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Long-term Performance of Engineered Barrier Systems

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Comparison of FEBEX Mock-up and China-Mock-up test

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ABSTRACT

According to the preliminary concept of the high level radioactive waste (HLW) repository, a large-scale mock-up facility was constructed in the laboratory. A heater, which substitutes a container of radioactive waste, is placed inside the compacted bentonite blocks and pellets. Water inflow through the barrier from its outer surface is to simulate the intake of groundwater. The current experimental data of the facility is reported and analyzed in the report.

In this report, a comparison between FEBEX Mock-up and China-Mock-up test is presented. The basic THM properties of bentonite are first briefly summarized and then, the experimental infrastructure and operational process are introduced. The principal experimental data acquired are presented and analyzed, including the variation of temperature, relative humidity, displacement of the heater and the total stress evolution. The important difference is that the FEBEX Mock-up is KBS-3H reference concept and the China-Mock-up is KBS-3V reference concept. The large scale Mock-up test is valuable in developing a good understanding of the behavior of the buffer material under THM coupled condition, and demonstrating the technical feasibility of the disposal concept.

KEYWORDS: High-level radioactive waste (HLW), geological repository, bentonite, thermo-hydro-mechanical(THM)

1. Introduction

i) FEBEX Project

ENRESA has undertaken in 1994 the task of demonstrating the feasibility of installing a clayey-engineered barrier surrounding a simulated canister in a gallery excavated in granite (Grimsel Test Site), in accordance with the ENRESA's AGP Granite reference concept (ENRESA, 1994, 1995).

An experiment at almost full scale and under controlled boundary conditions, the mock-up test was proposed as a complementary step. In contrast to the in situ test, full steady state conditions, both thermal and hydraulic, were expected to be reached in the scale model, as the processes would be accelerated by the injection of pressurised water around the barrier. This test is carried out at CIEMAT's facilities besides a set of additional laboratory tests envisaged to obtain the clay parameters, to identify the processes and verify the models by simulating the conditions of the installed barrier at laboratory scale.

ii) China-Mock-up Project

At the present stage, the Gaomiaozi (GMZ) bentonite is considered as the candidate buffer and backfill material for the Chinese repository. Lots of basic experimental studies have been conducted and favorable results have been achieved (Liu et al., 2003; Liu & Cai, 2007a; Ye et al. 2009a). In order to further study the behavior of the GMZ-Na-bentonite under relevant repository conditions, a mock-up facility, named China-Mock-up, was proposed based on a preliminary concept of HLW repository in China.

The overall approach is based on performing experiments according to the needs for additional studies on key processes during the early EBS evolution. The study will make use to the extent possible of on going experiments being conducted in the laboratory of Beijing Research Institute of Uranium Geology (BRIUG).

1.1. Aims of the mock-up experiment

i) FEBEX Mock-up

The aims intended are to demonstrate the technical feasibility; to know and understand the long term behavior of a clay barrier submitted to thermal and hydraulic gradients, and to validate and verify the near field THM models under controlled boundary conditions.

The study of the THM phenomena, mainly transport coupled processes, by full-scale and laboratory experiment presents difficulties, both technical and conceptual. The evolution and the distribution of their characteristic parameters show coupled phenomena dynamics. The variation seems to be also affected by the space-scale of the system observation.

The mock-up tests surpass the space-scale limitation of the laboratory tests, by adoption of the actual 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 incertitude to extrapolate the future behavior of the clay barrier from the experimental transient state (ENRESA, 1997). So, the qualitative analysis must allow to discriminate 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.

ii) China-Mock-up

The experiment is intended to evaluate THMC processes taking place in the compacted bentonite-buffer during the early phase of HLW disposal and to provide a reliable database for numerical modeling and further investigations.

The main objectives of the China-Mock-Up include:

(1) To study the behavior of GMZ-Na-bentonite under coupled THMC conditions;

(2) To study the bentonite-canister reaction under coupled THMC conditions;

(3) To simulate vertical placement of a container with radioactive waste;

(4) To monitor the behavior of GMZ-Na-bentonite barrier at high temperature and special water;

(5) To experiment the installation method and validity of sensors;

(6) To provide data for future design for engineered barrier system.

1.2. Description of the experimental infrastructure

i) FEBEX Mock-up

The main components of the experiment are described as follows (Fig. 1): a confining structure simulates the gallery, through which hydration takes place (Fig. 2); a Programmable Logic Control (PLC) manages the heater control system (HCS), composed of two electric heaters (0.17 m in diameter) concentric to the confining structure, that simulates the heat generation of the waste canisters; a hydration system supplies the water to hydrate the bentonite mass at a constant controlled N_2-pressure from two tanks working alternately; a 0.62 m-thick engineered barrier composed of two rings of compacted smectite blocks surrounding the heaters; instrumentation monitors the boundary conditions and the system behavior by sensors installed within and outside the buffer material; and a monitoring and control system records the data by a Data Acquisition System (DAS).

More than 500 sensors have been installed within the experiment to measure the most important parameters such as temperature, total pressure, pore pressure, water injection pressure, relative humidity (water content) and strains within the structure. They have been chosen to withstand mechanical stress, high temperature, humidity and salinity coming from harsh experimental conditions within the barrier.

The test design must support long-time operation with the instrumentation placed in harsh conditions, and most of the manufacturers cannot supply components with the required performances. Also, the experiment scale affects the equipment that supports them and the complexity of the associated infrastructure, both in the component types as in their operative connectivity (ENRESA, 2000).

Chemical tracers, as well as corrosion probes including different types of material, have also been placed within the bentonite.

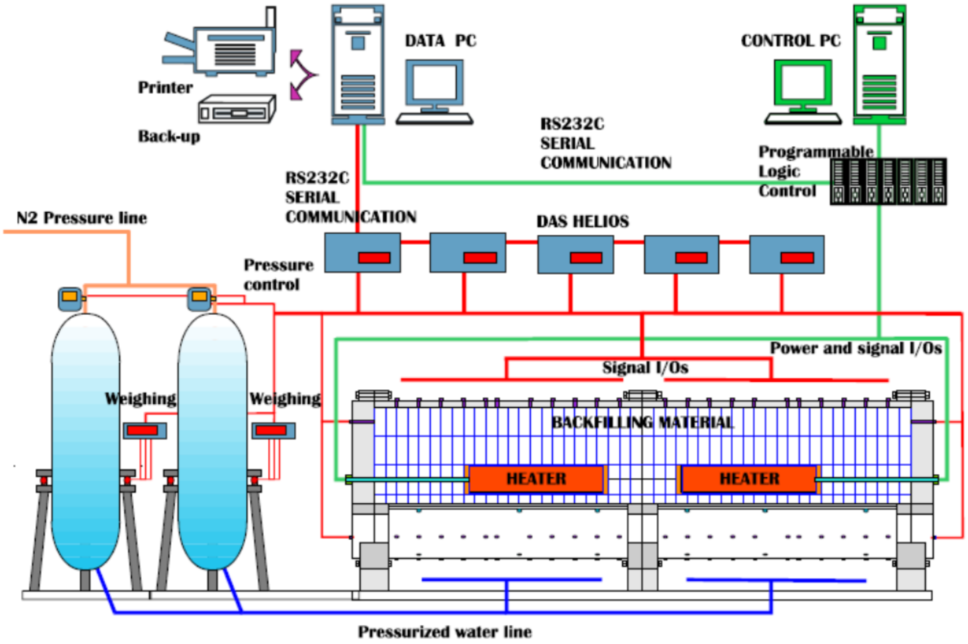

Figure 1 General layout of the mock-up experiment at CIEMAT.

Figure 2 Mock-up experiment: external view.

ii) China-Mock-up

The China-Mock-up has been constructed with compacted bentonite-blocks in a large steel tank of 900 mm internal diameter and 2200 mm height. An electric heater of 300 mm diameter and 1600 mm length, which is made by carbon steel as the substitute of a real HLW container, is placed inside the bentonite-buffer. The engineered barrier system (EBS) is heated by the heater from ambient temperature to 90°C. The outer layer of buffer material will be 60°C. The groundwater flow is simulated by injecting the formation water (obtained from the host granite rock in the Beishan site, NW China) around the outer surface of the barrier. It can be expected that complex T-H-M-C processes will occur in the bentonite-buffer, which will be monitored by a number of sensors to be installed at various locations in the buffer. The main parameters to be measured in the EBS include temperature, water inflow, relative humidity (suction), swelling and total pressure, as well as displacement of the heater inside the buffer. The experiment is conducting at the BRIUG laboratory in Beijing, China.

The China-Mock-up is mainly made up of eight components, namely compacted bentonite blocks, steel tank, heater and corresponding temperature control system, hydration system, sensors, gas measurement and collection system, real-time data acquisition and monitoring system (Fig.3).

More than 160 sensors have been installed within the experiment to measure the important parameter, including the temperature, pore pressure, relative humidity, water injection pressure and the total pressure.

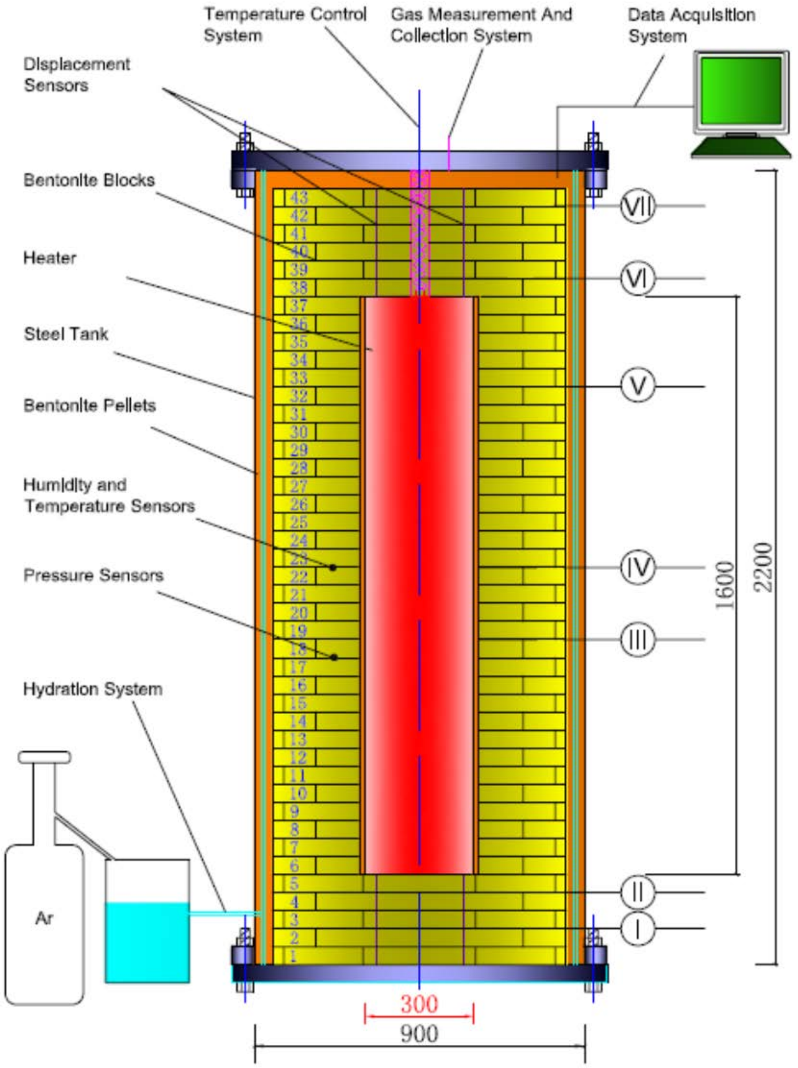

Figure 3 Sketch of the China-Mock-up facility (unit: mm).

1.3. Clayey-engineered barrier

i) FEBEX Mock-up

The material used for the manufacture of the blocks comes from Serrata de Nijar (Almeria, SE Spain). It is a Ca–Mg montmorillonite (92%) with low quantities of feldspars, biotite, quartz and fragments of volcanic rocks; and presents the required properties: thermal, hydraulic, mechanical and physical-chemical (ENRESA, 2000).

The specific weight of this bentonite is 2700 Kg/m^3, the swelling pressure is around 5MPa and the hydraulic conductivity is 10^{-14} m/s, at a dry density of 1600 Kg/m^3.

The blocks have been manufactured by uniaxial compaction of the clay with an average water content of 14% and to a dry density of 1770±20 Kg/m^3 (ENRESA, 1998a, b). The blocks have been arranged in 48 sections: 26 sections of two concentric rings around the heaters and 22 other sections of two rings and a core (Fig. 4, ENRESA, 2000). The total mass of bentonite is 22.5 t.

After saturation, the dry density of the barrier would decrease to the reference value in the AGP Granite, an average value close to 1650 Kg/m^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).

The final distribution of blocks is one of the most important factors affecting the mechanical and transport properties of the clay barrier. Its complexity could generate preferential flow paths and modify the mechanical behavior of the barrier (Fig. 6).

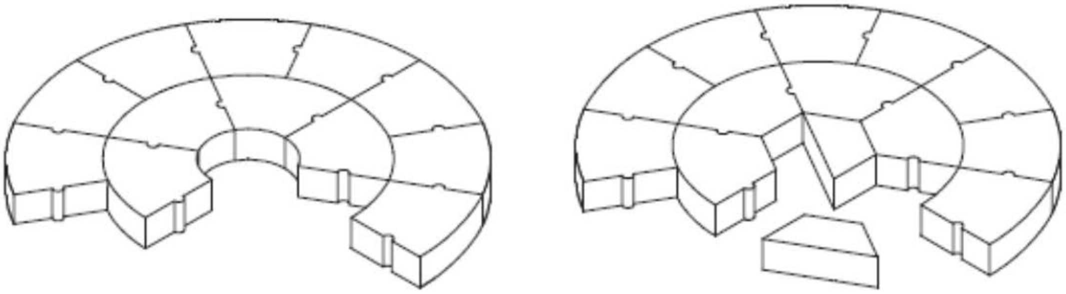

Figure 4 Block distribution: section with and without heater.

