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[Technical Paper]

Engineering-scale Validation Test for the T-H-M Behaviors of a HLW Disposal System

고준위폐기물 처분시스템의 열적-수리적-역학적 거동 규명을 위한 공학적 규모의 실증시험

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Abstract

The engineering performance of a high level waste repository is significantly dependent upon the T-H-M behavior in the engineered barrier system. An engineering-scale test facility (KENTEX) was set up to validate the T-H-M behaviors in the buffer of a reference disposal system developed in the 2002. The validation tests started on May 31, 2005 and is now in progress. The KENTEX facility and validation test programme are introduced, and pre-operation calculations are also presented to give information on the sensitive location of sensors and operational conditions . This test will provide information (e.g., large-scale apparatus, sensors, monitoring system etc.) needed for "in-situ" tests, make the validation of a T-H-M model for the T-H-M performance assessment of the reference disposal system, and demonstrate the engineering feasibility of fabricating and emplacing the buffer of a repository.

Key words: HLW disposal system, buffer, T-H-M behavior, validation test

요 약

고준위폐기물처분장의 공학적 성능은 공학적 방벽의 열적-수리적-역학적 거동에 의해 크게 좌우된다. 2002년에 제안된 기준처분시스템 완충재의 열적-수리적-역학적 거동 실증을 위해서, 엔지니어링 규모의 실증장치인 KENTEX를 제작설치 하였다. 이 실증실험은 2005년 5월 31일에

시작하여 현재 진행 중에 있다. 본 논문에서는 운전 중인 KENTEX시설과 이 시설에서 수행 중인 실험 및 향후 연구내용을 소개하고, 또한 센서 설치 및 운전조건 결정을 위해 수행한 운전 전 T-H-M 모델 계산결과도 기술하였다. 한국형 기준처분시스템의 실증연구와 관련하여, KENTEX 실증실험은 향후 추진될 지하시험시설에서의 현장시험에 필요한 자료와 경험을 제공하고, 기준처분시스템의 열적-수리적-역학적 거동특성과 평가모델을 검증할 것이다. 실험적으로는 처분장 완충재로 사용되는 벤토나이트 블록의 제작 및 설치에 대한엔지니어링 타당성을 보여 주는데 유용하게 활용될 것이다.

중심단어: 고준위폐기물처분시스템, 완충재, 열적-수리적-역학적 거동, 실증시험

I. Introduction

A high level waste (HLW) repository involves complex disposal conditions due to the radioactive decay heat from spent fuels, the infiltration of ground water from the surrounding rock, the thermal loading and the swelling pressure of the buffer, and the stress generated by overburden pressures. These disposal conditions complicates the thermal-hydro-mechanical (T-H-M) behaviors in the engineered barrier system (EBS) because the processes are not independent but may be strongly influenced by and coupled by with each other. Therefore, it is a very important part of the engineering performance of a HLW repository to investigate the coupled T-H-M behaviors in the EBS and to model them physically and numerically.

Many countries [1-6] have done engineering-scale and/or in-situ tests to investigate the coupled T-H-M phenomena in the more realistic disposal system of a HLW repository. As engineering-scale tests are conducted the Thermal Performance Test (Ontario Hydro, Canada), the BIG-BEN and COUPLE (PNC, Japan), the Mock-Up Test (CIEMAT, Spain), the Buffer Mass Test (SKB, Sweden), and the Bacchus Backfill Experiment (Mol, Begium), and as in-situ tests the Buffer/ Container Experiment (Whiteshell URL, Canada), the T-H-M Experiment (Kamaishi mine, Japan), the FEBEX (GTS, Spain), the Long-term Test of Buffer (Aspo Hard Rock Lab., Sweden), and the Tuff Water Migration/ Heater Experiment (YMP, USA). However, these tests did not result in the fully understanding of the coupled T-H-M behaviors in the EBS. The validation tests still have been conducting in those countries.

The Korea Atomic Energy Research Institute (KAERI) developed a reference disposal system for a HLW repository in 2002 and, to investigate the coupled T-H-M behavior in an engineered barrier system of the reference disposal system, planned the two stages of validation tests: an engineering-scale test and then full-scale "in situ" test.

