THE SURFACE MOCK-UP KENTEX: ON THE THERMAL-HYDRO-MECHANICAL BEHAVIORS IN THE BUFFER OF A KOREAN HLW REPOSITORY

Authors: Jae Owan LEE, Won Jin CHO, and Jong Won CHOI
KAERI (Korea Atomic Energy Research Institute)

Abstract

The disposal concept of a reference HLW repository in Korea was established in 2002. A surface mock-up KENTEX has been carried out to investigate the thermal-hydro-mechanical behaviour in a buffer. The KENTEX facility was designed to be an intermediate-scale of the reference repository, and has been under successful operation to date. As preliminary experimental results from the KENTEX, the temperature in the bentonite blocks reached a steady state in a short time and increased as the heater was approached; the water content is higher close to the hydration surface than in the heater part; the total pressure continuously increased by the evolution of the saturation front in the bentonite blocks and thereby the swelling pressure. The measured temperature and water content distributions were analyzed using a computer code TOUGH2. The calculated results agreed well with the measured ones, which suggests that the coupled thermal and hydro behaviours in the bentonite blocks may be simulated accurately enough with the code TOUGH2.

1 Introduction

The concept for a disposal of high-level wastes (HLW) in Korea is based upon a multi barrier system composed of engineered barriers and its surrounding plutonic rock (Kang et. al., 2002). A repository would be constructed in bedrock several hundred meters below the ground surface. The engineered barrier system (EBS), which is similar to a configuration considered by other countries, consists of a HLW-encapsulting disposal container, a buffer between the container and the wall of a borehole, and backfill in the inside space of the emplacement room, to isolate the HLW from the surrounding rock masses. **Figure 1** shows a schematic picture of the Korean reference disposal system (KRS) and its engineered barrier system.

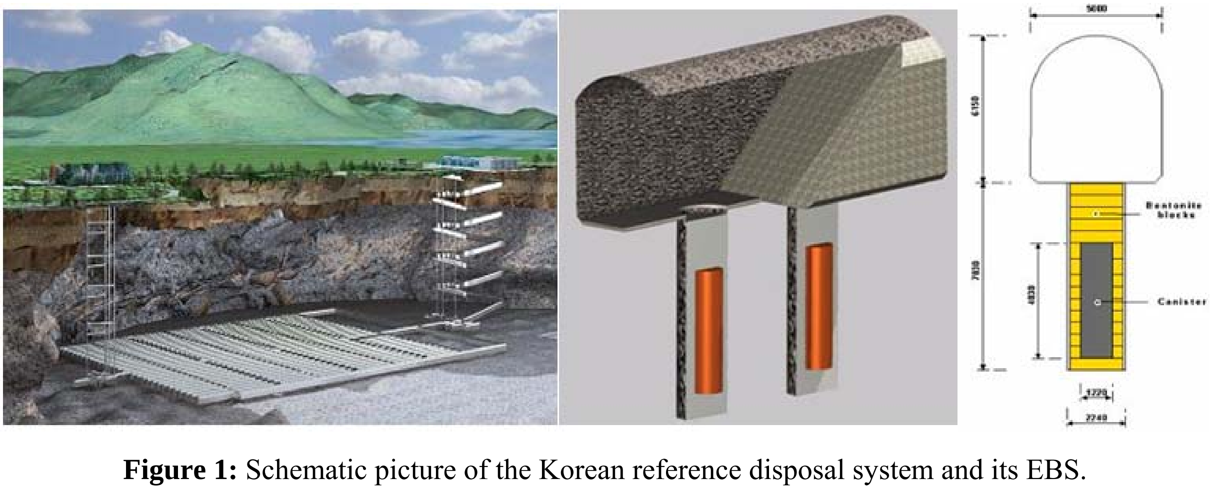


Figure 1: Schematic picture of the Korean reference disposal system and its EBS.

The engineering performance of a HLW repository may be significantly affected by the thermal-hydro-mechanical (THM) behaviours in a buffer which are complicated by the radioactive decay heat from a HLW, the infiltration of ground water from the surrounding host rock, the thermal loading and the swelling pressure of a buffer, and the stress generated by overburden pressures. Therefore, it is of considerable importance in the prediction of a repository performance and thus the evaluation of its long-term safety to investigate the THM behaviours in the buffer of a HLW repository.

The Korea Atomic Energy Research Institute (KAERI), for this reason, to investigate the THM behaviors in the buffer of the KRS, planned large-scale tests to be conducted in two stages: a mock-up test and then a full-scale "in situ" test. This paper introduces the surface mock-up KENTEX and presents the preliminary experimental results and their thermal-hydro analysis using a computer code TOUGH2.

