

# **SELF SEALING OF CLAY AT ELEVATED TEMPERATURES**

**(RTDC 4 - WP 4.4 - Task 4)**

**Hanskurt Fröhlich**

**BUTEC Umwelttechnik GmbH  
Kölner Strasse 6  
D-65760 Eschborn**

**Final Report**

**Eschborn, June 2005**

On behalf of the German Bundesministeriums für Wirtschaft und Arbeit (BMWA). FZ 02 E 9864

Project co-funded by the European Commission under the Euratom Research and Training Programme on Nuclear Energy within the Sixth Framework Programme (2002-2006)

## Content

<b>0</b>	<b>SUMMERY .....</b>	<b>1</b>
<b>1</b>	<b>INTRODUCTION.....</b>	<b>2</b>
<b>2</b>	<b>DESCRIPTION OF THE STATE-OF-THE-ART AND EXPERIMENTAL PLANNING .....</b>	<b>2</b>
<b>3</b>	<b>PROVISION OF SAMPLES AND PREPARATION .....</b>	<b>4</b>
<b>4</b>	<b>MODIFICATION OF EXISTING TEST EQUIPMENT .....</b>	<b>4</b>
<b>5</b>	<b>PRE-TESTS FOR MEASURING RELATIVE PERMEABILITY OF CLAY SAMPLES (GAS AND IMMISCIBLE LIQUID).....</b>	<b>7</b>
<b>6</b>	<b>SELF SEALING TESTS WITH FORMATION WATER FROM MONT TERRI AS MEASURING FLUID.....</b>	<b>16</b>
<b>6.1</b>	<b>Permeability test at room temperature .....</b>	<b>16</b>
<b>6.2</b>	<b>Permeability test at temperature of 90 °C.....</b>	<b>22</b>
<b>7</b>	<b>CONCLUSION .....</b>	<b>25</b>
<b>8</b>	<b>LITERATURE .....</b>	<b>27</b>

## 0 Summery

In the framework of the Integrated project NF-PRO of the sixth framework programme Euratom the near-field of a geological repository for radioactive waste and spent fuel will be investigated.

The objective of the here described work is to investigate in laboratory experiments the self sealing of clay stone in the EDZ at elevated temperatures. Therefore investigations with clay samples from the underground laboratory Mont Terri were conducted. To get a basis to compare the initial configuration of the samples, the intrinsic permeability was measured using nitrogen as measuring fluid. To investigate the effect of using an immiscible fluid without any chemical reaction isooctane was used as measuring fluid. The main tests were performed using formation water from Mont Terri at room temperature and at 90 °C. The essential difference between isooctane and formation water is that isooctane doesn't suspend clay and no chemical reactions occur to clay.

In summary the investigations show that using dried samples and nitrogen as measuring fluid a decrease of permeability only occurs if the confining pressure increases.

Using isooctane as measuring fluid, the permeability decreases continuously and the decrease is reversible. After removing the isooctane out of the sample, the intrinsic permeability was nearly the same as measured before the test with isooctane.

The use of formation water as measuring fluid results in a severe decrease of permeability. Within a few minutes no more flow is detectable. But depending on the initial permeability a water flow can be detected within a time period of several hundred hours. The now measured permeability is about 2 to 3 decades lower than the initial permeability. Independent on temperature only a very low decrease of permeability could be detected if the confining pressure was not changed. Not until the confining pressure increases the permeability decreases also. A confining pressure of 3 MPa leads to a total blockade of flow within 500 h.

Due to self-sealing effects no principle difference between the behaviour at room temperature and at 90 °C could be detected.

## 1 Introduction

This study is part of the EU Integrated project NF-Pro “Understanding and physical and numerical modelling of key processes in the near-field, and their coupling, for different host rocks and repository strategies”.

The objective of this work package is to generate in laboratory tests basic data of self sealing and swelling effects of indurate clay at increased temperatures during simultaneous transport of liquid. To get these informations, several permeability tests have to be preformed.

## 2 Description of the state-of-the-art and experimental planning

A review of relevant literature has been performed and based on the actual state-of-the-art the test plan has been elaborated.

In literature it was found that most of permeability tests were carried out with samples drilled perpendicular to the bedding, therefore our intention was to investigate samples drilled parallel to the bedding /Marschall et al. 2003; NTB 02-03/

To get basic information about the initial conditions of the clay samples, in pre-tests the permeability to gas and immiscible liquid has been determined with original samples and dried samples from Mont Terri. After these tests the main tests with simulation of formation water from Mont Terri were carried out for quantifying self sealing effects.

The test plan for the work to be carried out is shown in the following Table 1:

### Table 1: Test Plan

Tests at room temperature

Measuring of permeability with gas (original sample from Mont Terri):

Test conditions:

Measuring fluid: nitrogen

Confining pressure: 1 - 3 MPa

Gas injection pressure: 0.2 – 1 bar, depending on permeability

Desaturation test

Measuring of weight loss till weight constancy at Temperature of 105°C

Measuring of permeability with gas (dried sample from Mont Terri):

Test conditions:

Measuring fluid:	nitrogen
Confining pressure:	1 - 3 MPa
Gas injection pressure:	0.2 – 1 bar

Measuring of permeability with isooctane (dried sample from Mont Terri):

Test conditions:

Measuring fluid:	isooctane
Confining pressure:	1 - 3 MPa
Fluid injection pressure:	1 – 2 bar

Measuring of permeability with gas (same sample from Mont Terri which was used for the test with isooctane, dried after isooctane test):

Test conditions:

Measuring fluid:	nitrogen
Confining pressure:	1 - 3 MPa
Gas injection pressure:	0.2 – 1 bar

Sealing test, measuring of permeability with formation water from Mont Terri

Test conditions:

Measuring fluid:	nitrogen
Measuring liquid:	simulation of formation water from Mont Terri
Confining pressure:	5 - 10 MPa
Gas injection pressure:	0.2 bar
Liquid injection pressure:	1 – 5 bar

Tests at elevated Temperature (90 °C)

Sealing tests; measuring of permeability with formation water from Mont Terri

Test conditions:

Measuring fluid:	nitrogen
Measuring liquid:	simulation of formation water from Mont Terri
Confining pressure:	5 - 10 MPa
Gas injection pressure:	0.2 bar
Liquid injection pressure:	4 bar

### 3 Provision of samples and preparation

The Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover (BGR) made available 12 samples from Mont Terri, drilled parallel to the bedding. The samples were gas tight welded in metal plated foil. All samples were drilled parallel to the bedding. Details of the samples are shown in Table 2. Due to the modification of the autoclave the samples could be used for measurement without any adaptation.

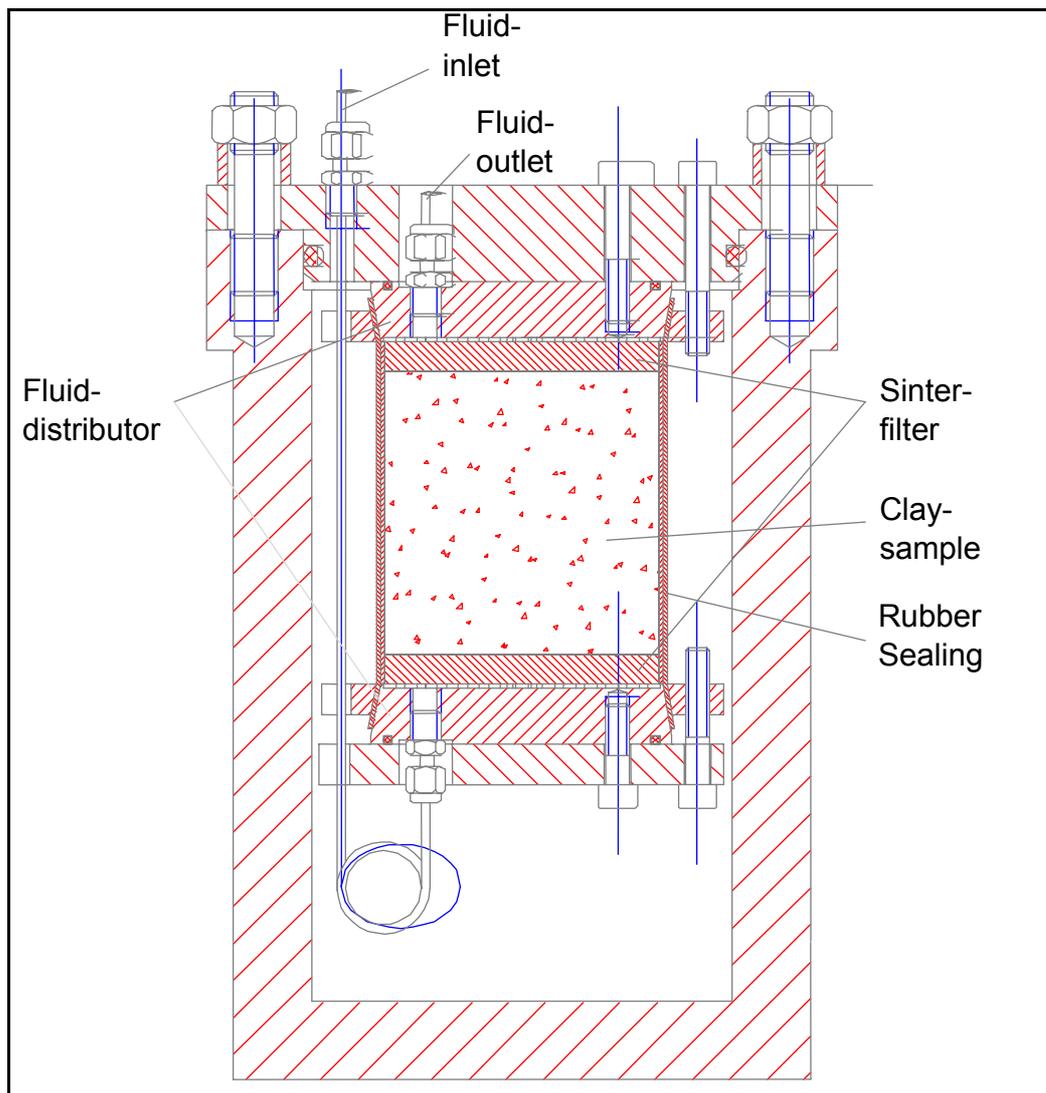
**Table 2: Samples from Mont Terri**

Number	Sample description	depth		dimensions	
		from [m]	to [m]	Diameter [mm]	Length [mm]
1	Mon Terri BLT-10/08/01	4,7	4,8	100	100
2	Mon Terri BLT-10/08/02	4,8	4,9	100	100
3	Mon Terri BLT-10/08/03	4,9	5,0	100	100
4	Mon Terri BLT-10/09/01	5,5	5,6	100	100
5	Mon Terri BLT-10/09/02	5,6	5,7	100	100
6	Mon Terri BLT-10/09/03	5,7	5,8	100	100
7	Mon Terri BLT-10/10/01	5,9	6,0	100	100
8	Mon Terri BLT-10/10/02	6,0	6,1	100	100
9	Mon Terri BLT-10/10/03	6,1	6,2	100	100
10	Mon Terri BLT-10/11/01	6,31	6,41	100	100
11	Mon Terri BLT-10/11/02	6,41	6,51	100	100
12	Mon Terri BLT-10/11/03	6,51	6,61	100	100

