), and orientated in the three main directions. The pressures are in agreement with the swelling pressure values of the bentonite measured in the laboratory.

The higher-pressure values are located within the outer ring due to the evolution of the saturation front. In fact, the average-pressure values in this zone and their slow increase could indicate a high degree or full saturation and, therefore, high swelling in the outer part of the buffer. The radial pressures have converged in a narrow range from 7.5 to 8.5 MPa (Fig. 16) after the important variations induced by an overheating (6.1.1) in the heater zones.

On the other hand, the wider range of values and the lack of pressure uniformity in the inner rings could indicate two different processes: mechanical stressing of the buffer by the swelling pressures in the outer rings or

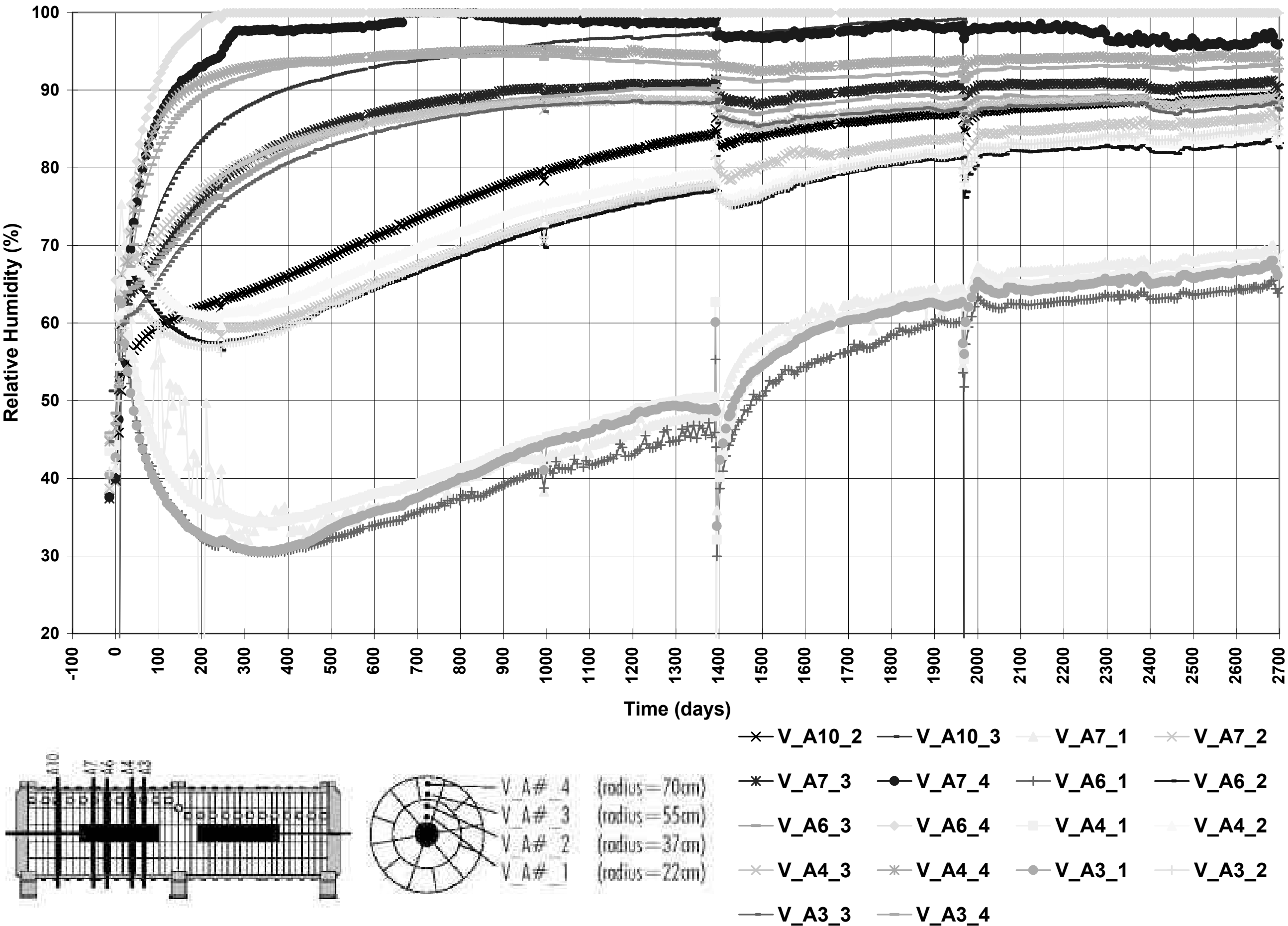

Fig. 15.- Evolution of relative humidity in zone A.
Fig. 15.- Evolución de La humedad relative en la zona A.

the extension of saturation into this zone. The radial pressures range from 2.0 to 11.0 MPa (Fig. 17). Lower values and higher relative variations after overheating are located in the zones around of the heaters, with a differential behaviour between the bentonite sections that include the heaters (hot sections), and those without heaters (cold sections).

