Physics and Chemistry of the Earth 36 (2011) 1729–1742

Contents lists available at SciVerse ScienceDirect

Physics and Chemistry of the Earth

journal homepage: www.elsevier.com/locate/pce

Large scale gas injection test (Lasgit): Results from two gas injection tests

Robert J. Cuss [a,*], Jon F. Harrington [a], Dave J. Noy [a], Anders Wikman [b], Patrik Sellin [b]

[a] British Geological Survey, Keyworth, Nottingham NG12 5GG, UK
[b] Svensk Karnbranslehantering AB, Brahegatan 47, Stockholm 10240, Sweden

ARTICLE INFO

Article history:
Available online 16 August 2011

Keywords:
Gas testing
Full scale test
In situ test
KBS-3
Lasgit
Bentonite

ABSTRACT

This paper describes the initial results from a large scale gas injection test (Lasgit) performed at the Äspö Hard Rock Laboratory, Sweden. Lasgit is a full-scale field-scale experiment based on the Swedish KBS-3V repository concept, examining the processes controlling gas and water flow in compact buffer bentonite. The first 2 years of the test focused on the artificial hydration of the bentonite buffer. This was followed by a programme of hydraulic and gas injection tests which ran from day 843 to 1110. A further period of artificial hydration occurred from day 1110 to 1385, followed by a more complex programme of gas injection testing which remains on going (day 1385+). After 2 years of hydration, hydraulic conductivity and specific storage values in the lower filter array were found to range from 9×10^{-14} to 1.6×10^{-13} m/s and 5.5×10^{-5} to 4.4×10^{-4} m^{-1} respectively, with the injection filter FL903 yielding values of 7.5×10^{-14} m/s and 2.5×10^{-5} m^{-1}. A second set of hydraulic measurements were performed over 1 year and a half later yielding similar values, in the range 7.8×10^{-14} m/s and 1.3×10^{-13} m/s. The hydraulic conductivity of FL903 had reduced slightly to 5.3×10^{-14} m/s while specific storage had increased to 4.0×10^{-5} m^{-1}. Both datasets agree with laboratory values performed on small-scale saturated samples.

Two sets of gas injection tests were performed over a 3 year period. During the course of testing, gas entry pressure was found to increase from around 650 kPa to approximately 1.3 MPa, indicative of the maturation of the clay. The sequential reduction in volumetric flow rate and lack of correlation between the rate of gas inflow and the gas pressure gradient observed during constant pressure steps prior to major gas entry, is suggestive of a reduction in gas permeability of the buffer and indicates only limited quantities of gas can be injected into the clay without interacting with the continuum stress field. Major gas entry occurs at a gas pressure close to, or slightly in excess of, the local stress state and is associated with a rapid increase in flux, linked to a series of kicks in axial and radial stress and porewater pressure. Post peak gas flux exhibits dynamic behaviour, symptomatic of unstable gas flow. When gas injection is stopped, flux into the clay rapidly reduces before entering an extended period of very small flows. This is accompanied by a rapid reduction in pressure which decays to an asymptotic value close to that of the total stress locally within the deposition hole. Examination of the data shows considerable evidence for the development of a highly-dynamic, tortuous network of pressure induced pathways which evolve both temporally and geospatially within the clay, opening and closing due to local changes in gas pressure and/or effective stress. These detailed observations do not conform to standard concepts of two-phase flow. The bentonite response to the passage of gas suggests that pathway dilation is the primary mechanism governing gas migration within the Lasgit system. The important coupling between gas, stress and porewater pressure at the repository scale is clearly evident with the data. The importance and interdependencies of this coupling will be investigated in future experiments planned at the Lasgit experimental site.

1. Introduction

In the Swedish KBS-3 disposal concept (SKB TR-09-22), copper/steel canisters containing spent nuclear fuel will be placed in large diameter disposal boreholes drilled into the floor of the repository tunnels. The space around each canister will be filled with pre-compacted bentonite blocks which, over time, will draw in the surrounding groundwater and swell, closing any construction gaps. Once hydrated, the bentonite will act as a low permeability diffusional barrier, severely limiting the migration of any radionuclides released from a canister after closure of the repository. While the waste canisters are expected to have a very substantial lifespan within the repository environment, it is important for purposes of performance assessment to consider the impact of groundwater

* Corresponding author.
E-mail addresses: rjcu@bgs.ac.uk (R.J. Cuss), patrik.sellin@skb.se (P. Sellin).

1474-7065/$ - see front matter
doi:10.1016/j.pce.2011.07.022

penetration of one of the canisters. Under certain repository conditions, corrosion of the steel inner will lead to the formation of hydrogen gas. Radioactive decay of the waste and the radiolysis of water will produce additional gas within the container void. Depending on the rate of gas production and the rate of diffusion of gas molecules in the pores of the bentonite, it is possible a pressurised gas phase will accumulate in the void space of the canister (Horseman 1996; Horseman et al., 1997, 1999). Gas will then enter the bentonite when the gas pressure exceeds some critical entry pressure specific to this material. Since water penetration into the canister is a prerequisite for the generation of hydrogen gas in the buffer, the timing of gas movement in the clay might coincide with that of radionuclide release into the buffer porewater. The possibility of an interaction between gas and radionuclide migration therefore emerges as an important issue in performance assessment.