This paper presents the KENTEX facility which is for engineering-scale T-H-M validation tests in the buffer of the reference disposal system, together with test programme. The results of its pre-operational calculation are also presented to provide information on the sensor locations and operational conditions.

II. HLW Disposal System

The concept of a Korean High Level Waste (HLW) repository, which is constructed in bedrock of several hundred meters in depth below the ground surface, is based upon a multi barrier system composed of engineered barriers and the surrounding plutonic rock [7, 8]. A reference disposal system [9] developed by KAERI in the year 2002 is as shown in Figure 1. The reference disposal system includes the disposal area, the serve shaft complex, and the ventilation exhaust shaft complex. The disposal area in which CANDU wastes are emplaced separately from the PWR wastes consists of 8 disposal panels. Based on 40m emplacement tunnel spacing, each panel for PWR consists normally of 42 emplacement tunnels. The CANDU panel, located at the lower left, consists of 38 emplacement tunnels. Each emplacement tunnel is 250 m long. In each emplacement tunnel the borehole spacing is allowed to be 6m for PWR and 3m for CANDU, to ensure neither the maximum container surface temperature nor the maximum buffer temperature of 100 ℃.

The Engineered Barrier System (EBS) in the reference disposal system includes wastes, disposal containers, buffer/backfill, and a concrete plug. The HLWs are encapsulated in disposal containers, which are deposited into boreholes on the floor of the emplacement rooms. The gap between the container and the wall of a borehole is then filled with a buffer material and the inside space of the emplacement rooms with a backfill material. In the Figure 1(b) is specified the dimension of the components of the EBS.

III. Validation Test Facility

1. Design Concept

The validation test in this study was focused on investigating the T-H-M behaviors in the buffer of a HLW repository. The test facility was designed to be a third scale of the reference disposal system. In order to simulate the disposal conditions in the reference disposal system, it included five major components: a heating system, a confining cylinder, a hydration tank, bentonite blocks, and sensors and instruments. The heating system was fabricated to simulate the heat generated from a high level waste (e.g., PWR or CANDU spent fuel) and then released through a disposal container. The confining cylinder plays a role of the wall of a borehole excavated in the host rock. The hydration tank is for the supply of ground water flowing in around the borehole. The bentonite blocks were fabricated to have the same

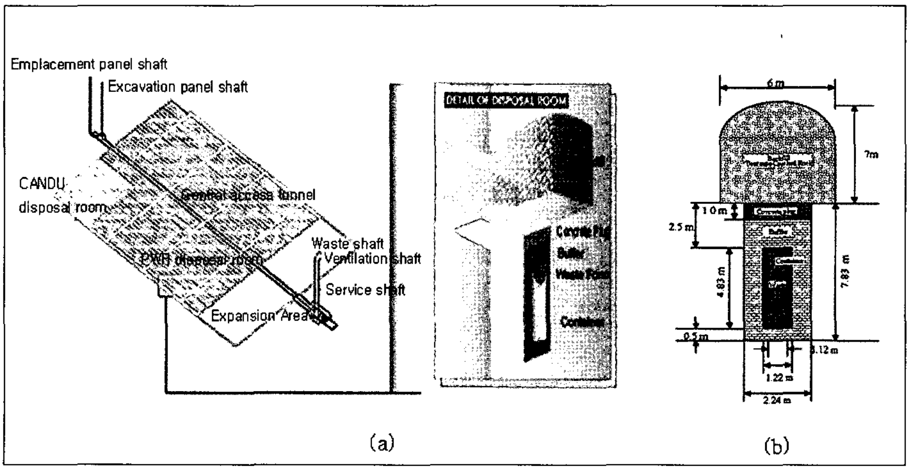


Figure 1. Schematic picture of a reference disposal system developed in 2002.

specification as those to be used for the buffer of the reference disposal system. And several kinds of sensors were installed to monitor the facility and measure the data of thermal-hydro-mechanical behaviors in the bentonite blocks. The validation test facility for this study is called "KENTEX" facility, which is the abbreviation of "KAERI Engineering-scale T-H-M Experiment for Engineered Barrier System".