6.1.4. Fluid pressure

The measured values cannot be assigned to water or gas pressure without uncertainty, mainly in the inner ring. Only some variations seem to be related to the arrival of water, always for sensors located in the outer rings. In all cases, the fluctuations seem to be related to temperature variations.

A gradual pressure increment, that achieve higher and more stable values in the hot zones (Fig. 18), could show a dependence of the fluid temperature (through water viscosity); meanwhile, the internal rings show a similar behaviour in hot and cold zones, (Fig. 19).

6.1.5. Sensor performance

Almost all the sensors installed currently continue to operate, after having been inside the bentonite for more than eight years. More than 90 % of the total number of sensors remains operative, but this percentage is 70% for tangential pressure (PT) and 80 % for axial pressure (PZ) and RH.

7. Analysis of data

There is a differential behaviour between the bentonite sections that includes the heaters (named as hot sections) and those without heaters (cold sections). It seems that the physic-chemical processes controlling the evolution of the measured parameters suffer deviations related to the temperature field generated in the barrier, either as thermal gradient-driven processes (thermo-hydraulic coupled phenomena), or as temperature increased-rate processes (chemical ones or Arrhenius type). This behav-

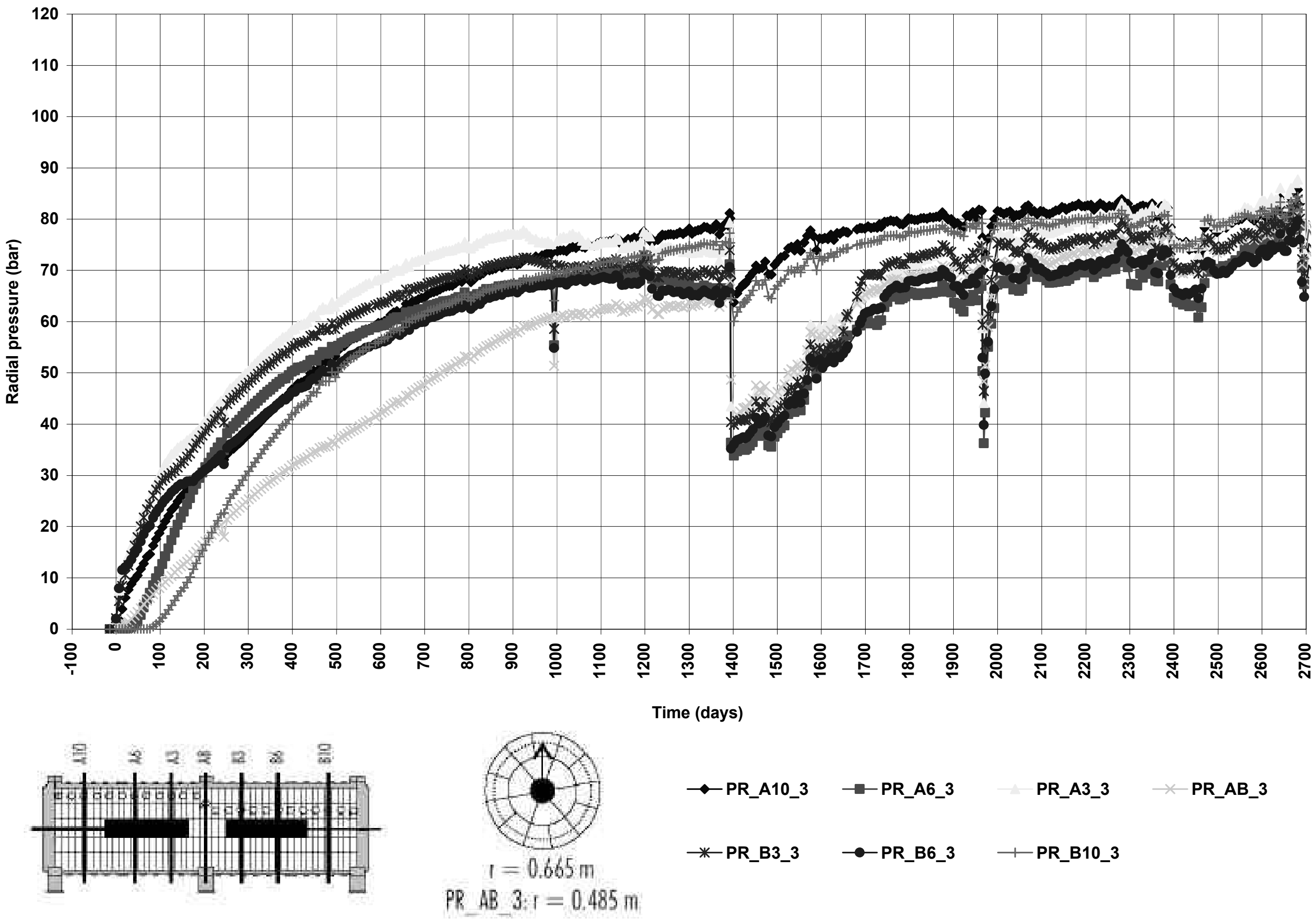

Fig. 16.- Evolution of radial pressure in the outer ring.
Fig. 16.- Evolución de la presión radial en el anillo exterior.

iour is better shown by the suction values and the total pressure values associated with.

