

# HRL Äspö Sweden :

## Experimental and Modelling Approaches with Respect to Two-Phase Flow Conditions in Granite

*Eckhard Fein, Herbert Kull*

### 1. Introduction

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In 1995 the Swedish Svenska Kärnbränslehantering AB (SKB) and the German Federal Ministry of Education, Science, Research and Technology (BMBF) signed a co-operation agreement. Within the framework of this agreement the German two-phase flow experiment is conducted at the Äspö Hard Rock Laboratory in Sweden (1997-1999). GRS<sup>1</sup> and BGR<sup>2</sup> are partners in charge for the performance of the project, while PTE<sup>3</sup> co-ordinates the co-operation with SKB.

The objective of the project is the support of long-term safety analyses for repositories of radioactive wastes. Significant amounts of gas are expected to be generated by anaerobic corrosion of canisters, radiolyses, and by microbial degradation of organic substances in repositories for LLW and ILW wastes. For that reason overpressures could be build up and affect the integrity of geotechnical barriers. To predict the migration of gases released from emplaced wastes via fractures geosphere calibrated two-phase flow models are needed.

The two-phase flow project consists of two parts: the field experiments and the modelling. The site to perform the in-situ tests, the niche 2715 at the 360 m-level, was selected within a pre-investigation programme performed by GRS in 1996 / 1 /, / 2 /. Since 1998 the basic water flow parameters are determined by hydrotesting. Measurements of two-phase flow parameters, eg the gas threshold pressure, started in 1999. In addition patterns of borehole packers for a dipole test configuration are installed to perform gas tracer tests.

To analyse the measured data the computer programs Rockflow /3/ and Mufte /4/ are used to model single-phase - and two-phase flow, respectively. For that the results of the site characterisation are used to set up the models. Besides that the code Mufte-ug is developed

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<sup>1</sup> Gesellschaft für Anlagen- und Reaktorsicherheit mbH, Köln

<sup>2</sup> Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover

<sup>3</sup> Projektträger des BMWi und BMBF für Entsorgung, Karlsruhe

by CAB<sup>4</sup> on behalf of GRS. In contrast to the Mufte code the new developed Mufte-ug /5/ takes into account advanced numerics and is applicable to fractured-porous media modelling the fractures explicitly.

## **2. Experimental Work**

Overall objectives of the in-situ experiments are to provide field data which are necessary for the set-up and the calibration of flow models. In particular, the following objectives are to be considered:

- to develop a geological model describing the hydraulic conditions in niche 2715, including the relevant fracture systems and the petrophysical properties of the rock mass,
- to determine the distribution of hydraulic pressure and effective flow parameter values for a single fracture and the surrounding rock mass including the gas threshold pressure measurements on fracture and matrix.

In the near-field of the front face of the niche boreholes intersect the main water-bearing subvertical fracture system. Other boreholes were drilled into the matrix in the vicinity of the water-bearing fracture (about one metre distance), crossing a horizontal fracture plane half to three metre apart (figure 1).

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<sup>4</sup> Institut für Computeranwendungen im Bauwesen, Technical University of Braunschweig,