2 Surface Mock-Up KENTEX

The mock-up KENTEX (KAERI Engineering-scale T-H-M Experiment for an Engineered Barrier System) was designed to be an intermediate-scale test of the reference disposal system (**Figure 2**). It includes five major components: a heating system, a confining cylinder, a hydration tank, bentonite blocks, and sensors and instruments. The heating system simulates the heat generated from a high level fuel waste (e.g., PWR or CANDU spent fuel) and then its release through a disposal container. The heater is 0.41 m in diameter and 0.68 m in length and includes three heating elements in its inside, capable of supplying a thermal power of 1 kW each. The confining cylinder simulates the wall of a borehole excavated in the host rock. It is a steel body with a length of 1.36 m and an inner diameter of 0.75 m, the inside wall is lined with layers of geotextile and the outside wall of which is mounted with 24 nozzles with two metal filters inserted into the inside of each, to uniformly apply the groundwater to the outer surface of the bentonite blocks (i.e., hydration surface). The bentonite blocks are fabricated from “Kyungju” bentonite (Lee et al., 2004) which is being considered as a candidate buffer of the KRS. Total of 176 blocks are emplaced in 16 sections of the confining cylinder. The bentonite blocks have an average gravimetric water content of 13 % and the average dry density of the bentonite blocks in the confining cylinder is 1,500 kg/m^3. The sensors used for the KENTEX are a total of sixty eight, which are installed within the test facility to measure the following variables: temperature, humidity (eventually, water content), and total pressure. And the heater control and data acquisition are operated automatically by means of a computer program.

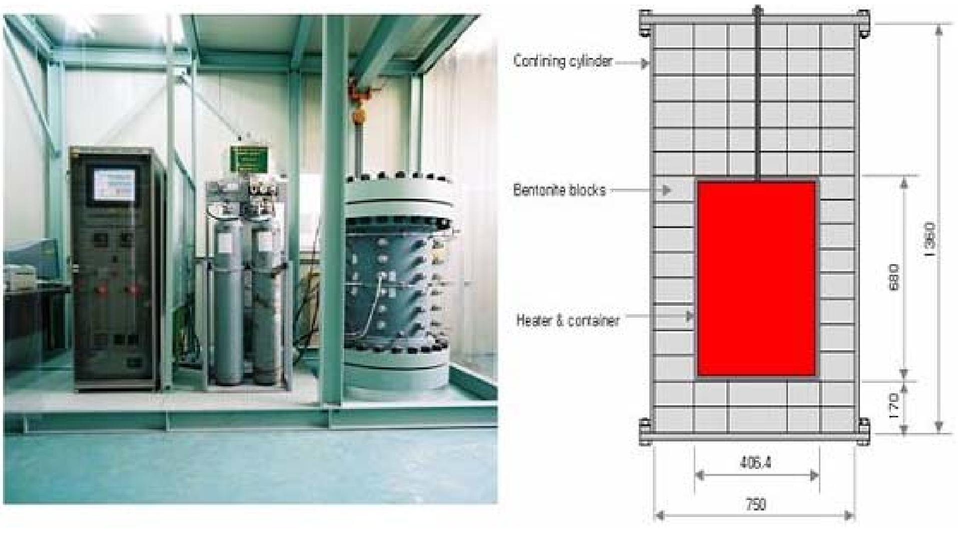


Figure 2: Picture and schematic diagram of the "KENTEX" facility.

The operation of the KENTEX facility includes a heating and hydration, which are done in such a manner as to obtain the initial and stable boundary conditions and to eliminate possible heterogeneities. For accomplishing this, initial heating to 90℃ at the interface of a heater and bentonite blocks is done by a stepwise heating to reduce the risk of damaging the heating elements. Once 90℃ is reached, the temperature is automatically regulated by a computer program, to maintain a constant temperature of 90℃ at the heater/bentonite blocks interface. An initial hydration is undertaken to eliminate the air existing between the blocks and between these and the confining structure. This is done to eliminate or reduce the discontinuities due to the configuration of the bentonite blocks, and to obtain a gradual and radial hydration towards the heating system. The first step is to fill the hydration piping and rings which is followed by the confining cylinder, using the upper valves. When the water reaches the upper valves, the lower valves and the valve connecting the tank to the distribution network are closed. The system is then left for 2 days to allow the injected water to induce a swelling of the bentonite blocks and consequently a closing of the joints. The actual hydration and heating (operational stage) begin following the two-day equilibrium period. The temperature at the heater/bentonite blocks interface is controlled at 90℃ and the injection pressure of the water is a constant 5 bars throughout the entire operational stage. The room temperature is maintained as 25℃, providing a fixed outer boundary condition.