From data set, distributions of temperature and RH have been estimated at several times. The simultaneous measurement of temperature and RHE at the same location let us determinate the water potential (suction; Fredlund and Rahardjo, 1988), at these times. The estimations are made by construction of a regular grid by a linear kriging method with an anisotropy factor; then, suction is calculated in an element-to-element scheme and converted to MPa.

The following figures show the distribution of some variables in the half-section of the experiment along the vertical axial plane, for different times (days is in the upper left corner of each graphic). The X-coordinate is the total length (from –300 to 300). The Y-coordinate is the radii (from 0 to 81). The X and Y units are centimetres.

7.1. Temperature

The thermal state is homogeneous and symmetric. The temperature quasi-stationary state in the clay barrier was achieved in a short time (Fig. 20, 14 days), and generated temperature gradients with maximum values close to the heater surface. The temperature distribution has not shown important changes during the following six years (Fig. 20, 1036 and 2072 days), mainly around the heaters. Here, the thermal gradient within the bentonite is around 0.03 ºC/m. The temperature distribution is controlled by thermal conduction, due to the slow transport processes involved in the saturation of the buffer material.

7.2. RHE and suction

The saturation of the bentonite barrier is behaving as expected, homogeneous and symmetric, although with slower rates than those foreseen in the preliminary cal-

