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ABSTRACT

The present report deals with the conditions under which gas will migrate from a radioative low-level waste repository located in a hard rock formation below the sea bottom. Chemical reactions resulting in gas (hydrogen) production will take place in the stored waste. Unless the gas produced can escape from the rock cavern an over-pressure that may bring about contamination of the groundwater regime may arize in the cavern. Therefore, it is of significant interest to investigate the transport properties of the surrounding rock formation and to study how the transport capability compares with the rate of the gas production. The purpose of the present study is to provide a rough estimate of the capability of the rock formation in consideration to convey the gas produced in the repository to the surface. The gas produced in the water filled repository will be subject to very fast gravitational segregation, and as a result a gas cushion will be created at the roof of the cavern. Three particular stages may be distinguished in the present flow problem, these are: (i) the accumulation of the gas at the roof of the cavern, (ii) the escape of the gas into the fractures, once the critical thickness of the gas cushion has been reached, and (iii) the flow of gas, once the water in the fractures has been displaced. A first part of the study is devoted to analysing the transport properties of a single fracture. The governing flow equations and expressions for the flowrates of the gas and break-through times of the gas front to reach the upper boundary (sea bottom) of the rock formation are derived. The physical properties of a single fracture are used for the modelling of the fractured rock mass in consideration. A second part of the study is devoted to a number of numerical examples worked out to study the conditions of the gas flow for the projected low-level radioactive waste repository. The following parameters are studied: (i) the critical thickness of the gas cushion, (ii) break-through times of the gas, and (iii) flowrates of the gas.

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SUMMARY

Introduction

The present report presents a preliminary study of the conditions under which gas will migrate from a radioactive low level waste repository situated in a hard rock formation below the sea bottom. The main purpose of the present study is to provide a rough estimate of the capability of the surrounding rock formation to convey the gas produced in the repository to the rock surface, i.e. the bottom of the sea.

The gas produced in the water filled repository will be subject to very fast gravitational segregation, and as a result a gas cushion will be formed at the roof of the cavern. Three particular stages may be distinguished in the present flow problem, these are: (i) the accumulation of the gas from the waste and the creation of a gas cushion at the roof of the cavern, (ii) the entry of the gas into the fractures and displacement of the water in the fractures, and (iii) the flow of gas once the water in the fractures has been displaced.

The motivation for the present study came as a result of the Swedish plans for storing low level radioactive waste in a hard rock cavern below the bottom of the sea. Chemical reactions in the stored waste will result in gas production (hydrogen). waste. Unless the gas produced can escape from the rock cavern an over-pressure in the cavern may arize. The over-pressure in the gas may then bring about contamination of the surrounding groundwater regime. Therefore, with regard to the safety analysis, it is of significant interest to investigate the transport properties of the surrounding rock formation and to study how the transport capability compares with the rate of the gas production.

A first part of the study is devoted to analysing the transport properties of a single fracture. The governing flow equations are derived as well as expressions for the flowrates of the gas and the break-through times of the gas front to reach the upper boundary (sea bottom) of the rock formation. The physical properties derived for a single fracture are used to derive the properties of the fractured rock mass in consideration.

A second part of the study is devoted to a number of numerical examples worked out to study the conditions of the gas flow for the projected low-level radioactive waste repository. The following parameters are studied: (i) the critical thickness of the gas cushion, (ii) break-through times of the gas, and (iii) flowrates of the gas. The results of the calculations will be briefly summarized in the sequel. A detailed presentation of the calculations is given in the appendix.

Critical thickness of the gas cushion

The calculations are based upon a fracture frequency of about 5-10 fractures per metre. In the rock configuration considered this leads to a fracture width in the range between 10^{-4} and 10^{-5}. The critical thickness of the gas cushion corresponding to these values was computed to be about 0.15 and 1.5 metres.

The critical thickness of the gas cushion is a function of the threshold pressure, i.e. the critical pressure difference at the gas-water interface required to start the displacement of the water in a fracture. The calculations of the threshold pressure were based on the properties of an ideal open fracture.

Break-through time of the gas

For a permeability of 10^{-12} m^2 and a thickness of the gas cushion between 0.2 and 0.6 metres, we obtained break-through times between 0.7 and 0.2 days, and for a permeability of 10^{-15} m^2, we obtained break-through times between 48 and 17 days.

In calculating the break-through time of the gas three different settings were considered: (i) a vertical fracture, (ii) a turtuous fracture consisting of segments of equal inclination, and (iii) an inclined fracture. The above-mentioned figures correspond to the setting with a vertical fracture.

The relationship between the break-through time for a vertical fracture and that of an inclined one is given in the report. This means that the figures of the break-through time given for a vertical fracture may be used also for the calculation of the break-through time in an inclined fracture. As an example it will be mentioned that the break-through time for a fracture with an inclination of 45° is twice that of a vertical fracture.

Flowrate of the gas

The calculations with a permeability of 10^{-12} m^2, a range of h_g - values, i.e. the critical thickness of the gas cushion, between 0.2 - 6 metres, and a fracture frequency of 10 fractures per metre resulted in flowrates of the gas of about 1.1×10^{-3} - 1.3×10^{-3} m^3/sm^2. For a rock permeability of 10^{-15} m^2, the resulting flowrates were about 2.0×10^{-6} m^3/sm^2.

These flow rates represent the maximum transport capability of the rock formation to convey the gas produced in the rock cavern. As already mentioned the prevailing condition is that all the water in the fracture system, with the exception of the irreducible water, has been displaced by the gas, implying that this condition is reached only after the break-through has occured.

The flow model

The flow model developed is based on the steady solution of Navier-Stokes' equation for viscous flow between two parallel plates (Poiseuille flow). The gas and water are treated as two immiscible and incompressible fluids. The difference in the gas pressure is considered fairly moderate (0.5 Mpa). Therefore, it is assumed in the calculations that the density of the gas may be approximated by the average value of the density in the present flow problem.

Input parameters

The key parameter in the present investigation is the fracture permeability. However, there are no data available about this parameter in the rock formation considered. Therefore, the fracture permeability to the gas has been derived from the conceptual model adopted to describe the rock formation.

In the present investigation a homogeneous equivalent medium is considered. Thus, the rock formation is conceived as a configuration of equally spaced fractures of equal width. This means that for a given fracture frequency, a simple relationship between the rock permeability and the width of the fractures can be established.

The fracture frequency has been estimated by the inspection of drillhole cores, and the rock permeability has been measured indirectly by means of packer tests in vertical boreholes at the site selected for the the radioactive waste repository. The fracture frequency was reported to be in the range between 5 and 10 fractures per metre, and the hydraulic conductivity, being the parameter measured, was reported to be about 10^{-7} m/s. In the present calculations the hydraulic conductivity in the surrounding rock mass is assumed to be in the range between 10^{-5} and 10^{-8} m/s, corresponding to a rock permeability of about 10^{-12} and 10^{-15} m^2.

To approximate the threshold pressure (for the calculation of the critical thickness of the gas cushion), and to approximate the fracture permeability (for the calculations of the break-through times and flowrates of the gas) the value of the fracture width is required. For a fracture frequency in the range between 5 and 10 fractures per metre and a value of the rock permeability in the range between 10^{-12} and 10^{-15} m^2, one obtains a fracture width in the range between 10^{-4} and 10^{-5} m.

The repository

The radioactive waste repository is going to be located at a depth of 50 metres below the bottom of the sea. The size of the proposed cavern is about 150x15x6 metres, and the depth of the sea above the rock formation, in which the repository is to be located, is about 6 metres. The rock cavern will be filled with low-level radioactive waste without any solidification or artificially impervious barriers, allowing water to infiltrate and completely fill up the remaining space in the cavern. Unless the gas produced can escape from the cavern contaminated water in the cavern might be pushed into surrounding rock mass.

Discussion

This section will be devoted to a discussion about some of the implications of the assumptions and simplifications that have been made in the present flow study. In the discussion that will follow, a marked attention will be paid to the consequences of using a homogeneous and isotropic equivalent medium to describe the physical properties of the rock formation considered.

In the present approach the measured values of the rock permeability are used for reconstructing a homogeneous and isotropic medium, in which the orientation, spacing and width of the fractures are assumed to be constant over the flow domain. This is indeed a highly idealized envision of the rock formation in consideration, since in reality all the three previous parameters should be expected to be statistically distributed over the flow domain.

The implication of having a statistical distribution of the fracture permeability is not considered significant to the results of the calculations of the flowrates. The reason for this is that the flowrates computed refer to a flow regime, in which the water in in the initially water filled fractures already has been displaced by the gas. Consequently, in calculating the flowrates of the gas, fracture distributions leading to the same rock permeability may be considered equivalent.

The previous conclusion is, however, not true of the results of the calculations of the critical sizes of the gas cushion and the break-through times. Then, it may be very important to account for the actual fracture distribution. However, the use of a homogeneous equivalent medium in the calculations may in general be considered conservative with regard to the safety aspect of the present problem. This is due to the fact that by using a homogeneous equivalent model instead of a statistically distributed model, the effect of the large fractures in the actual fracture distribution will be disregarded. Consequently, the homogeneous equivalent model will usually result in higher values of the threshold pressure than that of a statistically distributed model.

A further implication of dealing with a rock formation with a statistical fracture distribution is that the displacement of water by the gas will first take place in the large fractures. This is due to the fact that the required thickness of the gas cushion, before any displacement of water will take place, is smaller for the large fractures than for the small ones. This means that if small fractures are being intersected by large ones, columns of water still occupying the small fractures may be circumvented by the gas flowing in the large fractures. Because of the gravity effect, the water in these fractures will be drained downwards and flow into the cavern. As a consequence, the rate of the gas flow will be increased.

