SE9200X8X

STATENS
KÄRNBRÄNSLE
NÄMND

NATIONAL BOARD FOR SPENT NUCLEAR FUEL

SKN REPORT 63

SKN--63

Hydraulic Gradients in Rock Aquifers

MAY 1992

Where and how will we dispose of spent nuclear fuel?

There is political consensus to dispose of spent nuclear fuel from Swedish nuclear power plants in Sweden. No decision has yet been reached on a site for the final repository in Sweden and neither has a method for disposal been determined. The disposal site and method must be selected with regard to safety and the environment as well as with regard to our responsibility to prevent the proliferation of materials which can be used to produce nuclear weapons.

In 1983, a disposal method called KBS-3 was presented by the nuclear power utilities, through the Swedish Nuclear Fuel and Waste Management Company (SKB). In its 1984 resolution on permission to load fuel into the Forsmark 3 and Oskarshamn 3 reactors, the government stated that the KBS-3 method - which had been thoroughly reviewed by Swedish and foreign experts - "was, in its entirety and in all essentials, found to be acceptable in terms of safety and radiological protection."

In the same resolution, the government also pointed out that a final position on a choice of method would require further research and development work.

Who is responsible for the safe management of spent nuclear fuel?

The nuclear power utilities have **the direct responsibility** for the safe handling and disposal of spent nuclear fuel.

This decision is based on the following, general argument: those who conduct an activity are responsible for seeing that the activity is conducted in a safe manner. This responsibility also includes managing any waste generated by the activity. This argument is reflected in the wording of major legislation in the field of nuclear power, such as the Act on Nuclear Activities (1984) and the Act on the Financing of Future Expenses for Spent Nuclear Fuel etc. (1981).

The Act on Nuclear Activities and the Act on the Financing of Future Expenses for Spent Nuclear Fuel etc. stipulate that the nuclear power utilities are responsible for conducting the research which is necessary for the safe management of spent nuclear fuel. This legislation stipulates that the utilities are also responsible for the costs incurred in connection with the handling and disposal of the waste.

There are four nuclear power utilities in Sweden: Vattenfall AB, Forsmarks Kraftgrupp AB, Sydsvenska Värmekraft AB and OKG AB. Together, these four utilities own the Swedish Nuclear Fuel and Waste Management Company (SKB). SKB's tasks include the practical execution of the work which the utilities are responsible for carrying out.

The government has **the overall responsibility** for safety in connection with waste handling and disposal. Three authorities - the National Board for Spent Nuclear Fuel (SKN), the Swedish Nuclear Power Inspectorate (SKI), and the National Institute of Radiation Protection (SSI) - are responsible for different aspects of government supervision of the utilities' waste activities. The government has also appointed a scientific advisory board, the National Council for Nuclear Waste - KASAM, to deal with these matters.

Continued on the back inside cover.

STATENS
KÄRNBRÄNSLE
NÄMND

NATIONAL BOARD FOR SPENT NUCLEAR FUEL

SKN REPORT 63
MAY 1992

DNR 100/90

Hydraulic Gradients in Rock Aquifers

PETER DAHLBLOM
LUND UNIVERSITY,
DEPARTMENT OF WATER RESOURCES ENGINEERING
APRIL 1992

THIS WORK HAS BEEN FINANCED BY THE NATIONAL BOARD FOR SPENT NUCLEAR FUEL.
THE AUTHOR IS RESPONSIBLE FOR OPINIONS EXPRESSED IN THIS REPORT.

Kommentus Förlag 757 2 010
Tryck: Graphic Systems AB, Göteborg 1992

HYDRAULIC GRADIENTS IN ROCK AQUIFERS

by

Peter DAHLBLOM

ABSTRACT

This report deals with fractured rock as a host for deposits of hazardous waste. In this context the rock, with its fractures containing moving groundwater, is called the geological barrier. The desired properties of the geological barrier are low permeability to water, low hydraulic gradients and ability to retain matter dissolved in the water. The hydraulic gradient together with the permeability and the porosity determines the migration velocity. Mathematical modelling of the migration involves calculation of the water flow and the hydrodynamic dispersion of the contaminant. The porous medium approach can be used to calculate mean flow velocities and hydrodynamic dispersion if a large number of fractures are connected, which means that a large volume have to be considered. It is assumed that the porous medium approach can be applied, and a number of idealized examples are shown. It is assumed that the groundwater table is replenished by percolation at a constant rate. One-dimensional analytical calculations show that zero hydraulic gradients may exist at relatively large distance from the coast. Two-dimensional numerical calculations show that it may be possible to find areas with low hydraulic gradients and flow velocities within blocks surrounded by areas with high hydraulic conductivity.

CONTENTS

LIST OF SYMBOLS

C	= concentration	(M/L^3)
D	= dispersion coefficient	(L^2/T)
D_1	= longitudinal dispersion coefficient	(L^2/T)
D_2	= lateral dispersion coefficient	(L^2/T)
D_m	= diffusion coefficient	(L^2/T)
F	= rate of transfer of mass per unit area	(M/L^2)
g	= acceleration due to gravity	(L/T^2)
h	= hydraulic potential	(L)
I	= rate of percolation to the groundwater	(L/T)
K	= hydraulic conductivity	(L/T)
k	= permeability	(L^2)
n	= porosity	(-)
p_w	= pressure	$(M/(T^2L))$
q	= Darcy velocity	(L/T)
Re	= Reynolds number	(-)
u	= mean flow velocity in a tube	(L/T)
v	= propagation velocity for contaminants	(L/T)
z	= altitude	(L)
μ	= dynamic viscosity	(M/LT)
ρ	= density of the water	(M/L^3)

1 INTRODUCTION

In recent years a lot of research has been carried out concerning groundwater flow and migration of contaminations in aquifers consisting of fractured rock. This research activity has to a large extent been initiated by plans to utilize the underground for disposal of hazardous waste, as for example radioactive waste from nuclear power plants.