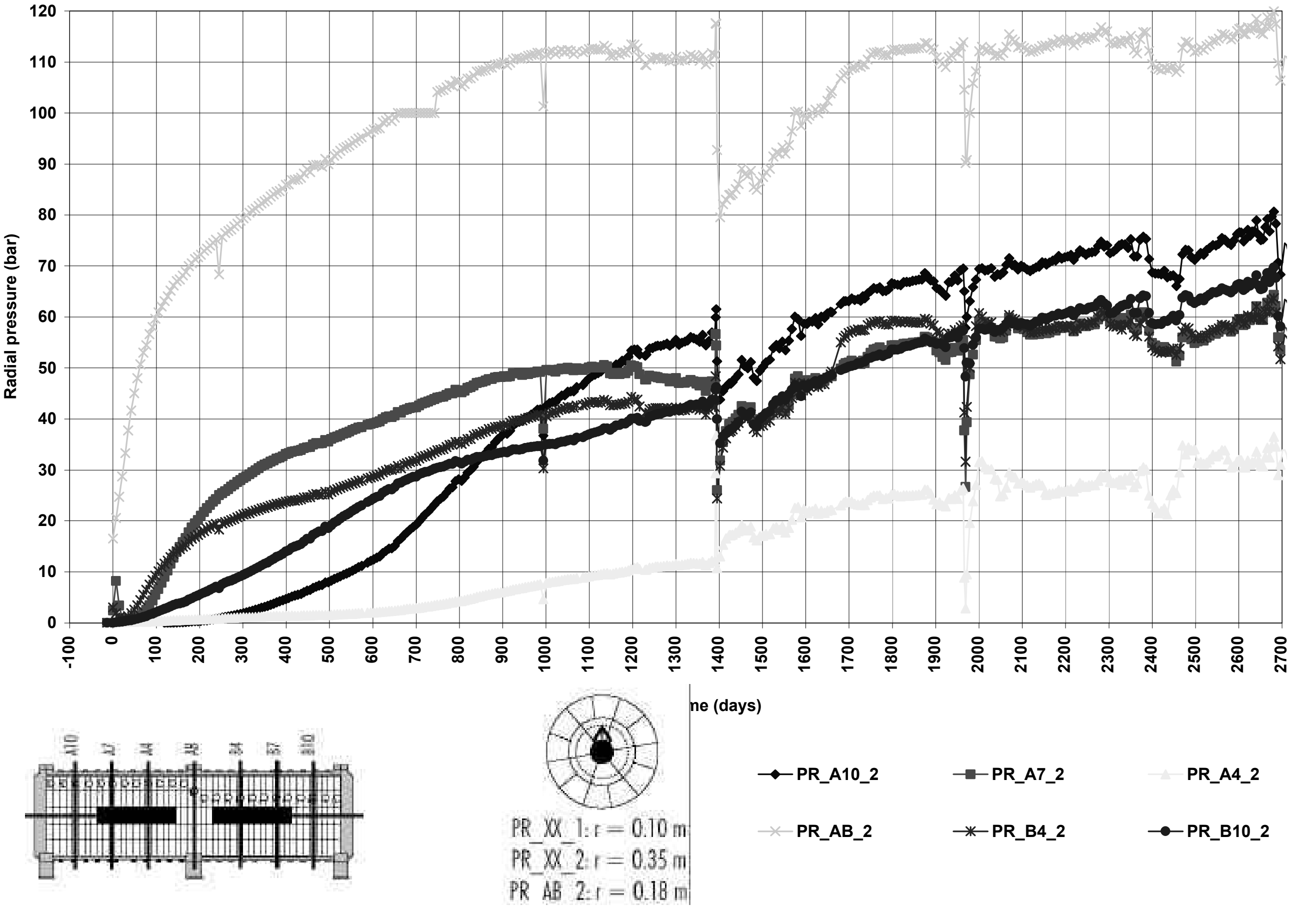

Fig. 17.- Evolution of radial pressure in the inner ring.
Fig. 17.- Evolución de la presión radial en el anillo interior.

culations. The process is apparently controlled by the hydraulic properties of the bentonite and the thermal gradient imposed by heating. The RH sensors are working well within the RH and temperature ranges of the test. This allows for tracking of the hydration process.

In general, a drying-wetting process is observed. First, the water vapour generated by the heating migrates through the buffer from the heater to the colder zones that generates an intermediate zone with higher values (lower suctions; Figs. 21 and 22, 14 days). Secondly, heating produces extended drying of the clay close to the heaters that added to the advance of the saturation front produces high gradients of HRE and suction (Fig. 20 and 21, 1036 days). Finally, hydration reaches the dried zone and overcomes the drying process, increasing the RHE values measured and decreasing the gradients of RHE and suction (Figs. 21 and 22, 2072 days).

7.3. Total pressure

The recorded values are in accordance with the swelling pressures (confined bentonite develops a mechanical pressure by swelling under hydration) measured in the laboratory: 10.0 and 6.0 MPa for dry densities of 1700 and 1600 Kg/m^3, respectively (Villar, 2002; Lloret *et al.*, 2004). Thus, radial pressures range from 5.0 to 8.0 MPa (Martin, 2004). The higher average-values in the outer zone indicate full saturation of the buffer; while the smaller values in the inner zone could indicate either the redistribution of stresses coming from the outer zone or the extension of saturation into this zone. The smallest variations of the pressure evolution appear to be linked to external temperature variations.