An important problem to be considered concerns the possibility of dealing with an anisotropic rock formation. The outflow of the gas from the repository will largely take place at the roof of the cavern, implying the importance of the vertical fractures to the capability of the surrounding rock to divert the gas. Consequently, the flowrate of the gas will mainly be governed by the vertical permeability. This means that from this point of view it is inappropriate to use the isotropic equivalent permeability in the calculations, should the rock formation be vertically anisotropic (i.e. the vertical permeability is higher than the horizontal permeability).

In the present investigation the hydraulic conductivity is used to determine the fracture permeability to the gas. The hydraulic conductivity is measured under fully saturated conditions. When using this value to determine the permeability to the gas, generally, the result will be a minor overestimation of the gas permeability. This is due to the fact that not all water in the fractures will be displaced by the gas. A small quantity of water, the so-called irreducible water will always remain in the fractures. Therefore, the actual void space being available to the gas flow, is in reality slightly less than it is to the saturated water flow. This effect is usually comparatively small and is not expected to be of any significance to the results of the present calculations.

The excavation of the rock cavern itself will cause a redistribution of the stress conditions in the vicinity of the cavern, which may result in an increase as well as a decrease in the permeability. Generally, there is a possibility that tensile stresses will be induced at the roof of the cavern, causing an increase in the width of the fractures intersecting the top of the cavern, thus increasing the rock permeability. As a consequence, the escape of the gas from the cavern will be facilitated, since the threshold pressure of the gas will be lower. However, the final stress distribution after the excavation will among other things depend on the intial stress distribution, the fracture pattern and the elastic properties of the rock formation. Therefore, it is very difficult to state anything about the order of magnitude of the effect of the excavation in the present flow problem.

Concluding remarks

Generally, the assumptions being made in the present investigation should be considered to be conservative with regard to the safety aspects of the flow problem. However, with regard to the previous discussion about the implications of having a statistical distribution of the fracture permeability over the flow domain and furthermore that the distribution may be such that the resulting rock permeability will become anisotropic, it seems advisable to mention some of the shortcomings with presently used permeability measurements.

First, it should be mentioned that the rock permeability values obtained from field tests, such as packer tests represent average values that may have been taken over a wide range of fracture permeability values in the tested region. Consequently, no information will be obtained about the distribution of the fracture permeability in the tested region. Another shortcoming with packer tests in vertical boreholes is that these tests essentially reflect only the horizontal permeability (Braester and Thunvik, 1982)+, which means that practically no information is obtained about the vertical permeability.

Therefore, in consequence of the previous discussion, certain care is recommended to be taken in drawing conclusions from results of calculations such as the present ones, in which the fracture permeabilities are based exclusively on permeability measurements performed by means of packer tests in vertical boreholes, especially if the orientation of the fractures is such that horizontal anisotropy in the rock permeability might be expected.

+ Braester, C., Thunvik, R., 1982, Numerical Simulation of Double Packer Tests, SKBF-KBS-TR-82:06, Stockholm, Sweden.

LIST OF FIGURES

NOMENCLATURE

symbol	description	dimension
b	fracture width	L
d	distance between adjacent fractures	L
g	acceleration of gravity	LT^{-2}
h_g	thickness of the gas cushion	L
H	distance between the top of the cavern and the bottom of the sea	L
H_s	water level above the sea bottom	L
H_{w1}	depth of the cavern roof below the sea level	L
H_{w2}	depth of the water level in the cavern below the sea level	L
k	permeability	L^2
K	hydraulic conductivity	LT^{-1}
L	fracture length	L
m	mass rate of flow per unit area	$ML^{-2}T^{-1}$
M	molecular weight of the gas	M/mole
n	fracture frequency per unit length	L^{-1}
p	pressure	$ML^{-1}T^{-2}$
p_c	capillary pressure	$ML^{-1}T^{-2}$
q	volumetric rate of flow per unit area	LT^{-1}
R	gas constant	$ML^2T^{-2}K^{-1}$ mole
R_1, R_2	radii of curvatures	L
s	coordinate taken along a fracture	L
t	time	T
$t_{b\alpha}$	break-through time for gas for an inclined fracture (α is the angle with the horizontal)	T
t_{b90}	break-through time for the gas in a vertical fracture	T
T	temperature	K
v	velocity	LT^{-1}
z	coordinate in the vertical direction	L
Z	correction factor for real gases	-

greek	description	dimension
θ	contact angle	-
ρ	density	ML^{-3}
μ	dynamic viscosity	$ML^{-1}T^{-1}$
$\Delta\rho$	difference between water and gas densities ($\Delta\rho = \rho_w - \rho_g$)	ML^{-3}
σ	interfacial tension	MT^{-2}
α	angle with the horizontal plane	-
Φ	pressure head $\Phi = p + \rho g z$	$ML^{-1}T^{-2}$
ξ	local coordinate of the gas-water interface in the s-direction	L

subscripts

b	break-through
f	fracture
g	gas
w	water

1. INTRODUCTION

The purpose of the present investigation is to study the conditions under which gas will migrate from a radioactive waste repository through the surrounding rock formation to the top surface at the bottom of the sea. The study is particularly directed towards studying the flowrates of the gas which may take place in the rock formation.

The motivation for the present study came as a result of the Swedish plans for storying low-level radioactive waste in caverns at the coast below the bottom of the sea. The dimensions of such a proposed cavern are 150 metres length, 15 metres width and 6 metres height. The cavern is to be located about 50 metres below the rock surface. The sea water level above the rock surface is about 6 metres (Fig. 1).

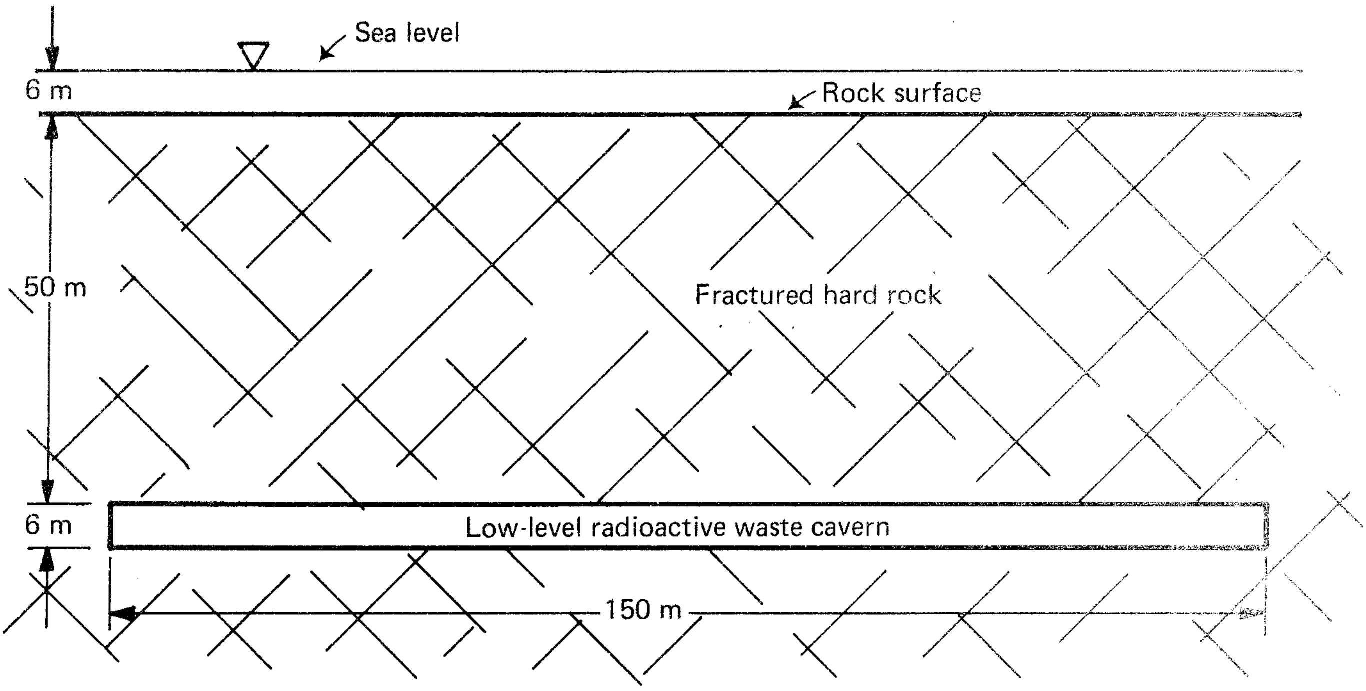

Figure 1. Longitudinal cross-section through the radioactive waste repository.

The main part of the cavern is filled with low-level radioactive waste, without any solidification or artificially impervious barriers of the cavern walls. This means that water will infiltrate and fill the cavern after the emplacement of the radioactive waste.

Chemical reactions in the stored waste will result in the formation of hydrogen in the cavern. Unless the gas can escape from the rock cavern, the increase in the gas pressure may result in the displacement of the water in the cavern into the surrounding rock formation.

One may distinguish the following stages in the gas migration from the cavern to the rock surface:

(i) The gas will accumulate below the roof of the cavern and create a gas cushion. To migrate from the cavern to the surface, through the initially water saturated fractures, a critical gas presssure (threshold pressure), or equivalently a critical thickness of the gas cushion must be reached. The parameter of interest during this stage is the critical thickness of the gas cushion that must be reached to start migration of gas through the fractures.

(ii) Once the critical thickness of the gas cushion is reached gas will start to move through the fractures and displace the water. The parameter of interest during this stage is the break-through time of the gas, i.e. the time required for the gas to displace completely the water in the fracture and reach the surface.