There are, broadly speaking, three categories of radioactive waste: intermediate and low-level wastes, which do not generate heat; and high-level or heat generating waste (Heath, 1985). The Swedish plan for disposing of high-level waste involves placing canisters containing the used fuel from reactors in holes that have been drilled from a system of galleries (SKBF, 1983). Blocks of highly compacted bentonite shall surround the canisters in the holes. These blocks form a buffer, which swells when wetted to produce an almost impermeable barrier. The galleries themselves are then back-filled with a mixture of sand and bentonite. The repository is planned to be situated at a depth of about 500 metres below the ground-surface.

The purpose of the final storage of the nuclear waste is to protect the humans and life on the earth from all impact from the waste. If, in spite of the protecting environment in the disposal, damage on any canister although should occur, the traces of the waste that might reach the surface with the groundwater shall be negligible compared to the natural amount of radioactive species in the water. The principle of the final storage is multiple long-lived barriers, which can be divided into man-made and natural barriers. The natural barrier, also called the geological barrier, is in this context the fractured rock containing moving groundwater. The behaviour of the geological barrier is dependent upon two essential properties: the low permeability to water and the ability to retain matter dissolved in the water. The low permeability to water implies a slow transport to the ground surface. The amount of groundwater flowing through a particular location is proportional to the permeability of the rock, which generally decreases with depth. The sorption qualities of the fissure surfaces and the diffusion of dissolved species into micro fissures is further retaining the transport of the radioactive species. Radionuclides which do leak out of the immediate vicinity of the repository will be diluted by a number of mechanisms including hydrodynamic dispersion. Finally, any radionuclides reaching the surface will be diluted in a large body of water such as a lake, river or sea (Herbert et. al., 1985).

The combined amount of time for penetration of the man-made barriers and transport through the geological barrier have to be long in comparison with the half life of the radioactive species. The half lives for fission products lies between 29.9 sec for Radium-106 and 15.9 mill years for Iodine-129 (Lindblom, 1977). The position and geometry of the repository is adapted to the geological properties of the rock. Of a special importance is that the groundwater flow is low in the vicinity of the capsules. The repository is intended to be designed so that the capsules are placed at least at a distance of 100 metres from the nearest known zone with an increased water flow or where the rock is so crushed and weakened that future rock movements may take place (SKBF, 1983). In some cases such large scale fault zones can have a beneficial effect since they tend to divert water which might otherwise have flowed through the repository.

A systematic description of the interrelations between the physical processes affecting the travel time and the concentration of hazardous material leaching to the biosphere was given by Lindh et al (1984).

The transport velocity for a pollutant in a liquid flowing through a porous medium is determined by the hydraulic conductivity, the porosity and the hydraulic gradient. For a barrier consisting of a clay material Lindblom (1977) assuming the hydraulic conductivity to be 10^{-10} cm/s, the hydraulic gradient 10^{-2}, and the porosity 0.2 obtained a transport velocity of 1 cm in 5000 years. Thus, a clay layer just 2 metres thick would produce a cross-flow travel time of 1 million years. It is evident that if a clay zone without cracks can be established in the repository, hydraulic transport of radionuclides through the clay layer from the canister towards the surrounding fractured rock would be a relatively insignificant process. The reduction of hydraulic transport rates to such very low rates however, would not, in itself, insure long term isolation of the radionuclides from the biosphere. It is necessary to consider a second transport process, known as molecular diffusion. Molecular diffusion will cause dissolved radionuclides to migrate from the waste canisters through the geologic materials in the cavity and then beyond into the fracture network in the crystalline rock. This migration occurs due to the concentration gradient. Under conditions of extremely slow hydraulic flow of pore water, molecular diffusion is the dominant process by which radionuclide migration occurs in saturated porous media. Radionuclides in water typically have molecular diffusion coefficients in the ranges of $1 \cdot 10^{-5}$ cm^2/s to $3 \cdot 10^{-5}$ cm^2/s (Lindblom, 1977). The slower diffusion that occurs in saturated porous media compared to aqueous systems can be accounted for by multiplying the diffusion coefficient with a factor in the range of 0.05 to 0.3 (Lindblom, 1977). Calculations using diffusion coefficients in this range indicate that radionuclide fronts can diffuse through clay zones several metres thick in time periods as short as several hundred years. Therefore, it is possible that radionuclides will move into the environment consisting of fractured rock long before radioactive decay reduces the activity to very low levels.

In the event that radionuclides are leached from the canisters and migrate through the clay material into fractures in the surrounding rock mass, transport of the radionuclides towards the biosphere may be caused by advection and molecular diffusion. If the groundwater velocities in the fracture network near the repository is sufficiently low, the molecular diffusion will be the dominant transport process. In the event of canister leakage, according to Lindblom (1977), fronts of dissolved radionuclides may migrate over distances of more than a hundred metres from a canister in a period of 10000 years after initiation of leaching. Radionuclides may then enter into a zone of active groundwater flow as for example in a fault or shear zone. Any chemical process that causes radionuclides to be transferred from the groundwater to the rock surface along the fractures causes retardation. If the transfer is irreversible, then the radionuclides are permanently lost from the transport system. If the processes are reversible, then eventually, the radionuclides will re-enter the aqueous phase, except for those quantities that are lost by radioactive decay. Re-entry will occur when the water moving through the fracture system declines in concentration with respect to the radionuclide species under consideration. Neretnieks and Rasmuson (1983) made numerical calculations of the impact of retardation mechanisms. Surface sorption and diffusion into the rock matrix was considered. It was indicated that the retardation in a lineament may be as important as the retardation in low permeability rock because of the larger surface areas available for sorption.

