# AN EXPERIMENTAL STUDY ON THE PERMEABILITY OF INTERFACE BETWEEN SEALING PLUG AND ROCK
## シーリングプラグと岩盤の境界面の透水特性について

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岩盤の浸透特性の評価は構造物の安定性や放射性廃棄物の地層処分の場合に地下水の挙動を把握するために最も重要であり、そのため様々な研究が行われている。本論文で、ある放射性廃棄物処分場を対象にして、シーリングプラグと岩盤の境界面の透水特性に関して行われた実験的研究について報告する。特にプラグと岩盤の間に利用されるメンブレーンの有無により境界面の透水特性に与える影響を実験的に明らかにする。

## 1 INTRODUCTION

In recent years, the disposal of high-level radioactive nuclear wastes is a major concern in many countries. For finding a safe long-term storage place for hazardous waste disposals, the number of intensive researches are continuing in many countries. Various geological media are considered for permanent disposal of nuclear wastes. For the following properties, rock salt is considered as a suitable medium for a permanent disposal of high-level radioactive nuclear wastes: (1) rock salt is usually found in stable geological area that has little or no earthquake activity, (2) there is no groundwater circulation, (3) it has low permeability and porosity, (4) it can be easily mined, and (5) it shows creep or time dependent deformation behavior under relatively low stresses. To reduce the permeability of interface between the sealing plug and surrounding rock, the use of a synthetic membrane is considered. However, very few experimental studies have been undertaken so far. An experimental study on the permeability along the grout/membrane/halite interface of a sealing plug and rock mass for a nuclear waste repository under various loading conditions was carried out. The results of experiments are presented and discussed in this paper.

## 2 EXPERIMENTAL SET-UP AND TESTING PROCEDURES

In this study, a laboratory testing program for a nuclear waste project designed to be representative of the oading conditions expected in-situ using two different configurations is briefly described (see Üçpırtı et al. (1992) for details)[1]. One is for the longitudinal-flow tests and the other one is for the radial-flow tests. These tests cover a range of loading conditions. The longitudinal-flow test configuration was selected to perform flow-tests with normal stress on the membrane up to $14.8 MPa$. Radial-flow tests were conducted without confinement of the sample. The normal stress for the radial-flow tests ranged from 0.2 $MPa$ to 4.1 $MPa$.

### 2.1 Material description

The materials used in this testing include halite, very low density polyethylene with a thickness of 1 mm as a membrane and concrete. Halite was delivered to the laboratory in the form of a 91.4 cm diameter core, about 1 m long. The concrete was machined into cylinders.

Halite and concrete samples were cut with a standard core saw to create half cylinders for longitudinal flow testing. These pieces were mated with membrane, and then flow tested using the configuration shown in Figure 1. All tests were conducted with nitrogen as the permeating fluid.

For the unconfined radial-flow tests, the samples consisted of a transversely sliced halite cylinder (nominal 10.2 cm diameter, 10.2 cm length), a similarly sliced concrete cylinder, and a circular piece of very low density polyethylene membrane. These three components were assembled as shown in Figure 2.

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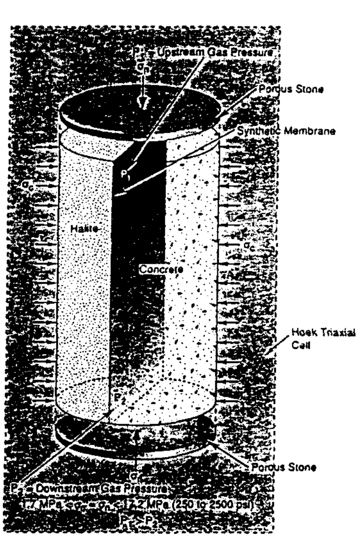


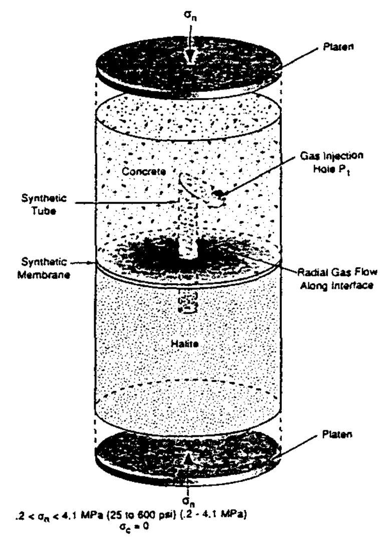




Figure 1 Experimental set-up for longitudinal flow test

Figure 2 Experimental set-up for radial flow test

### 2.2 Test set-up and testing techniques

The general configurations for the interface longitudinal and radial flow tests are given in Figures 1 & 2. A typical longitudinal flow test has the following steps: (1) saturating the test sample, (2) healing the test sample, (3) conducting flow test under a series of externally applied stresses and fluid pressure conditions.