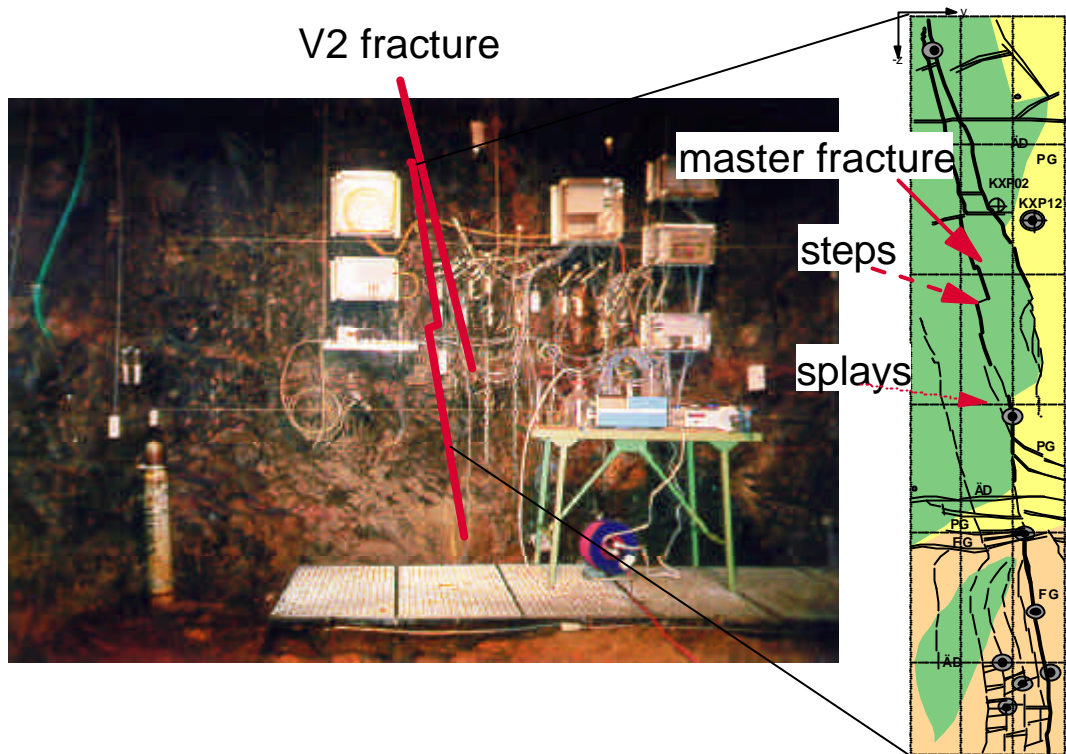


Figure 1: Left: Instrumentation of the experiment in the niche 2715 at the 360 m level. The red lines indicate the V2 fracture. Right: Map of the complex V2 fracture system (30 cm to 150 cm).

## 2.1 Geology

The rock mass consists of Äspö diorite and fine-grained granite. Several subvertical ESE-WNW water bearing fractures and horizontal calcite-filled fractures are the main structures in the niche. Depending on the scale used fracture system which is called V2 was determined to be the master fracture system in that area. Figure 1 shows the complex system of the master fracture with steps and splaysees. From surface mapping the range of the effective aperture of the master fracture was determined to be one millimetre or less.

## 2.2 One-Phase Flow Parameters

The hydraulic pressure distribution, the effective hydraulic gradient and hydraulic conductivity were measured in the near field of the tunnel. Extensive gas threshold pressure tests were carried out to measure the gas entry pressure and to determine the most suitable location for the gas dipole test.

The initial pressure distribution is determined from long-term pressure measurements in the fractures and the rock matrix. Considering the overburden the maximum pressure was expected to be about 3.5 MPa. The monitored data indicate a steady state pressure distribution lower than the expected one. Directly behind the front face of the niche the pressure seems to be influenced by the excavation (figure 2). The initial pressure in the V2 fracture beyond the excavation disturbed zone is about 1.8 MPa.

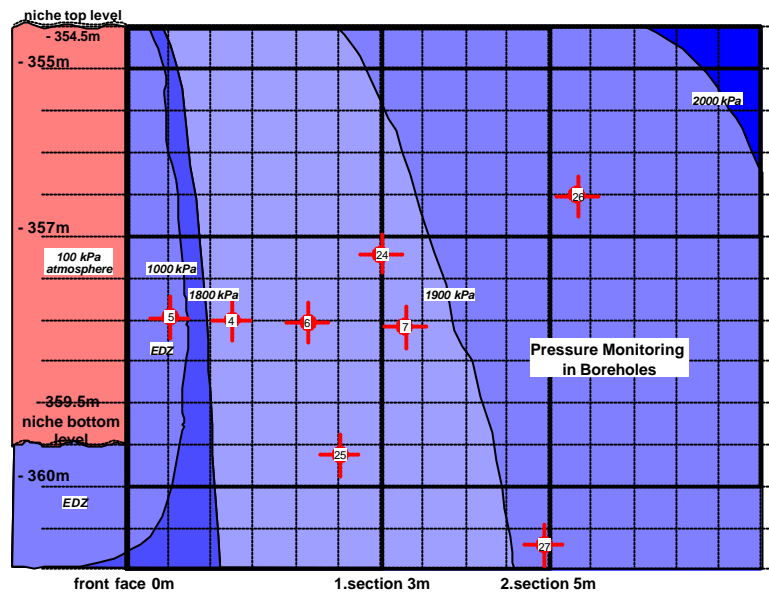


Figure 2: The initial pressure distribution in a vertical section of the V2 fracture.