(iii) After the break-through, gas will flow through the fractures. The parameter of interest during this stage is the rate of flow of the gas that the fracture system may convey under the prevailing pressure difference between the gas pressure in the cavern and the surface pressure imposed by the sea level.

A minimum rate of gas production will be required to maintain a continuous gas flow through the fractures. If the rate of gas production will decrease below the critical limit, water will penetrate the fracture from the surface towards the cavern, and gas flow will restart after a new gas cushion of critical thickness will be formed in the cavern.

2. THE THRESHOLD PRESSURE FOR GAS-WATER DISPLACEMENT IN A SINGLE FRACTURE

The gas production in the water filled cavern will result in a fast gravitational segregation, and as a result a gas cushion will be formed at the roof of the cavern. A schematic representation of the flow problem considered is presented in Figure 2.

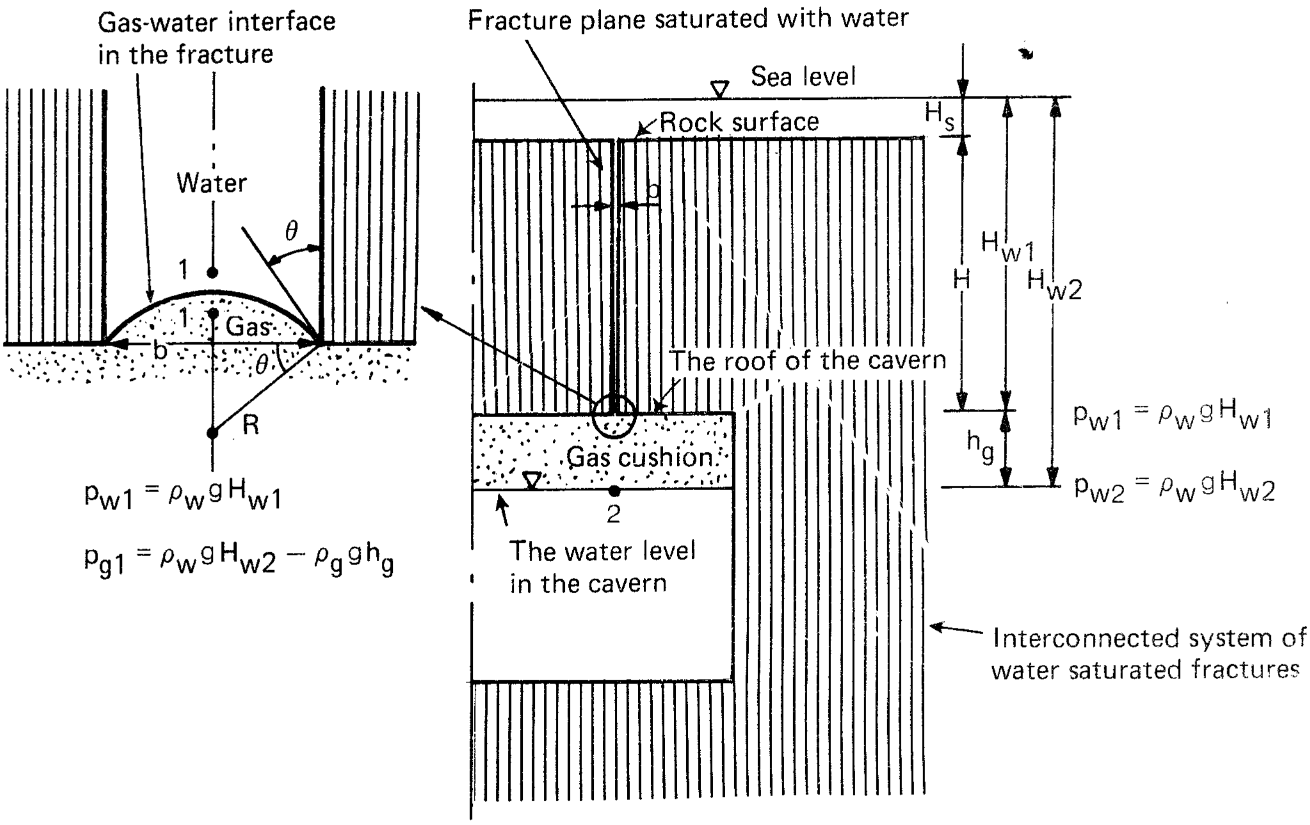

Figure 2. Schematic representation of the flow problem.

Migration of gas from the cavern to the surface, through the initially water saturated fractures, requires that the critical pressure of the gas in the cavern be reached. For an ideal open fracture the threshold pressure can be calculated from (i) the properties of the fluid and (ii) the geometrical parameters of the flow domain.

The threshold pressure, i.e. the critical pressure difference at the gas-water interface required to start the displacement, is constant and equals the capillary pressure p_c. The capillary pressure at the interface between two immiscible fluids is positively defined as the difference between the nonwetting fluid (gas) and the wetting fluid (water)

$$p_c = p_g - p_w \tag{1}$$

With the geometrical parameters defined in Fig. 2, one may calculate this pressure difference at point 1 just below and above the gas water interface, as follows:

At point 1 the pressure in the water phase is

$$p_{w1} = \rho_w g H_{w1} \tag{2}$$

At point 2 the pressure in the water phase is

$$p_{w2} = \rho_w g H_{w2} \tag{3}$$

The pressure in the gas phase is

$$p_{g1} = p_{w2} - \rho_g g h_g = \rho_w g H_{w2} - \rho_g g h_g \tag{4}$$

The capillary pressure at point 1 is then

$$p_c = p_{g1} - p_{w1} = \rho_w g H_{w2} - \rho_g g h_g - \rho_w g H_{w1} =$$

$$= \rho_w g (H_{w2} - H_{w1}) - \rho_g g h_g = (\rho_w - \rho_g) g h_g \tag{5}$$

If the gas density is neglected in comparison to that of the water, one obtains

$$p_c = \rho_w g h_g \tag{6}$$

The Laplace formula relates the capillary pressure to the interfacial tension and the radii of curvature of the meniscus between the the two fluids

$$p_c = \sigma(1/R_1 + 1/R_2) \tag{7}$$

For a fracture plane $R_2 \rightarrow \infty$, and one obtains

$$p = \sigma/R \tag{8}$$

The radius of curvature R, of the meniscus between the gas and the water can be related to the fracture width b and to the contact angle ($\theta < 90^o$, defining the wetting fluid).

One obtains (Fig. 2)

$$R = b/2\cos\theta \tag{9}$$

which substituted into (8) yields

$$p_c = 2\sigma\cos\theta/b \tag{10}$$

Comparing equations (6) and (8), one finally obtains

$$h_g = 2\sigma\cos\theta/b\rho_w g \tag{11}$$

The contact angle is a property of the couple of the fluid and the solid boundary. As no data are available for the contact angle θ we will consider the value leading to the maximum h_g, i.e. $\cos\theta = 1$ and obtain

$$h_g = 2\sigma/b\rho_w g \tag{12}$$

Equation (12) gives the critical value of the thickness of the gas cushion in order to start the displacement of the water from a fracture of width b.

3. GAS-WATER DISPLACEMENT IN A SINGLE FRACTURE

The purpose of the calculations being presented in the sequel is to find the break-through time of the gas, from the cavern to the rock surface through an initially saturated fracture, as well as to calculate the rate of flow of gas.

The fracture, in the s-direction inclined by the angle α with the horizontal (Fig. 3) is one of the assumed to connect the roof of the cavern (s=0) with the rock surface (s=L)

Assuming that the critical value h_g of the gas cushion in the cavern has been reached and that at a certain moment the gas-water interface is located at a distance ξ from the origin, one may distinguish the two different flow domains, viz. the gas and the water flow domains.

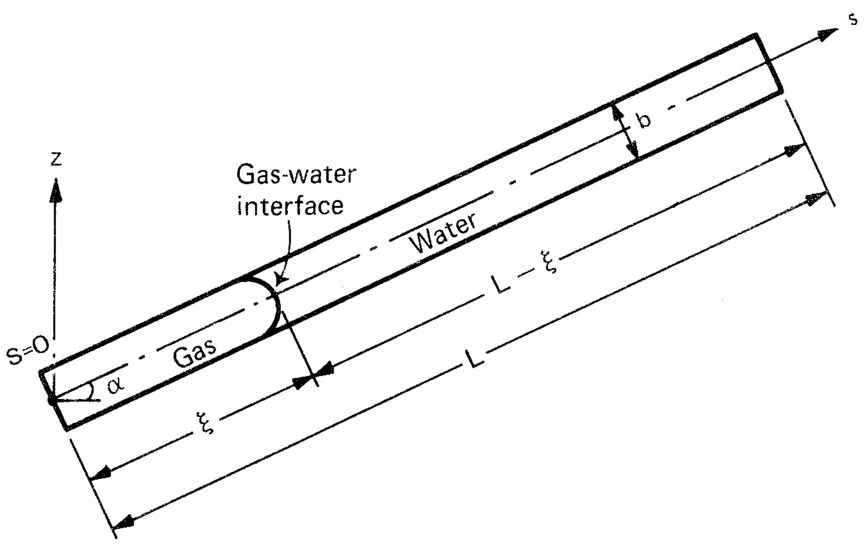

Figure 3. Sketch for the nomenclature to the gas-water displacement in a fracture plane.

3.1 Equations of flow

The governing flow equations are:

(i) The equation of the mass conservation for the gas in the fracture. Gas will flow under a pressure difference between that of the gas in the cavern and the pressure on the top of the rock surface. In the present case this pressure difference is about 0.5 MPa.