### 4 Modification of existing test equipment

From former investigations to measure permeability of rock salt, the test equipment was available /FRÖ 99; FRÖ 03/

To carry out the measuring of permeability and self sealing tests with clay samples the existing equipment had to be modified. Fig. 1 shows a drawing of the autoclave in which the clay samples were fixed. The sample is surrounded by an elastic rubber sealing, which transfers the simulated rock pressure from the oil to the sample. The oil pressure is generated by an oil pump outside the measuring box. In order to keep the rock pressure constant, with decreasing porosity, oil has to be supplied to equalise the loss of volume. For the here performed tests the inner configuration of the autoclave had to be modified, because of the dimensions of the clay samples.



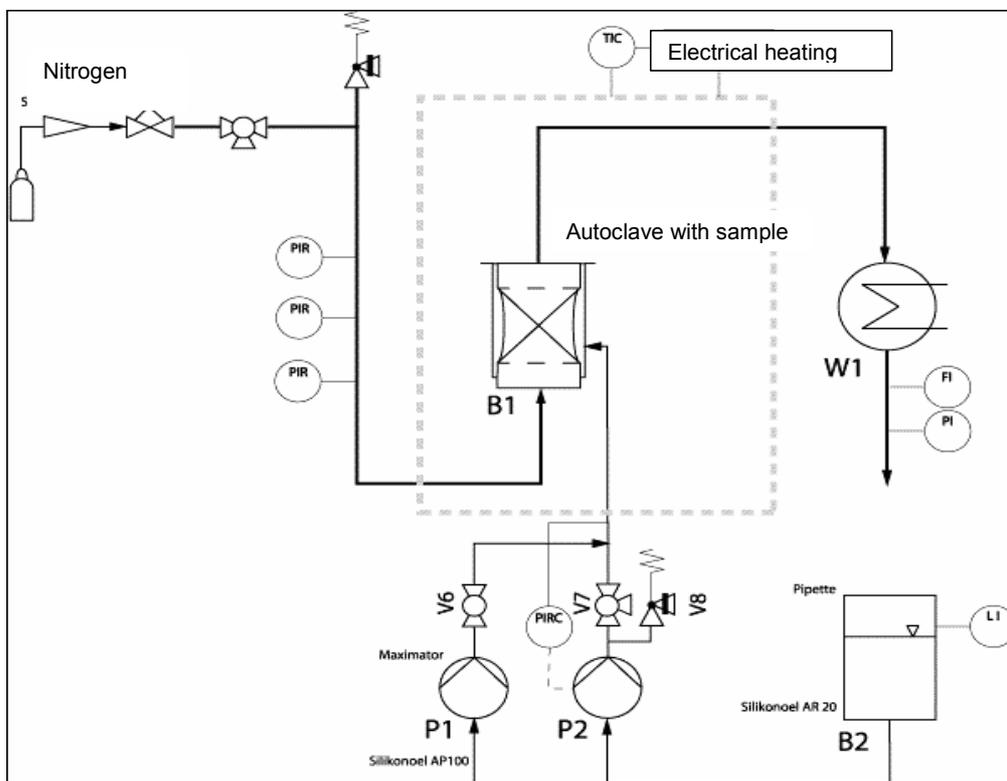
**Fig. 1: Autoclave for measurement of permeability**

Fig. 2 shows a photo of the lab set-up which was designed for permeability and diffusion tests at max. temperature of 150 °C. In this test equipment tests can be carried out with liquid as well as with gas as measuring fluid. Temperature is adjustable from room temperature up to 150 °C with a temperature constancy of  $\pm 0.2$  °C. This set-up was completely available for the self sealing tests with clay stone samples.

The design for measurement of gas permeability is shown in the flow sheet in Fig. 3. In the permeability tests with gas, nitrogen was used as measuring gas. Sample inlet pressure was adjusted by pressure reducing valves and measured by high precision pressure detectors. Sample outlet pressure correlates to ambient pressure. The flow rate of gas was measured by so called "film flow meter". Permeability is calculated according to Darcy's law.



**Fig. 2: Photo of lab set-up, designed for permeability and diffusion tests at max. Temperature of 150 °C**



**Fig. 3: Flow sheet of test device for measurement of gas permeability**

## 5 Pre-tests for measuring relative permeability of clay samples (gas and immiscible liquid)

To get comparable results at different in- and outflow pressure and using different measuring fluids the self healing experiments were analysed using the Darcy equation.

The principle for measuring with gas is based on Darcy's equation:

$$k = \frac{2 * Q}{A} * p_a * \eta \cdot \frac{L}{p_i^2 - p_o^2}$$

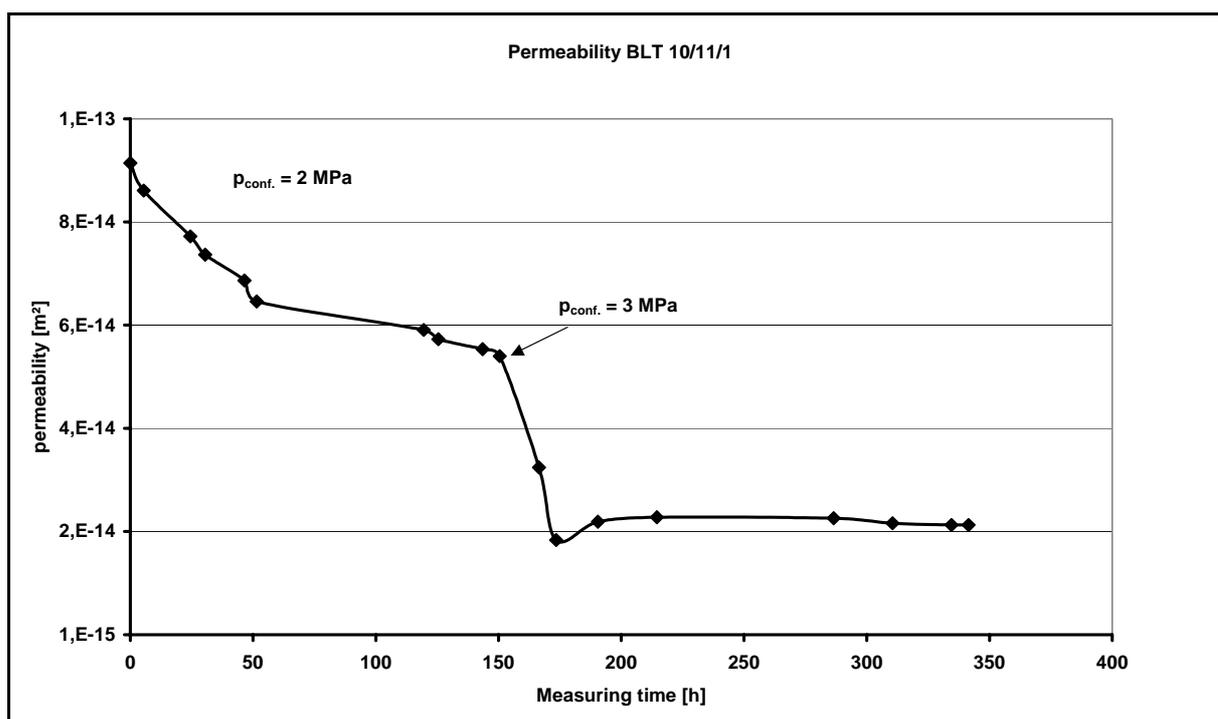
with:

k = intrinsic permeability	[m <sup>2</sup> ]
Q = flow rate	[m <sup>3</sup> /s]
A = cross-section of the flow path	[m <sup>2</sup> ]
p <sub>o</sub> = fluid outlet pressure	[N/m <sup>2</sup> ]
η = dynamic viscosity	[N·s/m <sup>2</sup> ]
p <sub>i</sub> = fluid inlet pressure	[N/m <sup>2</sup> ]
L = length of sample	[m]

The tests for measuring the permeability with gas have been performed to get a basis to compare the initial configuration of the samples. Permeability tests were conducted using natural wet and dried specimens under different confining and in-flow pressures.

The first permeability test with nitrogen was performed with sample BTL 10/11/01. The sample was in the condition as received from BGR.

The result of this first test is shown in Fig. 4. The test was started with a confining pressure of 2 MPa. As can be seen in this diagram within about 150 h the permeability decreases from 9.2·10<sup>-14</sup> m<sup>2</sup> to 5.5·10<sup>-14</sup> m<sup>2</sup>. After 150 h the confining pressure was increased to 3 MPa, resulting in a decrease of permeability down to 2.2·10<sup>-14</sup> m<sup>2</sup>. The measurement was continued up to 350 h showing only a slight further decrease.