2 MODELLING OF WATER MOVEMENT AND MIGRATION IN THE ROCK

Mathematical models can be classified according to the degree of simplification introduced in the description of the physical processes prevailing in the prototype modelled. The main advantage in using simplified models is that the computational work and the amount of physical information will be less than for more accurate physically based models. When it concerns water movement and migration in fractured rock, the most simplified approaches are to regard the fractured rock as a ideal porous medium. The most accurate physical based model requires information about the position and the geometrical properties of all the fractures in the environment, while at more simplified approaches those properties are included in a few parameters, for example porosity, conductivity and dispersivity for the porous media approach. Application of mathematical models has to be preceded by field measurements where the measured properties have to be in accordance with the model parameters.

Wilson and Witherspoon (1970) use the notions statistical approach and enumerative approach. In the statistical approach a fractured rock mass is considered to be a statistically homogeneous medium consisting of a combination of fractures and porous media. The system is called statistically homogeneous because the probability of finding a fracture at any point in the system is considered to be the same as at any other point. This idealized fracture system is the considered to behave as a type of porous medium. In the enumerative approach a fractured rock mass is studied through the use of a model which attempts to duplicate the actual geometry of the fractures and porous rock blocks. In this model the location, orientation, and aperture variations for each individual fracture must be considered.

2.1 The porous medium approach

The porous medium approach is based on the assumption of a linear relation between hydraulic gradient and flow velocity. This relationship is expressed in Darcy's law which was found by means of experiments on sand filters (Darcy, 1856). Concerning transport of dissolved pollutants, it is postulated that there is a linear relation between the concentration and the migration, as described by Fick's law (Fick, 1855).

For three dimensions Darcy's law can be written:

$$q = - K \nabla h \qquad (1)$$

where

q = the Darcy velocity

K = hydraulic conductivity

h = potential.

The potential h is defined as:

$$h = \frac{p_w}{\rho g} + z \qquad (2)$$

where

p_w = pressure

z = altitude

The hydraulic conductivity K includes properties of both the porous medium and the fluid and has the dimension of velocity. The permeability k, however, is a pure material constant for the porous medium and has the dimension of (L^2). The relationship between permeability and hydraulic conductivity can be expressed (Snow, 1968, Carlsson et al, 1983):

$$K = \frac{g \rho k}{\mu} \qquad (3)$$

Together with the condition of mass conservation, a differential equation can be established and solved with given boundary conditions. The solution is the potential field from which the Darcy velocity is achieved. In reality the Darcy velocity is the amount of water that passes through a unit area per time unit, and is equivalent to a mean velocity averaged over cavities as well as solid material. The propagation velocity, v, for particles transported by the water is larger than the Darcy velocity while only the cross section areas of the cavities are taken into account. The propagation velocity can be calculated:

$$v = \frac{q}{n} \tag{4}$$

where

n = the porosity.

This propagation velocity can be regarded as a mean velocity for the transport of dissolved pollutants in the water. In general, no relation between porosity and permeability exists. The shape and size of the cavities are also important. The permeability of for example a water saturated sand can be calculated if the porosity and the specific surface are known (Carman, 1939). This author also points out that clays may have zero permeability at quite considerable porosities.

The flow velocities within single cavities might deviate a lot from this mean velocity which implies a further increase in the transport velocity for some part of the pollution (Dahlblom, 1985).

This deviations around the mean propagation velocity are referred to as hydrodynamic dispersion. According to the porous medium approach, the hydrodynamic dispersion is regarded as analogous to the molecular diffusion.

Fick (1855) made experiments with salt dissolved in non moving water in vertical cylinders. Fick states that there is a linear relation between the concentration gradient and the transport of dissolved matter and points out the similarity with Fourier's law for heat flow. A similarity with the later published Darcy's law is also at hand. For three dimensions Fick's law can be written:

$$F = - D_m \nabla C \tag{5}$$

where

F = the rate of transfer per unit area

C = concentration

D_m= diffusion coefficient.

The slower diffusion that occurs in saturated porous media compared to aqueous systems can be accounted for by multiplying the diffusion coefficient with a cross sectional area, A', for diffusion (Perkins and Johnston, 1963). A comparison with the proposal of Lindblom (1977) suggests that the area should be in the range 0.03 to 0.3.

The law of mass conservation can be expressed:

$$\frac{\partial C}{\partial t} + \nabla \cdot F = 0 \tag{6}$$

The quantity F according to equation (5) can be inserted into equation (6) which gives (provided that D_m is an isotropic property independent of the concentration):

$$\frac{\partial C}{\partial t} - D_m \nabla^2 C = 0 \tag{7}$$

For the case when the water is moving with a constant velocity an advection term has to be added to equation (5):

$$F = -D_m \nabla C + vC \tag{8}$$

which can be inserted into equation (6):

For the case of one dimensional movement the equation can be written:

$$\frac{\partial C}{\partial t} - D_m \frac{\partial^2 C}{\partial x^2} + v_x \frac{\partial C}{\partial x} = 0 \qquad (10)$$

Analytical solutions are given by Crank (1975), Ogata and Banks (1961), Lenda and Zuber (1970), and Fried and Combarnous (1971).

Although this equation is developed for molecular diffusion, it is often used to describe migration and hydrodynamic dispersion in connection with flow in porous media. The last term is then the advection term where v is the mean propagation velocity according to equation (4). The term containing the second order derivative describes the dispersion of the pollutant around this mean velocity whereby D_m is exchanged with a dispersion coefficient D.

2.1.1 Efforts to justify the porous medium approach.

Fick's law for molecular diffusion was formulated by means of experiments, but has been applied to hydrodynamic dispersion in shape of the diffusion equation (10). Application of empirical models beyond the circumstances that prevailed during the experiments might be hazardous, but some theoretical studies have been performed in order to justify the approach.

According to Fried and Combarnous (1971) the hydrodynamic dispersion in connection with flow in a porous medium is caused by three different phenomena:

1. the velocity is zero at solid surfaces, which creates a velocity gradient in the fluid phase, as in a capillary tube;

2. the variation of pore dimensions cause dis-

crepancies between the maximum velocities along the pore axes;

3. the streamlines fluctuate with respect to the mean direction of flow.

