터널과 지하공간, 한국암반공학회
Vol. 9, 1999, pp. 83~88

TUNNEL & UNDERGROUND Vol. 9, 1999, pp. 83-88
J. of Korean Society for Rock Mech.

[redacted]

고준위 방사성폐기물 처분개념 실증을 위한 히터 실험 현황

황용수1) · 강철형2) · 이연명2) · 박병윤1)

1)정회원, 한국원자력연구소
2)한국원자력연구소

1. Introduction

Temperature is a particularly important parameter in the near-field assessment of heat-producing nuclear waste. There are three modes of heat transfer; conduction, convection and radiation. Repository heat transfer is normally dominated by conduction, but may involve significant contributions from convection by groundwater and radiation. The balance between these processes is dependent on both the hydrogeological conditions and the engineered barrier such as an waste packaging, a canister, backfill materials etc. Theoretical studies of high level waste repositories indicate the modified temperature field would extend several hundred metres into the rock, and rise and fall on time scales of centuries and millennia respectively.

Confined thermal expansion of the host rock induces stresses which modifies the natural stress field and therefore could influence the long-term stability of the repository and the mobilisation of the waste. Transport of radionuclides in groundwater is considered to be the most important path to the biosphere. Hence, it is important to understand how thermal stresses affect the groundwater flow paths through fractures in the rock.

The purpose of research and development in heater experiments is to quantify and to demonstrate understanding of heat-producing wastes on a variety of scales, in particular it should :

- demonstrate understanding of the key processes in coupling of thermal, groundwater and stress;
- quantify parameters to confirm that thermal properties obtained from the laboratory are relevant to in-situ conditions;
- quantify the effect of the elevated temperatures on accelerating the mineralization of the backfill material;
- quantify the potential to cause buoyancy driven groundwater flow;
- quantify the influence of the thermal stress on mechanical stresses;
- assist in the optimal design of the emplacement of waste (including their spatial arrangement);
- identify key uncertainties relevant to performance assessment;
- quantify the importance of heat production in relation to the other factors that affect the repository performance.

The purpose of this paper is to illustrate the historical context of such work and to provide a framework for the kinds of experiments which are relevant to the above points.

2. Current Status

2.1 Background

The temperature of waste to be placed in a repository will depend on the length of time allowed for radioactive decay prior to disposal. Radiogenic decaying heating will raise the temperature of the rock and groundwater. Such heating will result in a change in the stress in the rock. Heating fractured crystalline rocks such as granite can result in fracturing due to differential thermal expansion between the constituent minerals. Such fracturing may have the effect on the transport of radionuclides; an increase in the rate of flow of groundwater is possible but this is counter-balanced by the increase in the sorption of those radionuclides due to the greater surface area of the rock exposed by the fracturing.

One method of monitoring the degree of fracturing in a rock is by measuring Young's modulus. This has been carried out in granite and other rocks using sonic resonance techniques1). More recently, successful acoustic emission has been applied *in-situ* at Aspo2) to look at the micro-cracking occurring at the excavated drift wall using both Drill and Blast (D & B) and by the Tunnel Boring Machine (TBM). This paper reviews some of the laboratory scale experiments that have been performed to address the thermal problem. The determination of thermal conductivity, heat capacity, coefficient of thermal expansion, as well as deformability at ambient and elevated temperatures, do not pose significant technical problems[2]. The most R & D effort is concerned with the behaviour of rock fractures in relation to their deformability and associated changes in water conductivity.

Higher temperature testing of fractured samples for coupled T-H-M purposes is an area of active research.

2.2 Stripa

Laboratory investigation were carried out to determine thermomechanical property of Stripa granite for use in modelling the *in-situ* experiments at Stripa. A triaxial test machine, capable of providing a maximum confining pressure of 70 MPa and a maximum axial load of 1.4 MN. Independent systems for heating and cooling the cell can provide a maximum sustained cell temperature of 200℃. The test cell can accommodate either a 52 mm diameter or 62 mm diameter core with a aspect ratio of 3 (i.e. the types of core that were to be extracted from the site). Thermomechanical properties were determined from samples of dry, intact 62 mm diameter core taken from the same instrumentation holes in which measurements of displacements and stresses were made during the *in- situ* experiment. To bracket *in-situ* temperatures and stress conditions, measurements were made over a range of confining pressures from 2 to 55 MPa and a range of temperatures from 25 to 200℃.