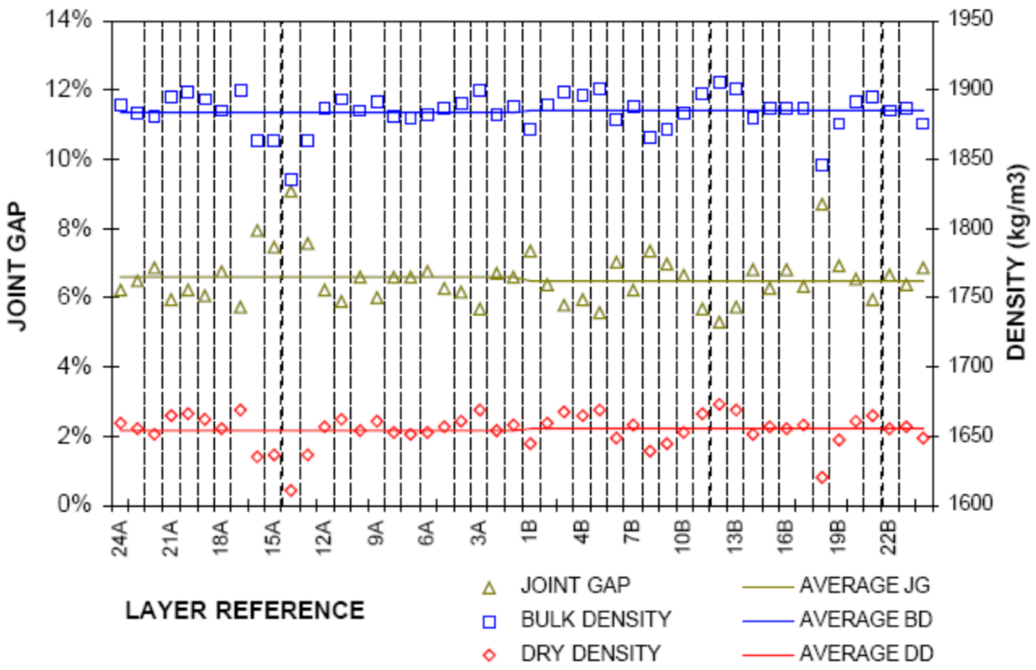

Figure 5 Void ratio and density distribution of the installed barrier before saturation.

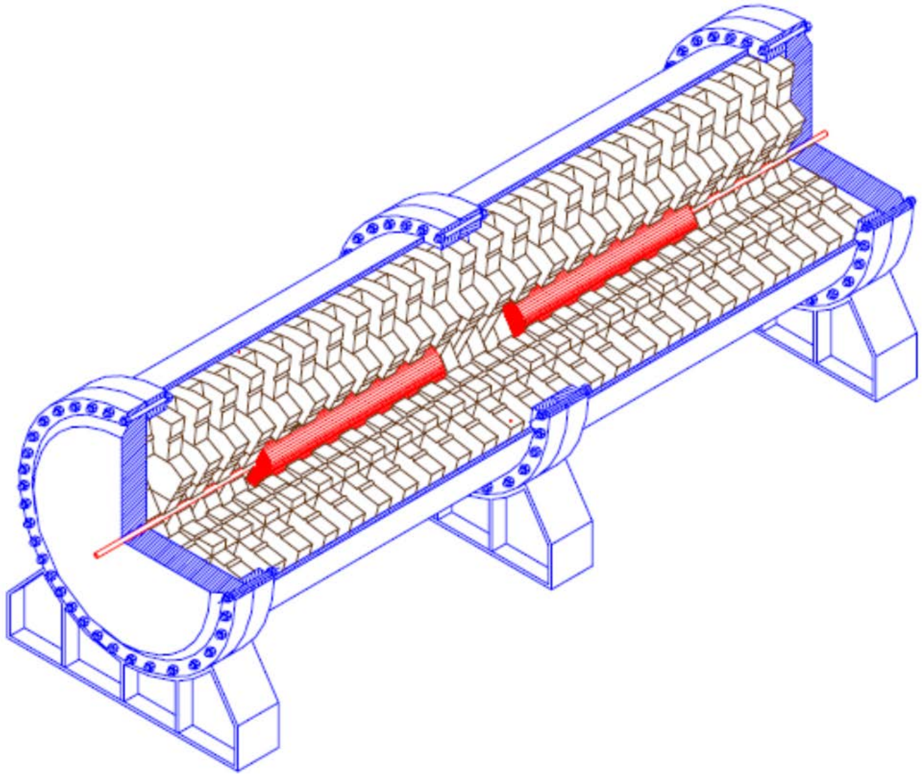

Figure 6 Mock-up experiment: distribution of blocks and heaters.

ii) China-Mock-up

The bentonite used for the China-Mock-Up comes from the GMZ-bentonite deposit, which is located in Inner Mongolia Autonomous Region, 300 km northwest of Beijing. The deposit, with bedded ores, was formed in late Jurassic. Clay minerals include montmorillonite and quartz, feldspar, cristobalite,etc. The reserve is about 160×106 tons, while with 120×106 tons of Na-bentonite. The major bentonite clay layer of the deposit extends about 8,150 m with thickness ranging from 8.78–20.47 m.

The GMZ-bentonite deposit has been selected as the most potential buffer/backfill material supplier for China's HLW repository (Liu et al., 2001). Comprehensive studies have been conducted on the GMZ-Na-bentonite(Wen, 2006; Chen, 2006; Liu & Cai, 2007b; Ye et al. 2009b). The previous study on GMZ-Na-bentonite shows that the bentonite is characterized by high content of Montmorillonite (70%) and low impurities. Various experiments have revealed that the GMZ-Na-bentonite has cation exchange capacity 77.30 mmol/100g, methylene blue exchange capacity 102 mmol/100g, and alkali index 1.14. The main properties of the bentonite compacted to a dry density of 1.8g/cm^3 are: thermal conductivity of around 1.0 W/m·K at water content of 8.6%, hydraulic conductivity of 1×10^{-13} m/s, and swelling pressure of 10 MPa. Those characteristics indicate that the GMZ-Na-bentonite has the very similar properties as those of the mostly investigated MX-80 and FEBEX bentonites to be used as buffer/backfill material.

Compacted bentonite blocks are used as buffer material for HLW disposal. Granular mixtures made of high-density pellets of bentonite are being evaluated as an alternative buffer material for waste isolation (Alonso et al., 2010).

A computer-controlled triaxial experiment machine in combination with specially designed steel molds is used to compact the GMZ-Na-bentonite powders into blocks with five different shapes (Fig. 7). The square bar-shaped bentonite blocks are subsequently crushed into small pellets in different grain sizes showed in Fig. 8 in order to fill the space between the bentonite blocks and the heater/steel tank walls. The total dry density of compacted bentonite blocks and pellets is 1600 kg/m^3.

Figure 7 compacted bentonite blocks.

Figure 8 Crushed pellets used to fill the space between bentonite blocks and steel tank walls.

For the China-Mock-up, 44 bentonite block sections, each with a thickness of 50 cm, are installed across the entire length of the tank. Each complete buffer section consists of two or three concentric rings, which are dependent on the space in which the heater is placed, formed by compacted bentonite blocks with different shapes and numbers. The inevitable spaces between buffer layers and blocks may provide the preferential paths for water penetration, resulting in a negative impact on the inner THM environment and sensors' working performance. To reduce or eliminate the effect of adverse penetration paths and maintain a uniform and stable water penetration rate in the bentonite, a standard layer (i.e. the bottom layer) has been designed. Once the bottom layer is determined, the second layer above the standard layer can be rotated 15° clockwise or counterclockwise so that the potential coalescence of penetrating water between the bentonite layers can be suppressed as far as possible. Every two layers/sections follow the same principle, and the optimal overlapping layer can be found. The determination of the standard and overlapping layers provides with a basis precondition for the further layout design of sensors.

1.4. Instrumentation

i) FEBEX Mock-up

A total amount of 481 signals are automatically registered in the experiment. These 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 extensiometric gauges and some temperature sensors) or within the heating and hydration systems (water pressure and mass, and heater temperature). Operators periodically record other 19 signals.

1.4.1. Distribution of the sensors

The sensors within the bentonite barrier have been 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 A*nn* or B*nn*, *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 have been installed, associated with extensiometric gauges, on the surface of the structure, some time after the beginning of the test. Four groups of signals were defined: those coming from the bentonite barrier, the heaters, the surface structure, and the external sensors and instruments.

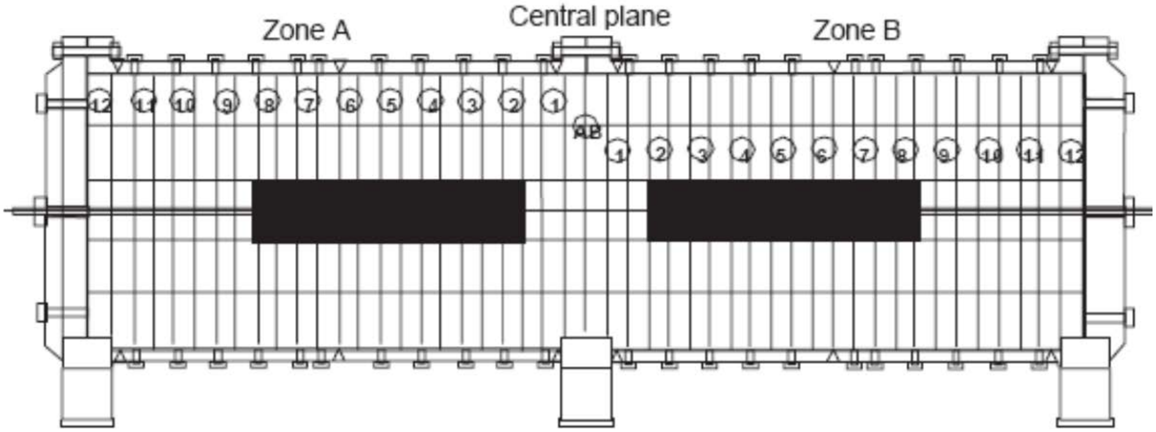

Figure 9 Distribution of the instrumentation levels.

1.4.2. Codification of the sensors

A cylindrical co-ordinate system has been chosen to identify the sensors in the experiment. An alphanumerical code describes the position of the sensor, both in the experiment and in the instrumentation level.

ii) China-Mock-up

The China-Mock-up is equipped with 10 different types of sensors to monitor the comprehensive performances of GMZ Na-bentonite under coupled THMC conditions. The 6 sensor types inside the China-Mock-up include stress sensor, hydraulic pressure sensor, LVDT displacement sensor, temperature sensor, RH sensor and electrochemical corrosion sensor. In addition, a series of metal corrosion samples are placed inside the bentonite blocks and crushed pellets to investigate the influence of internal environment of the Mock-up on metal corrosion behaviors. Another 4 sensor types consisting of Coriolis mass flowmeter, fiber Bragg grating (FBG) strain/temperature sensor, resistance strain gauge and dial gauge are located outside the Mock-up.

Measurements based on the 10 types of sensors are mainly carried out at seven measurement profiles located from the top to the bottom of the Mock-up vertical model (see Fig.3). Different types of sensors are placed within each section to investigate the variation of temperature, hydration process and the behavior of buffer material under complex coupling condition. The sensors were placed within the grooves cut in the compacted bentonite blocks or in the surrounding pellets. The overall sensing system involved in the Mock-up is expected to provide reliable data for numerical modeling and future design of EBS.

According to the reference concept of HLW disposal in China, the canister is completely supported by the surrounding buffer material. Therefore, the mechanical performance of buffer material may influence the overall stability of the canister. In order to evaluate this potential influence, six LVDT sensors are installed on the top and bottom of the heater to monitor its vertical displacement.

1.5. Monitoring and control system

i) FEBEX Mock-up

A Data Acquisition System (DAS) and a Heater Control System (HCS) that regulate the thermal power (Fig. 1) compose this set. An Uninterrupted Power Supply (UPS) prevents power breakdowns.

The DAS includes all the components, hardware and software, needed to supervise, record and store the data generated in the experiment. Also, it makes the conversion of the analogic signal from the transducers into numerical values.

The HCS supervises the operation of the heaters and controls the power supply by closed loops. It acquires data from the heaters, sends them to the monitoring system, takes steps to assure the heating system stability, and activates alarms and processes in case of a component failure. All this supervision is independent of the main DAS.

The software managing the experiment information permits the visualisation of all the instantaneous values recorded in the experiment. All the data are registered with the SCADA software every 30 min and converted into data files with 24h values.

ii) China-Mock-up

The heater and corresponding temperature control system (HCS) regulate the thermal power automatically, and the Data Acquisition System (DAS) has been automatically recorded every 10-30 minutes since the start of testing. Each kind of sensor has its own software and hardware to record all the values in the experiment. An Uninterrupted Power Supply (UPS) prevents power breakdowns.

1.6. Geochemical behavior

i) FEBEX Mock-up

The geochemical key-parameters, indicating processes induced by the water–bentonite interaction under a coupled hydrothermal gradient, were not recorded on line due to the lack of available sensors to measure geochemical parameters under these conditions. An alternative approach has been taken: the inclusion of tracers and corrosion probes in the bentonite to analyse the migration of components after dismantling of the experiment.

1.6.1. Migration of radio-nuclides (RNs)

Enough knowledge exists about the geochemical processes in the clayey barrier during the transient thermo-hydraulic state; but the dynamics of the evolution of these parameters is unknown. Particularly, there is a lack of information on radionuclide (RN) transport in the expected environmental conditions once the RNs will leave the waste.