A comparison between the first mentioned phenomenon and the other two suggest that dispersion may be regarded with respect to different scales: a pore scale, or a microscopic scale in which the dispersion is caused by velocity differences within the pores, and a macroscopic scale where the dispersion is caused by differences in the mean velocity between different pores.

The impact of microscopic velocity differences on the dispersion was studied by Taylor (1953) by means of a tube with circular cross section and laminar flow. The approach was generalized to irregularly shaped straight capillaries by Aris (1956). Taking into account the molecular diffusion perpendicular to the flow direction only, Taylor shows that the longitudinal transfer of matter can be described by the dispersion equation and derives a value of the dispersion coefficient that decreases with the diffusion coefficient, and increases proportional to the squares of the flow velocity and the radius of the circular cross section of the pipe. When diffusion occurs radially, it tends to equalize concentrations in a cross section, thus opposing the formation of a parabolic surface of separation between solute and solvent caused by the distribution of flow velocities. Aris (1956) gives a general expression for the dispersion in a tube:

$$D = D_m + \kappa \frac{(au)^2}{D_m} \tag{11}$$

where κ is a coefficient depending on the shape of the cross section and the velocity distribution. For circular cross section and laminar flow λ is equal to 1/48. For so-called piston flow or for the case of zero velocity, $D = D_m$ as it should. The coefficient of molecular diffusion in a saturated porous medium, under zero convection, was shown by Gupta et. al. (1981) to be always less than the coefficient of molecular diffusion in an aqueous solution.

Levenspiel and Smith (1957) have studied the case of a tube into which a quantity of tracer is rapidly injected and the concentration versus time is observed downstream at a distance L from the injection point. The shape of the concentration-time curve is dependent on the value of the quantity D/uL which is the reciprocal of the Peclet number where u is an average velocity. It was shown that the skewness increases with D/uL, and that the concentration curve for small values of D/uL approaches the normal error curve. For this case D/uL is equal to half of the variance of the error curve. A method to estimate the quantity D/uL from an observed concentration-time curve is also given.

Simple models of parallel capillaries for the explanation of the properties of a porous medium has been suggested in the literature. Scheidegger (1953) made comparisons between a model based on a bundle of capillaries and Darcy's law. A linear relation exists between pressure gradient and flow velocity according to Hagen-Poiseuille's law for laminar flow in tubes which is in analogy with Darcy's law. The porosity was expressed in terms of tube diameter and the number of tubes per unit area. The hydraulic conductivity according to Darcy's law could then be expressed in terms of porosity, average pore diameter, and a "tortuosity-factor" expressing the length of the flow paths in relation to the shortest distance. It was shown that the conductivity increased with the porosity provided that the number of tubes and the tortuosity-factor were constant. A generalization to systems of spheres or cubes in a three dimensional pattern was given by Irmay (1965). The system of cubes have a resemblance with an idealized fractured rock with three orthogonal sets of equally spaced fractures with constant apertures.

Calhoun (1949) used a model consisting of a number of straight capillaries in parallel, all capillaries being of the same radius and length to investigate relationships between porosity and permeability. It was shown that no relationship can be established without the knowledge of an extra variable such as tube radius or specific area. For a system consisting of smooth parallel-walled channels of equal opening Snow (1968) expressed the permeability in terms of mean distance between the channels and their opening. It was also shown that a relation between porosity and permeability exists provided that the mean distance between the channels is given.

Klinkenberg (1957) and Erbe (1933) described methods for determination of the pore size distribution of a porous medium. The porous formation was assumed to consist of a set of cylindrical parallel capillaries, not interconnected. With this models, results from experiments with displacement of a liquid by another liquid are interpreted and the pore size distributions are given in graphical form. The method of Erbe provides that the liquids are not miscible, and a meniscus with surface tension exists between the two liquids.

Dahlblom and Hjorth (1986) made a theoretical study on an ensemble of parallel tubes having cross sectional areas belonging to an exponential distribution. It was assumed that the cross sectional areas where circular and that the flow was laminar. The concentration as function of time and length could be expressed for the case of a step function input of contaminated fluid at one end. Comparison was made with the classical theory for dispersion in a porous medium. A dispersion coefficient could be calculated which was shown to be dependent on the tube area distribution and the distance between injection and detection points. The model was generalized to gamma distributed cross-section areas and a finite number of tubes (Dahlblom, 1990). It was shown that a more narrow distribution of the cross-section areas gives a steeper breakthrough curve, and that a prediction of the concentration tends to be little reliable when the conducting medium consists of a few flow paths. Applications of the tube model to field studies show that important inhomogeneities exist within a scale of 1.5 metres.

Scheidegger (1954) investigated dispersion on the assumption that a fluid particle carries out a random walk consisting of a succession of statistically independent straight steps in equal small intervals of time. It follows from the central limit theorem that the probability distribution function of the displacement is Gaussian, and hence that the dispersion can be described by the diffusion equation. The approach was criticized by Saffman (1959) partly because the time intervals were equal and it would be expected intuitively that a particle stays longer in a region where the velocity is small than where it is large, and also because it seems to predict that the dispersion is isotropic. Scheidegger (1954) characterizes his approach as opposite to the models based on a bundle of capillaries: a completely disordered model, but admits that an actual porous medium will perhaps not be exactly represented by either type of models, but that it may lie somewhere in between the two.

Experimental tests by Day (1956), who used a column of water saturated sand and a NaCl solution as displacing liquid, show up agreement with Sheidegger's theory. Day concludes that the experiments were to limited to verify the theory, but the variations of effluent concentration with time were sufficiently similar to the theoretical variations to indicate that the theory is useful as a working hypothesis.

A random network of capillaries was used by de Josselin de Jong (1958) for modelling of dispersion in a porous medium.