Test results provided data on the temperature and stress dependence of the volumetric and linear coefficients of thermal expansion (α_V, α_l), tangential Young's modulus(E_T) and Poisson's ratio (ν). To varying degrees, all properties were affected by changes in confining pressures and temperature. The most significant trend in thermal expansion results was the effect of increasing temperature at constant pressure. Average values of α_V, and α_l were approximately 50% of those at 180℃.

Full details of the apparatus, application and results are given in[3]. Fig. 1 shows a cross section of the test cell. Fig. 2 shows the test cell temperature control and Fig. 3 illustrates the test machines hydraulic system.

2.3 Ecole des Mines de Paris

Early work on the high temperature testing of fractured samples for hydromechanical purposes were conducted by Coudrain *et al*[4]. This work consisted of looking at the effect of thermal stresses on a single natural fracture in a rock core which was confined in a rubber jacket in a triaxial cell. In the experiment the temperature of the fractured core was maintained at a constant value after which it was uniformly heated. The flow of water injected in the fracture through an axial hole was monitored as temperature increased. The main results of the experiment was that the transmissivity of the fracture decreased exponentially with the temperature rise applied. Fig. 4 shows the triaxial cell for high temperature testing of a fractured granite.

2.4 PNC Big Ben

As part of the study of coupled T-H-M, an ex-

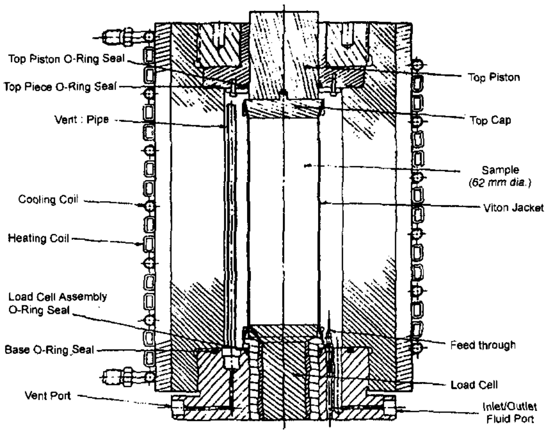

Fig. 1. Cross section of the test cell.

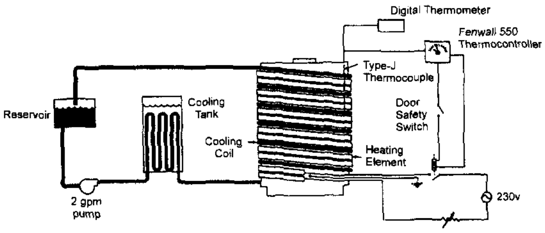

Fig. 2. Test cell temperature control system.

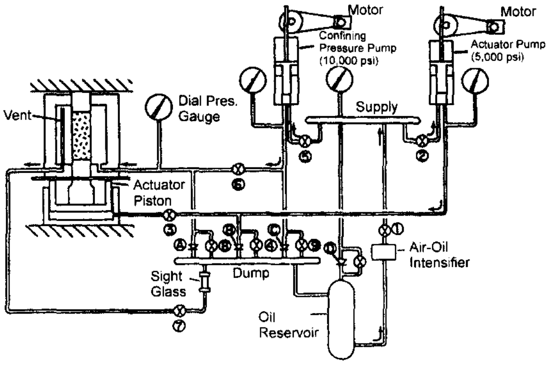

Fig. 3. Schematic representation of test machine hydraulic system.