To obtain complementary information about the barrier hydration, the water–bentonite interaction, and the transport processes, tracers have been included in the mock-up. To gain knowledge of the sorption properties and the transport of the RNs in the barrier, several non-radioactive tracers were chosen to be installed in the bentonite (ENRESA, 1998b, 2000) following these criteria:

i) Geochemical analogy with respect to the key-RNs in the performance assessment (P.A.) exercises;

ii) Tracer type (conservative or non-conservative);

iii) No alteration of the physical-chemical properties of water; iv) High detection limits to measure the tracer concentration, both in the pore water and in the solid matrix of the bentonite (this condition implies the absence or reduction of analytical interference with other species present in the water).

All the chemical species having a high concentration in the pore water of bentonite (chloride, bromide and sulphate anions) and those that form insoluble salts with Ca and Mg (p.e. fluoride anion) have been disregarded as tracers. Some non-conservative tracers (as Sr) were also disregarded to prevent errors due to its high natural background in the bentonite. Tracers have been dissolved in the hydration water or located in several ways (filter paper impregnation, plugs of compacted mixture of bentonite and tracer, and sintered stainless steel capsules) within the bentonite. Tracers are defined as conservative (D, I, B) and non-conservative (Re, Se, Eu, U, Th, Nd, Cs).

1.6.2. Corrosion behavior

As a complement to the geochemistry, metallic probes located within the bentonite must permit the study of corrosion processes in the components of the EBS, including both materials and welding methods.

Several probes on carbon steel, stainless steel, titanium, copper and different welding of these metals had been installed within the barrier; to study the corrosion processes in environmental conditions close to those expected in an AGP. The heaters, manufactured on carbon steel, are themselves the major elements to be considered.

ii) China-Mock-up

1.6.3. Water-bentonite interaction

To understand and guarantee the long-term safety of the engineered barrier, it is of importance to conduct research on coupled THM behaviors of bentonite under simulative geological disposal conditions, and determine the property variation of the bentonite over a long period of time.

In China-Mock-up test, the Beishan underground water is used in the experiment to simulate the relevant repository condition, and it is sampled from the deep borehole at the depth of 500m. Beishan area, located in Northwest China, is currently considered as the most potential area for HLW repository in China.

1.6.4. Corrosion behavior

Several probes on carbon steel, stainless steel, titanium, copper and different welding of these metals had been installed within the bentonite blocks and the pellets, to study the corrosion processes in repository conditions. And meanwhile, an electrochemical workstation is used to observe the corrosion of these metals.

2. Mock-up test operation

i) FEBEX Mock-up

The installation phase of the mock-up has been carried out between October 96’ and January 97’.

2.1. Pre-operational phase

Three days before the beginning of the operation phase, a volume of 634 l of water injected at high flow (3.5 l/min) flooded completely the voids, and made possible the closure of the gaps between blocks by the swelling of the bentonite.

2.2. Operational phase

The operational stage of the “mock-up test”, with simultaneous hydration and heating, started on February 4th 1997 at 12:45 P.M (ENRESA, 1998a, 2000), “day 0” in the time scale, and continues to date (Martin and Barcala, 2001a). A routine control is carried out weekly since then.

2.2.1. Hydration

The pressure of the hydration system was initially set to 0.55 MPa. The water injection pressure has been between 0.5–0.6 MPa since that date. The rate of injection follows an asymptotic curve, as expected, system has not been affected by major changes. Injection pressure has been re-established to its nominal values several times, when needed. On September 23rd 2001, the total injected volume of water was 950.1 l (Fig. 10).

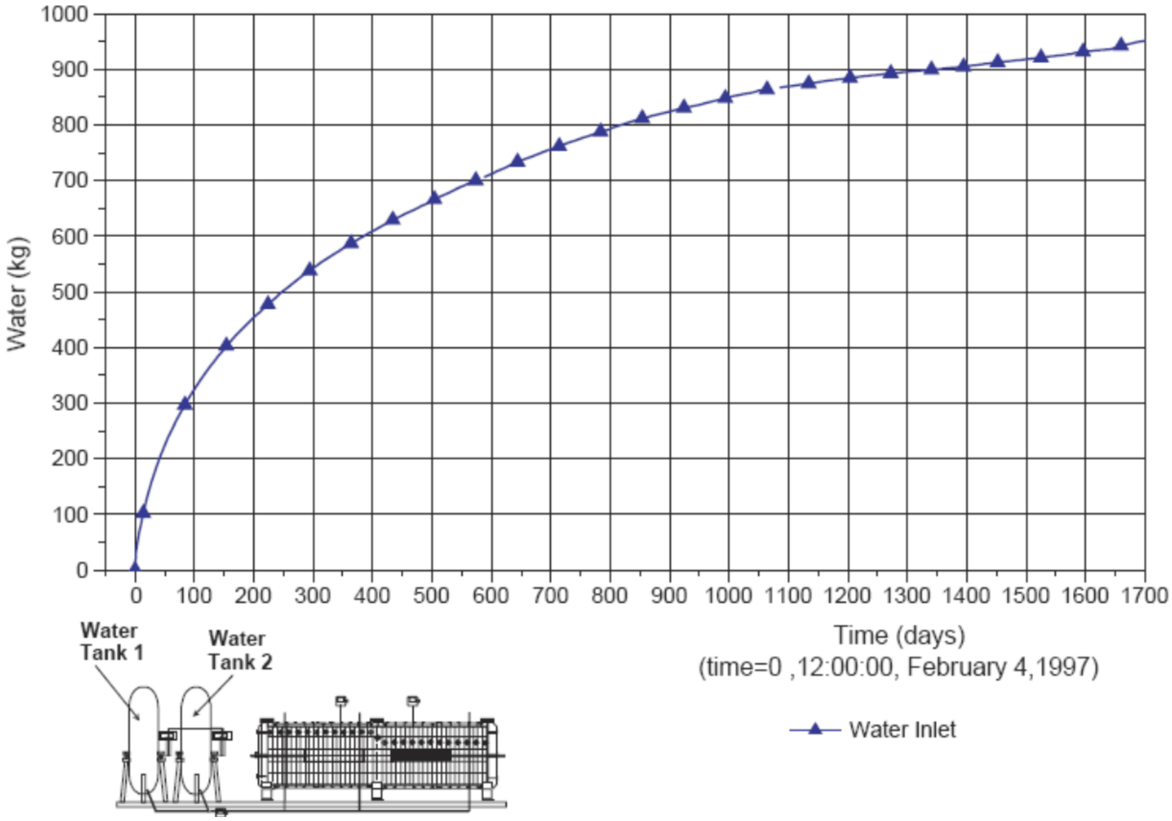

Figure 10 THM behavior: injected water volume evolution.

2.2.2. Heating

The power supply to the heater has been made in three phases: 250 W/canister during the first 6 days of operation (to 65 ℃ measured in the heater–bentonite interface), 500 W/canister during the next 4 days (to 95 ℃ measured), and automatically controlled from there (to fit the target temperature of 100 ℃ at this interface). The average power consumption is about 550 W/canister.

As shown in Fig. 11, the temperature steady state in the clay barrier is achieved in a short time (15 days) and generates temperature gradients with maximum values around 0.03℃/m, close to the heater surface.

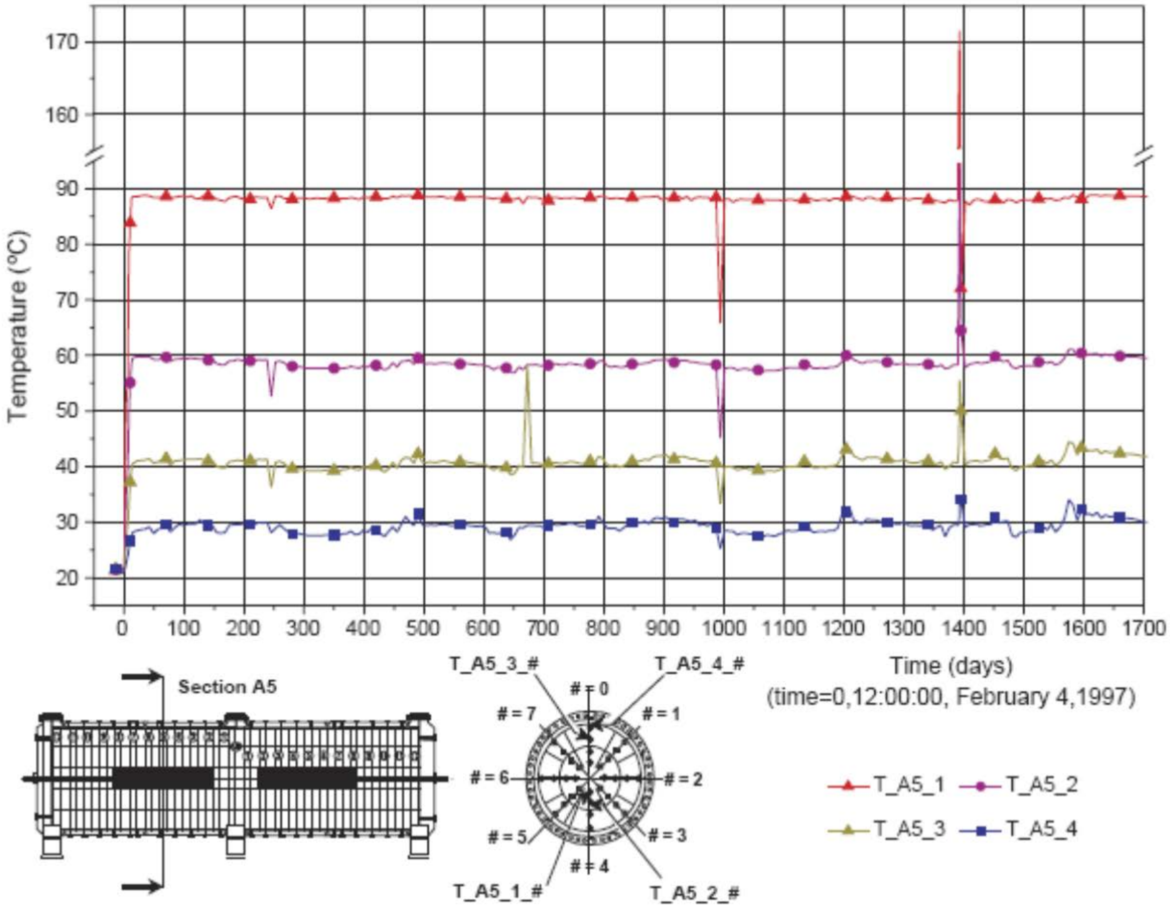

Figure 11 THM behavior: temperature evolution within the bentonite (average values at a given radius).

2.2.3. Data acquisition and communications

The DAS has worked as expected. The data set has been recorded every 4 h in an owner binary file format, and exported as needed in ASCII files.

2.3. Sensor performance

More than 85% of the installed sensors remain in operation, after having been within the bentonite for more than fifty-five months. These sensors work correctly in spite of the harsh environmental conditions. The instruments associated with the hydration and heating systems are also working properly.

Most of the faulty sensors are temperature sensors and have been removed from the database. The faulty pressure and relative humidity (RH) sensors remain in the database, until the confirmation of their failure.

2.4. Major incidences in the test operation

Two major incidents during the operation of the test altered the function of the heating system: an overheating episode (November 2000) and the loss of two out of three resistances (heating elements) on heater B (June 2001).

2.4.1. Overheating

Due to a wrong function, towards the end of November 2000 (day 1400), the control program supplied the total heating power (around 3000 W/canister) during more than 36 h, until the temperature at the heaters reached the resistance safety value (300 ℃). The overheating was automatically stopped but temperature within the bentonite had achieved values higher than 200 ℃ (Fig. 12).This dried the bentonite around the heater and generates a thermal pulse (Martin and Barcala, 2001b).

2.4.2. Resistance damage

Some voltage peaks have damaged two out of three resistances in the heater B in June 2001. Both heaters go on functioning with only one resistance, with filtered power supply, from this date on.

2.5. Minor incidences in the test operation

Minor incidents during the operation of the test altered the function of several systems, including heating, hydration and data acquisition systems.

2.5.1. Power supply

The heating system has endured minor failures in the general power supply, with temporary losses of less than 20℃ at the heater–bentonite interface. No major consequences occurred and these failures do not appear in the daily readings because the target temperature is recovered in some hours.

2.5.2. Hydration

When the injection pressure value shows a small decreasing behavior, it is re-established to its nominal values.

2.5.3. Data acquisition and communications

Most of the incidents were caused by loss of communication between the DAS, the PLC or the control PC, due to transmission errors. The resetting of the DAS main frame, as foreseen in the operation procedures, recovered the communication and solved the problem in a few minutes.

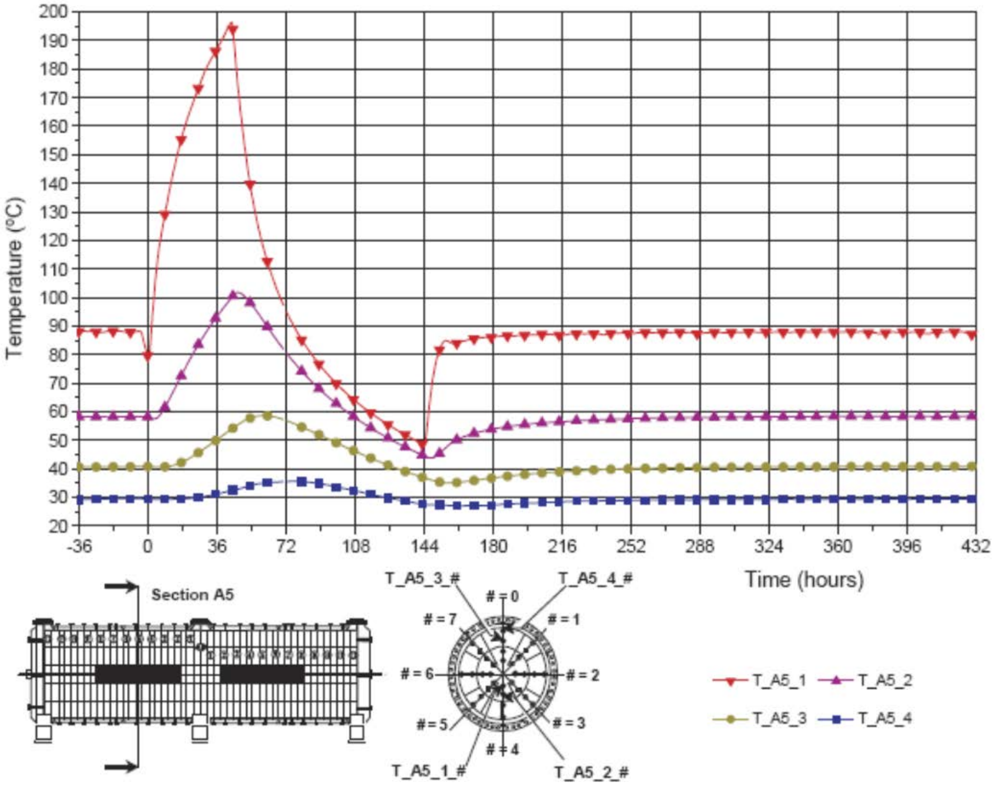

Figure 12 Temperature evolution of section A5: overheating detail (average values at a given radius, day 1400).

ii) China-Mock-up

The China-Mock-up experiment was assembled completely on 10th September 2010. After a pre-operational phase, the operational stage of the China-Mock-up test started on April 1st 2011, the date identified as “day 0” on the time scale.