**Fig. 4: Permeability to gas (Sample 10/11/01)**

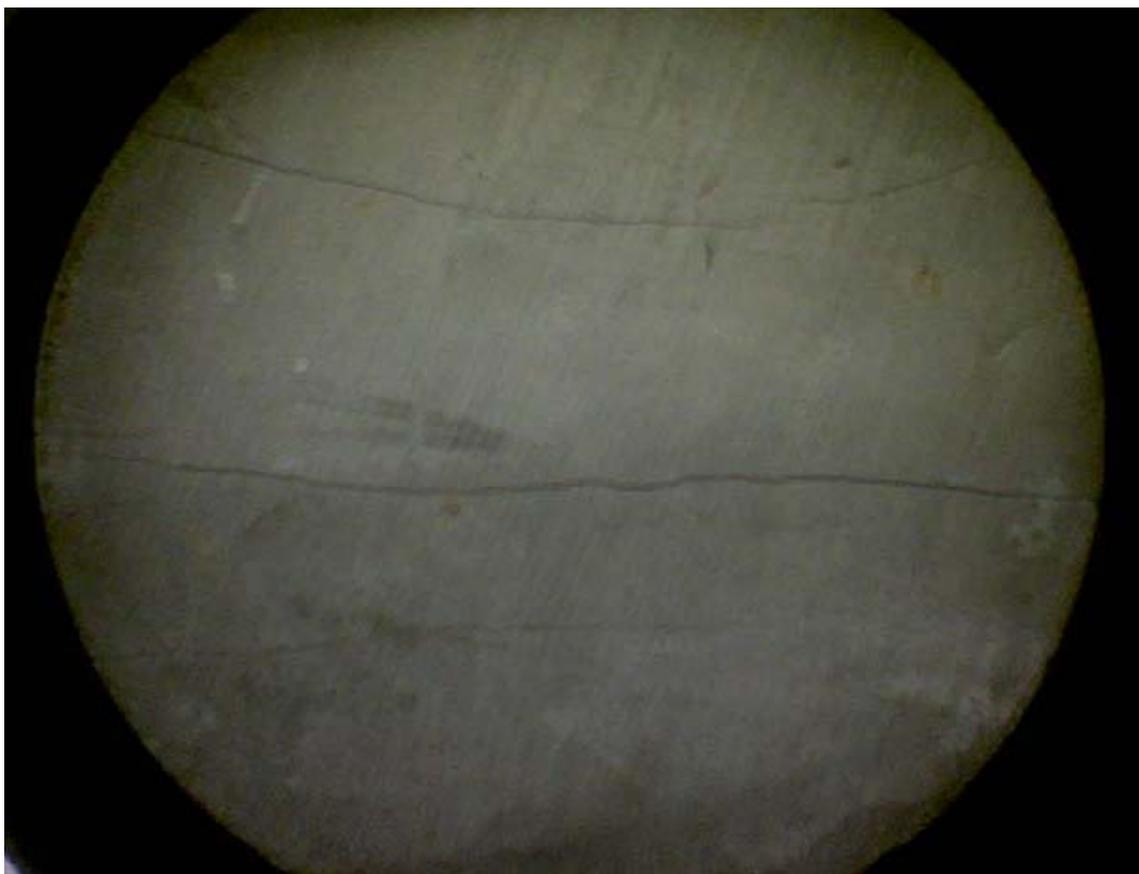
The next test was performed with sample 10/8/01. A photo of the end wall of this sample is shown in Fig. 5. The sample as delivered by BGR was shrunk in metal plated, steam tight plastic foil. As can be seen from this photo, there are two micro cracks visibly. It can be assumed that the permeability of this clay sample will be mainly affected by these micro cracks. This sample was used for the first main gas permeability test.

The result of the permeability test is presented in Fig. 6. The test was started with the sample before drying. The starting confining pressure was 1 MPa. The initial relative permeability to nitrogen was about  $3.5 \cdot 10^{-17} \text{ m}^2$ . After a test time of about 100 h, the permeability decreased to  $1.5 \cdot 10^{-17} \text{ m}^2$ . Then the sample was dried for 360 h at a temperature of 105 °C (see Fig. 7), due to this drying the permeability increased to  $5.9 \cdot 10^{-15} \text{ m}^2$ . Hence the confining pressure was increased to 2 MPa, followed by a jump in permeability down to  $3.7 \cdot 10^{-15} \text{ m}^2$ . A further increase of confining pressure from 2 MPa to 3 MPa was causing a further jump in permeability down to  $1.4 \cdot 10^{-15} \text{ m}^2$ . The permeability stays nearly constant at  $1.2 \cdot 10^{-15} \text{ m}^2$ . In all three steps there was no measurable decrease of permeability without increase of confining pressure.

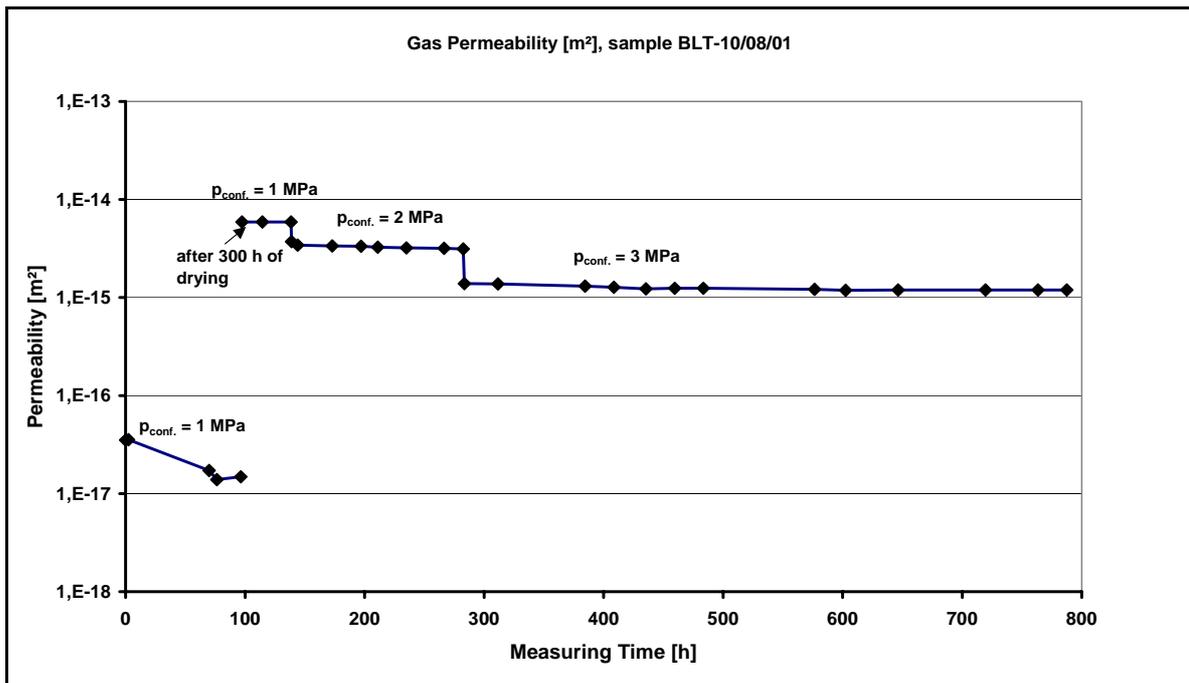
The deviation from Darcy's law using gas as measuring fluid caused by an additional sliding flow can be corrected by the Klinkenberg coefficient. The real permeability is lower than the measured apparent permeability by the sliding flow. Meas-

uring the permeability at different pressure an extrapolation can be performed to determine the real permeability.

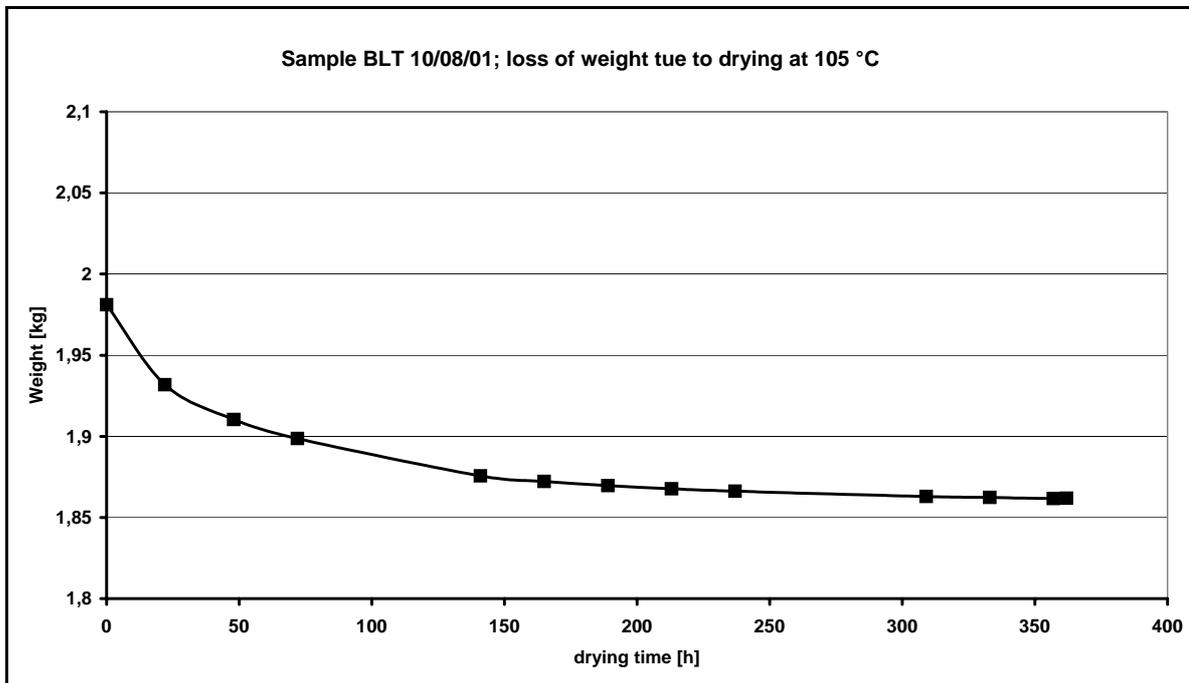
By plotting the calculated apparent permeability by Darcy's law over the inverse average gas pressure the curve shown in Fig. 8 is obtained. The intersection point of the regression line with the Y-axis that means at infinite gas pressure yields the real permeability. This value of real permeability is  $9.49 \cdot 10^{-16} \text{ m}^2$ .