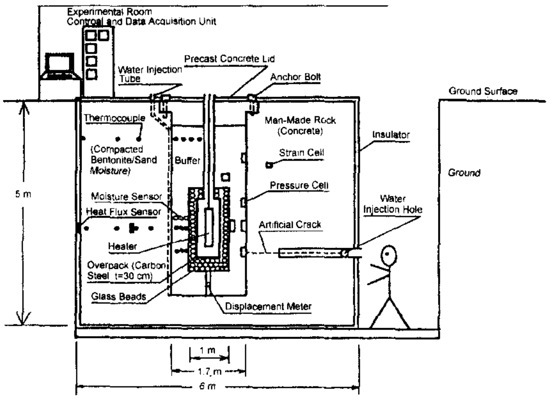

Fig. 5. Illustration of the Big Ben experiment.

periment called Big Ben, has been conducted by PNC for testing the Japanese concept for nuclear waste disposal. This test is a full scale laboratory test of a deposition hole. Fig. 5 illustrates the experimental apparatus. An electric heater embedded in grass beads was confined by a steel container, which simulated the waste canister overpack. The deposition hole was constructed with a diameter of 1.7 m and a depth of about 4.5 m in an artificial rock of concrete with a radius of 3 m and height of 5 m. The deposition hole was filled with buffer material (30% sand and 70% bentonite) compacted to the dry density of 1.6 t/m^3. The water ratio was 16.5%.

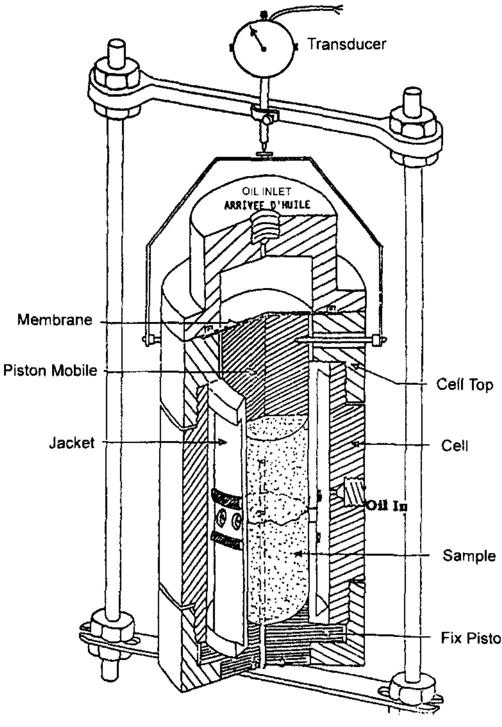

Fig. 4. Triaxial cell for high temperature testing of a fracture granite core.

The thickness of buffer material around the canister was 0.3 m. A 2 cm thick layer of dry sand was applied at the interface between the canister and the buffer. A similar layer of 3 cm thickness was applied between the canister and the buffer material and the simulated rock (concrete). This layer was filled with water at a water pressure maintained at 50 kPa.

A constant power of 800 W was applied to the heater at the start of the test at the same time as the outer layer of sand way filled with water. Several measurements were made during the test including :

1. measurement of temperature;
2. measurement of water content;
3. measurement of total pressure in the buffer material.

The water ratio was measured using sensors and after 5 months also by sampling. A series of experiments were carried out with this equipment.

- The following types of tests were performed :

1. Drying tests.

These tests were performed in order to determine the change in void ratio caused by the change in degree of saturation. These tests were performed to evaluate the moisture swelling process.

2. Moisture redistribution test.

These test were made under different temperature gradients and at different temperature levels and were terminated at different times. The test were made to evaluate the thermal water diffusivity.

3. Water uptake tests.

These tests were made to check that the rate of water uptake under isothermal conditions, which is controlled by the negative pore water pressure (suction) s and the hydraulic conductivity for partly saturated materials k_p.

Full details of these tests are given in Fujita *et al* [5]. Some calculations performed as part of the Big Ben Experiment using coupled modelling of the thermal, mechanical and hydraulic behaviour of water-saturated buffer material in a simulated deposition hole is given in Borgesson[6]. The calculations show that the inner half of the buffer material close to the canister will dry and shrink. The drying will decrease the water ration from 16.6% to 10% at the inner buffer boundary. The volumetric shrinkage will be 3.5% at the inner buffer boundary, which corresponds to a decrease in void ratio from 0.7 to 0.64. The calculations also show that there will be tension close to the inner boundary in the axial and tangential directions. Although the failure behaviour of the unsaturated buffer material is not known, cracking close to the canister is possible.