The hydraulic gradient in the V2 fracture smoothly decreases towards the niche. An explanation for the sharp pressure drop within the excavation disturbed zone could be the decrease of fracture permeability caused by additional rock mechanical pressure on the fracture.

The hydraulic conductivity of the V2 fracture was determined to be in the range of  $10^{-5}$  m/sec which corresponds to an effective water permeability of approximately  $10^{-12}$  m<sup>2</sup>. This permeability value correlates to a transmissive zone with a thickness of 5 cm. The extension of the fracture was calculated to be larger than 30 m in distance to the test area. Homogeneous fracture flow was assumed to be the appropriate flow model. The results of a flow test simulation show a relative good fit of measured and calculated data for the flow and pressure recovery period.

Horizontal calcite filled fractures were determined to have permeabilities in the range of  $10^{-20}$  m<sup>2</sup> – equal to the permeability of the rock matrix.

### 2.3 Gas Entry Pressure

Gas injection tested in packered boreholes is used to determine the **Gas Threshold Pressure (GTHP)** and the gas mobility in fractured and homogeneous tight rock (cf figure 3).

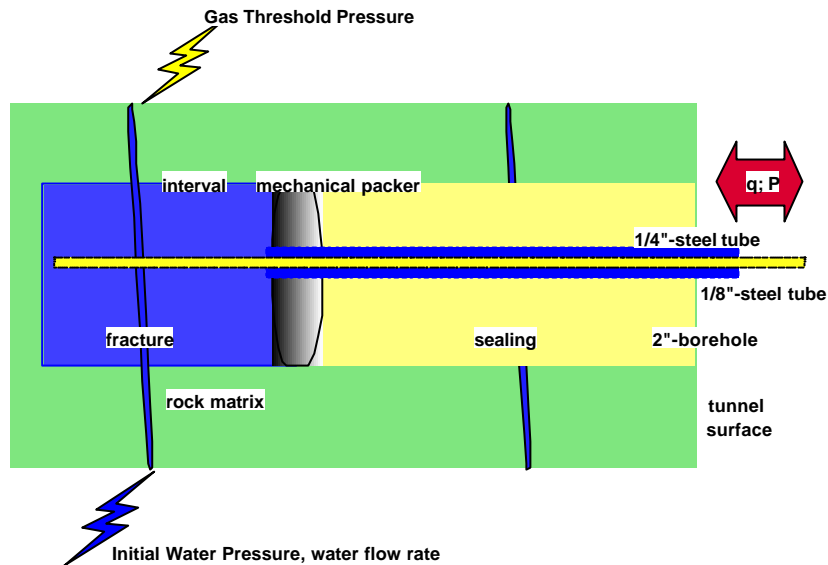


Figure 3: Scheme of gas threshold pressure tests.

GTHP (or gas entry pressure) is one of the relevant parameters controlling gas and water flow in fractured crystalline rock. By definition GTHP describes the pressure which is necessary to replace the wetting phase (i.e. water) by the non-wetting phase (i.e. gas) in a fully water saturated pore volume. Due to the surface tension and the size of the pores GTHP can be orders of magnitudes higher than the initial hydraulic water pressure. Fractures with an aperture in the range of millimetres are expected to have negligible GTHPs. With respect to an advective gas flow in the connected pore space of the matrix the gas pressure must be much higher. It was the purpose of the gas injection tests to verify the expected low entry pressure in fractures and to determine the high entry pressure into the matrix.