The equation of the conservation of mass is

$$\frac{\partial \rho_g}{\partial t} = \frac{\partial}{\partial s} (\rho_g v_g) = 0 \qquad (13)$$

where v_g is the velocity given by

$$v_g = - \frac{k_f}{\mu_g} \rho_o \frac{\partial \Phi_g^*}{\partial s} \qquad (14)$$

For a fracture plane $k_f = b^2/12$.

In a rigorous formulation the gas must be considered to be compressible and in such a case Φ^* is defined by

$$\Phi_g^* = \int_{p_o}^{p} \frac{dp_g}{\rho(p_g)} + gz \qquad (15)$$

where density is related to pressure by the equation of state

$$\rho_g = Mp_g /ZRT \qquad (16)$$

where Z=Z(p,T) is characterizing the deviation of the real fluid from an ideal one, M is the molecular weight of the gas, R is the gas constant and T is the temperature.

The problem becomes simplier if the temperature is constant and the pressure difference is moderate so that Z may be considered to be independent of pressure. Substitution of equations (14), (15) and (16) into (13) leads to a non-linear equation in pressure, which can be solved only by means of numerical methods.

As the purpose of the present investigation is to obtain a rough estimate of the gas migration conditions, we will carry out the ensuing calculations by treating the gas as incompressible. Thus, density will be approximated by the average density corresponding to the pressure conditions in the cavern and at the rock surface. If a greater degree of accuracy will be required, then the calculations will have to be refined and a numerical method must be employed.

Treating the gas as incompressible, then the equations for the conservation of mass may be written as

$$\frac{\partial^2 \Phi_g}{\partial s^2} = 0 \qquad 0 \leq s \leq \xi \tag{17}$$

$$\frac{\partial^2 \Phi_w}{\partial s^2} = 0 \qquad \xi \leq s \leq L \tag{18}$$

where $\Phi_i = p_i + \rho_i gz$ and i denotes the gas (i=g) or the water phase (i=w).

(ii) The equations of motion

$$v_g = -\frac{k_f}{\mu_g}\frac{\partial \Phi_g}{\partial s} \tag{19}$$

$$v_w = -\frac{k_f}{\mu_g}\frac{\partial \Phi_w}{\partial s} \tag{20}$$

where $k_f = b^2/12$.

The boundary and initial conditions considered are

$$s = 0 \qquad \Phi_g = \Phi_{go} \tag{21}$$

$$s = \xi \qquad \Phi_g = \Phi_{g\xi}\ , \quad \Phi_w = \Phi_{w\xi} \tag{22}$$

$$s = L \qquad \Phi_w = \Phi_{wL} \tag{23}$$

3.2 The rate of the gas flow

Integrating equations (17) and (18) under the previously given conditions (21), (22) and (23), we obtain

$$\Phi_g = \Phi_{go} + \frac{\Phi_{g\xi} - \Phi_{go}}{\xi} s \tag{24}$$

$$\Phi_w = \Phi_{w\xi} + \frac{\Phi_{wL} - \Phi_{w\xi}}{L-\xi} (s-\xi) \tag{25}$$

The linearity of equations (24) and (25) in s shows that the fluid velocity in each of the two regions, gas and water, is constant over the domain occupied by the respective fluid. Moreover, from the condition of the equality of the velocity of the front between the two fluids, it follows that, at any instant, the velocities are equal over the entire flow domain, i.e. $v_g = v_w$.

Substitution of equations (24) and (25) into (19) and (20) yields

$$v_g = \frac{k_f}{\mu_g} \frac{\Phi_{go} - \Phi_{g\xi}}{\xi} \tag{26}$$

$$v_w = \frac{k_f}{\mu_w} \frac{\Phi_{w\xi} - \Phi_{wL}}{L-\xi} \tag{27}$$

or in terms of pressure

$$v_g = \frac{k_f}{\mu_g} \frac{p_{go} - p_{g\xi} - \rho_g g \xi \sin\alpha}{\xi} \tag{28}$$

$$v_w = \frac{k_f}{\mu_w} \frac{p_{w\xi} + \rho g \xi \sin\alpha - p_{wL} - \rho_w g L \sin\alpha}{L-\xi} \tag{29}$$

$$= \frac{k_f}{\mu_w} \frac{p_{w\xi} - p_{wL} - \rho_w g (L-\xi) \sin\alpha}{L-\xi}$$

Adding equations (28) and (29) and with $v_w = v_g$, we obtain

$$v_g = \frac{k_f}{\mu_g} \frac{p_{go} - p_{wL} - (p_{g\xi} - p_{w\xi}) - gL\rho_w \sin\alpha + g\Delta\rho\xi\sin\alpha}{\xi + \frac{\mu_w}{\mu_g}(L-\xi)} \tag{30}$$

where $\Delta\rho = \rho_w - \rho_g$ is the density difference between water and gas.

In equation (30) the difference in pressure $p_g - p_w$ between the gas and the water at the interface equals the capillary pressure,

i.e. $p_c = p_{g\xi} - p_{w\xi}$. Introducing the capillary pressure in equation (31), one finally obtains

$$v_g = \frac{k_f}{\mu_g} \frac{p_{go} - p_{wL} - p_c - g\rho_w L\sin\alpha + g\Delta\rho\xi\sin\alpha}{\xi + \frac{\mu_w}{\mu_g}(L-\xi)} \tag{31}$$

Equation (31) gives the velocity of the gas as a function of the length of the displacement ξ . After the complete displacement of the water from the fracture, i.e. for $\xi = L$ in equation (31), one obtains the gas velocity through the gas saturated fracture

$$v_g = \frac{k_f}{\mu_g} \frac{p_{go} - p_{wL} - g\rho_g L\sin\alpha}{L} \tag{32}$$

Using the relationship $H = L \sin\alpha$, where H is the vertical distance between the roof of the cavern and the rock surface, we obtain

$$v_g = \frac{k_f}{\mu_g} \frac{p_{go} - p_{wL} - g\rho_g H}{L} \tag{33}$$

In equation (33) $p_{go} = p_{g1}$, equation (4), and equals

$$p_{go} = g(\rho_w H_{w2} - \rho_g h_g) = g(\rho_w H_{w1} + h_g \Delta\rho) \tag{34}$$

p_{wL} is the pressure at the rock surface imposed by the sea water column (H_{ws} in Fig. 2) and equals

$$p_{wL} = \rho_w g H_s \tag{35}$$

Substituting these pressure values into equation (33), one obtains

$$v_g = \frac{k_f g \Delta\rho}{\mu_g L} (H + h_g) \tag{36}$$

and using the relationship $L = H/\sin\alpha$, one finally obtains

$$v_g = \frac{k_f \; g\Delta\rho \; \sin\alpha}{\mu_g} (1 + h_g/H) \tag{37}$$

This equation provides also a simple relationship between the velocity through a fracture with an inclination α with the horizontal direction ($v_{g\alpha}$) and through a vertical one (v_{g90})

$$v_g = v_{g90} \; \sin\alpha \tag{38}$$

3.3 The break-through time of the gas

The advance of the gas front through a fracture can be calculated using equation (31). As already pointed out, at a given instant the velocity of the fluid over the entire fracture length is constant and equals the veloci*y of the front $d\xi/dt$.

Using the definition of the velocity in equation (31), one obtains

$$\frac{d\xi}{dt} = \frac{k_f}{\mu_g} \frac{\Delta p - g\rho_w L\sin\alpha + g\Delta\rho\xi\sin\alpha}{\xi + \frac{\mu_w}{\mu_g}(L-\xi)} \tag{39}$$

where

$$\Delta p = p_{go} - p_{wL} - p_c \tag{40}$$

Integration of equation (39) with the intial condition $t = 0$, $\xi = 0$, yields

$$t = \frac{\mu_g}{k_f} \frac{1}{g\Delta\rho\sin\alpha} \left[\left\{ \frac{\mu_w}{\mu_g} L - \frac{(1 - \frac{\mu_w}{\mu_g})(\Delta p - \rho_w gL\sin\alpha)}{g\Delta\rho\sin\alpha} \right\} \times \right.$$
$$\left. \times \ln\left(1 + \frac{\rho\Delta p\xi\sin\alpha}{\Delta p - \rho_w gL\sin\alpha}\right) + \left(1 - \frac{\mu_w}{\mu_g}\right)\xi \right] \tag{41}$$

with the restriction $\alpha \neq 0$. Equation (41) gives the advance in time of the gas-water interface.

For horizontal displacement, the advance of the front may be obtained by integration of equation (31) with $\sin\alpha = 0$. Alternatively, the advance of the front may be obtained by series expansion of the logarithmic term in equation (41).

One obtains

$$t = \frac{\mu_g}{k_f \Delta p} \left\{ \frac{\mu_w}{\mu_g} L\xi + \left(1 - \frac{\mu_w}{\mu_g}\right) \frac{\xi^2}{2} \right\} \tag{42}$$

The break-through time is obtained for $\xi = L$ in equation (41). Using also the relationship $L = H/\sin\alpha$, we obtain

$$t_b = \frac{\mu_g}{k_f} \frac{1}{g\Delta\rho \sin^2\alpha} \left[\left\{ \frac{\mu_w}{\mu_g} H - \frac{\left(1 - \frac{\mu_w}{\mu_g}\right)(\Delta p - \rho_w g H)}{g\Delta\rho} \right\} \times \right. \tag{43}$$

$$\left. \times \ln\left(1 + \frac{g\Delta\rho H}{\Delta p - \rho_w g H}\right) + \left(1 - \frac{\mu_w}{\mu_g}\right) H \right]$$

As previously defined by equation (40)

$$\Delta p = p_{go} - p_{wL} - p_c \tag{44}$$

Substituting equations (34), (35) and (10) into (44), one obtains

$$\Delta p = g(\rho_w H_{w1} + h_g \Delta\rho) - g\,\rho_w H_s - 2\sigma/b =$$

$$= g(\rho_w H + h_g \Delta\rho) - 2\sigma/b \tag{45}$$

Substituting the previous expression into equation (43), one finally obtains the following formula for the break-through time.

$$t_b = \frac{\mu_g}{k_f} \frac{1}{g\Delta\rho \sin^2\alpha} \left[\left\{ \frac{\mu_w}{\mu_g} H - \frac{(1 - \frac{\mu_w}{\mu_g})(gh_g \Delta\rho - \frac{2\sigma}{b})}{g\Delta\rho} \right\} \times \right.$$

$$\left. \times \ln\left(1 + \frac{g\Delta\rho H}{gh_g\Delta\rho - 2\sigma/b}\right) + \left(1 - \frac{\mu_w}{\mu_g}\right) H \right] \tag{46}$$

where

$$h_g > 2\,\sigma/bg\,\Delta\rho \tag{47}$$

conditioned by the critical thickness of the gas cushion to initiate the displacement of the water in the fractures.