When comparisons are performed with calculation, the results illustrate simulated and measured temperatures agree. In addition the changes in water ratio agree to some extent. However, the total pressure measured at the outer bentonite boundary were generally higher than the calculated values. In addition, the void ratio was not compared as this was not measured after the test.

2.5. The Large Block Test (Yucca Mountain)

The Large Block Test (LBT)[7] is designed to provide experiments with boundary conditions so that they will be useful for testing concepts of the coupled THMC processes.

- The LBT consists of two parts :

1. test on individual parts (small blocks and individual fractures)
2. and coupled process with multiple fractures in a large block.

- Small block tests in the laboratory have been conducted including:

  - thermal-mechanical deformation,
  - thermal fracturing,
  - displacement across a fracture due to heating and cooling,
  - drying and imbibation of intact and saw-cut blocks,
  - vapour diffusion in matrix,
  - examined for rock-water interactions;
  - condensation along a fracture, and
  - condensate refluxing in a thermal gradient.

The Large Block has dimensions of 3 by 3 by 4.5 metres and is tuff, isolated at Fran Ridge, USA. Heater holes will be drilled into the block and maintained at a constant temperature for two months. Instruments will be installed in boreholes to monitor the responses of the block in three dimensions. The following measurements are planned to be made :

- air injection tests before and after heating to estimate air permeability;
- stress-strain curves of the block will be obtained before, during and after heating;
- displacements measured continuously along boreholes;
- temperature within the block and on its surface;
- moisture distributions determined from sensors at points;
- neutron logging along holes;
- electrical resistivity tomography in 2-D sections;
- acoustic emission (during heating and cooling phases);
- thermal conductivity and diffusivity from thermal probes in three directions;
- pore gas pressure.

This work is being supported simultaneously my scoping modelling calculations to analyse various boundary conditions and heating strategies.

2.6 U.K. Experiences

The following sections describe some previous experiences that are relevant to the assessment of the THM problem associated with HLW.

2.6.1 Physical Properties of Granite Relevant to Near Field Conditions in a Nuclear Waste

Repository

This work was funded by the UK Department of the Environment and the Commission of the European Community. It focused on obtaining physical properties of granite relevant to near field conditions in a nuclear waste repository.

This work examined the effect of heat on samples of granite obtained from boreholes as a function of temperature and time in laboratory conditions by determining Young's modulus8). Attempts were made to quantify the size and number of fractures producing such effects on the Young's modulus and the resulting increase in fracture surface area. The effect of the overburden pressure of preventing the formation of or the subsequent closure of fracturing was not investigated in this study. The conclusions were that the Young's modulus is approximately constant from room temperature to 60~80℃. From 60~80℃, Young's modulus falls in nearly linear fashion to the quartz transition temperature at 550℃ (with a value of Young's modulus of approximately 10% of that at 60℃). It was observed significant modulus changes such as these are irreversible. Modulus change may be equated with an increase in surface area (of fractures) of the rock of between 100 and 1000 m^2/m^3 at 200℃.

2.6.2 Degradation of Rocks Through Cracking by Differential Thermal Expansion, in Relation to Nuclear Waste Repositories9)

The report by Davidge develops a theory that may be used to compare the suitability of various rocks for the stability in situations in which heating is likely. He observes that there is striking similarity in qualitative form between the theoretical curve and the curves measured for a range of various rocks. Data used in conjunction with the theory has been conducted on laboratory specimens when tests have been conducted in the absence of any confining hydrostatic compressive stress. The constraining hydrostatic pressure could inhibit the formation of cracks. The type of degradation of rocks described in their report is best described as 'worst case' and clear that it is eventually necessary to carry out *in-situ* experiments. An additional complication is that *in-situ* values of E, ν and α will vary considerably from those measured on intact samples in a laboratory because of the effects of fractures and joints10).

This work was performed as part of the UK programme of research into the burial of radioactive waste for the Commission of the EC.

2.6.3 Analytical/Numerical Studies

As part of the Department of the Environment radioactive waste management research programme a number of papers have been written to help evaluate the effect of thermal stresses on rock stress and groundwater flow. For example, a mathematical model of thermally induced water movement in the vicinity of a hard rock (low permeability) repository for radioactive waste has been developed in11,12). For low permeability rocks envisaged for geological disposal the equations describing heat and mass transfer become uncoupled and linear. Analytical solutions to the linearised equations are derived for an idealised spherical model in a uniformly permeable rock mass. These solutions can be used to estimate the relative importance of thermal convection to a regional groundwater flow.