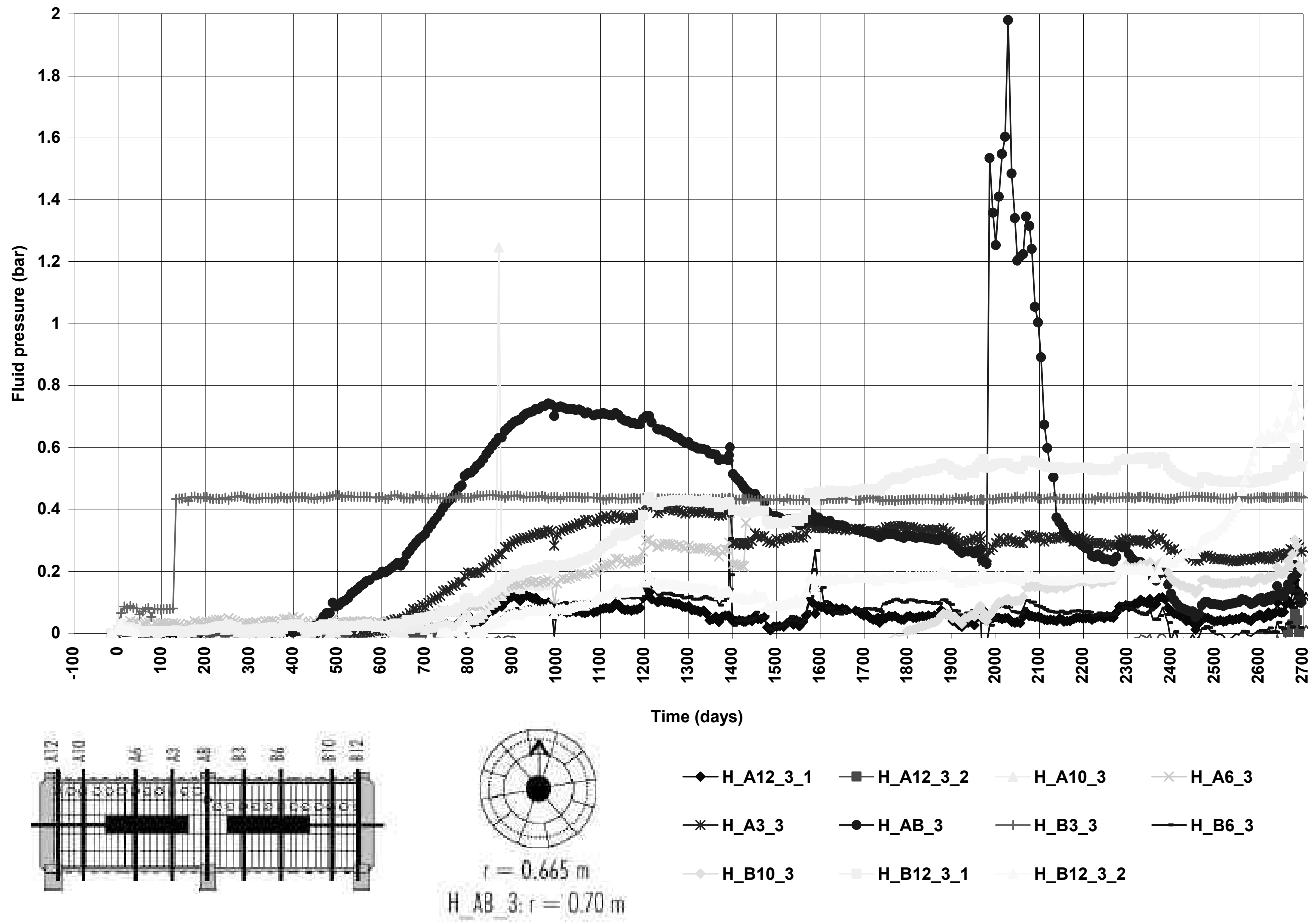

Fig. 18.- Evolution of fluid pressure in the outer ring.
Fig. 18.- Evolución de la presión de fluido en el anillo exterior.

8. Summary and conclusions

The THM phenomena in the clay barrier present a complex analysis due to the coupling between processes of diverse origin and the complicated response of the bentonite.

Large-scale long-term tests with extensive and adequate instrumentation are needed to allow the monitoring of the coupled processes in the barrier.

Eight and a half years after the start of the operational phase of the mock-up test of the FEBEX project, it can be concluded that it is a valuable instrument to improve the knowledge of the coupled THM processes in the Engineering Barrier System, both in number of involved processes and duration of the experiment.

The database generated in this mock-up experiment verified most of the hypothesis on the THM processes in the transition saturated/no-saturated of the barrier material; although comparison with actual values from the test after dismantling will be the definitive trial.

The comparison between database and models has conducted to improved formulations of the *THM* coupled models (Sánchez *et al.*2001, 2004 and 2005), to explain the observed THM behaviour. The database has also been used to model the reactive solute transport in non-isothermal unsaturated compacted clays (Samper *et al.*, 2005).

Some qualitative conclusions may be established, mainly the differences in the behaviour between “hot” and “cold” zones of the buffer, indicating major implications of the thermal aspects in the transport processes, which must be applied to obtain reliable numerical codes to accomplish the Performance Assessment of a Deep Geological Repository.