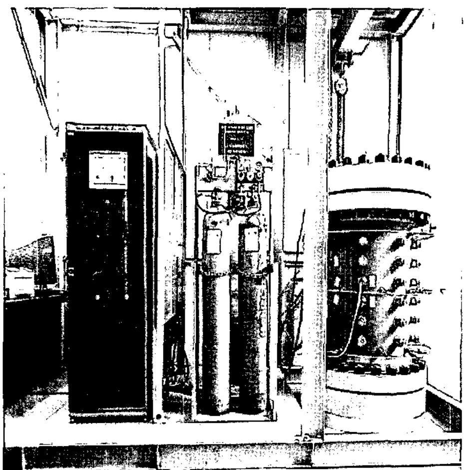
2. KENTEX Components

In the Figure 2 are shown a picture and a schematic diagram of the "KENTEX" facility which consists of major five components: a confining cylinder, a hydration tank, bentonite blocks, a heating system, and sensors and instruments.

As shown in the figure, the confining cylinder is a steel body with a length of 1.36 m and an inner diameter of 0.75 m. It was made of carbon steel with an interior cladding of stainless steel. The cylindrical surface of the confining cylinder was perforated in 72 points; 24 for water injection and 48 for the exit of sensor cables. In the upper end cover there is an exit for the power and temperature sensor cables from the heating system.

The hydration system consists of a water tank of approximately 0.46 ㎥ and pipes which are connected to 24 nozzles in the confining cylinder. The tank was located as close as possible to the confining cylinder, to reduce the dead volume of the system. To uniformly apply the groundwater to the surface of the bentonite blocks, each nozzle was inserted with two metal filters and the confining cylinder is lined with various layers of geotextile.

The bentonite blocks were fabricated of the bentonite which is taken from Jinmyeong mine located in Kyungju, Kyungsangbuk-do. The bentonite was prepared after its raw material is dried below 110 ℃, pulverized, and passed through No. 200 of ASTM (American Society for Testing and Materials) standard sieves. The fabricated blocks have average value of 13 % of water content and 1600 kg/㎥ of average target dry density. There are 176 blocks emplaced in 16 sections. The shape, dimension, and number of the bentonite blocks of three types are shown in Figure 3.



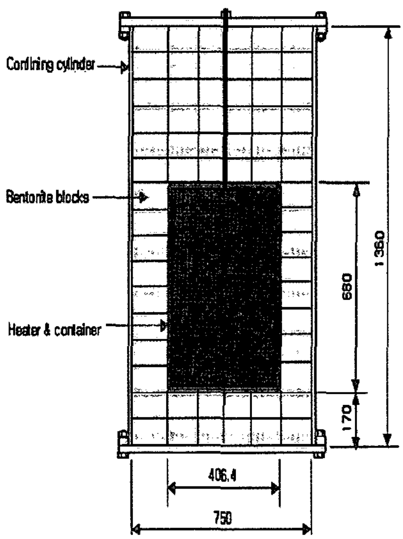
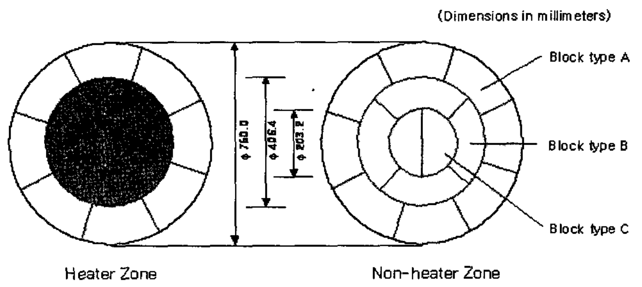


Figure 2. Picture and a schematic diagram of the "KENTEX" facility.



Block type	Radius mm		Angle in degrees α	Dimensions mm			Thickness mm	Number of blocks(*)
	R	r		a	b	c		
A	375.0	203.2	45	287.4	155.5	172.3	85	128
B	203.2	101.6	90	287.4	143.7	101.6	85	32
C	101.6		180	203.2	203.2	0	85	16

Figure 3. Specification of bentonite blocks used for KENTEX test.