Equation (47) also expresses in a simple way the relationship between the break-through time ($t_{b\alpha}$) through a fracture with the inclination α with the horizontal direction, and through a vertical one (t_{b90})

$$t_b = t_{b90}/\sin^2\alpha \tag{48}$$

4. RELATIONSHIP BETWEEN THE PERMEABILITY OF A SINGLE FRACTURE AND THE PERMEABILITY OF THE FRACTURED ROCK

As follows from the solution of the Navier-Stokes equation for the flow between two parallel plates, the permeability of a single fracture is

$$k_f = b^2/12 \tag{49}$$

where b is the fracture width.

The permeability value obtained from field tests, such as packer tests, on large scale rock volumes, is an average value of the rock permeability. This rock permeability value represents an average value of the permeability of the fracture network over the bulk rock volume.

The relationship between the rock permeability (k) and the permeability in the individual fractures (k_f) can be calculated from the geometrical parameters of the fracture network. For the sake of simplicity in the present calculations, an idealized network consisting of three orthogonal fracture systems will be considered (Fig. 4).

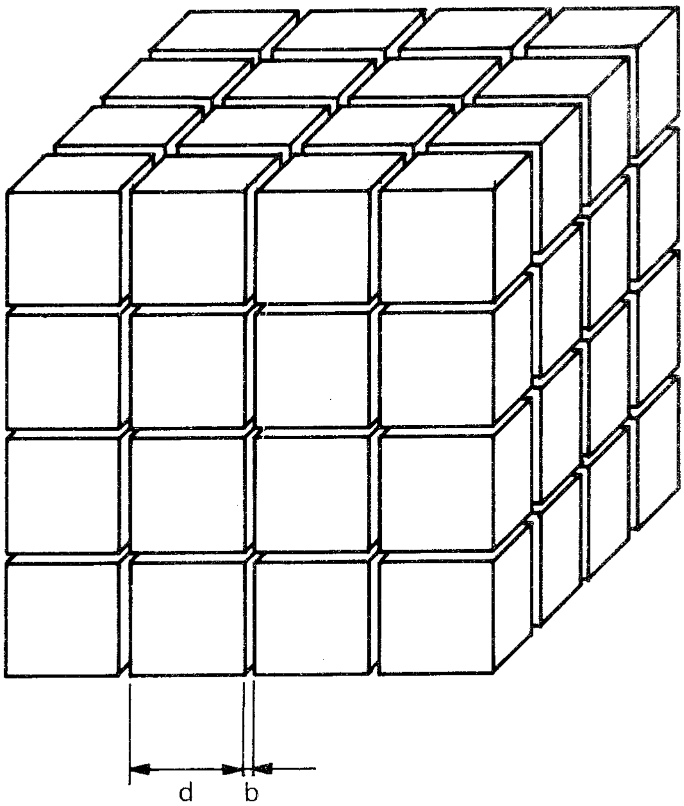

Figure 4. An idealized representation of a fractured rock mass.

In the system considered the fracture width (b) and the spacing (d) between the fractures are constant.

By averaging the fracture permeability over the bulk volume of the considered configuration, one obtains the rock permeability

$$k = b^3/6d \qquad (50)$$

Equation (50) relates the rock permeability (k) to the fracture width (b) and the distance between adjacent fractures (d).

If the frequency of the fractures is n fractures per metre, then $d = 1/n$, which subtstituted into equation (50) yields

$$k = b^3 n/6 \qquad (51)$$

5. NUMERICAL EXAMPLES

The fluids in consideration are hydrogen and water. The following material properties are used in the calculations:

temperature	10 ^{o}C
water viscosity	1.307×10^{-3} Ns/m^2
water density	0.999×10^{3} kg/m^3
hydrogen viscosity	8.5×10^{-6} Ns/m^2
hydrogen density at 0.25 MPa	0.2175 kg/m^3
hydrogen-water interfacial tension	0.07422 N/m
acceleration of gravity	9.81 m/s^2

5.1 The fracture width

The calculations are performed for a range of hydraulic conductivity values of the water between 10^{-5} m/s and 10^{-8} m/s. The fracture density is assumed to be 5 - 10 fractures per metre. The rock permeability can be obtained from the relationship

$$k = K\mu_w / \rho_w g \tag{52}$$

where K is the hydraulic conductivity. For $\rho_w = 10^3$ kg/m^3 and $\mu_w = 10^{-3}$ Pas, one obtains a range of permeability values between 10^{-12} m^2 and 10^{-15} m^2.

For a fracture frequency of 5 - 10 fractures, one obtains a range of the fracture width between about 10^{-4} m to 10^{-5} m.

5.2 The critical thickness of the gas cushion

To initiate the displacement of the water from a fracture the critical thickness of the gas cushion required is (eq. 12)

$$h_g = \frac{2x0.07422}{999x9.81} \frac{1}{b} = \frac{1.5146x10^{-5}}{b} \qquad (53)$$

In the range of the fracture width 10^{-4} m to 10^{-5} m obtained from the previous paragraph, one obtains h_g values in the range between 0.15146 and 1.5146 metres.

The fracture width of 10^{-5} metres, leading to the critical thickness of the gas cushion of about 1.5 metres is extremely small. In the rock formation in consideration the fracture width is varying over a wide range and statistically distributed.

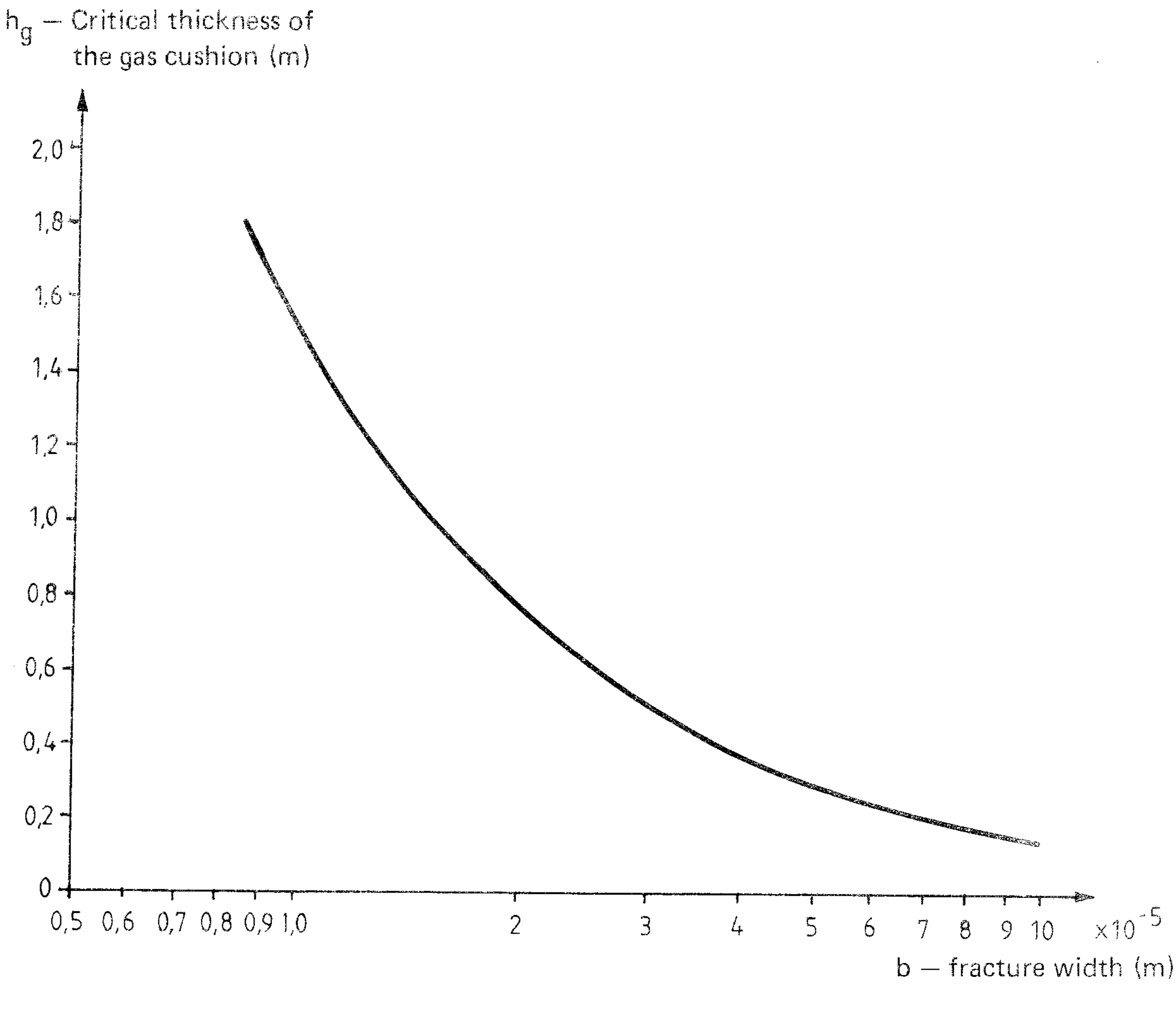

Figure 5. The critical thickness of the gas cushion as a function of the fracture width.