The orientation of the capillaries was uniformly distributed in all directions and their lengths and cross section areas were equal. It was assumed that the velocity of a foreign particle is equal to the mean velocity in the capillary. At the junctions the choice of direction is distributed in proportion to the quantity of water flowing in these directions taken as a fraction of the total discharge of the capillaries. The probability distribution for a particle to arrive at a certain point in the space at a given time is a measure for the concentration distribution and can be achieved by taking account of all possibilities for a particle to arrive at the point. If the number of capillaries and junctions passed by a particle is large, the central limit theorem implies a gaussian distribution. Longitudinal and transverse dispersion coefficients, proportional to the variance of the concentration distribution in the respective directions, could be calculated. The same approach was adopted by Saffman (1959), who discussed the impact of the molecular diffusion. It was shown that the dispersion was proportional to the product Ul (where U is the mean velocity of the fluid and l is the length scale of the capillaries), provided that the molecular diffusion is small compared to this quantity. A generalization to low values of Ul was made by Saffman (1960). For very low values of the flow velocity or the length scale of the pores compared to the molecular diffusion, the latter tends to dominate the dispersion. Sheidegger (1957) has shown that the dispersion coefficient D theoretically may be proportional to either U or U^2 and concludes that the magnitude of the coefficient should lie somewhere in between the two limits. Experiments on columns filled with glass spheres gave a dispersion coefficient proportional to $U^{1.08}$ and to the diameter of the spheres (Ebach and White, 1958). A literature study by Perkins and Johnston (1963), referring to similar experiments, does however suggest a linear relation. The ratio D/U is generally referred to as the dispersivity and is regarded as a length scale of the medium. Lenda and Zuber (1970) give values for the dispersivity for gravel from 10 cm to 1 m and for fissured rocks from 2 to 100 metres.

Bear (1961) points out that, after a period of uniform flow, lines of equal concentration resulting from a point injection of the tracer take the shape of ellipses centred at the displaced mean point and oriented with their major axes in the direction of the flow. Assuming isotropic medium, Bear makes a generalization to an arbitrary coordinate system in two dimensions with the help of tensor methods. A generalization to a three-dimensional anisotropic medium was published by Scheidegger (1961). It was found by experiments on a porous medium composed of plastic spheres (Harleman and Rumer, 1963) that the ratio of the coefficient of longitudinal dispersion D_1 to the coefficient of lateral dispersion D_2 is given by $D_1/D_2 = \lambda \cdot Re^n$, where λ and n are dimensionless coefficients dependent upon the pore-system geometry, and Re is the Reynolds number.

Bhattacharya and Gupta (1983) distinguish between three different scales: Kinetic scale, Microscopic scale and Darcy scale. In the kinetic scale the stochastic process of a solute molecule due to its interaction with the liquid and the solid phases is considered. The microscopic scale is commonly denoted pore scale. Transition from one scale to the next higher scale is performed according to the central limit theorem. It was concluded that for very small Peclet numbers, only the molecular diffusion provides the dominant contribution, while for intermediate values of Peclet numbers, both the liquid convection and the molecular diffusion contribute to the dispersion coefficients. In this range the dispersion coefficients are not linear dependent on the liquid convective velocity. For large Peclet numbers the coefficients of dispersion at the Darcy scale was shown to be linear in the liquid convective velocity. This result was achieved experimentally by Pfannkuch (1963).

In any model there are always a variety of assumptions which may or may not be justified. It is therefore to be expected that not all its predictions will borne out by experiments (Scheidegger, 1959).

It can so far be concluded that:

- The condition for the validity of the dispersion equation is that the central limit theorem can be applied. This again provides that the medium consists of a large number of interconnected channels.

- The dispersion coefficient is proportional to a characteristic length of the porous medium, and increases with the flow velocity.

- At very low flow velocities, the molecular diffusion is the dominating process, whereas at higher velocities, differences in flow velocities and lengths of flow paths are dominating.

2.1.2 Applications of the porous medium approach

The conclusions above indicates that the application of the porous medium approach when it concerns fractured rock, demands that the modelled region is large so that it contains a large number of interconnected fractures. Although this condition is not always fulfilled, several examples of its application can be found in the literature.

Application of the porous medium approach presumes knowledge of conductivity, porosity, viscosity etc. The approach involves calculation of the flow pattern by means of solving a flow equation based on Darcy's law and mass conservation together with appropriate boundary conditions. The resulting flow velocities are then used for calculation of the migration which requires knowledge of a dispersion coefficient.

The calculations are for practical applications mostly performed numerically according to finite-element (Atkinson et al, 1985) or finite-difference methods. Analytical methods in two dimensions have also been applied (Stokes and Thunvik, 1978).

The finite difference method has the drawback that the geometrical configuration of the modelled problem has to have a more or less regular shape. The method was used by Barbreau et al (1980) to investigate the sensibility of the travel time to for example the distribution of the permeability, porosity and retention of the contaminant by the rock matrix.

Thunvik and Braester (1980) used the finite-element method in two dimensions to analyze the flow pattern around a repository emitting heat due to radioactive decay. The calculations were based on the continuum approach with permeability and porosity decreasing with depth. No specific site was referred to in the analysis. Therefore, simplified assumptions were made regarding the physical properties as well as the geometry of the flow domain. Four idealized cases were studied: a repository situated either below a horizontal ground surface, below the crest of a hill, below a hillside, or between two major fracture zones. Travel times for water particles from the repository to the ground surface were calculated according to Darcy's law and dividing the results by the porosity. The variability in porosity in a real case makes application of this method very uncertain, but the examples show that heat released from a radioactive waste repository may have a significant impact on the flow regime around the repository.

- The approach can be used to calculate the flow pattern at large scale, but prediction of contaminant transport becomes uncertain.