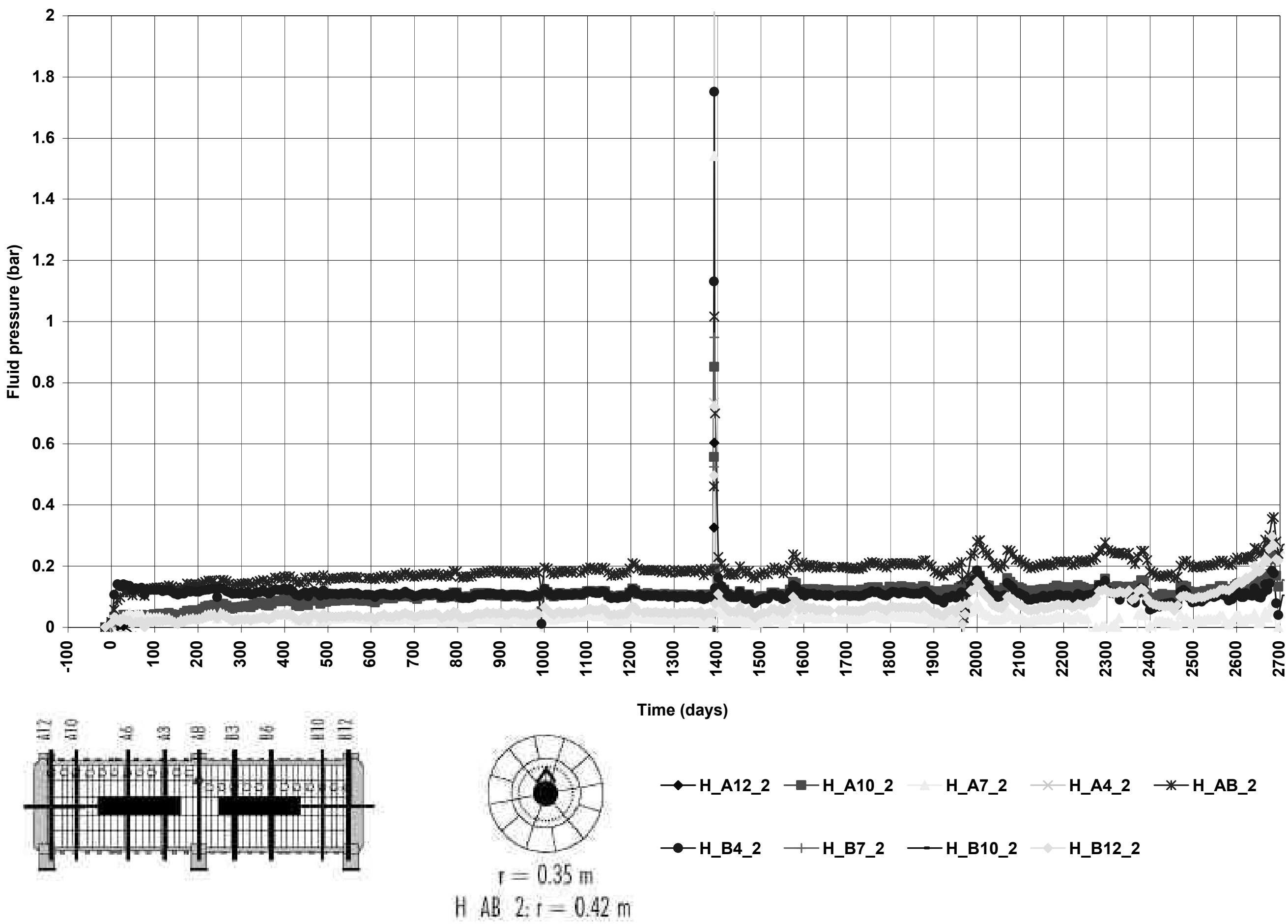

Fig. 19.- Evolution of fluid pressure in the inner ring.
Fig. 19.- Evolución de la presión de fluido en el anillo interior.

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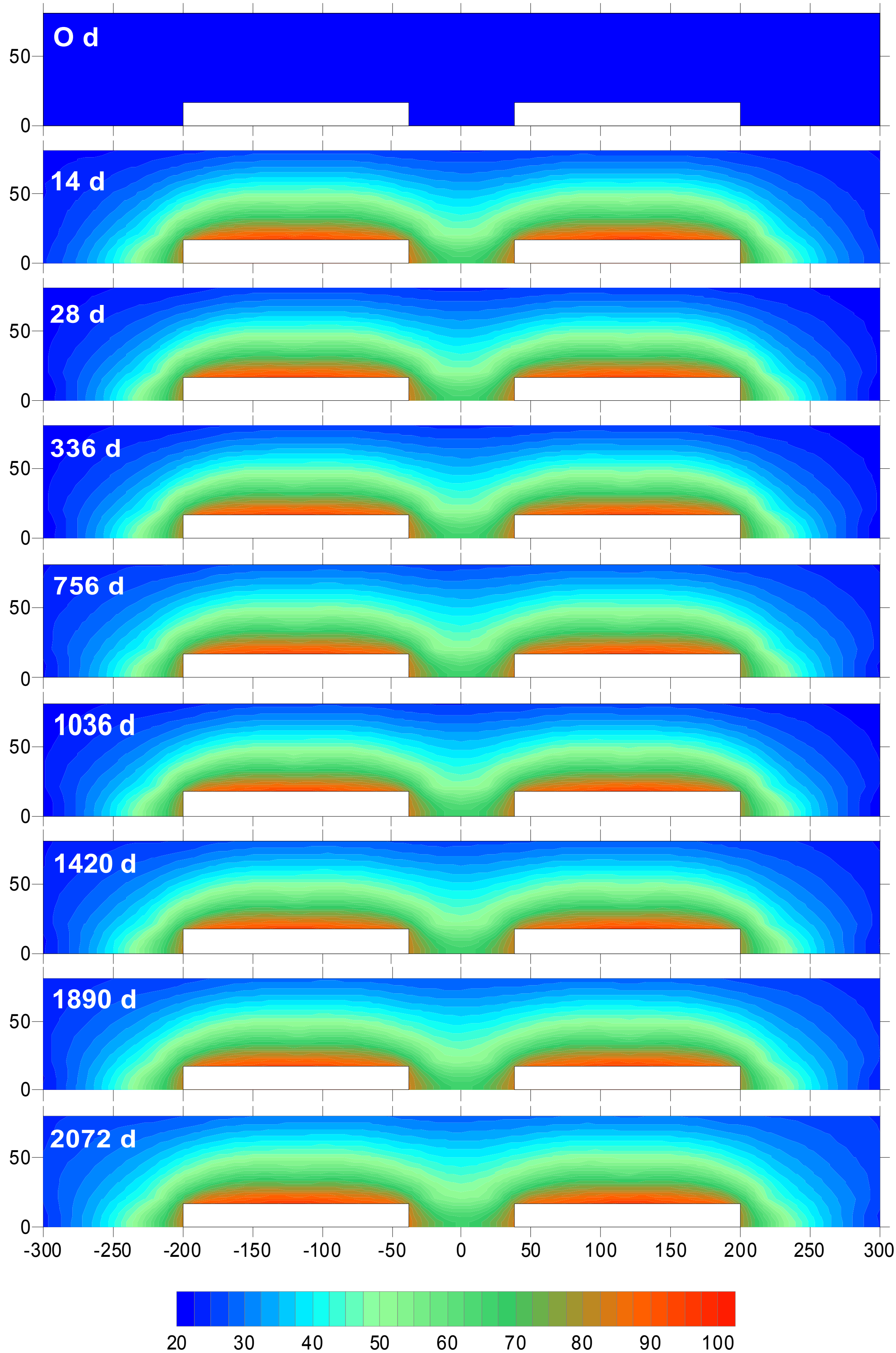