The displacement of the water will begin to take place in the large fractures, for which only a small thickness of the gas cushion is required. In the inital stage of the displacement of the water, the movement of the gas through the fractures is relatively slow. If the gas production will exceed the flow rate of the gas in the fractures being entered by the gas, then the thickness of the gas cushion will increase, and as a consequence the critical pressure required to start the displacement of the water also in the small fractures may be reached.

5.3 The break-through time of the gas

The calculations of the break-through times have been performed for the configurations being illustrated in Fig. 5. These configurations are: (a) a vertical fracture, (b) a tortuous fracture consisting of segments of equal inclination, and (c) and inclined fracture.

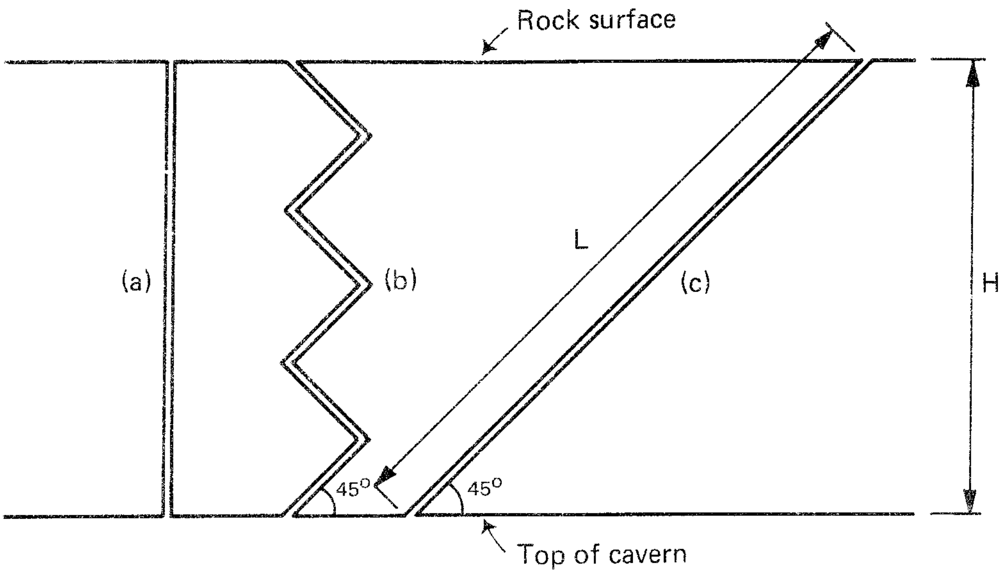

Figure 6. Schematic representation of the fractures considered in the present break-through time calculations.

The inclinations of the fractures segments in case (b) and the inclination of the fracture in case (c) are the same and the value of the inclination is assumed to be 45°. As a consequence, the fracture lengths are the same in these two cases. Since both the inclinations and the fracture lengths are identical, then also the break-through times will be identical.

According to equation (48) the break-through time of the fractures (b) and (c) with $\alpha = 45^{\circ}$ is twice that of the vertical fracture (a). Therefore, a vertical fracture has been considered only in the calculations presented (eq. 46).

The calculations have been carried out for a range of the rock permeability between 10^{-12} and 10^{-15} m^2, corresponding to a hydraulic conductivity between 10^{-5} and 10^{-8} m/s. The results of the calculations are presented in the Appendix.

The fracture widths corresponding to these permeabilities are 10^{-4} and 10^{-5} m , and the corresponding values of the critical thickness of the gas cushion are about 0.15 and 1.51 metres.

For a permeability of 10^{-12} m^2 and a range of the h_g - values between 0.2 - 6 metres, we obtained break-through times between 0.7 - 0.2 days, and for a permeability of 10^{-15} m^2, we obtained break-through times between 48 and 17 days.

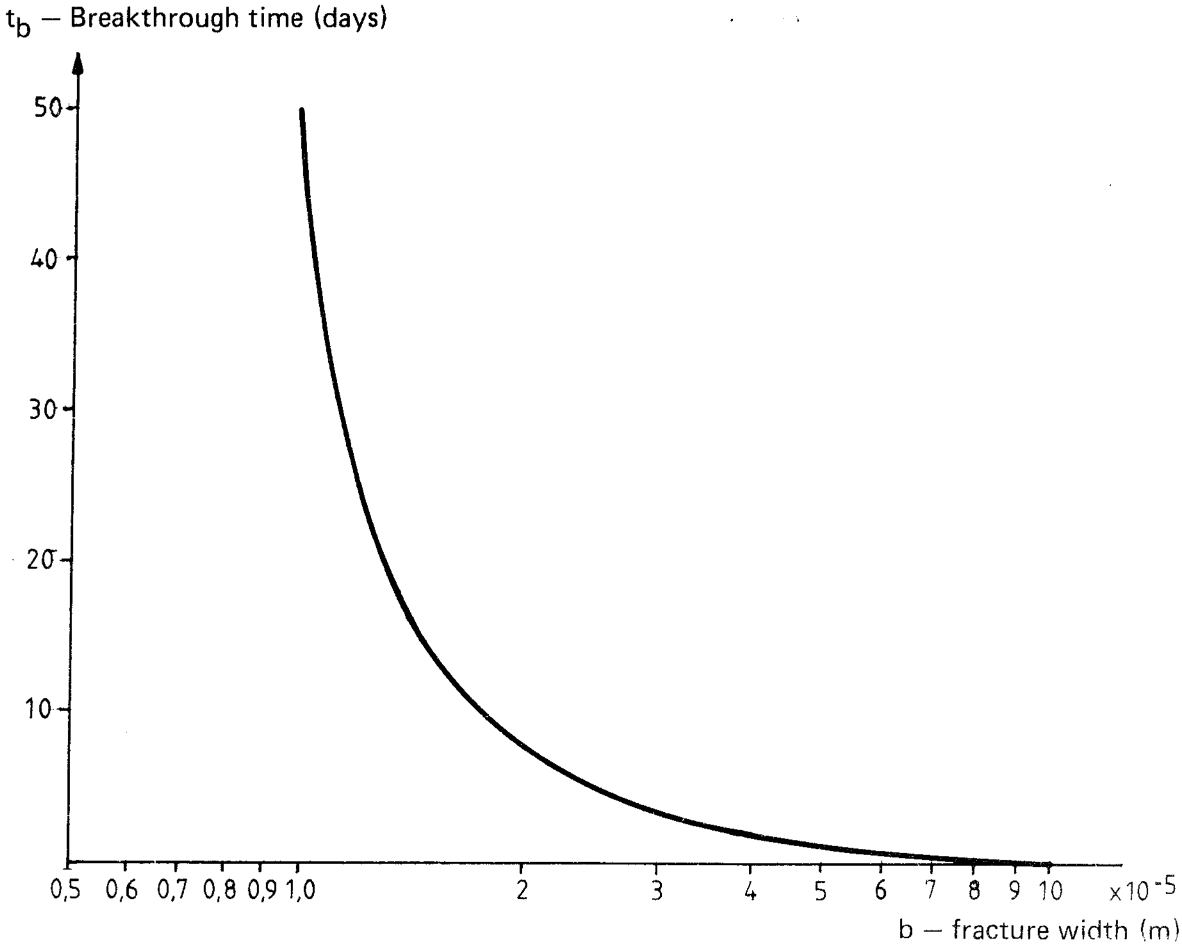

Figure 7. The break-through time of the gas as a function of the fracture width for a gas cushion of 2 metres.

5.4 The rate of the flow of the gas

The velocity of the gas through a single fracture is given by equation (37). The volumetric flowrate of the gas is obtained by multiplying the velocity by the area of the fractures.

For the fracture configuration considered (Fig. 4) with n fractures per metre in each direction, one obtains a volumetric rate of flow per unit (bulk) area of the rock

$$q_g = v_g 2nb \tag{54}$$

Substituting equation (37) for $\alpha = 90^o$ into the previous expression, one obtains

$$q_g = \frac{2nbk_f g\Delta\rho}{\mu_g} (1 + h_g/H) \tag{55}$$

and the mass rate of flow per unit area will be

$$m_g = \rho_g q_g \tag{56}$$

The calculations of the flowrates of gas have been performed for the same permeability values as for the calculations of the breakthrough times. The fracture frequency is assumed to be either 5 or 10 fractures per metre. The results of the calculations are presented in the Appendix.

The calculations with a permeability of 10^{-12} m^2, a range of h_g -values between 0.2 - 6 metres, and a fracture frequency of 10 fractures per metre resulted in flowrates of the gas of about $1.1x10^{-3}$ - $1.3x10^{-3}$ m^3/sm^2 (0.25 MPa). For a rock permeability of 10^{-15} m^2, flowrates of about $2.0x10^{-6}$ m^3/sm^2 were obtained.

Steady state flow of the gas may be reached if the rate of the gas production in the cavern will be equal to the flowrate of the gas through the rock. In this case the thickness of the gas cushion will be constant with time.