2.2 Discrete approaches

The discussion above points out that the porous medium approach demands that the scale of the problem is large so that many cavities are interconnected. If, however, the number of fractures at the problem scale is small, each single fracture may significantly affect the flow regime in the rock. Then the discrete character of the fracture network can not be neglected. In a real fracture system each of the fractures can be described by a list of properties. These include the size, shape, position, orientation in space, aperture, etc. Over all the fractures in a region these parameters have some sort of distribution. The practical application of discrete models is dependent on mapping of the fracture network. Andersson and Thunvik (1986) poses the question whether this can be possible to perform.

Several attempts to establish mathematical models for discrete fracture systems are found in the literature, including assumptions concerning these distributions. Most of the examples found in the literature consider two-dimensional networks of planar fractures having uniform aperture. Among those are found Andersson et al (1984), Andersson and Thunvik (1986), and Robinson (1984).

Andersson et al (1984) generated two-dimensional networks of planar fractures using the Monte Carlo method. The flow through these networks was calculated assuming laminar flow, and an equivalent hydraulic conductivity according to Darcy's law was determined for each network. It was supposed that a certain number of cores were drilled in order to determine the number of fractures in the considered region. It was found that the uncertainty in the estimation of the hydraulic conductivity decreased with the number of cores. The approach was also used by Andersson and Thunvik (1986) who extended it by a particle tracing technique in order to model the propagation of solutes through the rock mass.

Robinson (1984) considers three aspects of fracture networks: connectivity, flow and transport. The connectivity was investigated by means of generation of fractures in a two- and three-dimensional space and checking whether a cluster is formed. The purpose of the work concerning flow was to find how the hydraulic conductivity relates to the statistical properties of the fracture system. The method that was used was to generate two-dimensional fracture systems with given fracture statistics and to perform numerical experiments on these systems. In each fracture segment, that is between each pair of intersections, it was assumed that the flow was proportional to the pressure gradient, that is a so called Poiseuille flow. It was found that the variability in permeability was reduced as the network size increased. Transport calculations in generated fracture systems were done using a particle following program. The results were interpreted in terms of the dispersion equation, and it was concluded that a better understanding of hydrodynamic dispersion in fracture networks is still required.

Two-dimensional analysis has a limitation in that fractures which are not connected to the network in the plane of analysis may be connected in the third dimension. Thus two-dimensional analysis will tend to underestimate the permeability (Long et al, 1985).

Models in which the fractures are regarded as disc-shaped discontinuities in an impermeable three-dimensional matrix have been presented by Long et al (1985) and Andersson and Dverstorp (1987). The fracture discs can have arbitrary size, orientation, transmissivity, and location. Andersson and Dverstorp used a numerical simulation model which is capable of generating a fracture network of desired statistical properties and solving for the steady state flow. The statistical properties was described by distributions of orientation, transmissivity and location of the fractures together with a distribution of the disc radius. A series of networks was generated from the same statistical distributions and the flow was calculated. It was found that large fractures and high fracture density implies good connectivity in the networks, and that a high fracture density implies a small variance in the flow through the network.

Louis (1967) considered flow in the laminar and turbulent regimes using both smooth and rough-walled models. It was assumed that the rock is divided by sets of parallel fractures in different directions. It was found that the direction of flow is not necessary parallel to the gradient of the potential. This was due to different aperture for fractures in different directions. In a large scale this can be interpreted as anisotropy.

Wilson and Witherspoon (1970) apply the finite element method to develop a model for two dimensional fracture network. Fractures may have any spacing and orientation, any aperture, and may intersect at any angle.

In the above mentioned models, the fracture properties was assumed to be constant in each fracture. In the model of Wilson and Witherspoon (1970) it is possible two vary the aperture in the flow direction to some extent. Field experiments have shown, however, the flow in real fractures are unevenly distributed in the fracture plan (Abelin et al, 1983, Abelin, 1986). The phenomenon is called channelling.

Dahlblom and Jönsson (1990) performed mathematical modelling of flow and migration of a nonreactive contaminant in a single, irregularly shaped fracture. The spatial variation of the fracture aperture was considered as a two-dimensional stochastic process. A method for generating such a stochastic process with desired expected value, variance and correlation in the plane, assuming log-normal distribution of the aperture, was described. A stream function was defined with help of the Navier-Stokes equations. With selected boundary conditions, values of the stream function was calculated numerically in defined nodes in the fracture plane. Isolines of the stream function, limiting channels with equal flow, was interpolated. The travel time for each channel could be calculated to achieve a measure of the dispersion. It was found that only small parts of realistic shaped fractures could be modelled with reasonable execution time. Provided that the exchange of contaminations between the channels described above is negligible, a model based on isolated tubes may be appropriate.

About discrete modelling it can be concluded that:

- A realistic modelling has to be based on a discrete approach if the migration shall be predicted reliably.

- Networks in two and three dimensions can be modelled with regard to flow and contaminant migration if it is assumed that the fracture aperture is uniform in each fracture.

- Two-dimensional analysis will tend to underestimate the permeability because fractures which are not connected to the network in the plane of analysis may be connected in the third dimension.

- The channelling effect, due to variations in the fracture aperture, causes dispersion. Modelling of migration in fractures, taking the variation in fracture aperture into consideration, is connected with big computing efforts.

3 FIELD INVESTIGATIONS

The application of mathematical models requires that the parameter values are determined by field measurements. The interpretation of the field measurement shall be in correspondence with the type of mathematical model; for a model based on a continuous medium approach the field measurements shall be interpreted as from a continuous medium and for a discrete model the measurement shall be interpreted in a discrete way. When it concerns the continuous porous medium approach, the measured properties are usually the hydraulic conductivity and the porosity.

3.1 Measurements of the hydraulic conductivity etc

The traditional application is wells for water supply in large aquifers. In this case the integrated properties transmissivity and storativity are used in stead of conductivity and porosity. In this way the total thickness of the aquifer is taken into account. The method for estimating the transmissivity includes observation of the drawdown in connection with a pumping-test of a well. Carlsson and Carlstedt (1976) used the method to estimate the transmissivity and permeability in four different regions in Sweden with seven different types of bedrock.