2.6. Heating

The power supply to the heater has been made in four phases: during the first 2 days, the temperature of the heater is increased to 30°C; over the next 95 days, the temperature is maintained constant to verify the reliability of the installed sensors; then, during the period 98 to 255 days, the temperature is increased progressively to approximate the final value of 90°C which is the maximum temperature expected on the canister surface according the current disposal concept in China. Finally, the system was switched to the constant temperature control mode. The necessary electric power was adjusted to maintain 90°C on the surface of the heater.

2.7. Hydration

The water injection started from 8th July, 2011. In order to avoid potential damage to the sensors by a sudden saturation process, the hydration is initially controlled by a water injection rate which is increased gradually from 400 g/day to 1200 g/day in the first 500 days. The hydration process is illustrated in Fig.13. The injection rata of 1200 g/day is kept constant thereafter to 20th January, 2013, and then decreased to 400 g/day again. The water injection is controlled by a constant water pressure at 0.2MPa from 20th August, 2013 until now. As planned, a constant pressure of 2MPa is to be applied when the pellets become fully saturated. To mention here, the water supply was performed artificially every day, and the platforms illustrated in Fig.13 indicates that no water is injected during the corresponding period of time.

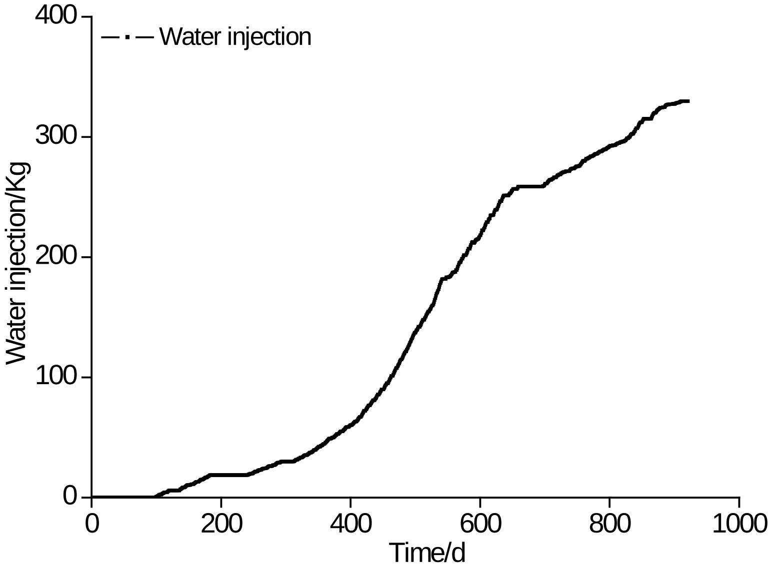

Figure 13 Illustration of water injection process.

2.8. Data acquisition and sensors performance

The experimental data has been automatically recorded every 10-30 minutes since the start of testing. The real-time data acquisition and monitoring system has recorded all the measurement data from 1st April 2011 to 8th October 2013. In the figures, the 1st April 2011 is defined as the first day. By 1000 days after the start of the operational phase, most sensors and the controlling system were still working properly in spite of the harsh environmental conditions. The sensors lost in the first 1000 days include 10 temperature sensors, 4 relative humidity sensors and 3 LVDT sensors. This is probably attributed to the water penetration into the sensors during the hydration process.

2.9. Major incidences in the test operation

Up to now, the only major incidents associated with test operation are some interruptions to the heating process induced by brief power interruptions. Consequently, some fluctuations of the saturation process are noticed, which are analyzed in the following section.

3. Test evolution: boundary conditions and THM behavior

i) FEBEX Mock-up

The data show good homogeneity throughout the test, between zones A and B and between points located at similar radial distances, which is the main requirement to be worth to validate and verify the models. Then, the dismantling of the mock-up and the study of the clay barrier within will supply more information to validate the conceptual THM and THG models and to verify and optimize the fitting between model predictions and the actual geochemical evolution at large scale.

3.1. Boundary conditions

Controlled boundary conditions are of major importance in the mock-up experiments throughout the world. These are the main requirements upon which the calibration and the validation of numerical codes are based. Controlled conditions include the temperature and the heating power of the heaters, the external temperatures, and the water injection pressure on the hydration surface.

3.2. THM behavior

Continuous recording of temperatures, volume of injected water, relative humidities, fluid pressures and total pressure (Figs.10–12, 14–19) allows to ponder the process, to fit the numerical codes and address the specific laboratory experiments.

3.2.1. Temperature

After a transient state of two weeks, the test was conducted in a quasi-stationary temperature state (Fig. 11). After overheating, quasi-stationary temperature state was completely recovered in less than 18 days (Fig. 12). The slight temperature waves observed are 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.

The data, in general, show good homogeneity throughout the test. The initial variations observed among sensors located at selected radial distances in the same section (0.20, 0.39, 0.58, and 0.77 m, respectively) are less than 2 ℃.

The properties that control the clay behavior under a thermal load are the thermal conductivity, the specific heat and the thermal expansion coefficient. In addition to these factors, the final temperatures in the barrier are strongly related to the degree of saturation of the bentonite.

3.2.2. Relative humidity (RH)

The RH sensors allow the monitoring of the hydration drying–wetting process. Fig. 14 shows the evolution of the relative humidity (RH) at several distances from the heater in a “hot” section.

Depending on the location of the RH measurement (distance to the hydration surface and thermal gradient imposed on the sensor) different behaviors can be observed. Values measured at 0.05 and 0.20 m from the heater surface show clearly the effects of evaporation (drying) and condensation (wetting) in different zones of the barrier. Values measured at 10 cm from the hydration surface of the structure suggest that bentonite in this external zone is fully saturated.

In sensors located close to the heater (sensor V_A4_1, Fig. 14) the following phases can be distinguished: (i) a sharp increasing RH value appears related to the vapor phase generated by the initial heating; (ii). continuous heat transfer from heaters produces the drying of clay that causes decreasing RH; (iii) after some time, hydration reaches the dried zone and overcomes the drying process, increasing the RH values.

During overheating, sharp peak values of RH were observed again in the inner rings (day 1400, Fig. 14). This fact supports the idea that a new drying of bentonite was produced and generated enough vapor to flow through the location of the sensor. This vapor outflow from the heaters seems to be radial and redistributes water within the bentonite.

The sensor placed in zones without heater (“cold” sections) show higher RH values, reaching almost full saturation according to retention curves (Fig. 15).

The RH evolution curves in all sections show tendencies similar to those described above. The only differences are related to the relative radial and longitudinal positions with respect to the heaters (hot and cold zones, Figs. 14 and 15).

The hydraulic conductivity and the retention curve, both critical parameters to evaluate the full-saturation time, regulate the hydration of the bentonite.

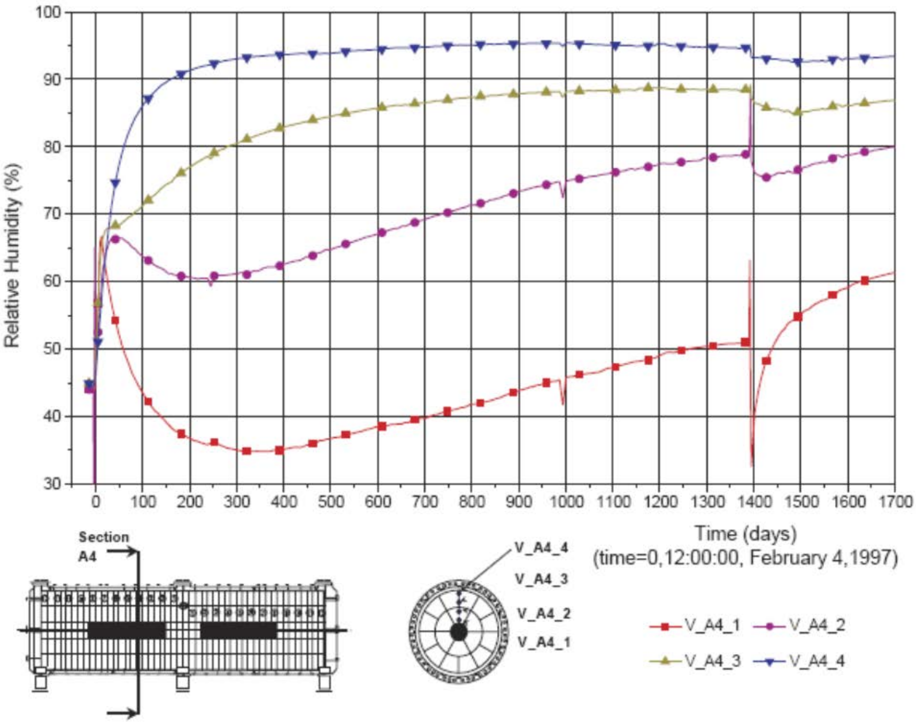

Figure 14 THM behavior: relative humidity evolution (heater zone).

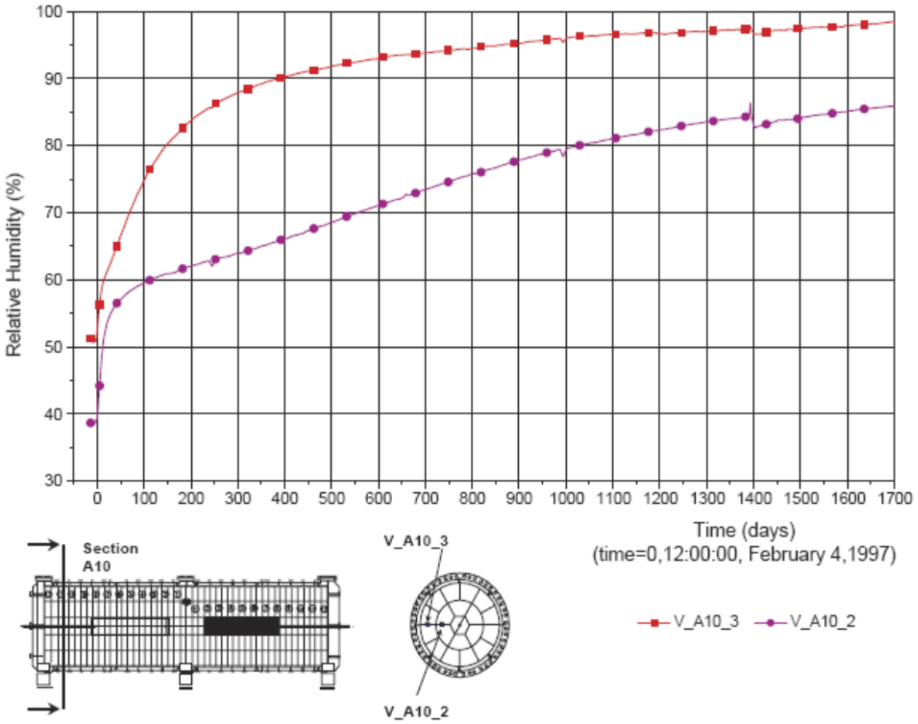

Figure 15 THM behavior: relative humidity evolution (cold zone).

3.2.3. Total pressure

Under hydration, bentonite develops a mechanical pressure by swelling recorded by the total pressure sensors located at selected radial distances (35.0 and 66.5 cm), and orientated in the three main directions.

Axial pressures range from 4.5 to 9.0 MPa, radial pressures from 5.0 to 8.0 MPa and tangential pressures from 5.0 to 10.0 MPa. The pressures are in accordance with swelling pressure values of the bentonite measured in the laboratory: 10 and 6 MPa for dry densities of 1700 and 1600 Kg/m^3, respectively.

The higher-pressure values are located within the outer ring due to the evolution of the saturation front (Fig. 16). In fact, the average-pressure values in this zone and their slow increase indicate full saturation of the buffer.

Other side, the smaller pressure values in the inner rings could indicate two different processes: the redistribution of stresses coming from the outer rings or the extension of saturation into this zone (Fig. 17).

Small variations of the pressure evolution appear to be linked to external temperature variations. Overheating produced small pressure value peaks and redistributed total stresses and water content within the bentonite by the heating–cooling cycle generated. Recovery of the values previous to overheating is more pronounced in the sensors placed in the outer ring. Sensors measuring axial and tangential stresses seem to be more affected (Figs. 16 and 17). Some local extremely high-pressure values (up to 10.5 Mpa) can be explained by considering the locally combined effects: XYZ co-ordinates, dry density of the block (higher than 1800 Kg/m^3 in the core blocks), sensor installation (place carved in the block), local swelling pressure (depending of hydration and temperature), and/or development and concentration of local stresses due to readjustment between blocks.