3 Operation and Experimental Results

The KENTEX has successfully operated since its start except for brief heater generation interruptions and repairs to the heater-controlling system. The performance of the heater and its controlling system are good. The power was rapidly increased until the temperature at the heater/bentonite blocks interface reached 90℃, and then it has been operated at about 160±10 W keeping the temperature at 90℃. The performance and reliability of the installed sensors and instruments have been good excepting for the humidity sensors. More than 99% of the temperature and total pressure sensors remain in operation. Only one humidity sensor is still operative and the rest have malfunctioned. The malfunctioning humidity sensors experienced strong fluctuations in the humidity readings from the time of an initial hydration. This is attributed to the applied water through the joint voids between the bentonite blocks or between the bentonite block and the sensor, thus flooding the sensor tips and inducing a sensor malfunction. The lack of hydro data due to the failure of the humidity sensors will be compensated for through a core sampling (drilling) method.

The temperature data acquired were relatively stable and uniform. **Figure 3** is a typical representation of the temperature distributions in the bentonite blocks measured using thermocouples for the first 350 days. The temperature distribution had a similar trend regardless of the position of the thermocouples.

It rapidly reached a quasi-steady state within a few weeks and, after that period, increased slowly toward a constant value. The closer it was to the wall (i.e., hydration surface) of a confining cylinder, the shorter the time was for the temperature to reach a steady state. This is probably due to an increase in the thermal conductivity at the groundwater-wetted part. At a certain height, there is a negligible difference between the temperature values of the two positions at the same radial distance. It is indicated that the temperature distribution along the longitudinal axis is symmetric. **Figure 4** is a typical example of the temperature distributions as a function of the longitudinal height. The temperature values at a radial distance of 0.246 m, which ranged between 65℃ and 33℃, were in the following sequence of their magnitude: middle part including a heater > lower part > upper part. This sequence remained irrespective of the time after the temperature reached a steady state.

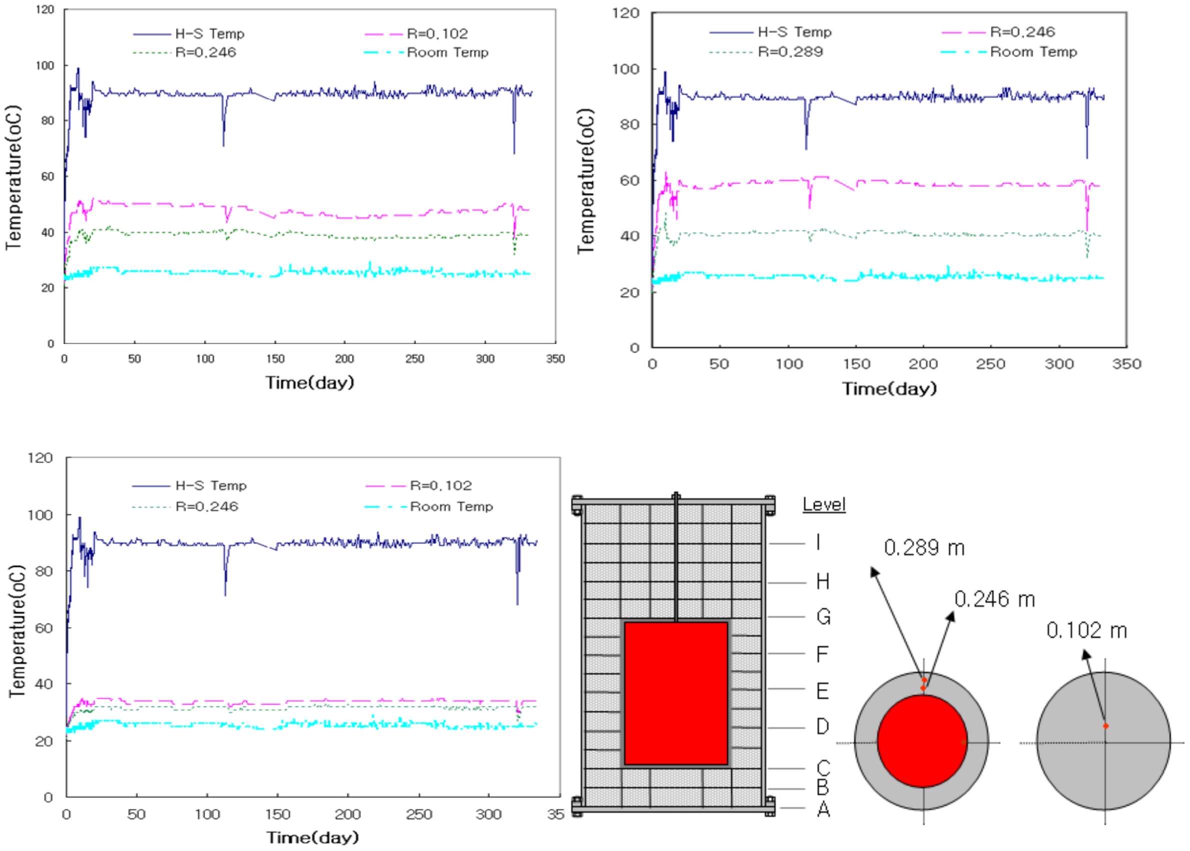


Figure 3. Temperature distributions in the bentonite blocks at various levels.
Top left: Level = B (0.085 m). Top right: Level = F (0.680 m).
Lower left: Level = H (1.190 m). Lower right: Location of the sensor