Fig. 20.- Temperature evolution (ºC) during experiment.
Fig. 20.- Evolución de la temperatura (ºC) durante el experimento.

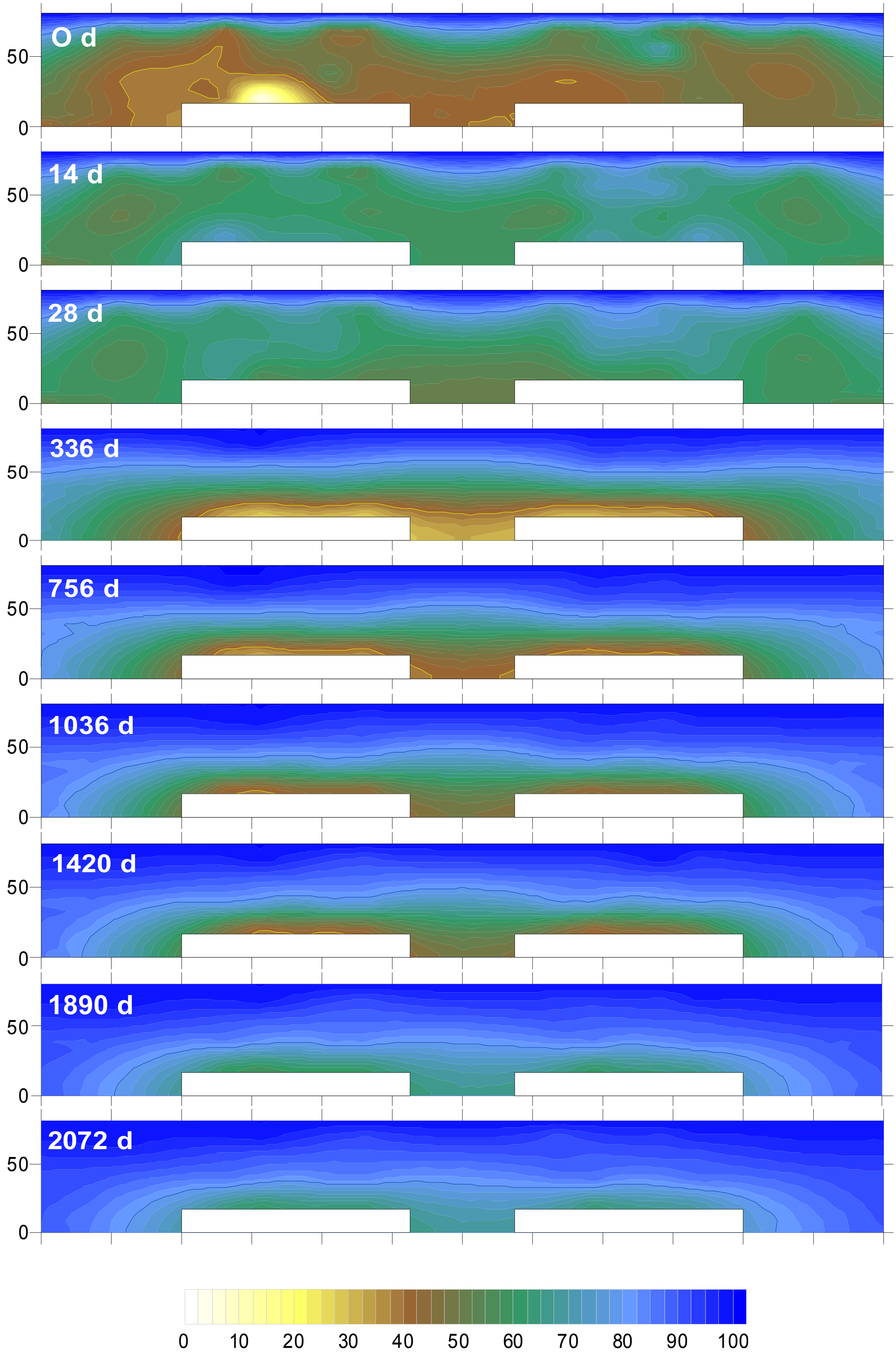

Fig. 21.- RHE evolution (%) during experiment.