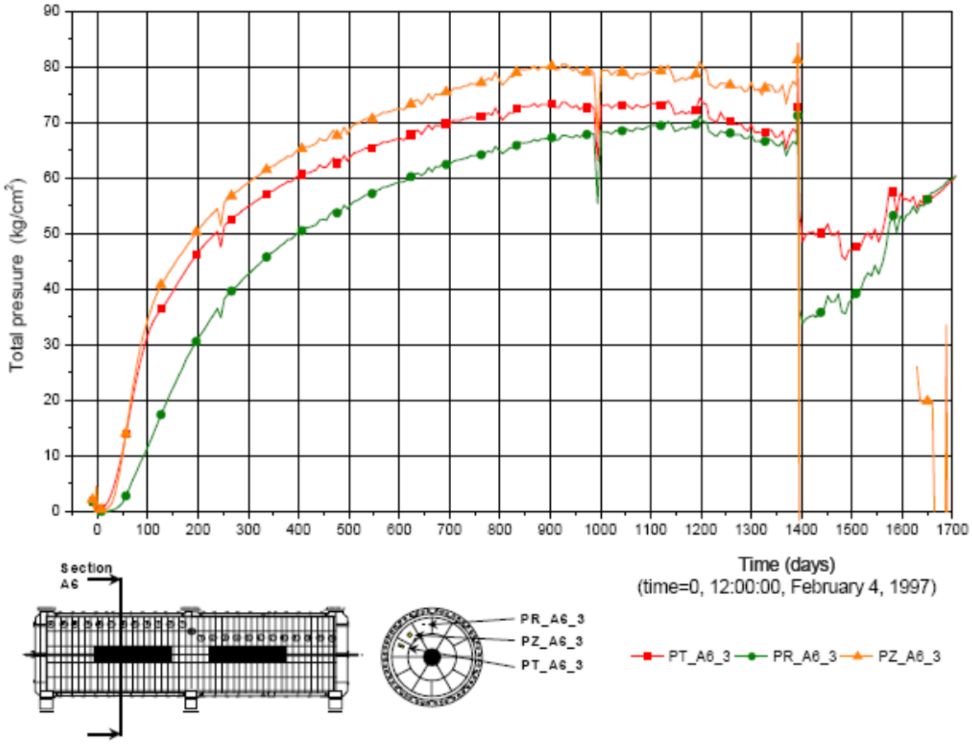

Figure 16 THM behavior: external total pressures (heater zone).

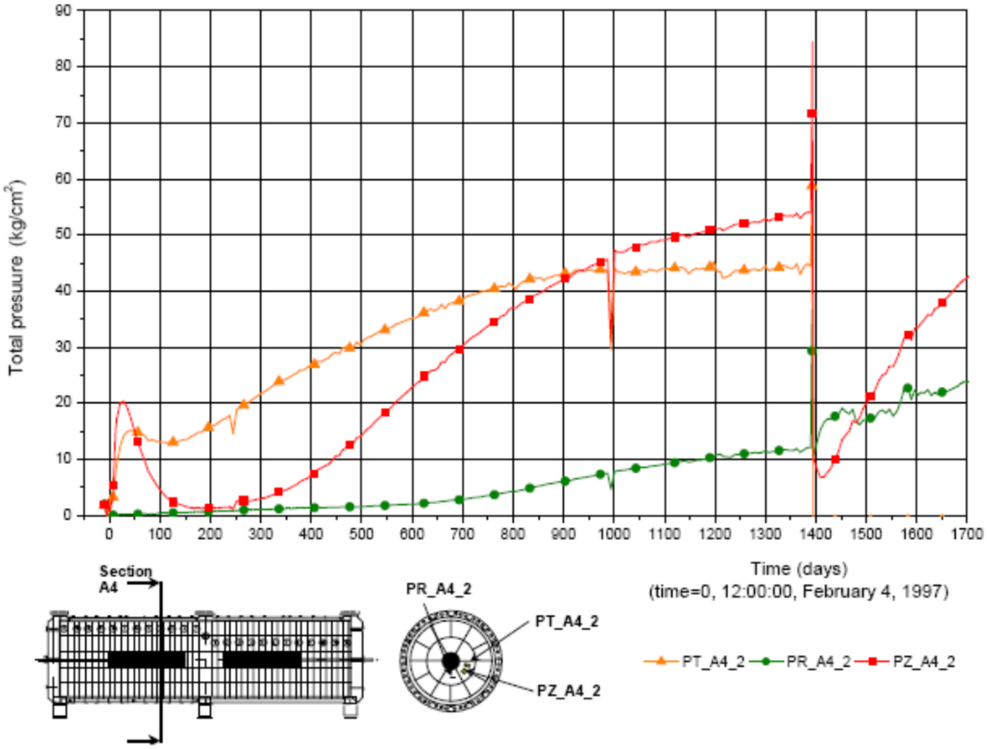

Figure 17 THM behavior: internal total pressures (heater zone).

3.2.4. 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 (Fig. 18). In all cases, the fluctuations seem to be related to temperature variations.

During overheating, sharp peak values of fluid pressure, generated in the inner rings, support the idea introduced above related to the drying of bentonite. Values are recovered in the outer rings after overheating; but values in the inner ring continue to vary slowly or remain almost negligible (Figs. 18 and 19).

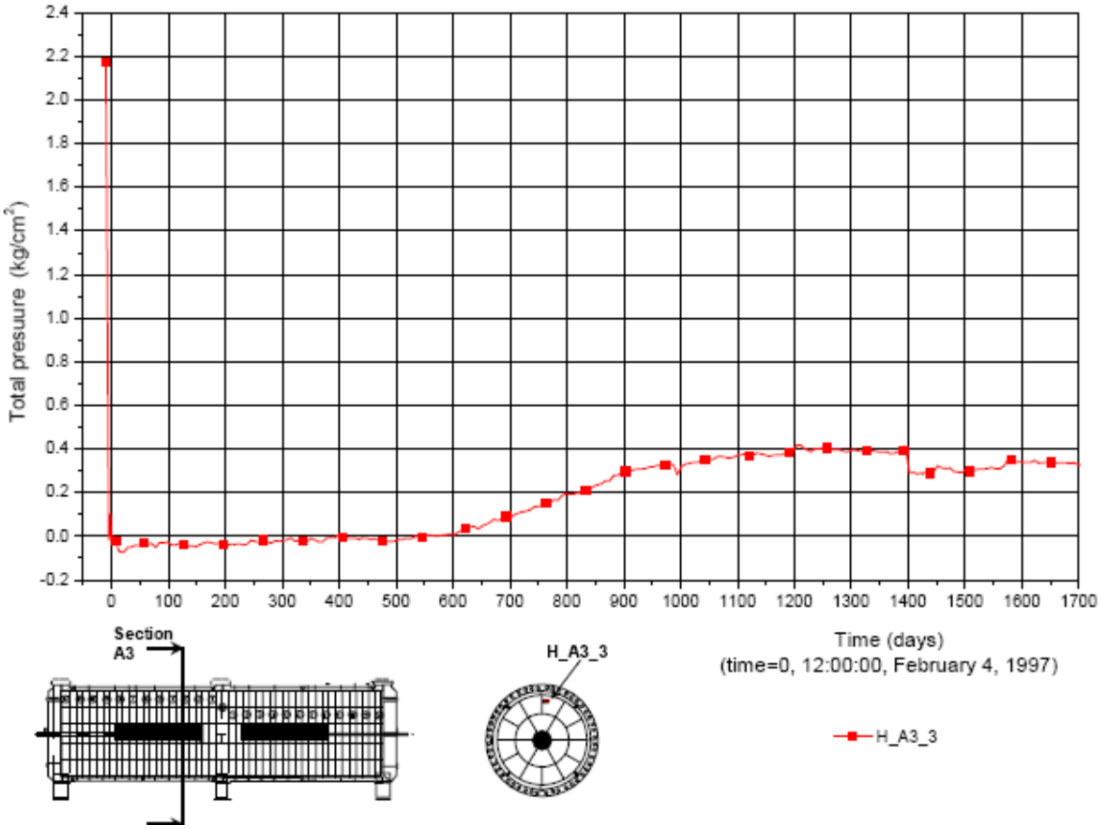

Figure 18 THM behavior: external fluid pressures (heater zone).

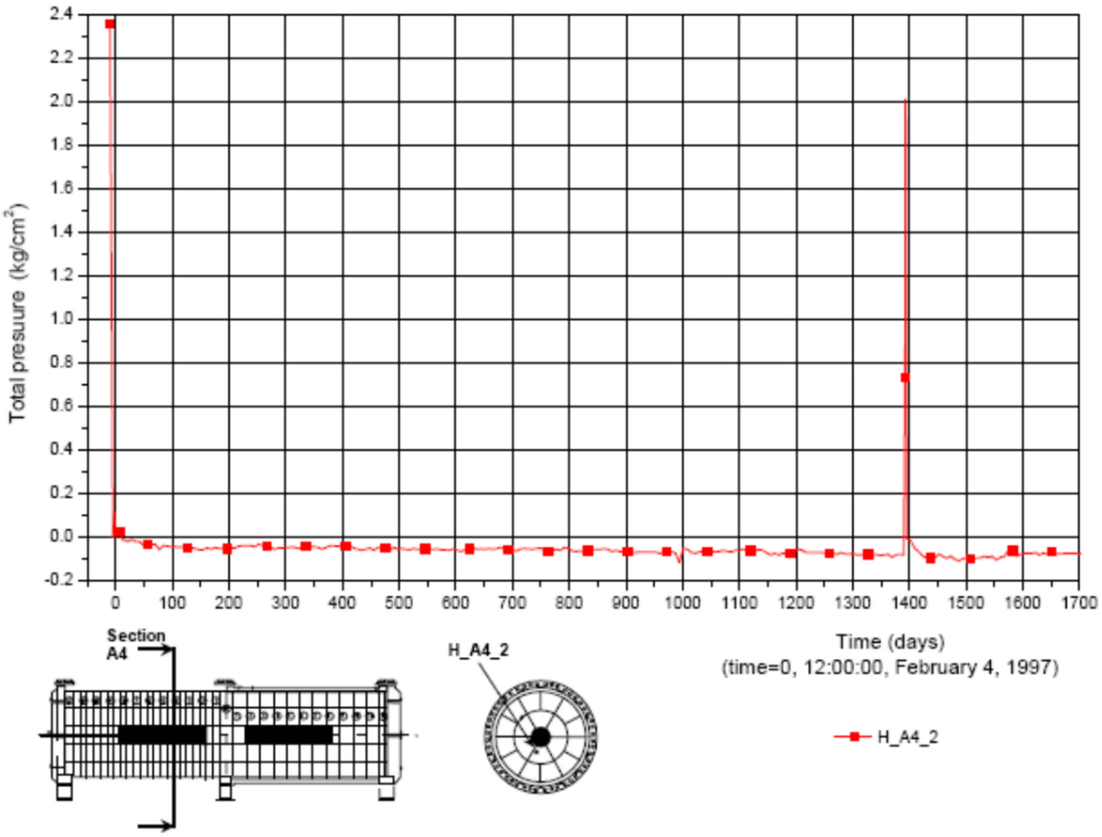

Figure 19 THM behavior: internal fluid pressures (heater zone).

3.3. Other sensor data

In this group are included all the signals that come from external sensors (like room temperature or water pressure in the inner surface of the structure), from special instruments (like signals from the hydration system: injection pressure and weight of tanks), and also the calculated values (like injected water volume, average control temperature and power supplied).

3.3.1. Temperature sensors on the heaters

The readings of the sensors installed on the surface of the heaters are close to 100 ℃ at the control zone and close to 90 ℃ at the end zones. During overheating, temperature sensors installed within the heaters reached 200 ℃ at the end zones, and the estimated maximum temperature was close to 300 ℃ at the control zone of the heater.

3.3.2. Temperature sensors on the surface of the structure

Changes in the confining structure temperature are due to important and sudden variations in the natural climatic condition. During summer, higher daily temperature variations are produced, which are not completely compensated by the air conditioning system (within ±4 ℃ difference). With these exceptions, the temperature waves on the structure are within ±2.0 ℃ difference (Fig. 20).

3.3.3. External sensors and instruments

The parameters from the hydration system are the injection pressure in the hydration line, the injection pressure on the hydration surface, the mass of the tanks, and the volume injected (Fig. 10).

The major deviation from the expected behavior is the divergence between the injection pressure in the hydration line and the pressure on the hydration surface (Fig. 21). This is interpreted as the clogging of the connection pipes to the sensors, caused by the clay intrusion and swelling, or the geotextile clogging by bentonite particles. The temperature at the test room is also measured close to the PLC rack and shows average variations within the ±2.0 ℃ difference.

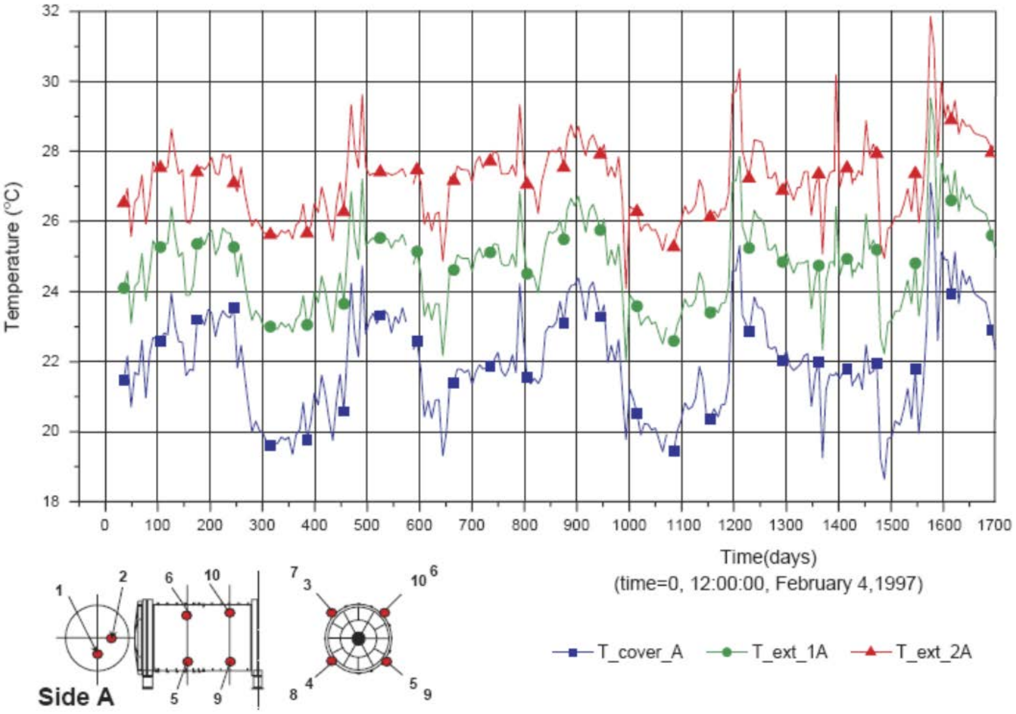

Figure 20 Controlled boundary conditions: external temperatures (average values at a given section).