A simplified mathematical model for which analytical solutions to the temperature and stress fields are derived in Reference13,14). The idealised elastic analysis has highlighted several ways in which thermal stresses may affect the long term safety and stability of burial of radioactive waste in hard rock. Tensile thermal stresses, which tend to increase permeability and porosity, are predicted in the rock overlying a repository. Unsurprisingly these effects can be reduced by increasing the burial depth and increasing the storage time before disposal.

3. Conclusions on Small Scale Experiments

The 'straight-forward' laboratory testing of the rock matrix properties of samples to determine heat propagation and rock mechanical properties requires little introduction or comment. There are no significant problems associated with determination of thermal conductivity, heat capacity, coefficient of thermal expansion, as well as deformability and strength behaviours at high temperatures. The bulk of the R & D effort is focused on the behaviour of rock fractures and their change in hydraulic conductivity. Typical laboratory experiments occur in rock samples confined in triaxial cells, of the sort described by Coudrain4). More ambitious experiments can be on a scale commensurate with the scale of a deposition hole, for example the Big Ben experiment$^{5)}$.

References

1. Wingquist, C. F. U. S., 1969, Dept. of the Interior, Bureau of Mines Report p.7269.
2. Heuze, F. E., *High temperature mechanical, physical and thermal properties of granitic rocks - a review.* Int. J. Rock Mech. Min. Sci. and Geomech. Abstr., Vol. 20, No. 1, pp. 3-10.
3. Myer L. and Rachiele R., 1981, Laboratory Investigations of Thermomechanical Properties of Strip Granite. Part I : Apparatus Part II : Application and Results, Lawrence Berkley Laboratory Report, LBL-13435, SAC-40, UC-70.
4. Coudrain, A. *et al, Etude des incidences du degagement thermique en milieu fissure suite a l'enfouissement de dechets nuclearires.* Report EUR 8186, European Commission, Luxenbourg.
5. Fujita T., Moro Y., Hara K., Kobayashi A., and Ohnishi Y - *DECOVALEX - Specifications for test case 3 - BIG BEN experiment* PNC, Japan.
6. Borgesson, L., and Hernelind, J., DECOVALEX I - Test Case 3 : *Calculation of the Big Ben Experiment - Coupled modelling of the thermal, mechanical and hydraulic behaviour of water-unsaturated buffer material in a simulated deposition hole.* SKB Technical Report pp. 95-29.
7. Lin W., *et al*, 1996, *The Large Block Test: A Progress Statement,* High Level Radioactive Waste Management, Proceedings of the 6th Annual International Conference.
8. McLaren J. R. and Titchell I., 1981, United Kindom Atomic Energy Authority Harwell Report, AERE - R 10046.
9. Davidge, R. W., 1981, *Degradation of Rocks, Through Cracking by Differential Thermal Expansion, in relation to Nuclear Waste Repositories,* AERE-R 10164.
10. Hood M., 1979, *Some Results from a Field Investigation of Thermo-Mechanical Loading of a Rock mass when Heater Canisters are Emplaced in the Rock,* presented at 20th U.S. Rock mechanics Symposium, Austin, Texas, June.
11. Hodgkinson D.P., 1979, *A mathematical model for Hydrothermal Convection around a Radioactive Waste Depository in Hard Rock.*
12. Hodgkinson, D. P., D.A. Lever and J. Rae, 1983, *Thermals Aspects of Radioactive Waste Burial in Hard Rock,* Progress in Nuclear Energy, Vol. 11 No. 2 pp. 183-218.
13. Hodkinson, D. P. and Bourke, P J., 1980, *Initial Assessment of the Thermal Stresses around a Radioactive Waste Depository in Hard Rock.,* Annals of Nuclear Energy, Vol. 7, pp. 541-552.
14. Hodgkinson, D., 1982, *Analytical Models for Thermal Rock Mechanics,* United Kingdom Atomic Energy Authority Report, AERE-R 10341.