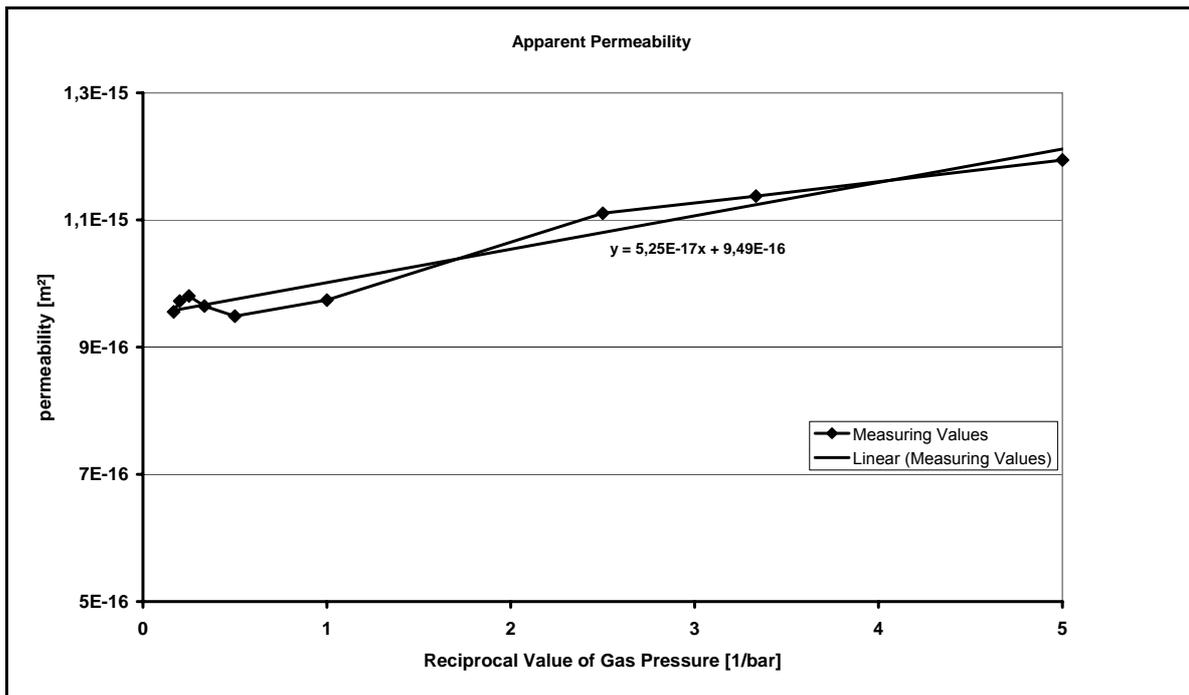
**Fig. 5: End wall of sample BLT 10/08/01**



**Fig. 6: Permeability to gas; before and after drying (Sample 10/08/01)**



**Fig. 7: Loss of weight due to drying at 105° C (sample BLT 10/08/01)**



**Fig. 8: Apparent permeability as a function of reciprocal value of mean gas pressure (Klinkenberg-coefficient)**

To investigate the effect of using an immiscible fluid without any chemical reaction isooctane was used as measuring fluid. The dynamic viscosity of isooctane at temperature of 25 °C is 0.52 mPa·s.

The principle for measuring permeability with liquid is based on Darcy's equation:

$$k = \frac{Q}{A} * \eta \cdot \frac{L}{p_i - p_o}$$

with:

- |  |          |
|--|----------|
| k = intrinsic permeability             | [m²]     |
| Q = flow rate                          | [m³/s]   |
| A = cross-section of the flow path     | [m²]     |
| p <sub>o</sub> = fluid outlet pressure | [N/m²]   |
| η = dynamic viscosity                  | [N·s/m²] |
| p <sub>i</sub> = fluid inlet pressure  | [N/m²]   |
| L = length of sample                   | [m]      |

---

The essential difference between isooctane and formation water is that isooctane doesn't suspend clay and no chemical reactions occur to clay. The test was carried out with the same sample BLT 10/08/01. The test was performed directly after the test with gas, without dismantling the clay sample. To calculate the permeability, the volume of isooctane which has passed the clay sample was determined by weighing.

The result of this test is shown in Fig. 9. As can be seen from this figure the starting permeability was  $3 \cdot 10^{-16} \text{ m}^2$ . Compared to the real gas permeability ( $9.5 \cdot 10^{-16} \text{ m}^2$ ) this corresponds to a reduction by a factor 3. This reduction could be caused by remaining quantity of nitrogen which also was flown through the sample but was not detected and furthermore by saturating the sample with isooctane during a 2 days period at a confining pressure of 2 MPa before starting permeability measurement. The permeability test was carried out at a constant confining pressure of 3 MPa.

Within the first 3 days the permeability decreases to  $1.5 \cdot 10^{-16} \text{ m}^2$ , followed by a quasi stationary curve. Within the next 12 days the decrease was about 13 %. Because of required refilling of the storage container for isooctane the measuring circuit had to be opened and it is assumed that air has been added into the supply pipe. The result of this air supply is shown in the significant decrease of permeability when starting measuring again. As only the volume flow of isooctane is measured, the two phase flow results in a loss of measured volume which leads to a pretended lower permeability. It took 6 days to remove all air and the permeability increased to nearly the same value as before the refilling of the storage tank. During the following measuring period there was a slight decrease down to  $2 \cdot 10^{-17} \text{ m}^2$ . From the extrapolated regression curve it can be calculated that the technical tightness of about  $1 \cdot 10^{-21} \text{ m}^2$  will be reached after about  $1 \cdot 10^{15}$  years.

Fig. 10 shows the loss of weight (isooctane) by extracting the isooctane from the sample in vacuum. From this weight loss the porosity open to fluid could be determined. The calculated value of 7 % is similar to Literature results from NAGRA.

The comparison of the isooctane drying tests with the previous extraction of water leads to nearly the same result for the dry weight of the sample (Fig. 11).

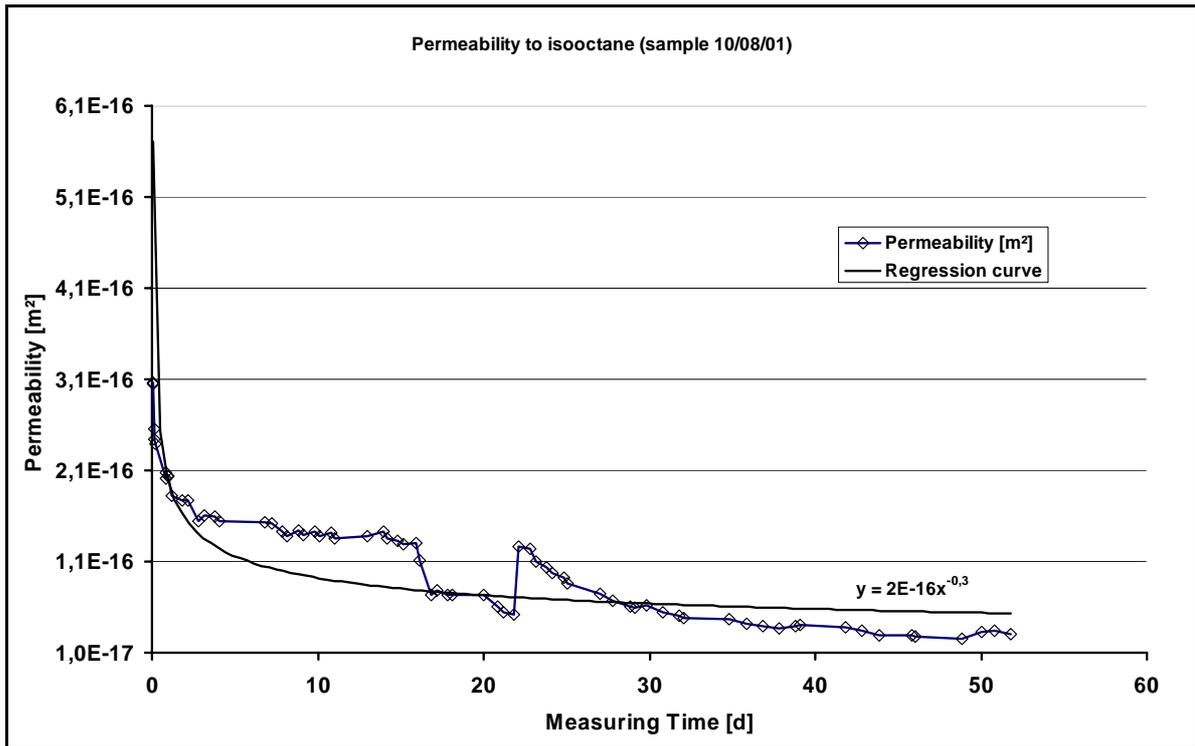


Fig. 9: Permeability to isooctane (Sample 10/08/01)