However, the quantitative treatment of gas migration in compact clays is a highly complex issue (Rodwell et al., 1999). In recent years, a number of laboratory studies of gas migration in repository buffer clays have been undertaken. These experiments have focussed on gas movement in initially saturated material (Donohew et al., 2000; Harrington and Horseman, 1999, 2003; Horseman and Harrington, 1994; Horseman et al., 1999; Hume, 1999; Ortiz et al., 1997; Tanai et al., 1997] and in unsaturated clays (Gallé, 1998; Gallé and Tanai, 1998; Gray et al., 1996; Hume, 1999; Tanai et al., 1997), with a review of past work provided in Rodwell et al. (1999). Results from these studies indicate breakthrough pressure is strongly dependent on the degree of water saturation of the bentonite. At water saturations less than 70% (Tanai et al., 1997) to around 80–90% (Hume, 1999), clay contains an interconnected network of air voids resulting in little or no pressure threshold for gas flow. As full saturation is approached, gas entry and breakthrough pressures increase rapidly (Gray et al., 1996; Hume, 1999). Horseman et al. (1999) questioned whether gas flow occurred through the original porosity of the clay or through a network of crack-like pathways which opened and closed dependant on the magnitude of the gas pressure. The view was expressed that bentonite close to full saturation is totally impermeable to gas and that conventional 2-phase flow is impossible in this material. Experiments reported by Donohew et al. (2000) suggest that a saturated clay must dilate (i.e. grow in volume) during gas entry and the initial changes in gas content are accommodated by an increase in the total volume of the clay. Although this is consistent with gas flow through a network of pressure-induced pathways, it cannot be described by the more usual soil mechanics concept of desaturation by direct displacement of porewater. If all gas entry in the clay is accommodated by dilatancy, this raises the important question of sensitivity of the gas transport process to the boundary conditions of an experiment (Horseman et al., 1999).

While these studies have improved our understanding of the gas-buffer system, recent laboratory work (Horseman et al., 2004) has highlighted a number of significant uncertainties, notably the sensitivity of the gas migration process to experimental boundary conditions and possible scale-dependency of the measured responses. This issue is best addressed by undertaking a large scale gas injection test or "Lasgit" (Sellin and Harrington, 2006).

Lasgit is a full-scale demonstration experiment operated by SKB at the Äspö Hard Rock Laboratory at a depth of 420 m. The objective of Lasgit is to provide quantitative data to improve process understanding and test/validate modelling approaches which might be used in performance assessment. This paper introduces the data generated during the first two gas testing stages. As part of the Lasgit project several numerical modelling groups are independently modelling the gas tests; these studies are on-going and are not discussed here.

2. Data reduction

The governing equation for flow in variably saturated porous media can be derived from Darcy's Law and the conservation of mass (Huyakorn and Pinder, 1983):

$$\nabla \cdot [K_r K \nabla(\psi + z)] + q = \left(\phi \frac{\partial S_w}{\partial \psi} + S_w S_s\right) \frac{\partial \psi}{\partial t} \tag{1}$$

where K_r is the relative permeability, K is the saturated hydraulic conductivity, ψ is the pressure head, z is the elevation, q is a fluid source rate, ϕ is the porosity, S_w is the water saturation, and S_s is the specific storage. The pressure head, ψ, is positive in the saturated region and negative in the unsaturated region. Eq. (1) is highly non-linear because both the relative permeability and the water saturation are functions of the pressure head. A number of such functions are available in the literature, but the most commonly used are those due to van Genuchten (1980):

$$S_w(\psi) = S_r + (1 - S_r)[1 + (-\alpha\psi)^n]^{-m} \tag{2}$$

$$K_r(\psi) = \sqrt{S_e}[1 - (1 - S_e^{1/m})^m]^2 \tag{3}$$

where m and S_e are given by:

$$m = 1 - 1/n \tag{4}$$

$$S_e = \frac{S_w - S_r}{1 - S_r} \tag{5}$$

and S_r is the residual water saturation. The parameters α, n, and S_r are obtained by fitting these functions to experimental data. Eq. (1) can be applied to the saturated region by setting S_w and K_r equal to 1 for all positive values of pressure head, ψ. The solution to Eq. (1) can be obtained by applying standard finite element techniques and supplying appropriate initial and boundary conditions (Huyakorn and Pinder, 1983). Picard iteration can be used to resolve the non-linearities.

3. Experimental concept

The aim of the Lasgit experiment is to perform a series of gas injection tests in a full-scale KBS-3 deposition hole. The objective of the experimental programme is to provide quantitative data to improve process understanding and test/validate modelling approaches used in repository performance assessment. Specific objectives include: perform and interpret a series of large-scale gas injection tests based on the KBS-3 repository design concept; examine issues relating to up-scaling and its effect on gas movement and buffer performance; provide information on the processes governing gas migration; and provide high-quality test data to test/validate modelling approaches. In essence, the Lasgit experiment consists of three operational phases; an installation phase, a hydration phase and a gas injection phase. The installation phase was undertaken from 2003 to early 2005 and consisted of the design, construction and emplacement of the infrastructure necessary to perform the Lasgit experiment (Cuss et al., 2010). The initial hydration phase began on the 1st February 2005 with the closure of the deposition hole. The primary aim of this phase of the experiment is to fully saturate and equilibrate the buffer. The saturation and equilibration of the bentonite is monitored by measuring pore pressure, total pressure and suction at both the buffer/rock interface and key locations within individual clay blocks. The hydration phase provides an additional set of data for (T)HM modelling of water uptake in a bentonite buffer. When