The heating system measures 0.41 m in diameter and 0.68 m in length. It has three heating elements in its inside which are capable of supplying a thermal power of 1000 W each, i.e., a total power of 3000 W. It was placed concentrically in the confining cylinder in direct contact with the bentonite blocks. In this test a constant temperature of 90 ℃ is maintained at the heater-bentonite interface by means of the heater control system. The heating system is redundant: each heating element is capable of supplying a higher thermal power than is strictly required.

The sensors and instruments used for the KENTEX were selected considering the working conditions: total pressure ≥ 10 MPa, temperature up to 100 ℃, and harsh saline environment. The same requirements are established for the cables and their connections to the sensors as well. Sixty eight sensors were installed in the bentonite blocks and in the rest of the components, to measure the following variables: temperature, humidity, and total pressure. Table 1 summaries the measurement parameter and the type, model, and number of sensors. The sensors in the bentonite blocks are grouped into 9 sections in the alphabetic order of A - I. The location of the sensors installed in the 9 sections, which was determined by pre-operational model calculation, is shown as an example in Figure 4.

3. DAS and HCS

The data acquisition system (DAS) was made up of all the electric and/or electronic components and a computer program required for the supervision, and it storages data on a secure magnetic device in an autonomous form. The system is capable of storing, analyzing and displaying the obtained data on a personal computer.

The heater control system (HCS) was made up of all the electric and/or electronic components and a computer program required to accomplish the

Table 1. Specification of sensors used for KETEX test.

Parameter	Sensor type	Model	Quantity
Temperature	Thermocouple	Watlow-Gordon T-type	42(10*)
Water content	RH & temp. transmitter Psychrameter	Vaisala HMP 234 (for < 15%) Wescor PCT 55 (for > 15%)	5 5
Swelling pressure	Pressure cell	Kulite BG 0234	6

(*) No. of thermocouples installed on the heater.

following functions: supervision of heater operation and control of the power supply, data acquisition and transfer to the DAS and activation of the processes, and alarms in the event of component failure.

The electric and/or electronic components of the DAS and HCS and the logic procedure of data acquisition and heater control are shown in Figure 5. The DAS and HCS are operated automatically by means of a computer program called "PRODASH-EN".

4. Operational Conditions

The operation of the KENTEX facility includes two processes (heating and hydration), which are done to obtain the initial and stable boundary conditions and to eliminate the possible number of heterogeneities. For this, the initial heating up to the first 90 ℃ temperature at the interface of a heater and bentonite blocks was done by progressive heating in order to reduce the risk of damaging the heating elements. The power supply, after that moment, was automatically regulated in accordance with the control program to maintain the constant temperature of 90 ℃ at the heater/bentonite blocks interface.

The initial hydration was taken to eliminate the

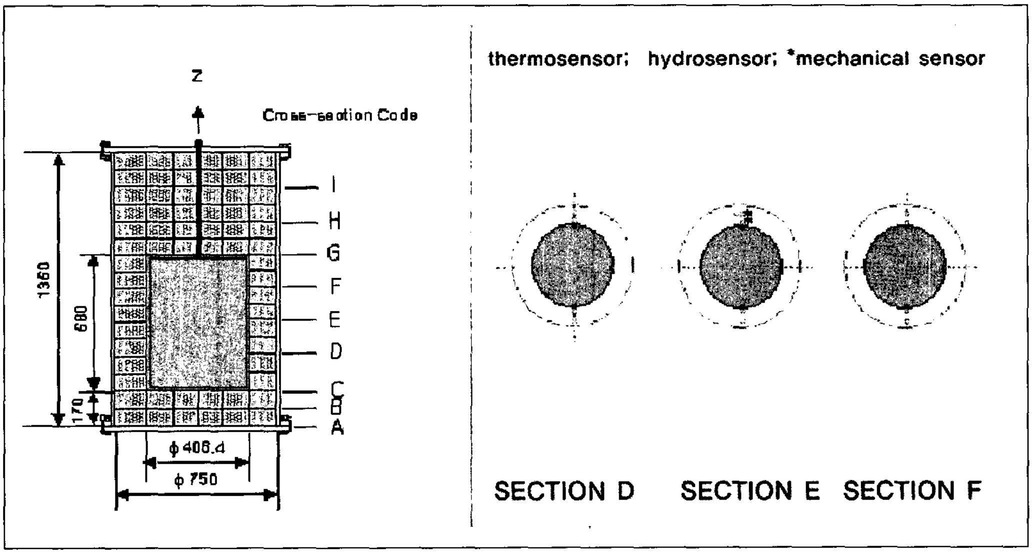


Figure 4. Example of the location of sensors to measure the temperature, relative humidity, and total pressure.