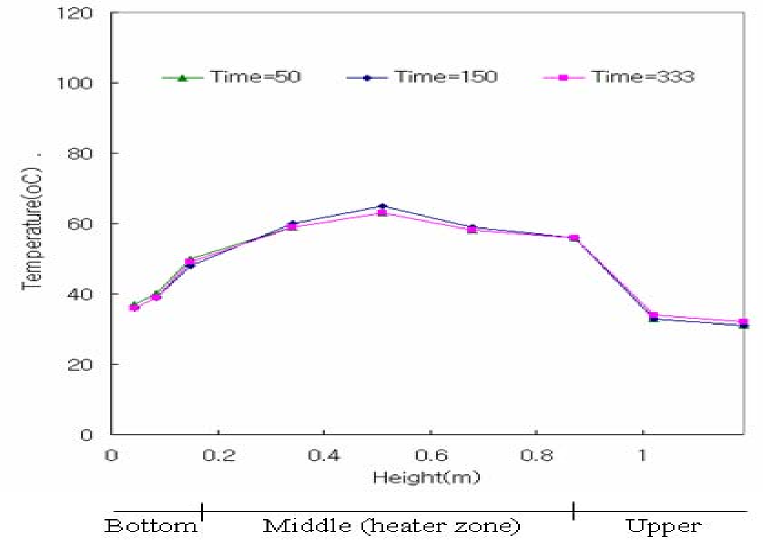


Figure 4: Temperature distributions as a function of longitudinal height at a radial distance = 0.246 m.

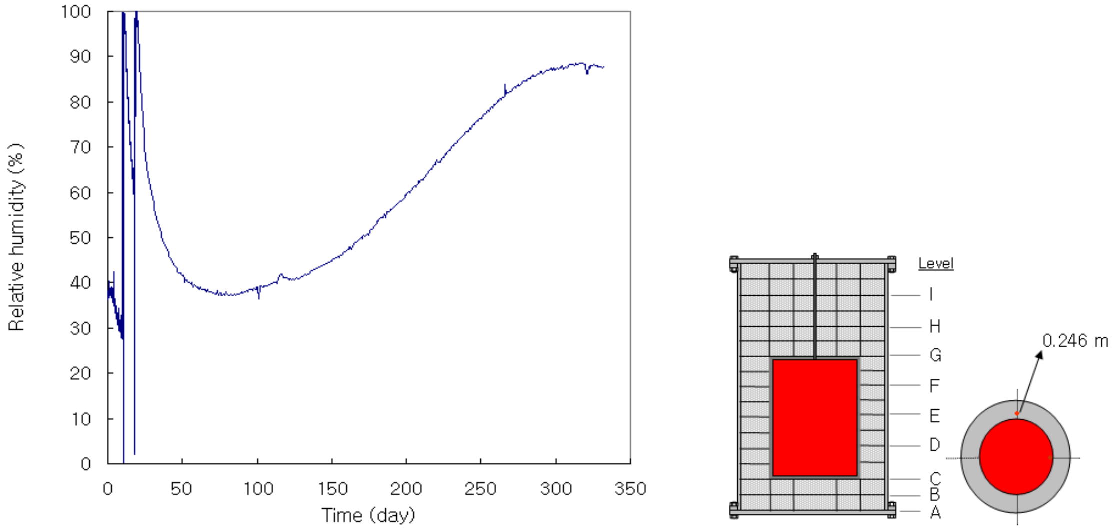


Figure 5: Evolution of the relative humidity acquired from a humidity sensor at a Level = D (0.34 m) and a radial distance = 0.246 m.

The humidity distribution is shown in **Figure 5**, which presents the output of the only-working humidity sensor (placed at a height of 0.34 m and a radial distance of 0.246 m). At this point, the humidity sharply increased during an initial hydration, and then it decreased followed by a gradual increase as time passed. This behaviour is explained as follows: first, the water intruded rapidly through crevices between the bentonite blocks and/or bentonite block and a sensor or its cable (which may be a preferential path for a water inflow), abruptly wetting the blocks; secondly, the wetted blocks desiccated as the water moved outwards due to a thermal gradient, leading to a decrease in the humidity; and thirdly, after the hydration overcame the drying process, the blocks were wetted again by the gradual inflow of water from the hydration surface. This study, as mentioned above, employed a core-drilling method to obtain the water contents in the bentonite blocks at 350 days, in order to supply the water content data lacking due to the humidity sensor failures. **Figure 6** represents the water content distributions ((a) a height of 0.61 m, and (b) a height of 1.03 m) determined by using a core sampling method. The water contents close to the hydration surface were higher than those in the heater part, and they approached a saturation value (ω =31.4%) beyond a point of about 0.32 m apart from the heater. In this figure, the abnormally high values of the water content near the hydration surface appears to be experimental errors which resulted from the inflow of water into the geotextile placed between the bentonite blocks and the wall of the cylinder during the core sampling.