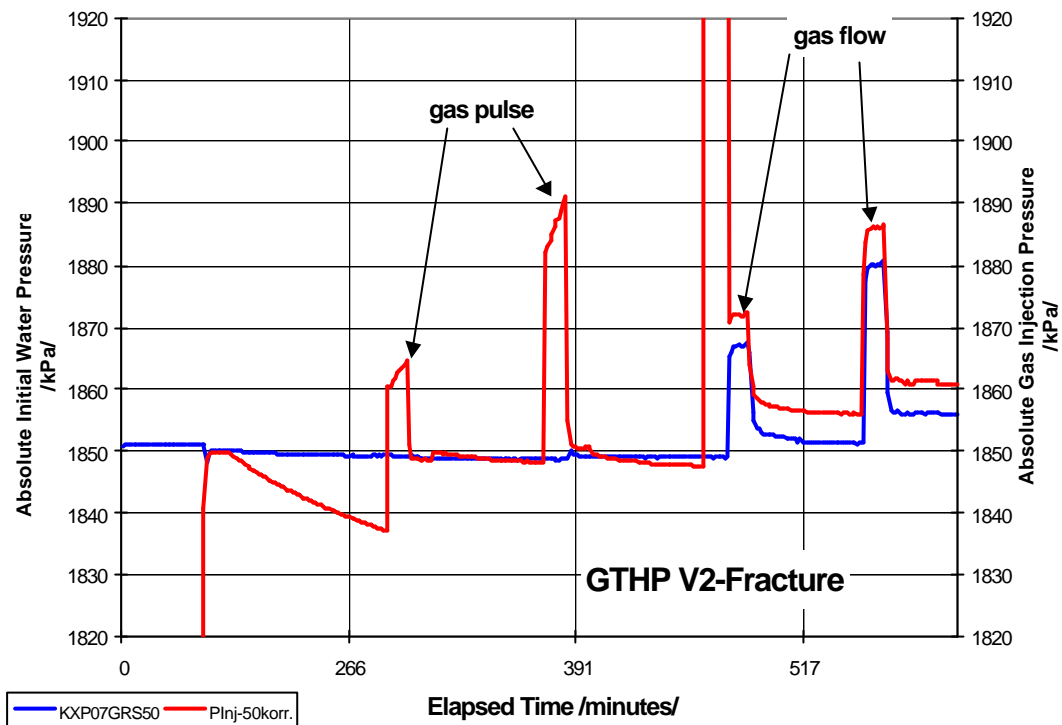


Figure 4: Results of gas injection in the V2 Fracture.

The results of gas threshold pressure measurements indicate no restrictions for gas entry into the water bearing V2 fracture, as is shown in figure 4.

In the matrix intervals gas was injected with pressures up to 5.0 MPa. From the very low decrease of pressure after the shut-in it was concluded, that the GTHP must be much higher than 5 MPa (The test equipment was limited to 5 MPa.).

### 3 Modelling

The modelling of the two-phase flow in the Äspö site was performed in three steps. The first was a three-dimensional single-phase flow model of the surrounding area of the niche 2715. In this model only the water flow was considered, since the main purpose of this model was the evaluation of hydrogeological parameters and the boundary conditions of the two-phase flow model. For symmetry reasons only half of the region was modelled using a 500 m × 500 m × 2.5 m piece of rock mass with a fracture with an aperture of 2.5 cm. Both the permeabilities of the fracture and the matrix, which were determined experimentally to be  $10^{-12} \text{ m}^2$  and  $10^{-20} \text{ m}^2$ , respectively, are assumed to be homogeneous.



Unfortunately, the comparison of calculated and at several locations in the fracture measured pressure data indicated that the assumption of homogeneous permeability of the fracture did not hold. In the second step instead of homogeneity three different zones of constant permeabilities were introduced to meet the measured pressure values. These permeabilities were varied under the constraints to achieve the pressure values, the pressure gradient in the middle zone, and to maintain the outflow rate of water into the niche of about 2 l/min. Under these conditions the permeabilities were fixed to the values  $2 \cdot 10^{-14} \text{ m}^2$ ,  $5 \cdot 10^{-12} \text{ m}^2$ , and  $6.6 \cdot 10^{-13} \text{ m}^2$ . It is not yet understood why the zone nearest to the niche has the smallest permeability. Anyway the use of these values resulted in a fairly good agreement of measured and simulated pressure values. This model served as the base for the two-phase flow model of the dipole test.