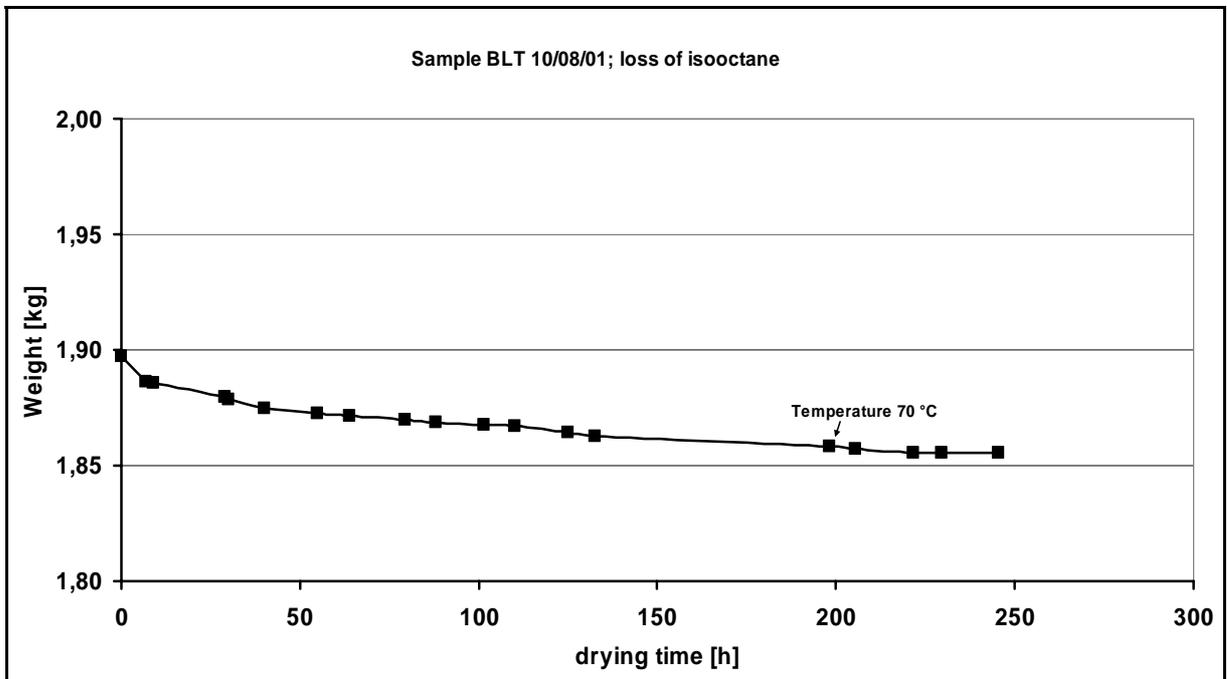
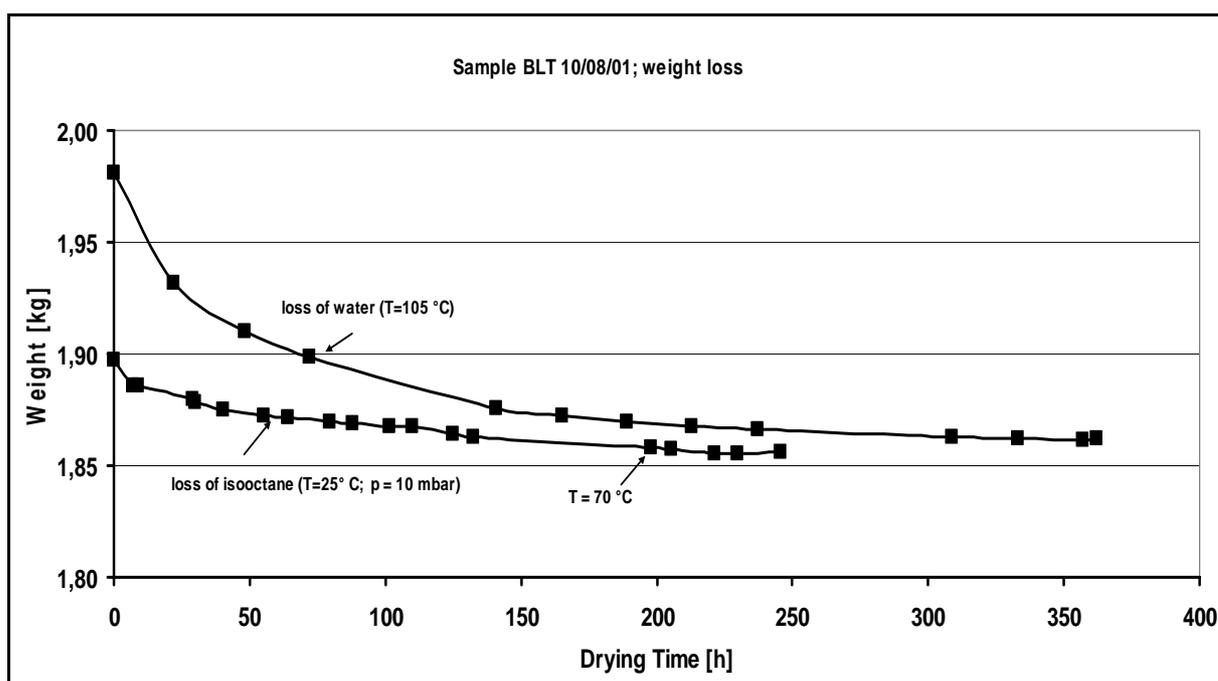


Fig. 10: Reduction of weight (isooctane loss) due to vacuum of 10 mbar



**Fig. 11: Reduction of weight due to temperature and vacuum drying**

After removing the isooctane the gas permeability was measured again (see Fig. 12). This was done in order to check whether the change of permeability during the test with isooctane was a reversible or an irreversible effect. The starting permeability of this test was the same as the test with gas before. But unfortunately a screwing in the fluid inlet pipe was leaky so that water (used for transferring the confining pressure) penetrated into the sample. This was causing a severe decrease of permeability. After 90 h the sample was completely tight against inlet pressure up to 3 bar. The drying of the sample after the test shows that 21 g of water had penetrated into the sample.

Fig. 13 shows a photo of the end wall of the sample after getting wet. This not planned result shows that clay samples within this permeability range in a short time present a strong self sealing effect caused by water.

After the water impact the sample was dried again and the measurement of permeability to gas was repeated. The result is shown in Fig. 14. Compared to the initial permeability (shown in Fig. 12) the permeability to gas is nearly the same. These results show that in this case the decrease of permeability due to isooctane and the following water impact was a reversible process.

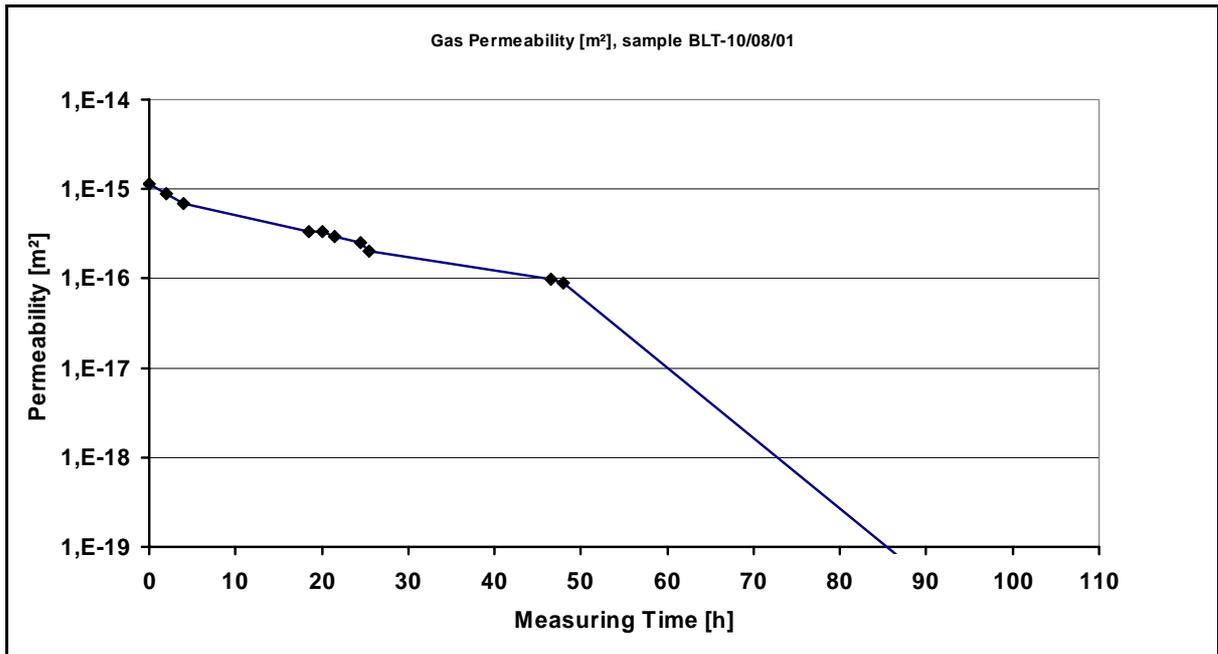
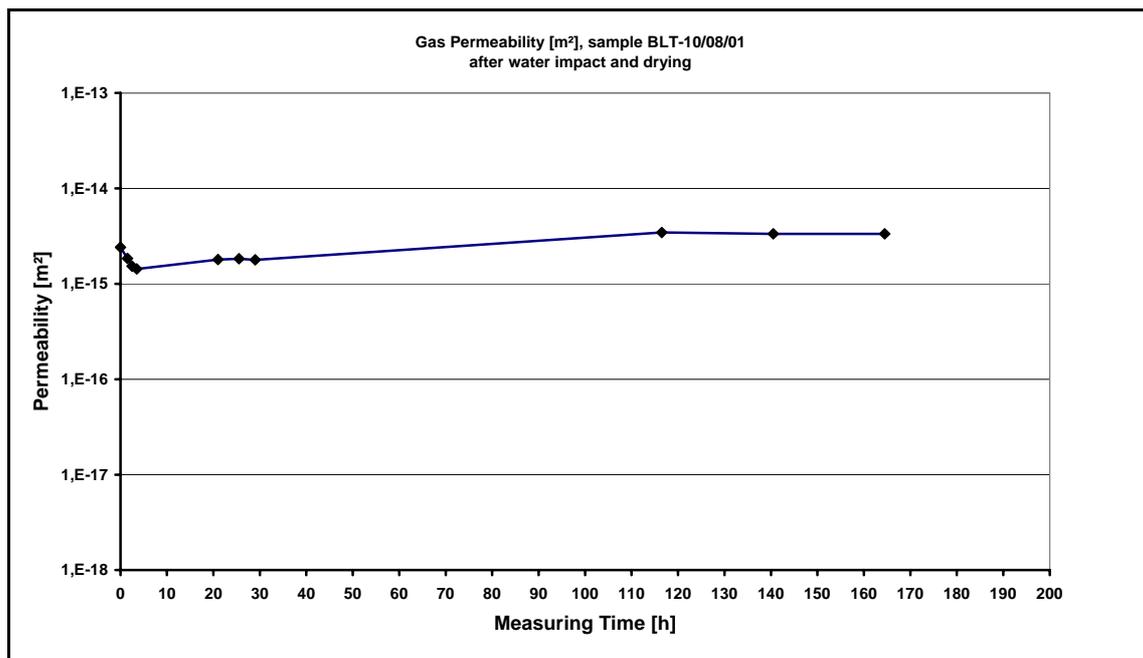


Fig. 12: Permeability to gas; water influx due to leakage in gas injection pipe



Fig. 13: End wall of sample BLT 10/08/01 after water influx due to leakage in gas injection pipe