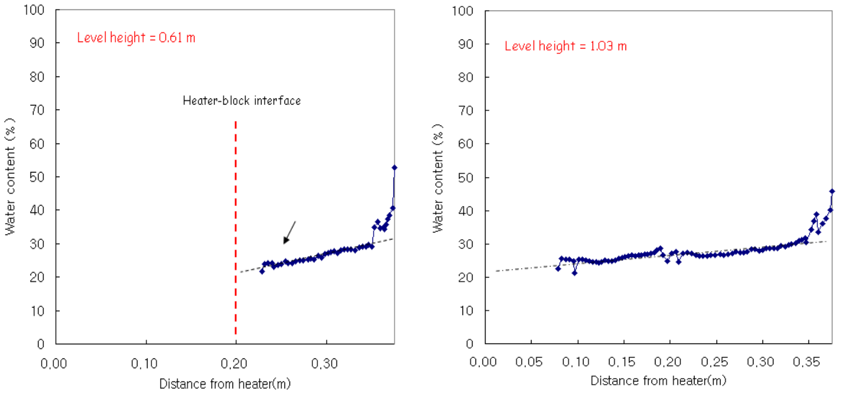


Figure 6: Water content distribution of the core-drilled samples as a function of the radial distance after 350 days.

The pressure data acquired from the pressure cells was stable and uniform, and they ranged from -0.8 to 16 bars. **Figure 7** represents a typical example of the total pressure distributions in the bentonite blocks. The pressure distributions, as shown in this figure, reveal a general trend where there is a gradual increase in the pressure values as time passes and the values near the hydration surface are higher than those at the heater side, which is probably attributed to the build-up of the swelling pressure caused by the evolution of the saturation front from the hydration surface. However, it can be seen at an initial stage of the operation below about 100 days that they had different patterns depending on the location of the pressure measurement. The total pressure distribution at a point close to the hydration surface immediately increased when the bentonite blocks were contacted with the water (**Figure 7(a)**), while that at points farther apart from the hydration surface followed an initial period during which there was a little positive reading (**Figures 7(b)** and **7(c)**) due to the thermal expansion of the bentonite blocks near the heater and then continuously increased as the bentonite blocks were saturated with the intruding water. For all the total pressures, the two peaks at the early stage seem to be a system-intrinsic behaviour, occurring by the water in-flowing rapidly through the crevices between the bentonite blocks and/or bentonite block and the sensor or sensor cable at the start of the test. There is no significant variation in the pressure values of the two points with the same radial distance, indicating that the pressure distribution is symmetric for the longitudinal axis.