Fig. 21.- Evolución de HRE (%) durante el experimento.

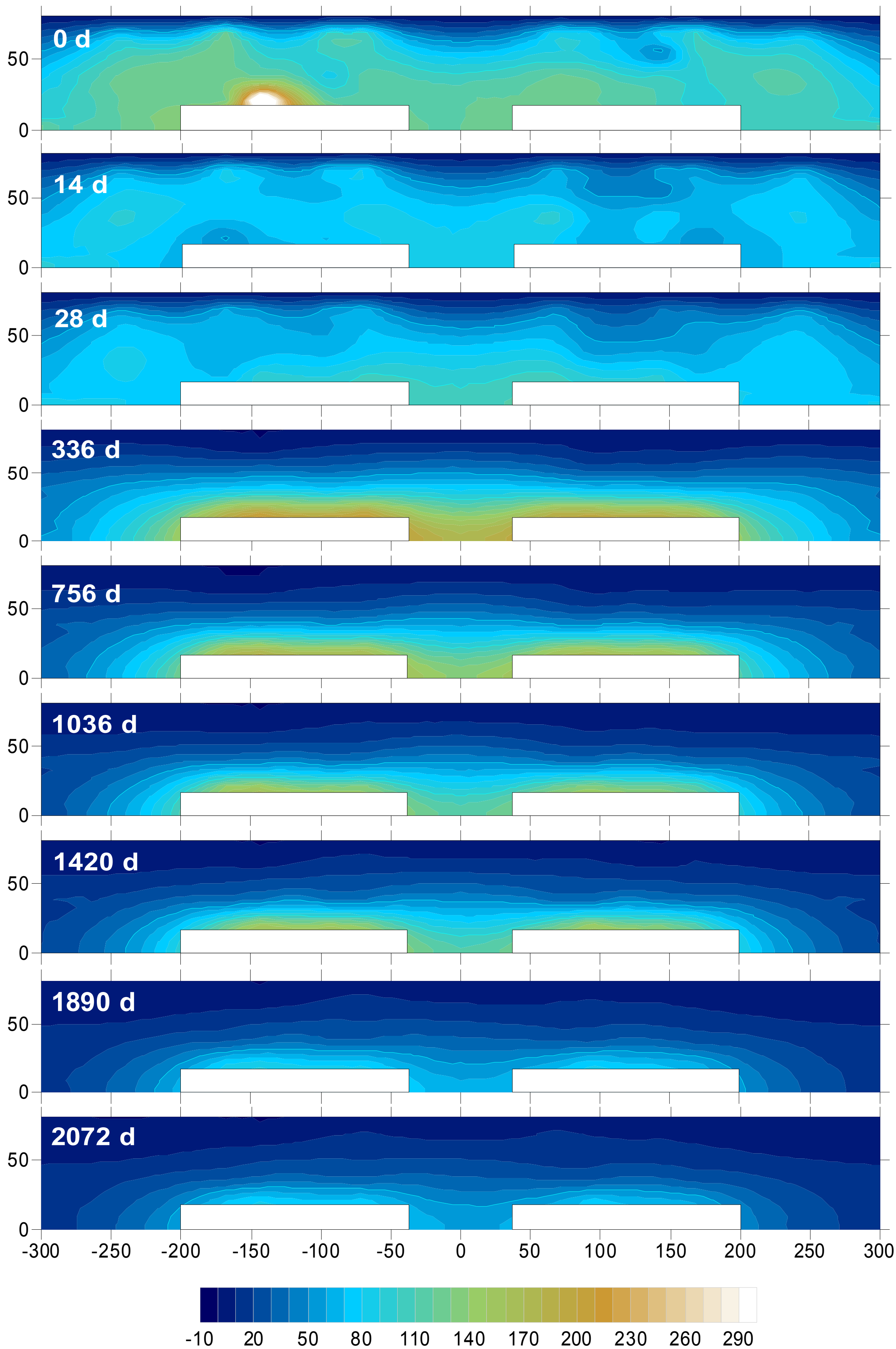

Fig. 22.- Suction evolution (MPa) during experiment.
Fig. 22.- Evolución de la succión (MPa) durante el experimento.

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