In order to get permeability values related to different depths below the ground surface, a method has been developed where the loss of water between two rubber packers with a relative distance of two or three metres in the borehole is measured. The water is supplied between the packers with a pressure between 0.2 and 0.6 MPa. This method was used by Hult et al (1978) to measure the permeability at four different locations in Sweden. It was shown that important differences in the permeability of the bedrock was at hand between and within the different locations. The calculated values were often below the lower limit of detection which was $2\cdot 10^{-9}$ m/s and in some cases $4\cdot 10^{-10}$ m/s. In several holes, it was observed that the upper parts of the bedrock have considerable larger frequency of open fractures than the deeper parts. In the deeper parts zones of fractures between sections with very low water loss were observed. In some of the boreholes measurements have been performed where the method was modified so that one packer is used and the entire borehole below the packer is taken into account (Gidlund et al, 1979). The values of the permeability was lower than for double packer measurements while high local values is averaged over the total length of the borehole below the packer. The method was also used by Carlsson and Olsson (1976) for 29 boreholes in the area "Forsmark" in Sweden. The result shows that the permeability tends to decrease with depth below the ground surface. A comparison with 40 drilled wells in the same area, tested with the above described method based on observation of draw down at pumping, showed a difference. According to the double packer test, the median value for all the boreholes were $1.0 \cdot 10^{-6}$m/s while the draw down tests gave $7.9 \cdot 10^{-8}$m/s. According to the authors, this difference can be explained by an enlargement of the fractures at high pressures by the double packer tests. Values of the permeability between 10^{-9} and 10^{-5} m/s was reported, and for the same level variations over one or two orders of magnitude was present. Olsson (1979) reports values between 10^{-10} and 10^{-4} m/s for crystalline rock, out of which the two largest orders of magnitude refers to the fractured zone. Also an important anisotropy of the conductivity was reported. The porous media approach was however contradicted by unevenly distributed water inflow observed in a tunnel. Values of the conductivity between 10^{-10} and 10^{-5} m/s were reported by Novakowsi and Lindberg (1984).

The conductivity as measured down a well should be continuous over limited sections if the porous medium approach shall be relevant. This is not the case for the observed values. Neither the borehole radius nor the distance between the packers were large enough to exceed the minimum demand (Stokes, 1980).

It can be concluded that:

- There is a tendency that the hydraulic conductivity decreases with depth. The explanation is that the upper parts of the bedrock have larger frequency of open fractures than the deeper parts.

3.2 Tracer experiments

An experimental installation on a fractured granite formation in France has been used for studying the movement of solutes in different directions with different tracers (Goblet et al, 1983). Samples were taken from a central well surrounded by five injection wells at a distance of 12 - 24 metres. The interpretation of the experiments was made by supposing the medium to be two-dimensional, homogenous but anisotropic. The traditional dispersion equation for porous medium together with a law of interaction between elements sorbed on the area of the fissures and the concentration in the flowing water. The results showed that the chosen model was capable of representing the in situ observations on this scale of a fissured granite formation. It was further concluded that fixation plays an important part in the transport. The sensitivity to the dispersion coefficient was not important, and the dispersion length for all the cases was 1.0 m.

Novakowski et al (1985) performed tracer experiments in a single horizontal fracture between two boreholes over a distance of 10.6 m at about 100 m depth. A conservative radioactive tracer was introduced into a steady flow field established between pumping and recharging boreholes, and the arrival of tracer at the withdrawal well was detected. The interpretation of the field data was made with help of a mathematical model based on analytical description of the flow field geometry. It was assumed that the fracture aperture was constant and the fracture was analogous to horizontal permeable layer with a unit porosity. A flow field defined by streamlines and equipotentials was used to define streamtubes for which the migration was calculated by solving the advection-dispersion equation in one dimension. Calibration of the model gave a value of the longitudinal dispersivity at about 1.4 m. A large difference between hydraulically determined aperture and an aperture determined from tracer experiments was observed. This could be explained by the heterogeneous characteristics of natural fractures, which seams to contradict the assumption of constant fracture aperture.

Abelin (1986) presented three different definitions of fracture aperture: mass balance fracture aperture, cubic law fracture aperture, and frictional loss fracture aperture. The mass balance fracture aperture is related to the average volume of the fracture, and can be calculated if the flow rate and the mean residence time are known together with the width and the length of the fracture. The cubic law fracture aperture is defined as an aperture between two parallel plates giving the same flow rate at a given pressure drop. It is assumed that laminar flow prevails. The third equivalent fracture aperture, the frictional loss fracture aperture, is that which would give a certain water velocity for a given pressure drop. Only the flow rate, pressure drop and geometric entities are needed to determine the cubic law fracture aperture. The other definitions of fracture aperture requires knowledge of the residence time for the water particles, which can be determined from tracer experiments. The cubic law aperture (hydraulically determined aperture) will be equal to the other defined apertures only for a fracture of uniform aperture.

A tracer experiment performed in a single fracture in the Stripa mine 360 m below the ground surface has been described by Abelin (1983), Abelin (1986), Abelin et al (1985a), Abelin et al (1985b) and Abelin and Gidlund (1985). The distance between injection and detection was 5 - 10 m. The result showed that channelling exist within single fractures. The water flows in channels which seem to be 10 - 100 cm wide. These channels make up only 5 - 20 % of the fracture plane. The different defined measures of the aperture was found to differ by some orders of magnitude. It was concluded that hydraulic tests will not give any direct information on actual flow porosity. The differences in aperture measures can be explained by the fact that the volume of the fracture, which determines the mass balance fracture aperture, is affected by enlargements, while the friction losses are determined by narrow sections in the flow paths. The impact of aperture variations on the difference between aperture measures was investigated theoretically by Dahlblom and Jönsson (1990).