Saturation of the test sample is achieved by applying a pressure pulse about 0.01 $MPa$ to the upstream reservoir at the top of the sample. For ideal conditions, the test specimen is assumed saturated while the pressure of upstream decreases and the pressure of downstream increases, respectively. During saturation, the test specimen is kept under a hydrostatic pressure ranging from 0.7 to 1.7 $MPa$. Before initiating flow tests, the halite used for the interface flow testing was kept under hydrostatic stress ranging from 1.4 to 6.9 $MPa$ for up to 100 hours.

A total of 241 radial-flow tests on halite/membrane/concrete and halite/concrete interfaces were completed. As stated previously, these tests were conducted without confinement of the sample. The axial stress for the radial-flow tests ranged from 0.2 to 4.1 $MPa$, and the injection pressure ranged from 0.03 to 0.6 $MPa$.

## 3 INTERPRETATION OF TEST RESULTS

### 3.1 Longitudinal flow tests

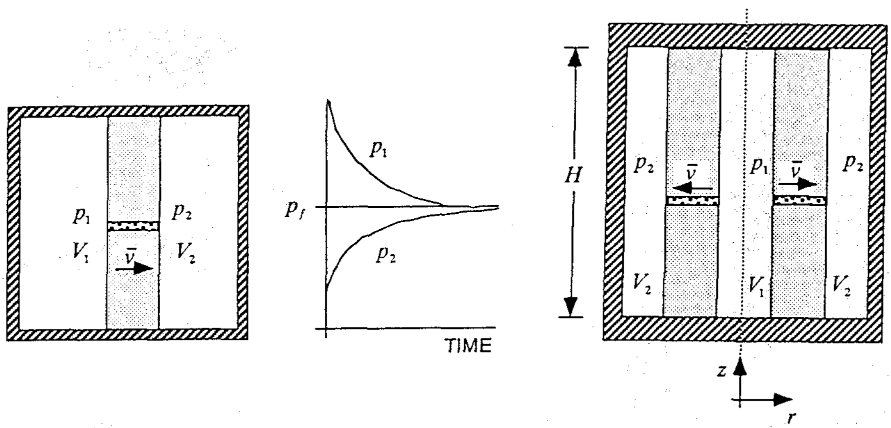
Longitudinal flow tests were carried out by using a transient pulse test device (Figure 3(a)). Permeability is obtained from pressure changes, which are applied to the ends of a specimen, with respect to time. The overall permeability of a specimen is computed from the following formula[2,3,4]:

$$k = \frac{\eta c_f L}{A}\frac{V_1 V_2}{V_1 + V_2}\ln(\frac{p_i - p_o}{p_1 - p_f}\frac{V_2}{V_1 + V_2})\frac{1}{t} \quad (1)$$

where $V_1$ and $V_2$ are volumes of reservoirs 1 & 2, $p_1$ is pressure at reservoir 1, $p_i$ and $p_f$ are initial and final pressures at reservoir 1, $p_o$ is initial pressure at reservoir 2, $\eta$ & $c_f$ are viscosity and compressibility of fluid, and $A$ and $L$ cross section area and length of specimen.