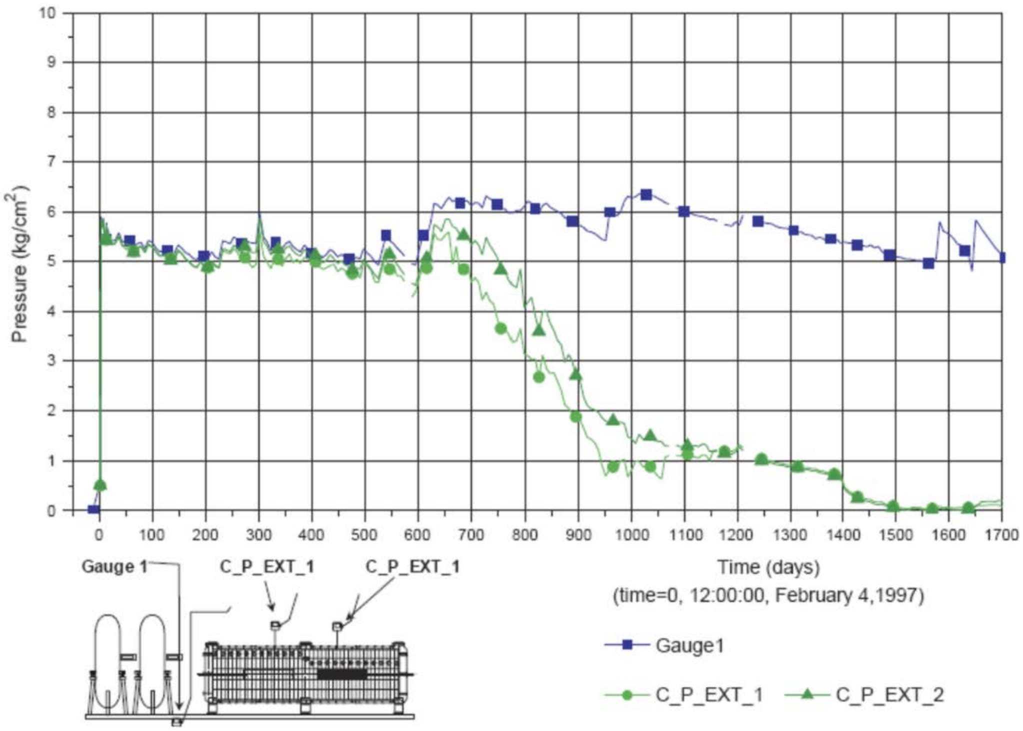

Figure 21 Controlled boundary conditions: water injection pressure.

ii) China-Mock-up

The sensors placed in the bentonite have provided reasonable and consistent outputs. In this paper, the experimental results recorded from 1st April 2011 to 8th October 2013 are presented and analyzed, including the variation of temperature, relative humidity (RH), swelling pressure and the displacement of the heater.

3.4. Temperature evolution

The temperature evolution in buffer sections II, III and VI is given in Fig 22 through Fig 24. It can be noticed that, the temperature has continuously increased with time, especially the sensors located in the inner rings. Moreover, the distribution of temperature is non-uniform vertically, and it is much higher in the central part (Section III). Even in section III, the temperature is still below 60°C. In the experiment, the relatively low temperature may be partly attributed to the existence of the installation space between the heater and compacted GMZ blocks, which is 5cm in width and filled with the pellets. This installation may reduce the thermal conductivity of the barrier in the area. In addition, as mentioned previously, the effective heating length is only 1.2m centrally located in the heater (1.6m). It could be an important factor resulting in the higher temperature in the central part of the barrier. The temperature distribution is also influenced by a complex coupling mechanism. Besides the thermal conductivity, the specific heat and the thermal expansion coefficient, the temperature distribution is also strongly related to the saturation process within the barrier.

Due to the interruptions of electric power supply, some fluctuations of temperature are recorded, in particular to the sections (III, IV and V) located within the heater zone. The fluctuations mainly happened in the period between 200 and 250 days. After 260 days, the temperature variation becomes less noticeable.

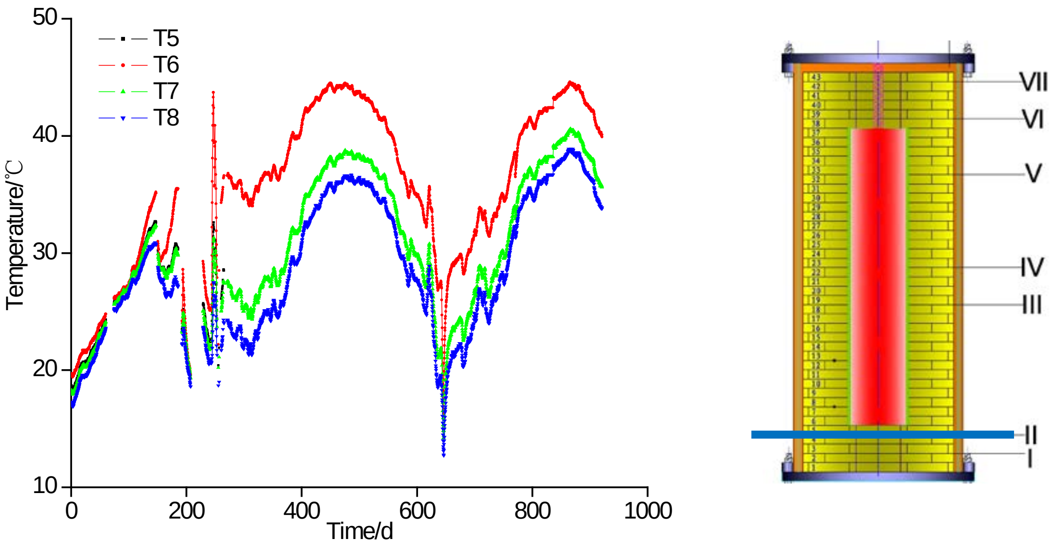

Figure 22 Temperature evolution in section II (T5 is out of work after about 280 days).

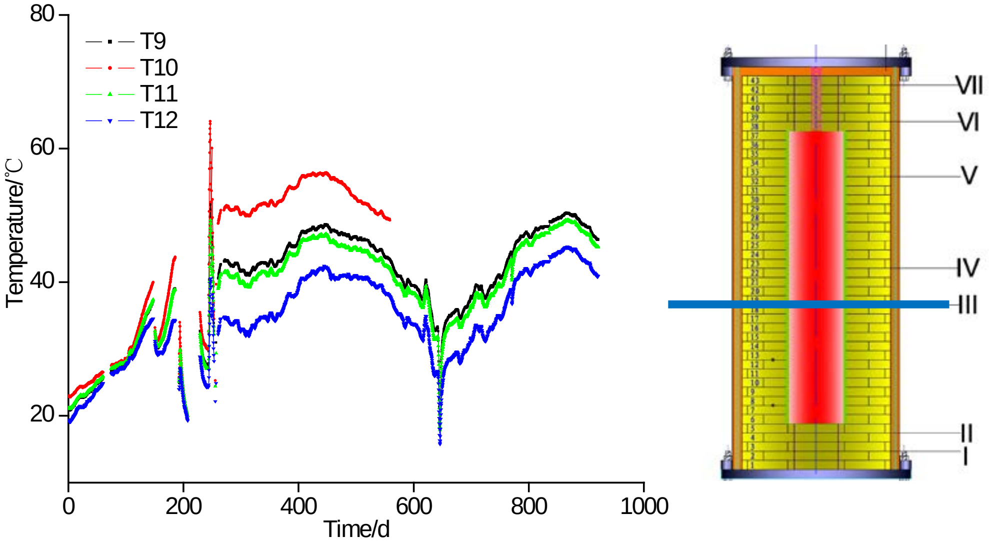

Figure 23 Temperature evolution in section III (T10 is out of work after about 590 days).

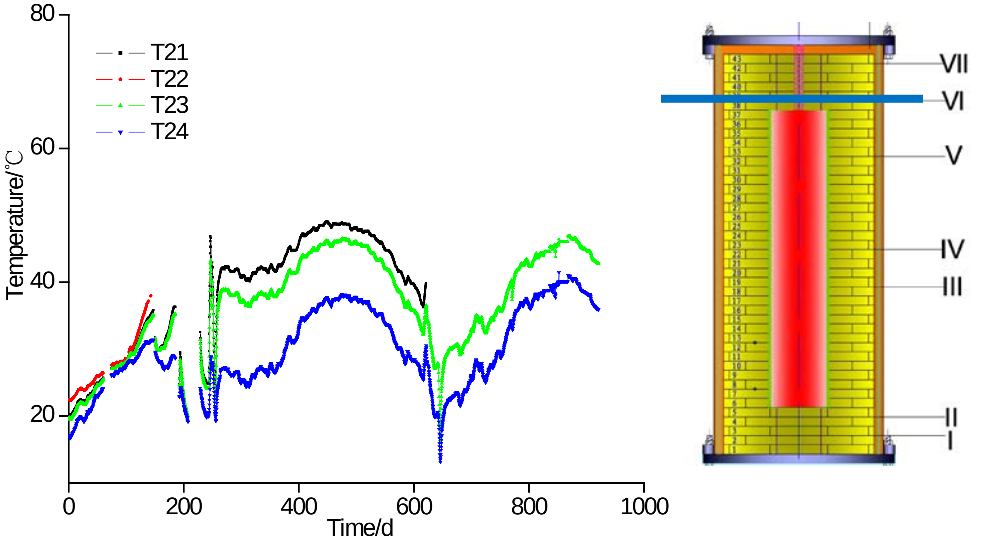

Figure 24 Temperature evolution in section VI (T21 is out of work after about 620 days, T22 is out of work after about 150 days).

3.5. Relative humidity (RH)

Fig. 25 and Fig. 26 present the evolution of the relative humidity (RH) at several distances from the heater in the relatively “cold” sections without heater (Section I and II). As illustrated, the compacted bentonite is progressively saturated in section I and II, and the distance to the heater has a significant influence on the saturation velocity. In outer rings, the compacted bentonite is almost completely saturated after 200 days. However, due to the extremely low permeability of the bentonite and the drying effect by the heater, the variation of relative humidity is rather limited in inner rings.

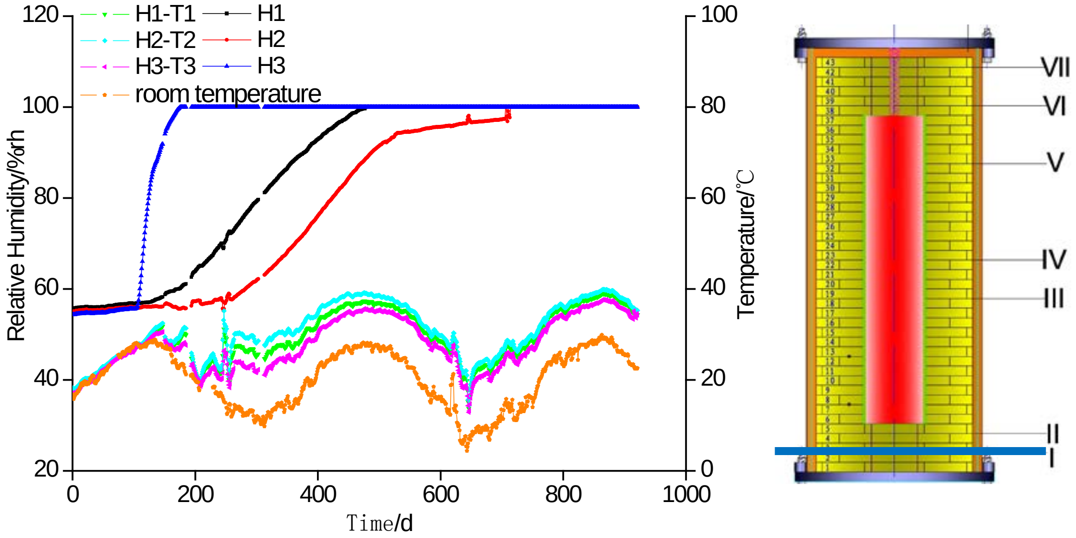

Figure 25 Relative humidity evolution in section I.