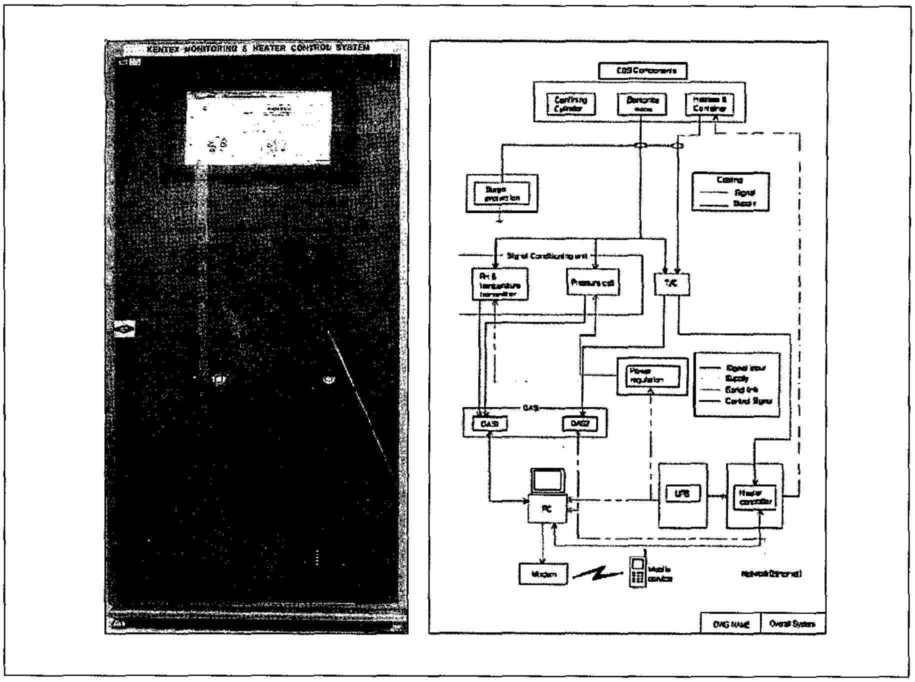


Figure 5. DAS/HCS and flow chart of data acquisition and heater control logic in KENTEX

air existing between blocks and between these and the confining structure, 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 action was to fill the hydration piping and rings, which was followed by purging of the system by the upper valves. The hydration sequence following the purging of the piping was to inject the ground water from a tank into the confining cylinder. When the water reached the upper valves, the lower valves and the valve connecting the tank to the distribution network were closed. The system was maintained for 2 days under the previous operation conditions, the time period of which was considered sufficient to have the injected water provoke the swelling of the bentonite blocks and, as a consequence, closing of the joints.

The actual hydration and heating (operational stage), following the two-day period, was initiated. The temperature at the heater/bentonite blocks interface was controlled to 90 ℃ and the injection pressure of the water was established to 0.5 MPa, which would maintained constant throughout the entire operational stage. The room temperature of the KENTEX facility was maintained to be 25 ℃ using two air-conditioners.

IV. Test Programme

The test programme is in Figure 6. As shown in the figure, the T-H-M test, after the installation and test-run of the KENTEX facility, is carried out in three stages: heating phase, cooling phase, and dismantling and sampling phase. In the heating phase test are investigated the T-H-M behaviors when the temperature at the heater/ bentonite blocks interface is maintained to be 90 ℃. That is, the temperature, humidity (then water content), and total pressure of the bentonite blocks are measured.