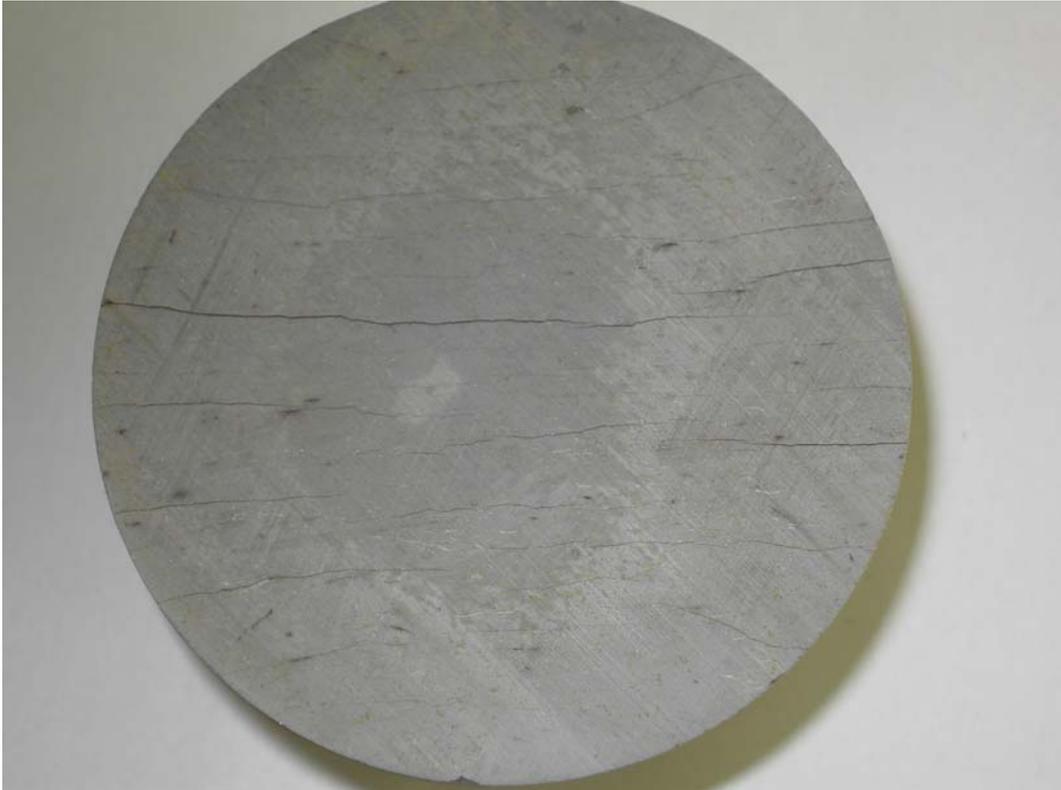
**Fig. 14: Permeability to gas after water impact, followed by drying at initial weight**

## 6 Self sealing tests with formation water from Mont Terri as measuring fluid

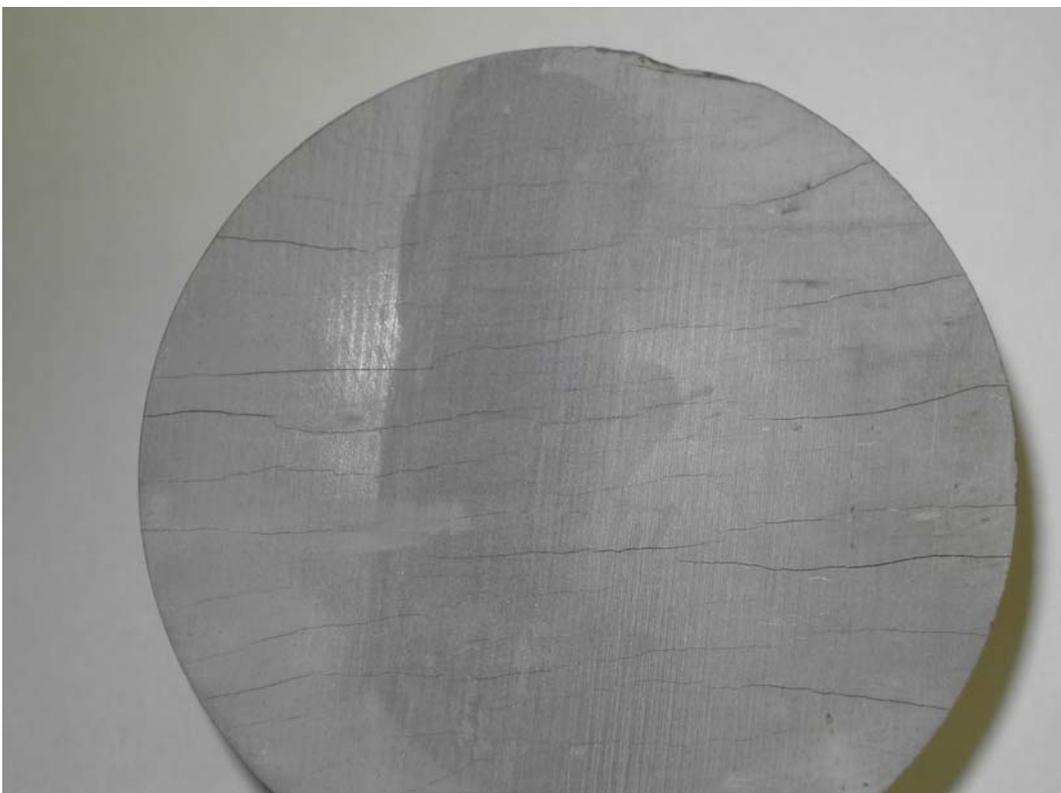
### 6.1 Permeability test at room temperature

The first test with a simulation of formation water from Mont Terri as measuring fluid was performed with sample BLT 10/09/02. To make the structure of cracks at the front and back-side visible, the sample was dried. As seen in Fig. 15 and Fig. 16 front side as well as back side of the sample show a large number of cracks.

In Fig. 17 the result of this test is presented. The test was started with nitrogen as measuring fluid to get the intrinsic permeability. The measured permeability was about  $1 \cdot 10^{-14}$ , with no detectable deviation during the first 200 h. After 200 h the formation water injection was started, resulting in a severe decrease of permeability. Within a few minutes no more flow through the clay sample was detectable. The system was kept at a confining pressure of 1 MPa and a fluid entrance pressure of 5 bar until finally after 1000 h a flow of water could be detected. Calculating the permeability using liquid flow only and ignoring the low gas flow, the permeability was 2 decades lower than measured with gas. The test was continued further 500 h showing no significant change of water permeability. Fig. 18 and Fig. 19 show photos of the back side of the sample BLT 10/09/02 after the test. Compared to the structure of cracks before the test (Fig. 16) a modified pattern becomes obvious.



**Fig. 15: Front side of sample BLT 10/09/02 (before test)**



**Fig. 16: Back side of sample BLT 10/09/02 (before test)**

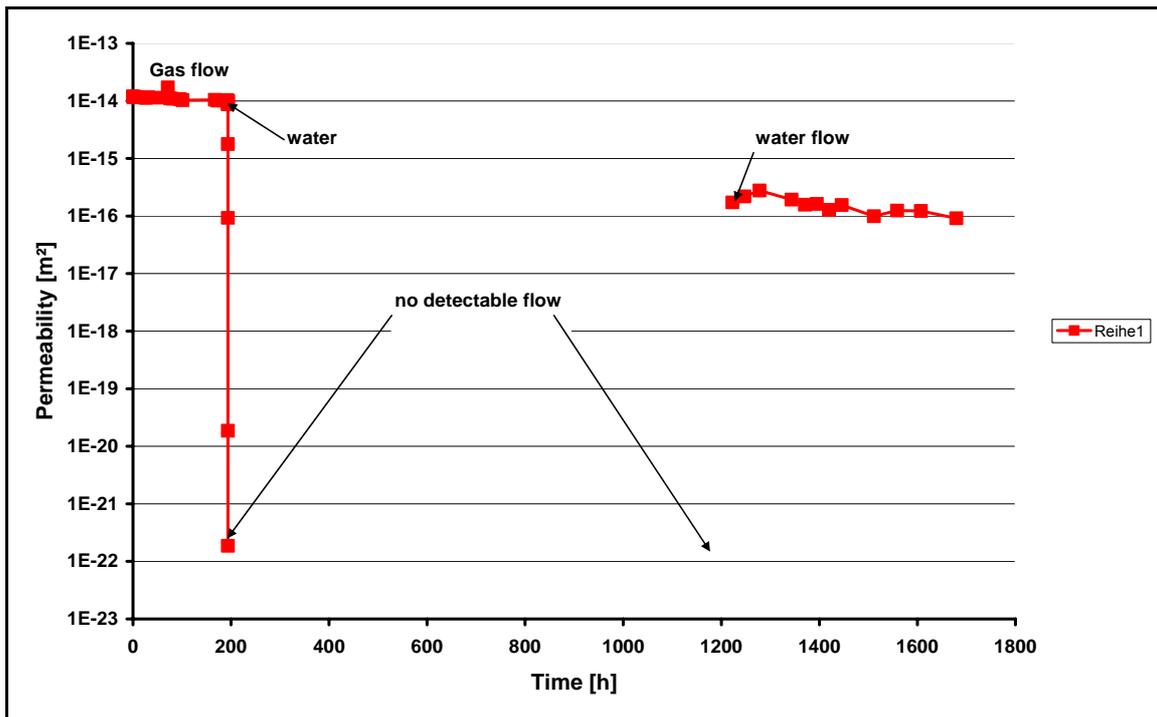
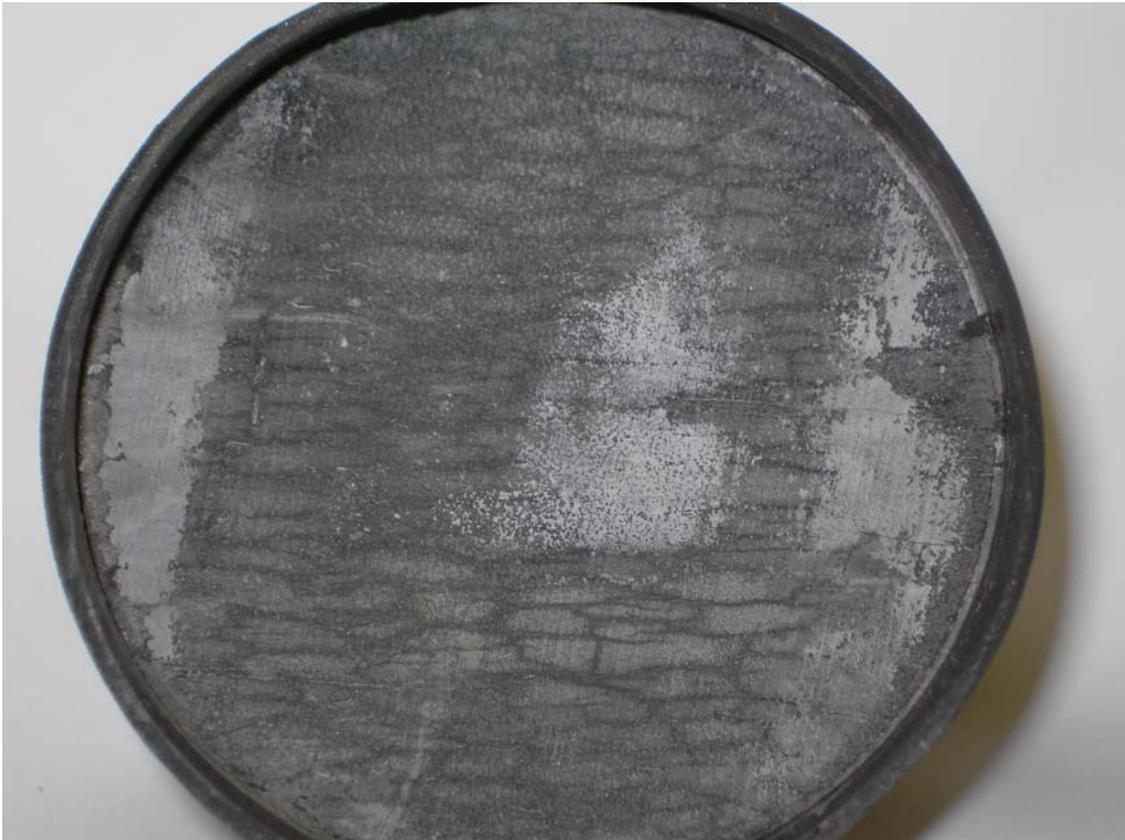