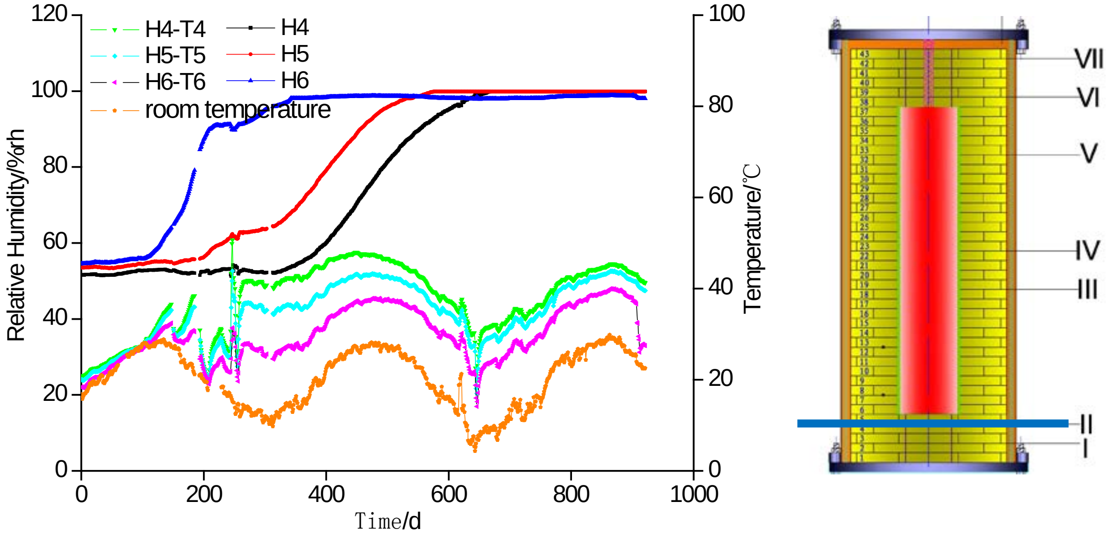

Figure 26 Relative humidity evolution in section II.

The RH evolution in the “hot” sections III is illustrated in Fig. 27. As noticed, the RH evolution in this area is much more complex. With the increase of temperature, the decrease of RH can be observed, particularly in the inner rings. In the “hot” zone (inner part), the following phases can be noticed: a) the stable RH with some fluctuations in the first 250 days; b) when the temperature is kept constantly on 90°C, continuous heat transfer from the heater leads to the drying effect that causes decreasing RH; c) after some time, hydration overcomes the drying effect and RH increases. This wetting tendency appears tightly related to the accelerated saturation process by the corresponding increased water injection rate. On the contrary, the desiccation is not noticed in the "cold" zone where the drying effect is not significant.

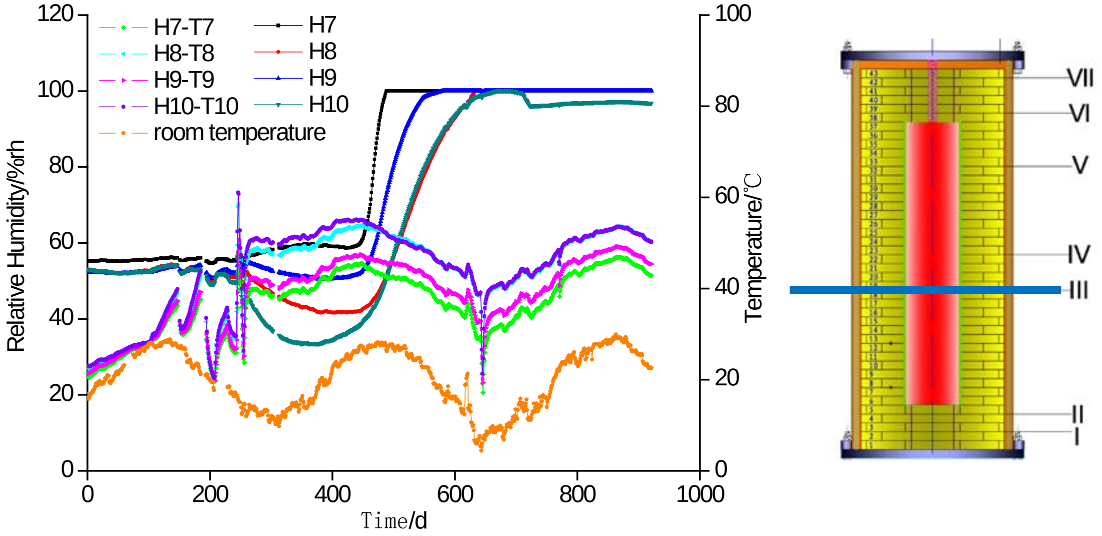

Figure 27 Relative humidity evolution in section III.

In conclusion, the RH variation in the inner rings is found to be strongly influenced by the competing mechanisms of the saturation process induced by the water penetration and the drying effect by the heater. The experimental result indicates that, due to the low permeability of the compacted bentonite, the drying effect is dominant in these sections at the beginning of the test. Similar phenomena are also reported in other research works (Martin and Barcala, 2005; Alonso et al., 2005; Villar et al, 2012).

It should be mentioned that, the hydration process is initially controlled by the water injection rate instead of constant water pressure, and the water injection has not been carried out continuously during the day. Considering the water supply is limited at the beginning (400g/day), the injected water would be mainly concentrated at the bottom of the vertical tank due to the effect of gravity. As a result, the saturation process is non-uniform vertically. It can be another factor responsible to the smaller saturation degree in the central part of the barrier.

The RH evolution on the top section of the China-mock-up facility (section VII) is given in Fig. 28. Due to the non-uniform water supply in the vertical direction, the saturation process in this section is not as pronounced as in the sections at the bottom (I and II). The desiccation phenomenon is also observed for the sensor located in inner ring. In addition, the fluctuation of RH induced by the heating interruptions is particularly evident in this section. It indicates that the generated vapor phase is diffused in both radial and longitudinal directions.

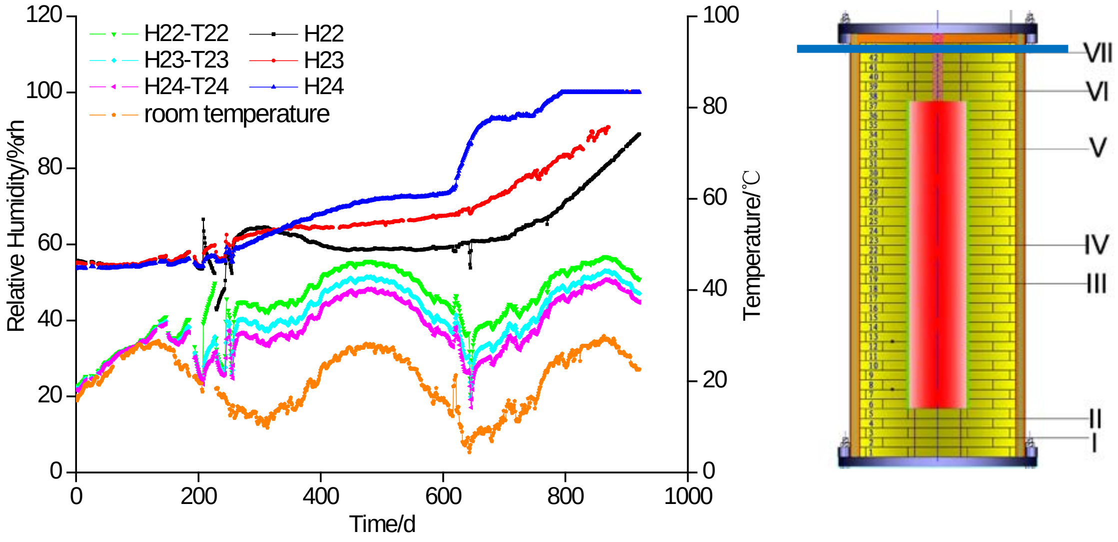

Figure 28 Relative humidity evolution in section IV.

3.6. Fluid pressure

In Fig.29, the measured fluid pressure in section II is presented. It can be noticed that, the liquid pressure is limited or negligible in the initial stage. Some fluctuations can be noticed which appears to be related with the temperature change. With the development of saturation, the fluid pressure is increased gradually, a value of fluid pressure around 0.2MPa is observed in the clay close to the chamber wall after 900 days. This is attributed to the arrival of the saturation front caused by the increased water supply.

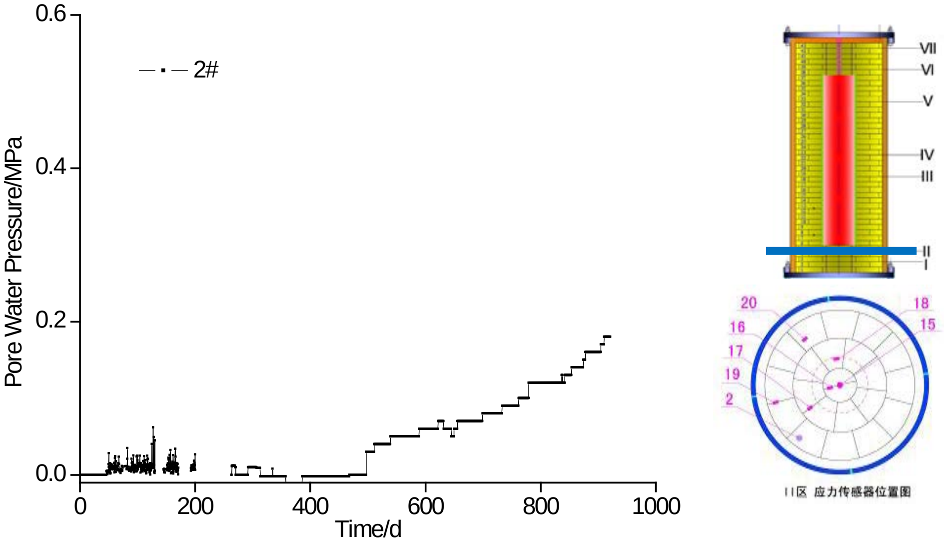

Figure 29 Variation of fluid pressure in the outer area in section II.

3.7. Total pressure

Under THM coupled condition, the stress evolution of the compacted bentonite may be influenced by several mechanisms, including the thermal expansion induced by high temperature, and the swelling pressure generated by bentonite saturation. The mock-up test started from 1st April 2011, and the stress started to increase at 12th December 2011. In Fig. 30-32, the stress evolution in section I, II and III are given. As shown in the figure, the total stress variation is rather limited or negligible in the initial stage. Then, with the increase of the injection water, the saturation process is dominant, and the stress in this area is increased gradually, and a maximum value around 2.0MPa is recorded within the inner ring after 900 days. In other sections, almost no significant variation of stress in compacted bentonite is observed up to now. As mentioned in the former section, the water pressure at this moment is rather limited. Therefore, this value (2.0MPa) can be considered as the swelling pressure which is much lower compared to the swelling pressure values of the GMZ bentonite measured in the laboratory: 4.3MPa for dry density of 1750 kg/m^3. In other sections, no significant stress variation in compacted bentonite is recorded to present. This could be attributed to two reasons: as previously mentioned, the saturation process of whole barrier is not finished yet; stress releasing induced by the initial gaps between the bentonite blocks and pellets, and also the gaps between the sensors and the blocks could be another reason.

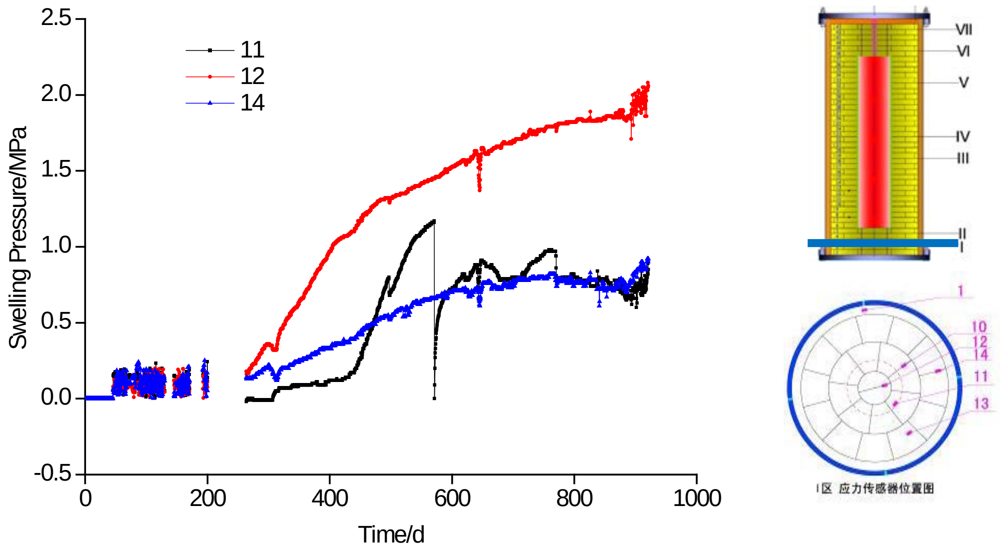

Figure 30 Variation of total pressure at the bottom of China-Mock-up.

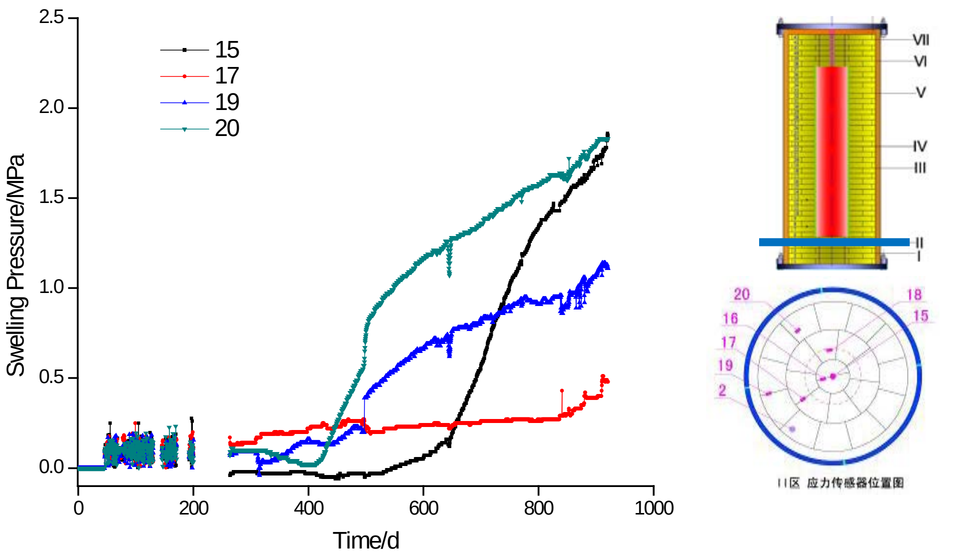

Figure 31 Total pressure evolution at section II.