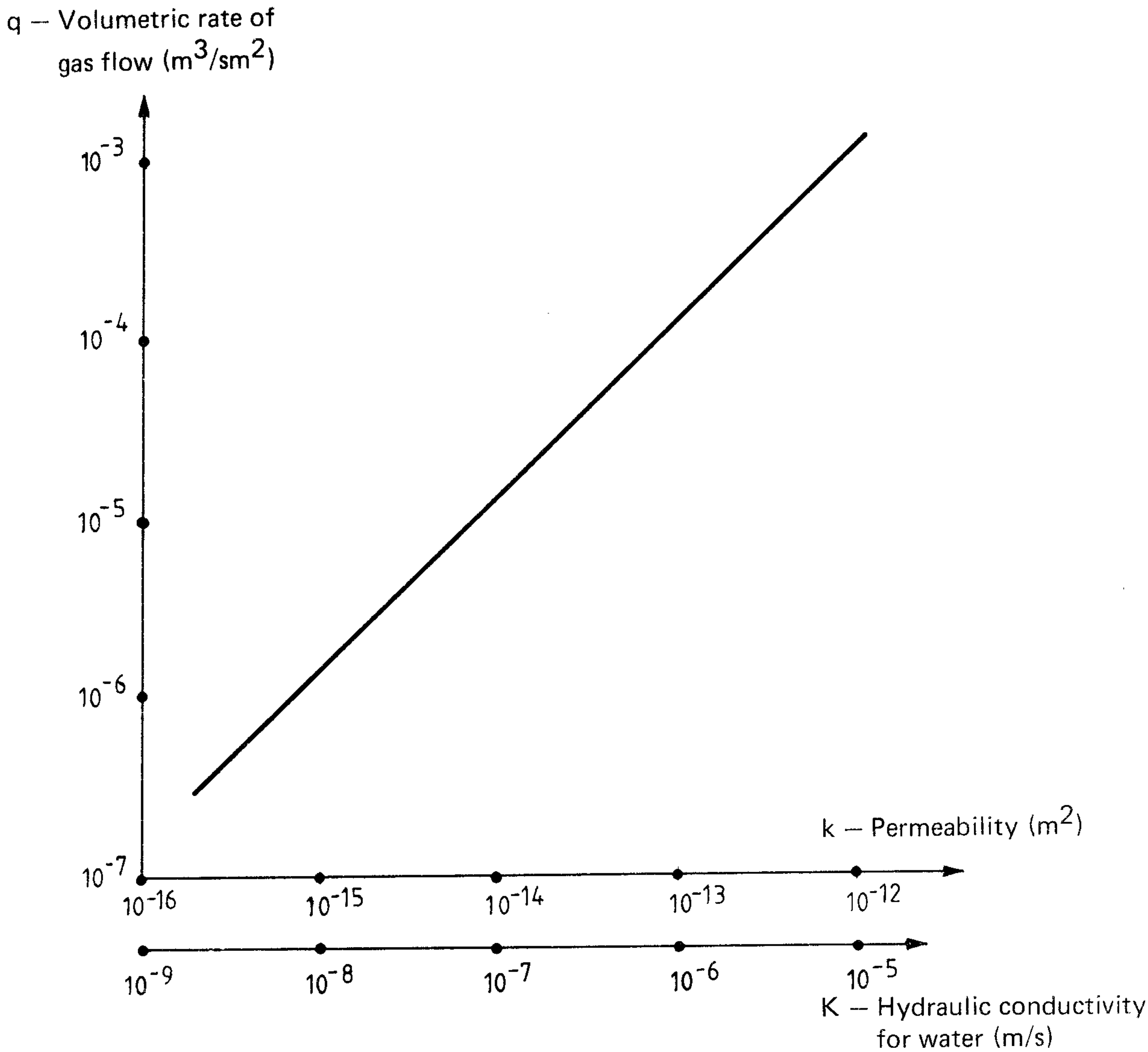

Figure 8. The flow rate of the gas as a function of the rock permeability or the hydraulic conductivity for a system of vertical fractures.

APPENDIX: Tables of break-through times and flow rates of gas from a low level radioactive waste repository located below the sea bottom

FRACTURE WIDTH .... = 0.840D-04 M.
FRACTURE PERMEABILITY .... = 0.588D-09 SQ.M.
CRITICAL THICKNESS OF THE GAS CUSHION .... = 0.180 M.

NR. OF FRACTURES PER METRE .... = 5
ROCK PERMEABILITY .... = 0.494D-12 SQ.M.
HYDRAULIC CONDUCTIVITY (FOR WATER) .... = 0.485D-05 M/S

THICKNESS OF GAS CUSHION (M)	BREAKTHROUGH TIME (DAYS)	FLOWRATE OF GAS (CUM/S SQM)
0.680	0.687	5.73D-04
1.080	0.481	5.77D-04
1.480	0.409	5.82D-04
1.880	0.365	5.86D-04
2.280	0.333	5.91D-04
2.680	0.309	5.95D-04
3.080	0.289	6.00D-04
3.480	0.273	6.04D-04
3.880	0.259	6.09D-04
4.280	0.247	6.14D-04
4.680	0.236	6.18D-04
5.080	0.226	6.23D-04
5.480	0.218	6.27D-04
5.880	0.210	6.32D-04

NR. OF FRACTURES PER METRE .... = 10
ROCK PERMEABILITY .... = 0.988D-12 SQ.M.
HYDRAULIC CONDUCTIVITY (FOR WATER) .... = 0.969D-05 M/S

THICKNESS OF GAS CUSHION (M)	BREAKTHROUGH TIME (DAYS)	FLOWRATE OF GAS (CUM/S SQM)
0.680	0.687	1.15D-03
1.080	0.481	1.15D-03
1.480	0.409	1.16D-03
1.880	0.365	1.17D-03
2.280	0.333	1.18D-03
2.680	0.309	1.19D-03
3.080	0.289	1.20D-03
3.480	0.273	1.21D-03
3.880	0.259	1.22D-03
4.280	0.247	1.23D-03
4.680	0.236	1.24D-03
5.080	0.226	1.25D-03
5.480	0.218	1.25D-03
5.880	0.210	1.26D-03

FRACTURE WIDTH .... = 0.100D-03 M.
FRACTURE PERMEABILITY .... = 0.833D-09 SQ.M.
CRITICAL THICKNESS OF THE GAS CUSHION .... = 0.151 M.

NR. OF FRACTURES PER METRE .... = 5
ROCK PERMEABILITY .... = 0.833D-12 SQ.M.
HYDRAULIC CONDUCTIVITY (FOR WATER) .... = 0.818D-05 M/S

THICKNESS OF GAS CUSHION (M)	BREAKTHROUGH TIME (DAYS)	FLOWRATE OF GAS (CUM/S SQM)
0.651	0.485	9.65D-04
1.051	0.340	9.73D-04
1.451	0.288	9.81D-04
1.851	0.257	9.88D-04
2.251	0.235	9.96D-04
2.651	0.218	1.00D-03
3.051	0.204	1.01D-03
3.451	0.192	1.02D-03
3.851	0.183	1.03D-03
4.251	0.174	1.03D-03
4.651	0.166	1.04D-03
5.051	0.160	1.05D-03
5.451	0.154	1.06D-03
5.851	0.148	1.07D-03

NR. OF FRACTURES PER METRE .... = 10
ROCK PERMEABILITY .... = 0.167D-11 SQ.M.
HYDRAULIC CONDUCTIVITY (FOR WATER) .... = 0.164D-04 M/S

THICKNESS OF GAS CUSHION (M)	BREAKTHROUGH TIME (DAYS)	FLOWRATE OF GAS (CUM/S SQM)
0.651	0.485	1.93D-03
1.051	0.340	1.95D-03
1.451	0.288	1.96D-03
1.851	0.257	1.98D-03
2.251	0.235	1.99D-03
2.651	0.218	2.01D-03
3.051	0.204	2.02D-03
3.451	0.192	2.04D-03
3.851	0.183	2.05D-03
4.251	0.174	2.07D-03
4.651	0.166	2.08D-03
5.051	0.160	2.10D-03
5.451	0.154	2.12D-03
5.851	0.148	2.13D-03

FRACTURE WIDTH .... = 0.390D-04 M.
FRACTURE PERMEABILITY .... = 0.127D-09 SQ.M.
CRITICAL THICKNESS OF THE GAS CUSHION .... = 0.388 M.

NR. OF FRACTURES PER METRE .... = 5
ROCK PERMEABILITY .... = 0.494D-13 SQ.M.
HYDRAULIC CONDUCTIVITY (FOR WATER) .... = 0.485D-06 M/S

THICKNESS OF GAS CUSHION (M)	BREAKTHROUGH TIME (DAYS)	FLOWRATE OF GAS (CUM/S SQM)
0.888	3.189	5.75D-05
1.288	2.234	5.80D-05
1.688	1.896	5.84D-05
2.088	1.691	5.89D-05
2.488	1.545	5.94D-05
2.888	1.432	5.98D-05
3.288	1.341	6.03D-05
3.688	1.265	6.07D-05
4.088	1.200	6.12D-05
4.488	1.144	6.16D-05
4.888	1.094	6.21D-05
5.288	1.050	6.26D-05
5.688	1.010	6.30D-05

NR. OF FRACTURES PER METRE .... = 10
ROCK PERMEABILITY .... = 0.989D-13 SQ.M.
HYDRAULIC CONDUCTIVITY (FOR WATER) .... = 0.970D-06 M/S