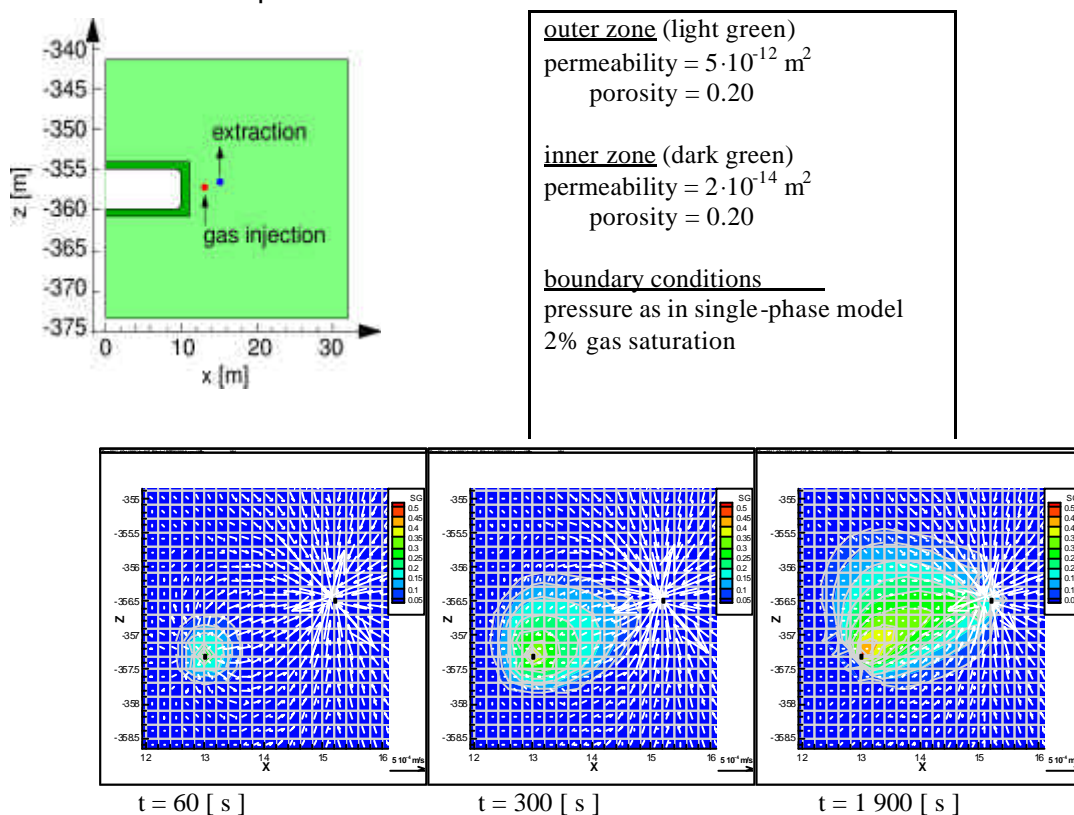


Figure 7 The dipole test: modelled region (top), and calculated gas saturation at several times (bottom)

In the third step the dipole test is modelled. To model it only a part of the two-dimensional fracture model is used. In the top of figure 7 the modelled area and the used hydraulic parameters are shown. The permeabilities as well as the values of the water pressure at the boundaries are taken from the single-flow model. As initial condition the gas saturation is assumed to be 2%. At the boundaries the gas saturation is fixed to 2%, too. Gas is injected at a constant flow rate of 2 l/min. The bottom of figure 7 shows the calculated gas saturation at different times. Whereas the shape of the saturation distribution after 60 s is radial

symmetric, it becomes more and more asymmetric with time due to the buoyancy of the gas in water. The model predicts a steady state distribution after 1 900 s. Since the dipole test is currently performed by BGR, no measured data are available to be compared with the simulation until now.

In parallel to this experimental and modelling work Prof. R. Helmig and his colleagues at the Technical University of Braunschweig developed on behalf of GRS the new computer code *Mufte-ug*. This code enables to model two-phase-two-component flow of air and water in three-dimensional porous and fractured-porous media. The fractures can be explicitly modelled as two-dimensional planes or one-dimensional lines. In this case the liquid phase consists of water and dissolved gas, while the gaseous phase consists of dry air and water vapour. It is assumed that the phase transition processes, i.e. dissolution, condensation, and vaporisation, are isothermal and in local equilibrium. Additionally the most advanced numerical techniques like multigrid algorithms and parallelisation are applied.