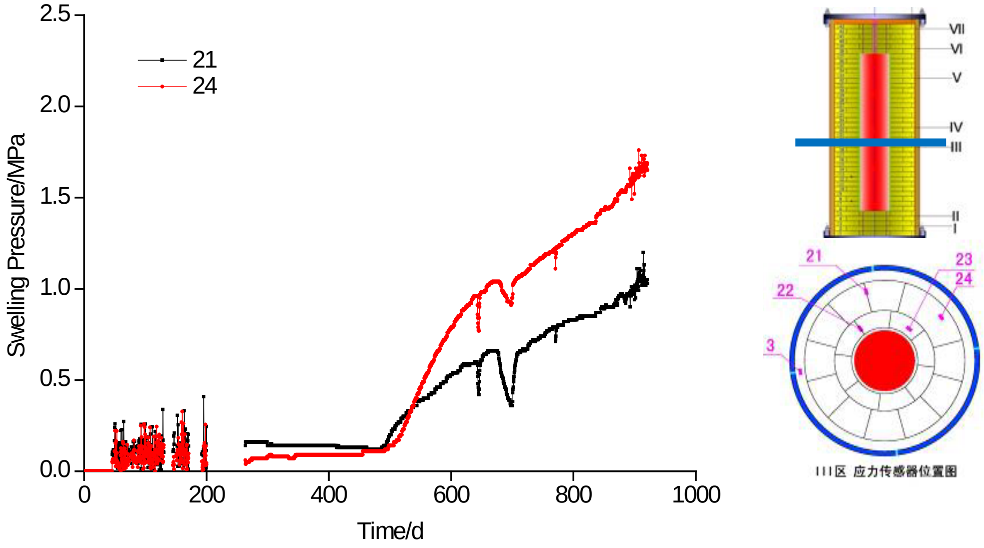

Figure 32 Total pressure evolution at section III.

3.8. Displacement of the heater

In order to investigate the potential movement of canister in long-term, six LVDT sensors are installed in the China-Mock-up test to monitor the vertical displacement of the electrical heater. Three of them are installed at the bottom of the heater, and the others are installed in the upper part. An upward displacement of the heater of 5mm is recorded, as shown in Fig. 33. This phenomenon can be explained by the thermal expansion and the inhomogeneous saturation process in vertical direction. As mentioned in section 3.5, the saturation process is mainly concentrated at the bottom of the facility. Consequently, the heater is pushed upward by the higher swelling pressure at the bottom. This result indicates that the saturation process of the buffer material may affect the stability of the canister, which should be considered in the design of the repository project.

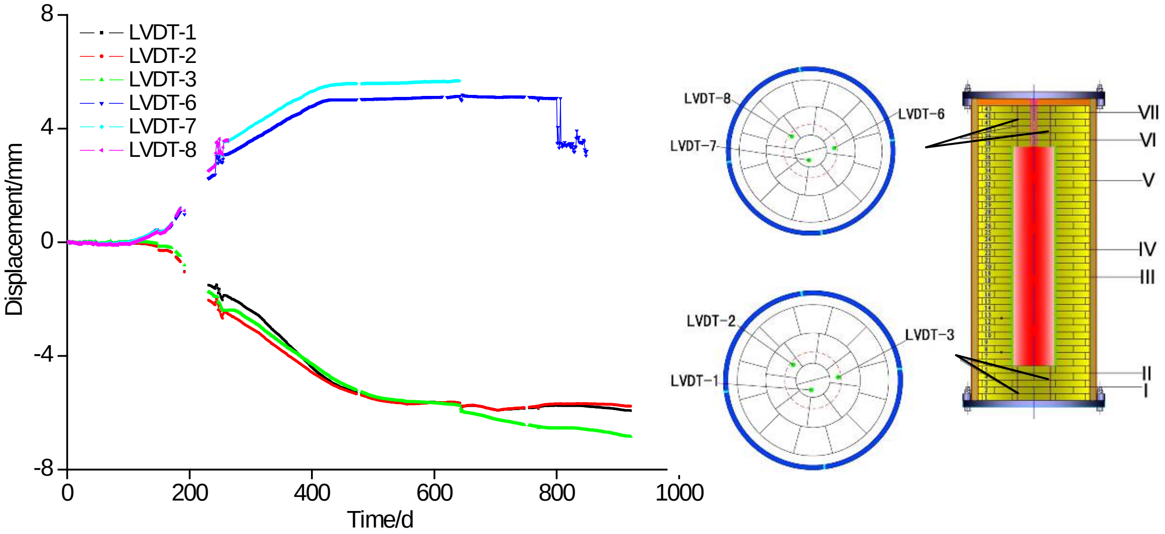

Figure 33 Vertical displacement of the heater with time.

4. Discussion and Conclusions

i) FEBEX Mock-up

The mock-up test was initially planned to last three years, but the reliability of all the test components (instruments, heaters and control systems) and high amount and quality of the data being generated persuaded us to prolong the operational phase to get as close as possible to the full saturation of the buffer.

This experiment allowed us to obtain knowledge about how to construct the different elements that constitute the test; how to control the conditions and to record the main parameters of the THM behavior within the barrier material; and how to analyze the long term safety evaluation of the clay barrier in the site. The validation and the calibration of the thermo-hydro-mechanic (THM) codes achieved with the experimental dataset fulfill the last requirement, in a performance assessment frame.

Fifty-five months after the start of the operational phase, it can be concluded that the synergy achieved from the simultaneous, integrated performance of tests on three scales within the FEBEX project: “in-situ”, “mock-up”, and complementary laboratory small scale tests, is a valuable approach for establishing the viability of the reference concept and making progress in the understanding and evaluation of behavior in the near field, especially the clay barrier.

4.1. Operational behavior of the experiment components

The mock-up test overpasses its design operative time, estimated in 3 years, functioning correctly and with most of the sensors still in operation.

The reliability of the instruments is fairly good. More than 85% of the sensors remain operative. However, it is not possible to guarantee their future behavior. The reliability and performance of the heaters and the power regulation systems are sufficiently high. The change in the functioning of the heaters (one resistance with filtered power supply) must extend their life expectancy and prevent them from any further damage. The data acquisition and control systems are working satisfactorily. No important damages can be attributed to the over-heating incident: the experiment seems to have worked like a thermal pulse test and remains operative. No variation is observed in the sensor functioning. The heating system has demonstrated its robustness. All the external sensors work correctly.

4.2. Conclusions on the measurement of THM parameters

After fifty-five months of mock-up test operation, some qualitative conclusions may be established in a preliminary way and some coupled processes have been clearly identified.

4.2.1. Temperature

The thermal regime is homogeneous and symmetric; both with respect to the central section and the longitudinal axis. Fluctuations of temperature are observed near the structure and are related to external variations.

The temperature distribution is controlled by thermal conduction, due to the slow rate transport processes involved in the saturation of the buffer material. Temperature calculation based on thermal conductivity, tuned by saturation of the material, produces good fittings to data (ENRESA, 2000). More complex models are not needed. A limited number of sensors are enough to display the temperature distribution and evolution.

4.2.2. Relative humidity

The RH sensors work well within the RH and temperature ranges of the test. This allows the monitoring of the hydration process during the time of this experiment. Both, water inflow and water vapor outflow, behave in a radial direction. The saturation of the bentonite barrier is apparently controlled by the hydraulic properties of the bentonite and the thermal gradient imposed by heating.

4.2.3. Total pressure

The total pressure measurement depends on the XYZ co-ordinates, the dry density of the block, the sensor installation, and/or the development and concentration of local stresses (due to the reactions between blocks). The pressure increases seem to be associated with the arrival of the hydration front. Measured values become stable as the buffer material saturates and the material reaction changes its structure. Values for the different directions (PR, PZ and PT) are converging in average values.

4.2.4. Fluid pressure

The values registered are so close to zero that they are greatly affected by the fluctuations of the external temperatures and the thermal waste due to natural convection on the structure. The fluid pressure measurements seem to be due to liquid in the external rings and to gas in the internal rings. It would be necessary to get enough free water (full saturation) within the inner rings of the buffer material to consider this pressure value as water pressure. Gas pressure depends on location and water pressure gives an average value.

4.3. Over-heating consequences

The thermal increase and the coupled processes generated by overheating compose an exceptional exercise to calibrate the numerical codes, because:

It has generated a vapor flow through saturated and non-saturated material. A homogeneous THM behavior of the system has been recorded with agreement between the RH and fluid pressure values. A radial redistribution of water in vapor phase within the bentonite seems to have occurred. The system recovering gives a good chance to compare actual values with models.

4.4. Implications for the performance assessment

The FEBEX mock-up test is being extremely useful to fit the main parameters of the clay behavior and the calibration of the numerical THM code, CODE-BRIGHT developed by UPC (ENRESA, 1998c), and the thermo-hydro-geochemical code, CORE-LE developed by UDC.

4.4.1. Code calibration

The homogeneous regimes established and the better knowledge of the boundary conditions facilitate the verification of the predictive capacity of the numerical codes developed for analysis of the behavior of the near field, as only the behavior of the clay barrier is considered. This verification is a necessary step prior to comparing the model results with the behavior under natural conditions as in the “in situ” test. Different parameters affect the development of the hydration, which seems to be extremely sensitive to them. Small variations in the system state (thermal or hydraulic) produce long term effects almost immediately (small decreases of temperature that modify the stress state and the hydration state). The stress distribution is not immediate and homogeneous, due to the low hydration velocity. The thermal pulse (overheating) and the coupled processes provide an opportunity to calibrate the numerical codes. Differences in the behavior between “hot” and “cold” zones of the buffer seem to indicate major implications of the thermal aspects in the transport processes.

4.4.2. Quality assurance

From the important variations in the development of total pressures, it can be concluded that a great homogeneity in the block compaction is necessary (from quality control); and to attain the theoretical minimum dry density required in the clay barrier (from a quality assurance program).

So, this mock-up test is a source of valuable data to improve the knowledge of the THM processes in the EBS, and to apply them to obtain reliable numerical codes to accomplish the performance assessment of a deep geological disposal.

ii) China-Mock-up

4.5. Conclusions of China-Mock-up

The buffer material is one of the main engineered barriers for the HLW repository. In order to study the behavior of the compacted GMZ-Na-bentonite under coupled THMC conditions, a large-scale mock-up facility, China-Mock-up based on a preliminary concept of HLW repository in China, has been designed and constructed in the laboratory of BRIUG.

The current experimental data is presented in the report, including the variation of temperature, relative humidity, stress and displacement etc. Except for the unexpected interruptions in power supply, the experiment facility has functioned correctly for 900 days after the start of the operational phase. It should be mentioned that, in order to avoid damage to the sensors by a rapid saturation process, constant liquid pressure is not applied immediately on the outer boundary, and the rate of water supply is limited in the initial stage. After the water injection, water may concentrate on the bottom due to the gravity effect, and the saturation process is vertically non-homogeneous which may cause difficulties to the definition of boundary condition in numerical studies. Considering that the saturation process of the pellets is almost finished and all the key sensors are working correctly up to now, it should be the right time to apply a constant pressure in the next step of testing. Based on the discussions of the currently recorded results, several preliminary conclusions can be drawn:

(1) Except for the temperature change induced by the interruption of electrical power supply, the temperature within the bentonite block has increased with time. Considering the limited hydration rate, the temperature variation appears mainly controlled by thermal conduction.

(2) The saturation process of the compacted bentonite is strongly influenced by the competitive mechanisms of the drying effect induced by the high temperature and the wetting effect by the water penetration. The fact that the bentonite has a very low permeability can make the arrival of water to the inner parts very slow, the drying effect is dominant, the desiccation phenomenon is observed at the beginning of the test, particularly in the zones close to the heater.

(3) The influence of the temperature change on RH variation is noticed. The RH fluctuations are generated by a complex mechanism, including the vapor generation, drying effect, and etc. These unexpected fluctuations can also be considered as a validation of the reliability and sensitivity of the sensors.

(4) Because of the low hydration rate and non-homogeneous saturation process in vertical direction, the stress variation is relatively limited and non-homogeneous. Moreover, for China-mock-up test the upward displacement of the heater suggests that the thermal expansion and saturation process of the buffer material may influence the stability of canister in the long-term, which should be considered in the design of the repository. To mention here, the displacement of canister is strongly influenced by the experimental configuration and boundary conditions. Moreover, considering the repository conception in China is not finished yet, the similar weight of the canister and electrical heater cannot be assumed.

Therefore, this result is not totally representative of the real ones, and further validation is still necessary.

(5) Based on the analysis of the current experimental data, the China-Mock-up test is considered as a source of valuable data to improve the knowledge of the THM process in the EBS, and to establish the reliable numerical method to predict the THM coupled behavior of EBS in long-term. With the progress of the experiment, the conclusions achieved will be further examined and refined.

The China-Mock-Up experiment is an important milestone of the buffer material study for HLW disposal in China. The observed THMC processes taking place in the compacted bentonite-buffer during the early phase of HLW disposal can provide a reliable database for numerical modeling and further investigations of EBS, and the design of HLW repository.

In this report, a comparison between FEBEX Mock-up and China-Mock-up test is presented. The basic THM properties of bentonite are first briefly summarized and then, the experimental infrastructure and operational process are introduced. The principal experimental data acquired are presented and analyzed, including the variation of temperature, relative humidity, displacement of the heater and the total stress evolution. The important difference is that the FEBEX Mock-up is KBS-3H reference concept and the China-Mock-up is KBS-3V reference concept. The large scale Mock-up test is valuable in developing a good understanding of the behavior of the buffer material under THM coupled condition, and demonstrating the technical feasibility of the disposal concept.

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