THICKNESS OF GAS CUSHION (M)	BREAKTHROUGH TIME (DAYS)	FLOWRATE OF GAS (CUM/S SQM)
0.888	3.189	1.15D-04
1.288	2.234	1.16D-04
1.688	1.896	1.17D-04
2.088	1.691	1.18D-04
2.488	1.545	1.19D-04
2.888	1.432	1.20D-04
3.288	1.341	1.21D-04
3.688	1.265	1.21D-04
4.088	1.200	1.22D-04
4.488	1.144	1.23D-04
4.888	1.094	1.24D-04
5.288	1.050	1.25D-04
5.688	1.010	1.26D-04

```
FRACTURE WIDTH                            .... =  0.490D-04 M.
FRACTURE PERMEABILITY                     .... =  0.200D-09 SQ.M.
CRITICAL THICKNESS OF THE GAS CUSHION     .... =      0.309 M.
```

```
NR. OF FRACTURES PER METRE                .... =          5
ROCK PERMEABILITY                         .... =  0.980D-13 SQ.M.
HYDRAULIC CONDUCTIVITY (FOR WATER)        .... =  0.962D-06 M/S
```

THICKNESS OF GAS CUSHION (M)	BREAKTHROUGH TIME (DAYS)	FLOWRATE OF GAS (CUM/S SQM)
0.809	2.020	1.14D-04
1.209	1.415	1.15D-04
1.609	1.201	1.16D-04
2.009	1.071	1.17D-04
2.409	0.979	1.18D-04
2.809	0.907	1.18D-04
3.209	0.850	1.19D-04
3.609	0.802	1.20D-04
4.009	0.760	1.21D-04
4.409	0.725	1.22D-04
4.809	0.693	1.23D-04
5.209	0.665	1.24D-04
5.609	0.640	1.25D-04

```
NR. OF FRACTURES PER METRE                .... =         10
ROCK PERMEABILITY                         .... =  0.196D-12 SQ.M.
HYDRAULIC CONDUCTIVITY (FOR WATER)        .... =  0.192D-05 M/S
```

THICKNESS OF GAS CUSHION (M)	BREAKTHROUGH TIME (DAYS)	FLOWRATE OF GAS (CUM/S SQM)
0.809	2.020	2.28D-04
1.209	1.415	2.30D-04
1.609	1.201	2.31D-04
2.009	1.071	2.33D-04
2.409	0.979	2.35D-04
2.809	0.907	2.37D-04
3.209	0.850	2.39D-04
3.609	0.802	2.41D-04
4.009	0.760	2.42D-04
4.409	0.725	2.44D-04
4.809	0.693	2.46D-04
5.209	0.665	2.48D-04
5.609	0.640	2.50D-04

FRACTURE WIDTH .... = 0.180D-04 M.
FRACTURE PERMEABILITY .... = 0.270D-10 SQ.M.
CRITICAL THICKNESS OF THE GAS CUSHION .... = 0.842 M.

NR. OF FRACTURES PER METRE .... = 5
ROCK PERMEABILITY .... = 0.486D-14 SQ.M.
HYDRAULIC CONDUCTIVITY (FOR WATER) .... = 0.477D-07 M/S

THICKNESS OF GAS CUSHION (M)	BREAKTHROUGH TIME (DAYS)	FLOWRATE OF GAS (CUM/S SQM)
1.342	14.969	5.71D-06
1.742	10.486	5.75D-06
2.142	8.903	5.80D-06
2.542	7.939	5.84D-06
2.942	7.253	5.89D-06
3.342	6.724	5.93D-06
3.742	6.296	5.98D-06
4.142	5.940	6.02D-06
4.542	5.635	6.07D-06
4.942	5.370	6.11D-06
5.342	5.136	6.16D-06
5.742	4.928	6.20D-06

NR. OF FRACTURES PER METRE .... = 10
ROCK PERMEABILITY .... = 0.972D-14 SQ.M.
HYDRAULIC CONDUCTIVITY (FOR WATER) .... = 0.954D-07 M/S

THICKNESS OF GAS CUSHION (M)	BREAKTHROUGH TIME (DAYS)	FLOWRATE OF GAS (CUM/S SQM)
1.342	14.969	1.14D-05
1.742	10.486	1.15D-05
2.142	8.903	1.16D-05
2.542	7.939	1.17D-05
2.942	7.253	1.18D-05
3.342	6.724	1.19D-05
3.742	6.296	1.20D-05
4.142	5.940	1.20D-05
4.542	5.635	1.21D-05
4.942	5.370	1.22D-05
5.342	5.136	1.23D-05
5.742	4.928	1.24D-05

FRACTURE WIDTH	.... =	0.230D-04 M.
FRACTURE PERMEABILITY	.... =	0.441D-10 SQ.M.
CRITICAL THICKNESS OF THE GAS CUSHION	.... =	0.659 M.

NR. OF FRACTURES PER METRE	.... =	5
ROCK PERMEABILITY	.... =	0.101D-13 SQ.M.
HYDRAULIC CONDUCTIVITY (FOR WATER)	.... =	0.995D-07 M/S

THICKNESS OF GAS CUSHION (M)	BREAKTHROUGH TIME (DAYS)	FLOWRATE OF GAS (CUM/S SQM)
1.159	9.168	1.19D-05
1.559	6.422	1.20D-05
1.959	5.453	1.21D-05
2.359	4.862	1.21D-05
2.759	4.442	1.22D-05
3.159	4.118	1.23D-05
3.559	3.856	1.24D-05
3.959	3.638	1.25D-05
4.359	3.451	1.26D-05
4.759	3.289	1.27D-05
5.159	3.146	1.28D-05
5.559	3.018	1.29D-05
5.959	2.903	1.30D-05

NR. OF FRACTURES PER METRE	.... =	10
ROCK PERMEABILITY	.... =	0.203D-13 SQ.M.
HYDRAULIC CONDUCTIVITY (FOR WATER)	.... =	0.199D-06 M/S

THICKNESS OF GAS CUSHION (M)	BREAKTHROUGH TIME (DAYS)	FLOWRATE OF GAS (CUM/S SQM)
1.159	9.168	2.37D-05
1.559	6.422	2.39D-05
1.959	5.453	2.41D-05
2.359	4.862	2.43D-05
2.759	4.442	2.45D-05
3.159	4.118	2.47D-05
3.559	3.856	2.49D-05
3.959	3.638	2.50D-05
4.359	3.451	2.52D-05
4.759	3.289	2.54D-05
5.159	3.146	2.56D-05
5.559	3.018	2.58D-05
5.959	2.903	2.60D-05

FRACTURE WIDTH	.... =	0.840D-05 M.
FRACTURE PERMEABILITY	.... =	0.588D-11 SQ.M.
CRITICAL THICKNESS OF THE GAS CUSHION	.... =	1.804 M.

NR. OF FRACTURES PER METRE	.... =	5
ROCK PERMEABILITY	.... =	0.494D-15 SQ.M.
HYDRAULIC CONDUCTIVITY (FOR WATER)	.... =	0.485D-08 M/S

THICKNESS OF GAS CUSHION (M)	BREAKTHROUGH TIME (DAYS)	FLOWRATE OF GAS (CUM/S SQM)
2.304	68.734	5.91D-07
2.704	48.148	5.96D-07
3.104	40.881	6.00D-07
3.504	36.455	6.05D-07
3.904	33.303	6.09D-07
4.304	30.875	6.14D-07
4.704	28.912	6.18D-07
5.104	27.275	6.23D-07
5.504	25.875	6.27D-07
5.904	24.659	6.32D-07

NR. OF FRACTURES PER METRE	.... =	10
ROCK PERMEABILITY	.... =	0.988D-15 SQ.M.
HYDRAULIC CONDUCTIVITY (FOR WATER)	.... =	0.969D-08 M/S

THICKNESS OF GAS CUSHION (M)	BREAKTHROUGH TIME (DAYS)	FLOWRATE OF GAS (CUM/S SQM)
2.304	68.734	1.18D-06
2.704	48.148	1.19D-06
3.104	40.881	1.20D-06
3.504	36.455	1.21D-06
3.904	33.303	1.22D-06
4.304	30.875	1.23D-06
4.704	28.912	1.24D-06
5.104	27.275	1.25D-06
5.504	25.875	1.25D-06
5.904	24.659	1.26D-06

FRACTURE WIDTH .... = 0.100D-04 M.
FRACTURE PERMEABILITY .... = 0.833D-11 SQ.M.
CRITICAL THICKNESS OF THE GAS CUSHION .... = 1.515 M.

NR. OF FRACTURES PER METRE .... = 5
ROCK PERMEABILITY .... = 0.833D-15 SQ.M.
HYDRAULIC CONDUCTIVITY (FOR WATER) .... = 0.818D-08 M/S

THICKNESS OF GAS CUSHION (M)	BREAKTHROUGH TIME (DAYS)	FLOWRATE OF GAS (CUM/S SQM)
2.015	48.498	9.92D-07
2.415	33.974	9.99D-07
2.815	28.845	1.01D-06
3.215	25.722	1.01D-06
3.615	23.498	1.02D-06
4.015	21.785	1.03D-06
4.415	20.401	1.04D-06
4.815	19.245	1.05D-06
5.215	18.258	1.05D-06
5.615	17.399	1.06D-06

NR. OF FRACTURES PER METRE .... = 10
ROCK PERMEABILITY .... = 0.167D-14 SQ.M.
HYDRAULIC CONDUCTIVITY (FOR WATER) .... = 0.164D-07 M/S

THICKNESS OF GAS CUSHION (M)	BREAKTHROUGH TIME (DAYS)	FLOWRATE OF GAS (CUM/S SQM)
2.015	48.498	1.98D-06
2.415	33.974	2.00D-06
2.815	28.845	2.01D-06
3.215	25.722	2.03D-06
3.615	23.498	2.04D-06
4.015	21.785	2.06D-06
4.415	20.401	2.08D-06
4.815	19.245	2.09D-06
5.215	18.258	2.11D-06
5.615	17.399	2.12D-06

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