If the volume of reservoir 2 is much greater than that of reservoir 1 (i.e. $V_2 \gg V_1$) (i.e. outer side of specimen is open to air) $p_0$ ve $p_f$ given in the above equation will be equal to atmospheric pressure ($p_a$). For this particular case, Eq.(1) takes the following form:

$$k = \frac{\eta c_f L V_1}{A}\ln(\frac{p_i - p_a}{p_1 - p_a})\frac{1}{t} \quad (2)$$




(a) longitudinal flow test

(b) radial flow test

Figure 3 Experimental set-up for transient pulse tests

### 3.2 Radial flow tests

#### 3.2.1 Pressure difference method [1]

For this kind tests, gas is used as a permeatation fluid. If the change of pressure with respect to time is linear, the velocity of gas will also change linearly. The final equation of permeability will take the following form[3,4,5]:

$$k = \frac{V\eta}{\pi H}\frac{ln(r_2/r_1)}{(p_1^2 - p_2^2)}\frac{dp_1}{dt} \tag{3}$$

where $V$ is the applicable volume, $H$ is height of specimen, $r_2$ is the radius of the outer periphery of the specimen, $r_1$ is the radius of the gas injection hole.

#### 3.2.2 Transient pulse test method

The transient pulse method is also extended to radial flow by Aydan and Üçpırtı[3,4]. This method is fundamentally very similar to that for longitudinal flow (Figure 3(b)). The final equation to compute the permeability of samples is

$$k = \eta c_f \frac{V_2 r_2 V_1 r_1 \ln(r_2/r_1)}{V_2 r_2 A_{p_1} + V_1 r_1 A_{p_2}} \ln\left(\frac{p_i - p_o}{p_1 - p_f}\frac{V_2 r_2 A_{p_1}}{V_2 r_2 A_{p_1} + V_1 r_1 A_{p_2}}\right)\frac{1}{t} \tag{4}$$

where $A_{p_1}$ and $A_{p_2}$ are peripherial areas at radii $r_1$ and $r_2$ of the specimen.

If the volume of reservoir 2 ($V_2$) is much greater than the volume of reservoir 1 ($V_1$), ($V_2 \gg V_1$) (i.e. outer side of specimen is open to air) $p_0$ ve $p_f$ given in the above equation will be equal to atmospheric pressure ($p_a$). For this particular case, Eq.(4) becomes

$$k = \eta c_f \frac{V_1 r_1 \ln(r_2/r_1)}{A_{p_1}} \ln\left(\frac{p_i - p_a}{p_1 - p_a}\right)\frac{1}{t} \tag{5}$$

### 3.4 Interface permeability

Total permeability measured in tests may be given as a sum of permeability of constitutients in the following form:

$$k = k_c + k_r + k_i \tag{6}$$

[1]This test is valid if pressure rate remains constant with time

where $k_c$, $k_r$ and $k_i$ are permeability of concrete, rock and interface respectively. Interface permeability can be obtained from subtracting permeability of concrete and rock from total permeability. If fluid flow through interface obeys to the well known *qubic law*, the effective aperture of interface may be also obtained from the following formula[4,6]:

$$h = \sqrt{12k_i} \tag{7}$$

# 4 EXPERIMENTAL RESULTS AND DISCUSSIONS

## 4.1 Experiments on porous rock salt (halite)

A total of 26 longitudinal-flow tests were conducted on 3 different 10.2 $cm$ diameter porous halite samples under different applied stresses and injection pressures. The externally applied stresses ranged from 1.7 to 17.2 $MPa$, and gas injection pressures ranged from 0.7 to 0.8 $MPa$. All tests were conducted with nitrogen as the permeating fluid.

Figure 4 shows the theoretical normalised pressure and time curve obtained from Eq. (1) together with the experimental curve. As seen from this figure, there is a difference between the curve obtained from the test and the curve from the theory, particularly in initial stages. In order to obtain permeability value, linearised part of normalized pressure change and time relation is generally used to compute permeability for a selected range.

The permeabilities measured in the longitudinal-flow tests range from $10^2$ to $10^{-2}$ $mdarcy$ at confining pressures ranging from 1.7 to 17.2 $MPa$. For the longitudinal tests of halite, gas permability measurements as a function of applied hydrostatic stress is shown in Figure 5. As seen from the figure, the gas permeability decreases with increasing hydrostatic stresses.

## 4.2 Tests on interface permeability

A total of 23 longitudinal - flow tests on halite / membrane / concrete interfaces were completed on three different samples with different confining and injection pressures. The externally applied stresses range from 5.2 to 17.2 $MPa$, and injection pressures range from 0.7 to 0.8 $MPa$. The total permeability measured in the longitudinal-flow tests ranges from $10^2$ to $10^{-2}$ $mdarcy$ at confining pressures ranging from 5.2 to 17.2 $MPa$.