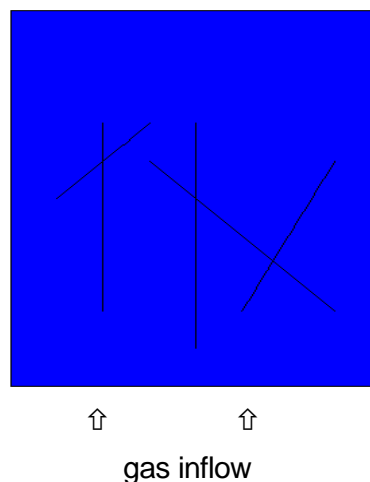


Figure 8 Homogeneous model area with five intersecting fractures

To demonstrate the feasibility of the new developed code a two-dimensional homogeneous area with five intersecting fractures is modelled (cp figure 8). In the initial state the gas saturation is zero and at the bottom of the model there are two pointlike gas sources. Figure 9 shows the temporal development of the gas saturation in the modelled area at five different times. It can be seen that plumes are built in the matrix.

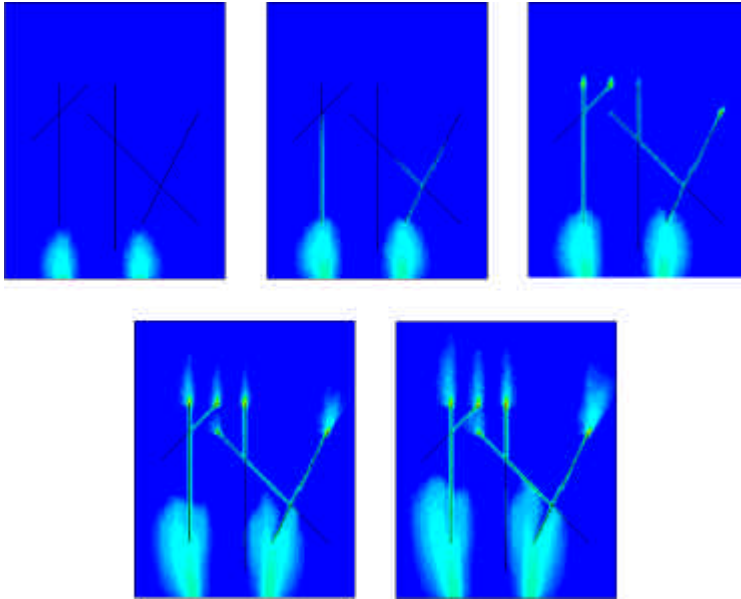


Figure 9 Temporal development of gas flow in porous medium with several fractures

After gas entered fractures it is transported immediately to the upper end of the fracture. After the built up of the gas entry pressure in the matrix gas gets into the rock matrix and builds plumes again. In the bottom pictures one can observe that no gas is transported across fractures.

## 5 Summary

The fracture system V2, which is a system of main faults intersected by steps and splays, dominates the flow field in the vicinity of the niche 2715. Measurements and simulations show evidence that the pressure distribution has become stationary after the excavation of the tunnel and the niche. Simulations indicate that the flow field in the rock matrix is negligible and does not contribute to the water inflow into the niche. But the observed pressure distribution within the fracture requires the consideration of heterogeneous permeabilities for the fracture in models. Gas threshold pressure tests clearly show that the gas entry pressure into the fracture is almost zero whereas into the rock matrix it is at least larger than 5 Mpa, i.e. two-phase flow phenomena are of minor importance in the far field of a repository at the Äspö site. On the other hand concerning the near field of a repository, especially in the presence of geotechnical barriers with bentonite, no conclusion can be drawn.

After completion of the development work the computer code Muftu-ug offers a tool with which two-phase-two-component flow of water and air through porous and fractured-porous

media can be modelled taking explicitly into account the fractures. With the use of massively parallel computers, the computing time can also be kept within acceptable limits.

## 6 References

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