Fig. 17: Permeability of sample BLT 10/09/02



Fig. 18: Back side of sample BLT 10/09/02 (directly after test)



**Fig. 19: Back side of sample BLT 10/09/02 (after test and drying)**

For measuring the permeability, the water which had penetrated the sample was collected and weighed. It became obvious that this water had significant fewer colours than the original formation water.

A fluorescence tracer with a concentration of 500 mg/l was added to the simulation of formation water from Mont Terri. The tracer Fluorescein has a maximum absorption wave length of 492 nm. The tracer is very sensitive to detect smallest quantities of the liquid.

To get information about the concentration of the tracer depending on test time a photo was taken of the samples using an UV lamp.

Fig. 20 shows a photo of samples of formation water, penetrated through the sample BLT 10/09/02. The sample glass on the right side is filled with distilled water. The glass on the left side is filled with the original concentrated solution. The glasses in between contain the samples taken after 55 h (1); 172 h (5+6); 288 h (9) and 456 h (12). It becomes obvious that the tracer is significantly enriched in the samples with increasing time of flow through the clay sample.

In order to get a quantitative description of the results, the samples have been measured with a photometer (Type WTW MPM 3000). The diagram in Fig. 21 shows that with increasing time after break through of liquid there is a nearly linear increase of extinction. The extinction presents the light absorption at a wave length of 490 nm.

The next diagram (Fig. 22) shows the calibration curve for the tracer. In this diagram the extinction is expressed in terms of concentration of the tracer in percent of the original solution concentration. There is a linear dependence of extinction on concentration.

It can be derived from these two sheets that the outflow liquid after 456 h has a tracer concentration of only 5 % of the original liquid. That means that about 95 % of the tracer is retained in the clay sample.



**Fig. 20: Photo of samples of formation water, permeated through sample BLT 10/09/02**

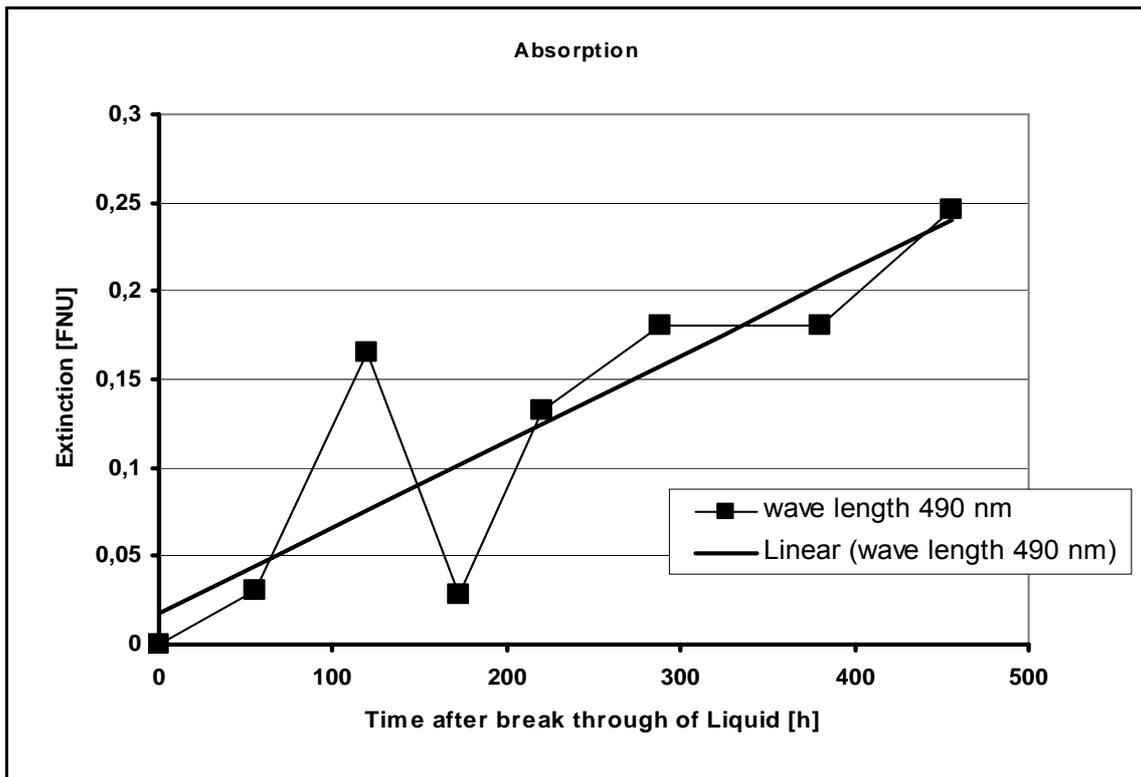


Fig. 21: Increase of tracer concentration in time (BLT 10/09/02)

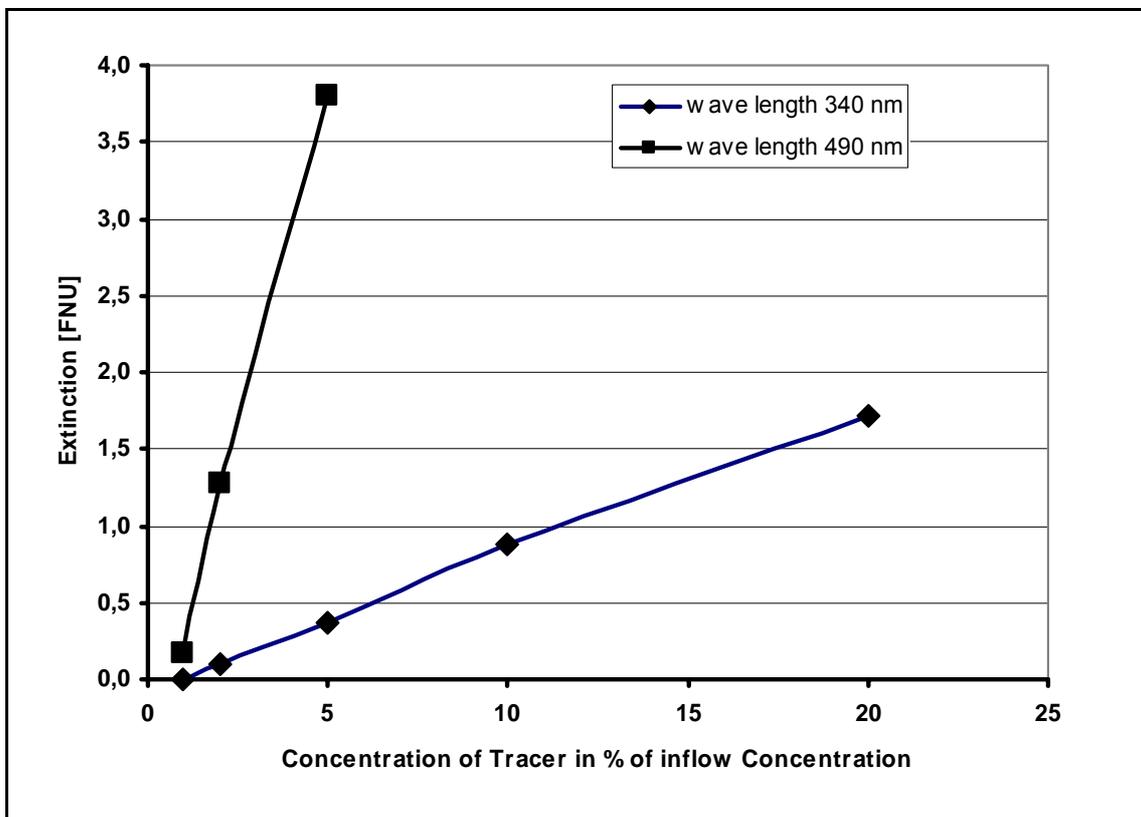


Fig. 22: Calibration of photometer

## 6.2 Permeability test at temperature of 90 °C

The self-healing test at a temperature of 90 °C was performed with sample BLT 10/11/02. Photos of the front- and of the backside of this sample before testing are shown in Fig. 23 and Fig. 24. As can be seen from these photos there are several cracks visible which penetrate the sample longitudinal to the bedding. It can be assumed that the permeability of this sample will mainly be caused by these cracks.