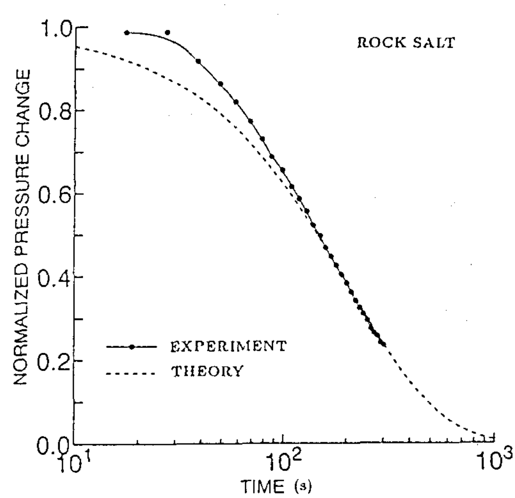


Figure 4 Comparison of predicted response with experimental one

Figure 5 summarizes gas permeability measurements as a function of applied hydrostatic stress for the longitudinal-flow tests of halite/membrane/concrete interfaces. In general speaking, the permeability decreases with increasing hydrostatic stress.

In computing gas permeability in radial flow tests, Eq.(3) was used by taking into account the observed response of pressure in laboratory tests, although testing set-up is similar to radial transient pulse method with a large volume of reservoir 2. In computing permeability, $p_2$ was assumed to be equal to atmospheric pressure $p_a$ as the outer perimeter of specimens was open to air.

Figure 6 summarizes gas permeability measurements as a function of normal stress (uniaxial stress) for the radial-flow tests of halite / membrane / concrete interfaces. To accomplish a limited healing progress, the test samples were kept under 6.9 MPa isotropic stress for 17.5 to 261 hours before testing. Generally, the change of the calculated average gas permeability with respect to normal stress is small. However, this is an early statement with the limited number of test results. On the other hand, there is a scatter on the test results which may be be due to the disturbance of the test sample and testing procedure. All calculated permeabilities from the radial-flow tests are relatively high, on the order of $10^2$ to $10^{-1}$ $mdarcy$.

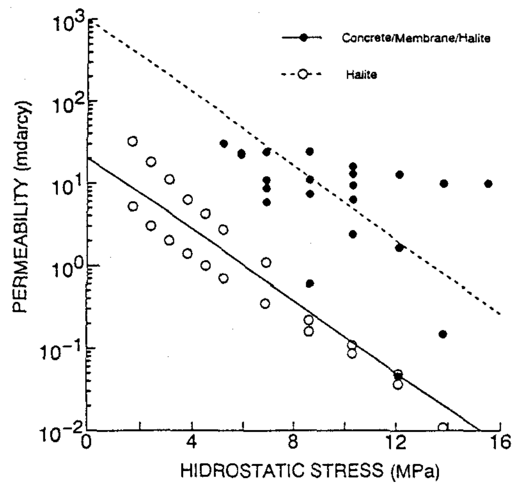



Figure 5 Comparison of permeabilities of halite and concrete/membrane/halite

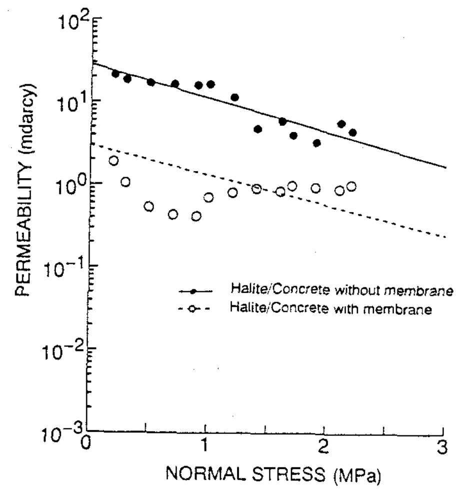



Figure 6 Comparison of permeabilities of concrete/halite and concrete/membrane/halite

## 5 CONCLUSIONS

The results of the tests described in this study suggest that a low density polyethylene membrane may provide a reduction in the flow potential along a halite/ membrane/concrete interface. Comparisons of radial-flow data with and without a membrane show that the membrane provides about a one to two order of magnitude reduction in calculated permeability. However, test results show some scatterring.

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