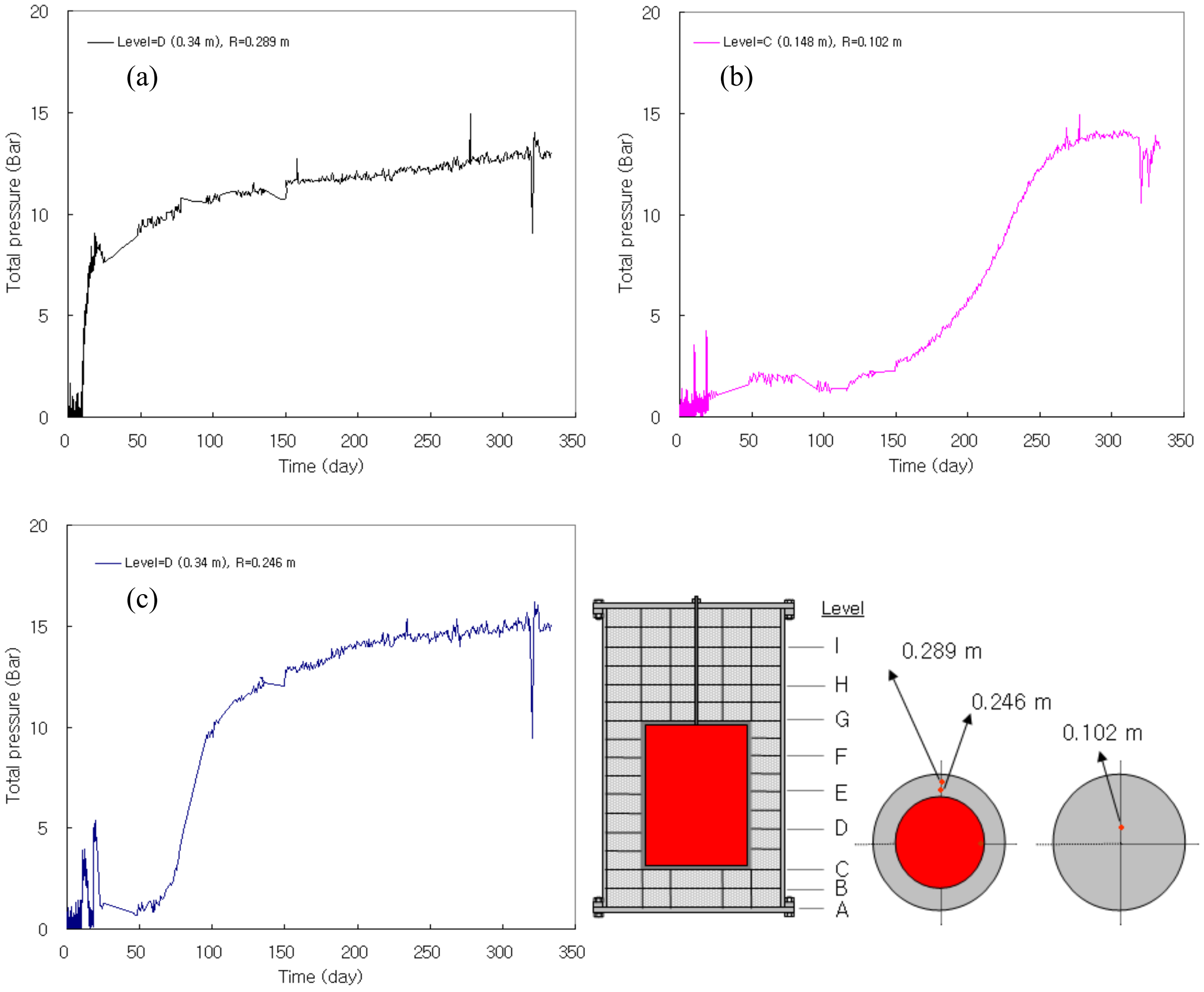


Figure 7: Total pressure distributions in the bentonite blocks at various measurement points.

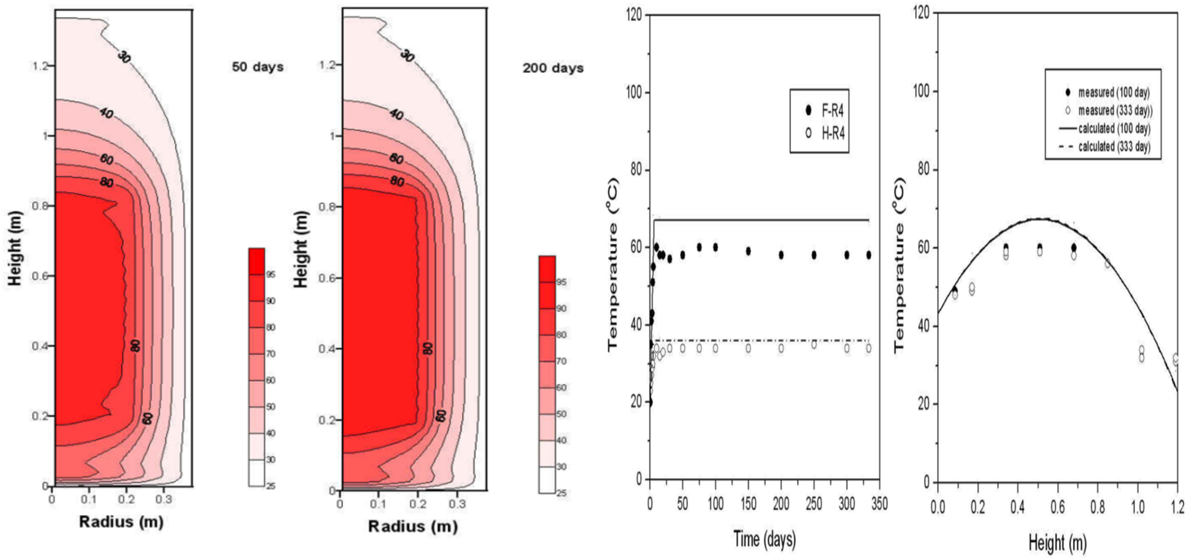
4 Hydro-Mechanical Modeling Using a Code TOUGH2