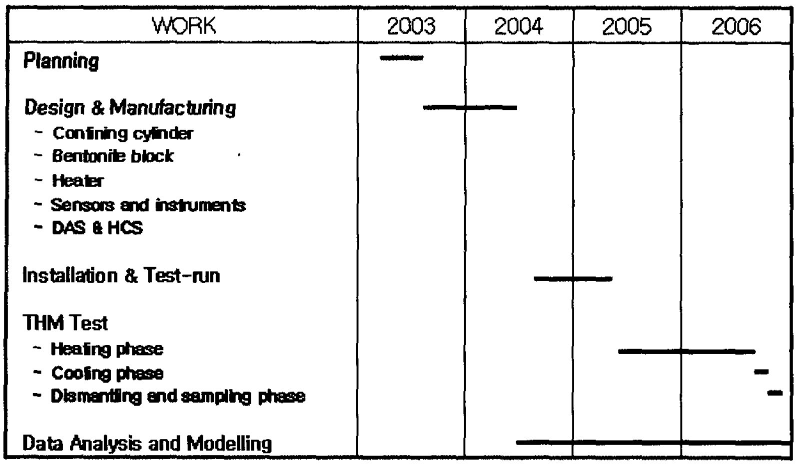


Figure 6. Time table of T-H-M tests in the KENTEX facility.

In the cooling phase with the heater turned off, the temperature is recovered into an initial state and the opposite T-H-M phenomena with the heating phase are measured. The sampling of the bentonite blocks is conducted at the end of the heating and cooling phase after dismantling the experimental setup, to identify the water content and to evaluate the material law of humidity and water content which is determined from the results of the laboratory tests. In addition, works are also done to verify hypotheses and to characterize the KENTEX components.

The heating phase test started on May 31, 2005 and is now in operation. The cooling phase test and sampling of bentonite blocks then will start from the beginning of December, 2006 in sequence. The interpretation of experimental data will be conducted in parallel with the mathematical modelling of coupled T-H-M behaviors in the bentonite blocks commenced from the middle of 2004.

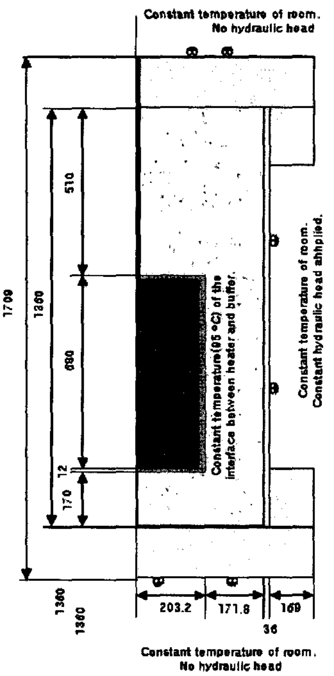
V. Pre-operational T-H-M Model Calculation

The T-H-M performance assessment of the reference disposal system was carried out using ABAQUS, a three-dimensional FEM code [9]. This study utilizes the ABAQUS code to make a pre-operational calculation for the KENTEX facility and then to obtain information on the sensitive location of sensors and the operational conditions. The system geometry and input data for the calculation is in Figure 7. The mathematical model is the combination of uncoupled heat transfer model and coupled pore fluid diffusion and stress analysis model. The procedure of the coupled T-H-M analysis is as follows:

- Construct the model mesh for the T-H-M analysis with boundary conditions.
- Determine the temperature distribution in the bentonite buffer from the T analysis.
- Construct a coupled H-M analysis for the bentonite buffer with the temperature input from the T analysis.
- Continue iterations until the predetermined time is reached.

As constitutive material laws for the coupled T-H-M model are employed Fourier 's heat conduction equation for thermal analysis, Darcy's equation and von Genuchten's suction pressure-saturation equation for hydraulic analysis, and Drucker-Prager plastic equation for mechanical analysis.

Figure 8 represents calculation results in contour patterns. The temperature decreases with increasing the distance from the heater, and there is a wider temperature distribution in the upper part of the