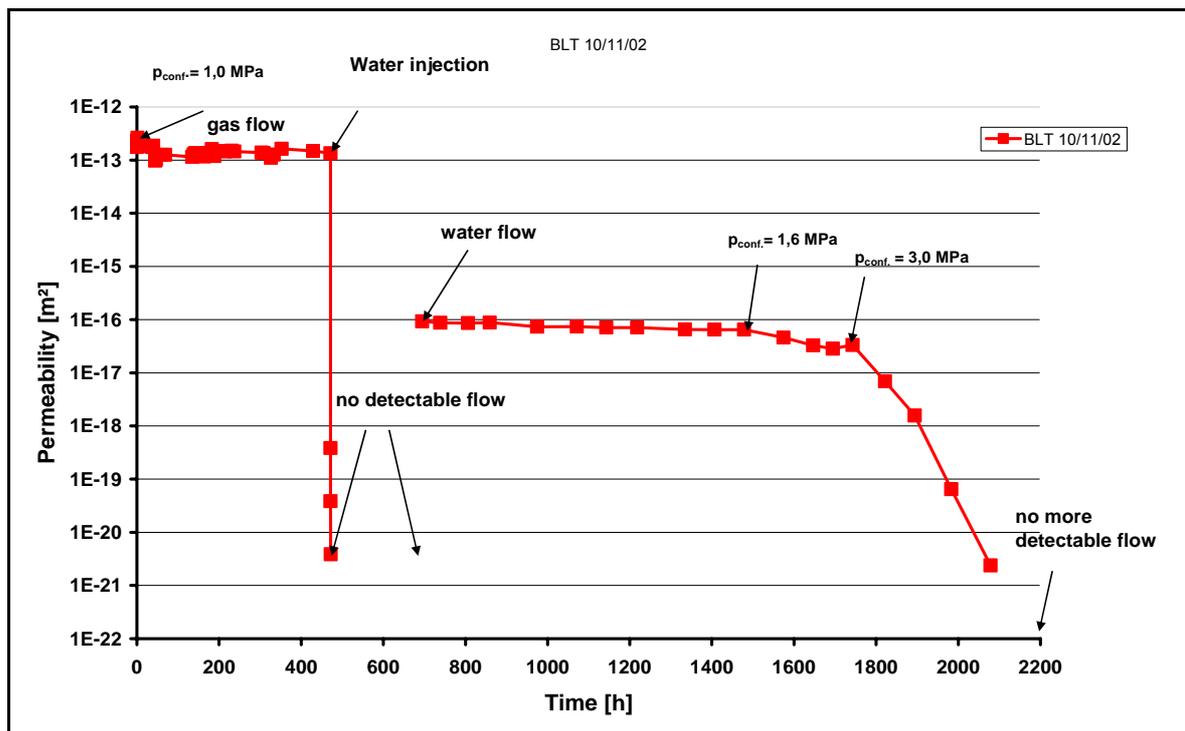
After heating the internal space of the measuring box, the autoclave and the sample up to 90 °C, the measuring was started. To get initial information of the sample the test was started with nitrogen as measuring fluid. The system was kept at a confining pressure of 1 MPa and a fluid entrance pressure of 1,02 bar. As can be seen from Fig. 25, the intrinsic permeability was about  $1,3 \times 10^{-13} \text{ m}^2$ . During the measuring time with gas of about 400 h, there was only a very low decrease of permeability. After about 480 h the injection of formation water was started, resulting in a severe decrease of permeability. Within a few minutes no more flow through the clay sample could be measured. Then the flow inlet pressure was raised to 5 bar until a flow of water could be detected after further 200 h. Calculating the permeability due to Darcy's law, but using liquid flow only and ignoring the low gas flow, the permeability was about 3 decades lower than measured with gas. The test was continued for further 900 h showing a very low decrease of permeability only. After about 1570 h of total test time the confining pressure was increased to 1,6 MPa followed by a stronger decrease of permeability. About 250 h later another increase of confining pressure up to 3 MPa was performed, followed by a significant decrease of permeability. After about 2200 h no more flow was detectable.



**Fig. 23: Front side of sample BLT 10/11/02 (before test)**



**Fig. 24: Back side of sample BLT 10/11/02 (before test)**



**Fig. 25: Permeability of sample BLT 10/11/02**

To get information about the concentration of the tracer depending on test time, the fluid which had penetrated the sample was measured with the photometer. The penetrated liquid had to be diluted with demineralised water at a ratio of 1:4 for getting measurable values. The results of this measurement are shown in Fig. 26. The comparison of these results with the calibration curve (see Fig. 22) shows that the outflow liquid after about 1100 h has a tracer concentration of about 11 % of the original liquid. That means that about 89 % of the tracer is retained in the clay sample. Compared to the results of the former test with sample BLT 10/09/02 the concentration of tracer in the outflow liquid has doubled. A reason for this duplication could be that in sample BLT 10/11/02 the permeability is dominated by a few large cracks, while in sample BLT 10/09/02 it is dominated by more but smaller cracks.

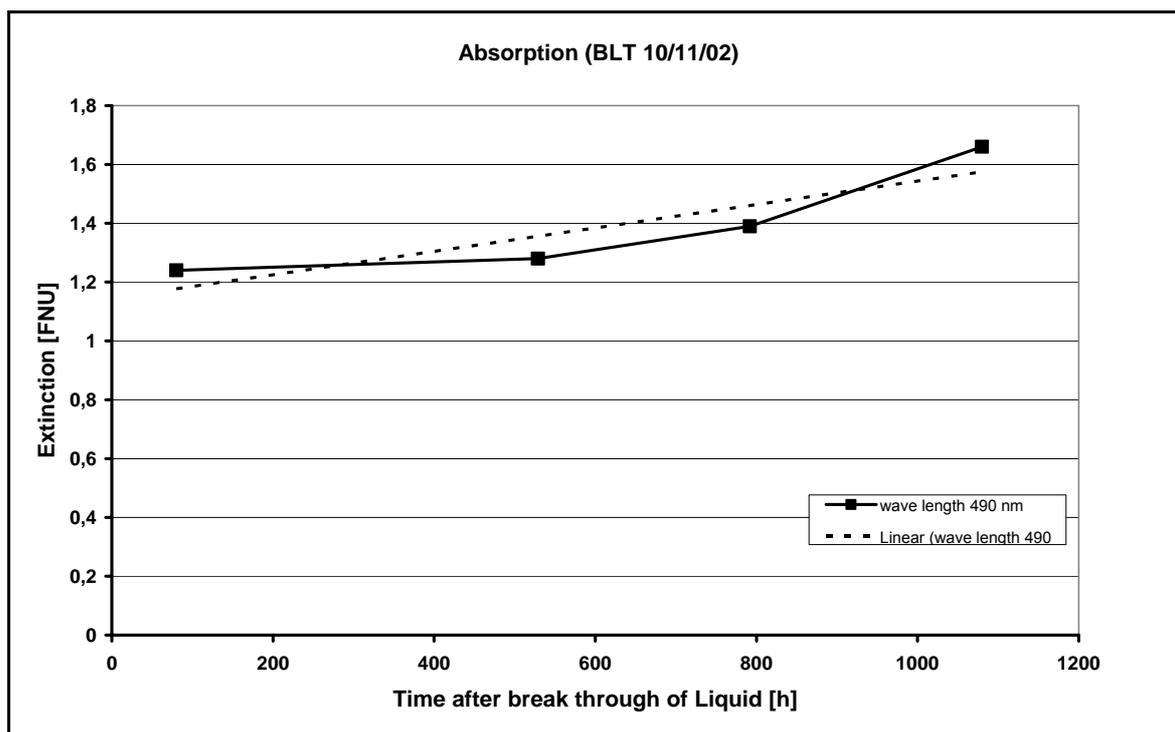


Fig. 26: Increase of tracer concentration in time (BLT 10/11/2)

## 7 Conclusion

The tests with clay samples with natural humidity, using nitrogen as measuring fluid show slow decrease of permeability over time. The use of isooctane as measuring fluid leads to comparable results.

The comparison of the tests with gas and isooctane as measuring fluid shows that using dried clay samples and nitrogen as measuring fluid, no significant decrease of permeability over time is measurable. A decrease of permeability was detected only when the confining pressure was increased.

Using isooctane as measuring fluid there is a continuous decrease of permeability over time and this decrease is a reversible process. After removing the isooctane out of the sample the now measured permeability is nearly the same as before the test with isooctane.

The use of formation water as measuring fluid results in a severe decrease of permeability within a few minutes, but depending on the initial permeability after several hundred hours, a water flow can be detected after the sample is saturated with water. The permeability measured with water is about 2 to 3 decades lower than the intrinsic permeability. Only a very low decrease of permeability could be detected during flow of water if the confining pressure did not change. Using a clay sample with an intrinsic permeability of about  $1,3 \times 10^{-13} \text{ m}^2$  the increase of confining pressure from 1 MPa to 3 MPa leads to a total blockage of flow within 500 h.

Due to self-sealing effects no principle difference between the behaviour at room temperature and at 90 °C could be detected. But this result is only based on the investigation of two samples.

## 8 Literature

/FRÖ 99/

Fröhlich, Hanskurt et.al., Durchlässigkeitsverhalten von Steinsalzversatz gegenüber Laugen unter Berücksichtigung von zeitlich veränderlichen Überlagerungsdrücken und Lösungsvorgängen; Battelle Ingenieurtechnik GmbH, Eschborn Dezember 1999

/FRÖ 03/

Fröhlich, Hanskurt et.al., Untersuchung der Durchlässigkeit von kompaktierten Salzgrus und Salzgestein gegenüber Laugen bei HAW-und DE-typischen Temperaturen; BUTEC Umwelttechnik GmbH, Eschborn, November 2003

/Marschall et al. 2003/

Marschall, Paul, Synthesis of hydro geological investigations at the Mont Terri site (Phase 1-5). Mont Terri Technical Report TR2001-02.

/NTB 02-03/

Technischer Bericht NTB 02-03, Projekt Opalinuston, Synthese der geowissenschaftlichen Untersuchungsergebnisse

Entsorgungsnachweis für abgebrannte Brennelemente, verglaste hochaktive sowie langlebige mittelaktive Abfälle, Dezember 2002