The experimental results on the water content and temperature distributions were analyzed using a computer code TOUGH2 (Pruess at al., 1990). The TOUGH2 code is a general-purpose numerical simulation program for a multi-dimensional fluid and heat flows of a multiphase, multi component fluid mixture in an unsaturated medium. A space discretization is made directly from the integral form of the basic conservation equation using the Integral Finite Difference method. Time is discretized fully implicitly as a first order backward finite difference. The thermo-physical properties of the fluid mixture needed for assembling the governing mass and energy balance equations are provided by the "equation-of-state" (EOS) modules, and EOS4 was used in this simulation. The detailed geometry of the KENTEX was modelled in a two-dimensional, radially-symmetric mesh, and the radial direction was divided into two zones. The first zone ($0 \le r \le 0.204$ m) was discretized into a constant step size equal to 0.017 m. In the second zone ($0.204 < r \le 0.375$), the step size was decreased to 0.0057 m. The axial direction was discretized into a constant step size equal to 0.0425 m. The bentonite blocks were initially at a gravimetric water content of 13%, a temperature of 25℃, and a pressure of 1.0 bar. A time-dependant heat output of the electric heater was applied to maintain the temperature at the interface of a cylindrical heater and the bentonite buffer at 90℃. The Grant curve (Grant 1977) was used to describe the two-phase relative permeability of the buffer material. The capillary pressure (P_c) of the buffer material was calculated by using the van Genuchten function (Van Genuchten, 1980). A summary of the thermal and hydro properties used for the calculation is given in **Table 1**. Along the water injection wall of the confining cylinder, a constant temperature (25℃), water pressure (5 bars) and saturated condition were assumed for the outer boundary. The top and bottom surfaces of the model were also maintained at a constant pressure (1 bar) and temperature (25℃).

Table 1: Summary of the material properties for the simulation of KENTEX.

Parameter	Value
Buffer	
> density (Kg/m^3)	2700 (grain)
> porosity	0.44
> absolute permeability (m^2)	6×10^{-20}
> specific heat (J/kg□)	980.0
> pore compressibility (Pa^{-1})	1.0×10^{-8}
> pore expansivity (1/□)	1.0×10^{-4}
Heater	
> density (Kg/m^3)	4600
> porosity	0.20
> specific heat (J/kg□)	590.0
> pore compressibility (Pa^{-1})	0.00
> pore expansivity (1/□)	3.5×10^{-5}
Parameters in the van Genuchten function	
> α	2.5493×10^{-3}
> n	1.4166

The calculated temperature contours throughout the bentonite blocks after 50 and 200 days are shown in **Figure 8(a)**. A typical comparison of the calculated time-dependent temperature profiles along the axis of the bentonite blocks with the measured ones from the KENTEX experiment at two locations is shown in **Figures 8(b)** and **8(c)**. On the whole, the computational predictions closely follow the temperature distribution patterns observed in the experiment. From the figures, it is found that the temperatures almost approach a steady state in a few weeks. At a height level of 0.81 m (H-R4), the calculated temperature values agree well with the measured ones. However at a level of 0.61 m (F-R4) which is the central plane of the heater, the calculated values are a little higher than the measured values. Discrepancies of approximately 7℃ are observed. This may be explained as follows. In the calculation, it was assumed that the water migrated through a homogeneous bentonite medium without fracture from start of the operation; Under the experimental condition, however, the water penetrated through the crevices among the bentonite blocks and/or the bentonite blocks and sensors at the early stage of an operation, and as time passed, the bentonite blocks swelled to seal the crevices. The water content in the bentonite blocks, thereby, may be higher than the calculated one (Refer to **Figure 9(b)** and 9(c)). The thermal conductivity of the bentonite blocks increased with an increasing water content, resulting in a decrease of the temperature. However the trends indicate that the calculated values are generally consistent with the experimental data. The longitudinal distributions of the temperature at a radial distance of 0.246 m were calculated and compared with the measured ones (**Figure 8(c)**). The results show that both agree with each other reasonably well.