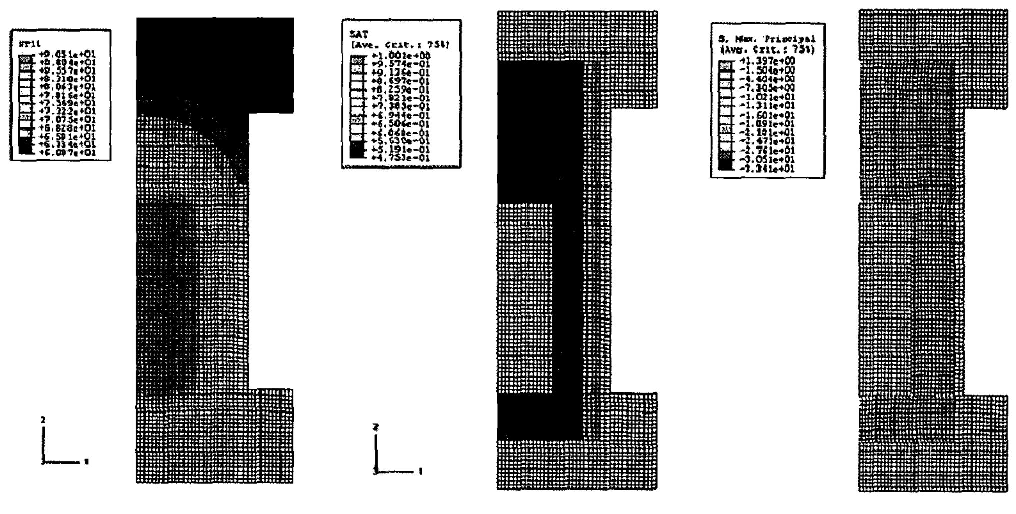


- Heater: 1 kW x 3ea
- Dry density of buffer = 1600 kg/m^3.
- Initial temperature of buffer = 25 °C.
- Initial water content of buffer= 13%.
- Applied hydraulic pressure to buffer= 0.5 MPa
- Thermal properties

Classification	Buffer	Confining cylinder
Thermal conductivity (W/m.K)	1	48.14
Specific heat (J/kg.K)	736	462
Thermal expansion coefficient (1/K)	3.8×10^{-4}	1.13×10^{-5}
Young's modulus (Mpa)	1080	-
Uniaxial compressive strength (Mpa)	4.3	-
Permeability (J/kg.K)	1.3×10^{-13}	-
Friction angle	37	-
Poisson's ratio	0.21	-
Cohesion	1.9	-

(-) Confining cylinder is not considered in hydraulic and mechanical analysis.

Figure 7. System geometry and input data for the model calculation.



(a) Temperature (b) Degree of saturation (c) Max. principal stress

Figure 8. Contour results of pre-operational T-H-M model calculation using the ABAQUS code (after 130 days).

bentonite blocks than in the side and in the bottom. In the calculation of temperature as a function of time, the temperature reached a quasi-stationary state approximately after 20 days and it took a longer time as the distance from the heater was farther and farther. For 130 days, the temperature at the bentonite blocks-confining cylinder interface of the central level is shown to be about 64 ℃. The contour pattern of the degree of saturation shows that the part of bentonite blocks near the wall of the confining cylinder is fully saturated with ground water and the saturation in the rest is proceeding toward the heater. However, the saturation front was not at a distance. The change of the degree of saturation in the axial direction is negligible. As shown in the maximum principal stress contour, the bentonite blocks displayed the lower values of compressive stress in the outer part than in the inner one. It explains that the bentonite blocks of the outer part had contact with ground water and then they exerted tensile stress due to their swelling, whileas the bentonite blocks of the inner part had more compressive stress by the pressure of ground water applied in through the wall of the confining cylinder and the pressure due to the thermal expansion of bentonite blocks, in the case of which the swelling pressure was not significant as the degree of saturation was not high in comparison with that in the outer part. The distribution of the maximum principal stresses was more sensitive in the radial direction than in the axial one.

VI. Conclusions

In order to validate the T-H-M behaviors in the buffer of the reference disposal system developed in the year 2002, KENTEX facility was designed, fabricated, and installed. The validation tests started on May 31, 2005 and are now in progress. These are carried out in the three stages of heating, cooling, and sampling, and are ended at the end of the year 2006. Pre-operational calculation was made to get information on sensor location and operation condition by using the ABAQUS code. Delicate model simulations will be conducted, based on experimental data obtained from the validation tests. This study is to provide information (e.g., large-scale apparatus, sensors, monitoring system etc.) needed for "in-situ" tests, to make the validation of a T-H-M model for the T-H-M performance assessment of the reference disposal system, and to demonstrate the engineering feasibility of fabricating and emplacing the buffer of a repository.

Acknowledgement

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