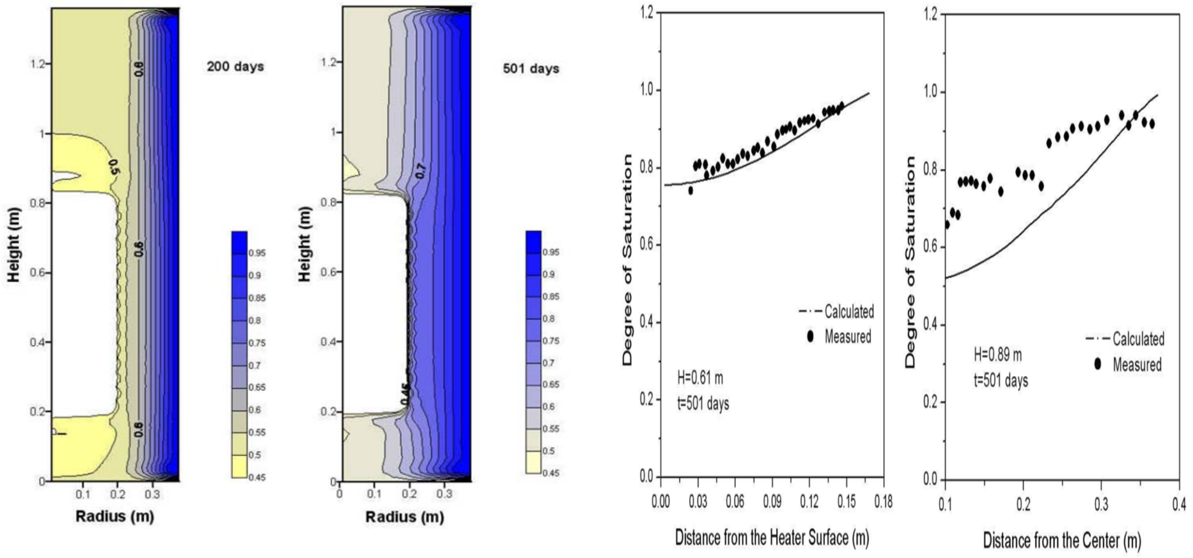


(a) (b) (c)

Figure 8: Calculated temperature contours and comparison of calculated and measured results of temperature distributions.

The same procedure is used to obtain the time-dependent variation in the water content. The water distribution in the bentonite blocks is expressed by the degree of saturation defined as a ratio of the water content and the saturated water content. The calculated ‘degree of saturation’ contours after 200 and 501 days are shown **Figure 9(a).** A comparison of the calculated degree of saturation distributions with the measured ones from the core drilling at a height of 0.61 m and 0.89 m after 501 days is shown in **Figures 9(b)** and **9(c)**. As shown in these figures, the measured degree of saturation is higher than the calculated one. This is caused by the water penetration through the crevices among the bentonite blocks at the early stage of an operation, and the larger discrepancy at the height of 0.89 m may be due to the possible contamination of the bentonite core by the water near the side wall of the confining cylinder during the core drilling. However in general the calculated water distribution values agree reasonably well with the measured ones.

These results show that the temperatures throughout the bentonite blocks rapidly reached a steady state, while the water distributions underwent a slow change. It may be explained by the fact that the heat propagates faster than the water. For the total region of the bentonite blocks, the calculated values of the temperature and the degree of saturation are in a good agreement with the measured values. These results indicate that the T-H coupled process in the KENTEX can be simulated reasonably well with the TOUGH2 code, and provides some confidence in the capacity of TOUGH2 to correctly describe the main mechanism that governs the water and heat flows in an unsaturated bentonite buffer.



(a)

(b)

(c)

Figure 9: Calculated water distribution contours and comparison of calculated and measured results of water content distributions.

5 Conclusions

The surface mock-up KENTEX has been operated successfully to date. The current T-H-M behaviour in the bentonite blocks allows us to draw preliminary and qualitative conclusions. The temperature reached a steady state in a short time after the test started. The temperature increased as the heater was approached. The water content is higher close to the hydration surface than in the heater part. The relative humidity data suggests that a hydration of the bentonite blocks may occur by different drying-wetting processes depending on their position. The total pressure was increased continuously by the evolution of the saturation front in the bentonite blocks and thereby the swelling pressure. There was also a contribution of the thermal expansion of the bentonite blocks near the heater. The calculated temperature and water content distributions from the computer code TOUGH2 were compared with the measured ones from the experiment. Both the calculated results and measured ones agree well with each other, which suggests that the coupled thermal and hydraulic process in the bentonite blocks can be simulated reasonably well with the TOUGH2 code.

Acknowledgement

This work has been performed under the Nuclear R&D Program by the Ministry of Science and Technology.

References:

Grant, M.A., 1977. Permeability Reducing Factors at Wairakei, paper 77-HT-52. AICHE-ASME Heat Transfer Conference, Salt Lake City, Utah.

Kang, C. H., Kim, J. W., Chun, K. S., Park, J. H., Cho, W. J., Choi, J. W., Lee, J. W., and Lee, Y. M., 2002. High level radwaste disposal technology development / Geological disposal system development. KAERI/RR-2336/2002, Korea Atomic Energy Research Institute.

Lee, J.O., Cho, W.J., and Hahn, P.S., 2004. Hydraulic-thermal-mechanical properties and radionuclide release-retarding capacity of Kyungju bentonite. J. of the Korean Radioactive Waste Soc., Vol.2(2), pp. 87-96.

Pruess, K., Oldenburg, C. and Moridis, G., 1990. TOUGH2 User's Guide, Version 2.0. LBNL-43134, Lawrence Berkeley National Laboratory.

Van Genuchten, M. Th., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J., 44, 892.