Klockars and Persson (1982) made a two-hole tracer test with a nonreactive tracer. It was found that the dispersivity was 0.3 - 0.8 m and that it increased with the travel time.

3.3 Mapping of fractures

It is impossible to exactly locate each individual fracture in a rock formation by measurements. The uncertainty involved in describing the fracture network is decreased when more information is collected (Andersson et al, 1984). Surface and subsurface exposures allow geologists to directly observe fracture systems. The exposures can range from natural surface outcrops to subsurface excavations and boreholes. Small-diameter boreholes provide the least expensive way to investigate an unexposed volume of rock. Different methods exist to collect information from boreholes, such as investigation of cores (Martel and Peterson Jr., 1990) and temperature logging (Persson, 1985). Magnusson and Duran (1978) applied some different methods to investigate boreholes: inspection with a TV-camera, observation of the variation in the salinity of the borehole fluid, and electromagnetic methods. It was shown that inspection with a TV-camera gave a very high resolution and very small fractures could be detected. The method can be used to estimate the aperture and evaluate the orientation of the fractures. The variation in salinity was assessed by means of measuring the resistivity of the borehole fluid. The variation in salinity is caused by inflow from fractures of water with higher salinity than the borehole fluid. This method does not give any measure of the fracture aperture.

The temperature logging method described by Persson (1985) implies that water of a temperature different from that of the natural formation is injected into the borehole. This water will then intervene into the fractures making it possible to discover them by temperature registration.

3.4 Observations of flow patterns in fracture systems

Several field experiments have been performed in the abandoned iron-ore mine at Stripa in central Sweden. A tracer experiment with flow path lengths of about 50 m has been performed at this place (Birgersson et al, 1985). The experimental site was located in a drift well below the groundwater table which implies that water flows constantly into it. Conservative tracers were injected into this water flow. Water was collected in a large number of sampling areas located at the ceiling of the test site, so that the entire surface was covered. Sampling over small areas made it possible to observe the spatial distribution of water flow. The result clearly shows that water does not flow uniformly in the rock over the scale considered (700 m^2), and that the water flow could not be described as a flow in a homogenous porous medium. On the contrary, these results indicate that flow takes place in only a few preferred paths.

4 DRIVING FORCES FOR GROUNDWATER MOVEMENT

The condition for water movement in the underground is primarily that there are connections and channels where the water can move freely, secondly that there are driving forces that provoke the movement of the water. The modelling work has until now been directed towards description of the fracture system and the distribution of water flow within it aiming at an understanding of the migration processes. The field of gradients evoking the water movement in the fractures has not been studied that closely.

Neretnieks and Rasmuson (1983) assumed that the hydraulic gradient in a fissure was inversely proportional to the depth below 25 m. Above this the gradient was assumed to be constant 0.04 m/m.

Louis (1967) showed that the direction of flow in a fracture system may be different from the direction of the gradient due to anisotropy caused by differences in fracture aperture in different directions. Wilson and Witherspoon (1970) simulated flow through two dimensional networks of fractures and showed that its orientation had a great effect upon water pressure distribution.

Important questions among others are the magnitudes of the gradient at large depths, what influence does the topographic variations that may be observed at the ground surface and have an impact on the gradient for shallow groundwater have on the groundwater at larger depths.

It is desirable, that the hydraulic gradient in the surrounding of a repository is as low as possible. A possible way to achieve this is to locate the repository in a block with low conductivity surrounded by fracture zones with high conductivity. The high conductivity implies that only low gradients can exist in the surrounding of the block, which in turn implies a low gradient within the block containing the repository. The desired high conductivity of those fracture zones necessitates not only a large amount of fractures, but also a good hydraulic connection between them. A possible risk is that if a pollution reaches such a fracture zone, it may migrate rapidly.

A low gradient and a low conductivity together provide a slow transport velocity within the block. A slow transport velocity is favourable for the impact of retardation and radioactive decay. Other phenomena may, however, independently of the hydraulic gradient provoke migration from a repository towards the surrounding fracture zones. Examples of such phenomena are molecular diffusion and osmosis. On the other hand, it is possible that very small dimensions of the cavities may imply that no water flow occurs below a threshold value of the hydraulic gradient. Those problems may constitute future areas of research.

Implementation of this concept involves calculation of desired properties of the geological formation, and then efforts to find a site that fulfills the conditions. Field investigations may indicate if it is possible to find such sites. Those investigations involves observation of water levels in wells having connection with the same geological formation.

4.1 Mathematical modelling

Some attempts to use mathematical models to investigate the sensitivity of travel times or hydraulic gradients to variations in the hydraulic conductivity at large or regional scales can be found in the literature. Barbreau et al (1980) applied relationships of exponential type to describe the decrease of the hydraulic conductivity with the depths below the ground surface. It was found that the sensibility of the travel time to variation in the hydraulic conductivity was important. Wei et al (1990) considered a large regional system. It was observed that the calculated hydraulic heads were very sensitive to the vertical permeability.

4.2 Some idealized examples

4.2.1 One dimensional modelling

In order to show the impact on the hydraulic gradient of the variation in hydraulic conductivity and percolation to the groundwater storage, and to investigate if there might be at least any theoretical possibility to find locations with zero hydraulic gradient, some simple examples are shown below. The calculations are performed in one dimension. It is assumed that the scale is very large (such that it is comparable with the distance from coast to coast in scandinavia), and Darcy's law is applied. Steady state conditions are assumed.

Figure 4.1 defines the problem. An unconfined aquifer is recharged with a constant (in time) rate I(x) which may be dependent of the space. The total distance between the boundaries is called L. The boundary conditions are equal to the level of the groundwater surface above an impermeable medium, denoted h_0 and h_L respectively. Considering mass conservation and Darcy's law, it can be shown that the following differential equation describes the groundwater table for steady state conditions:

$$\frac{d^2h^2}{dx^2} = -\frac{2I}{K} \tag{12}$$

where I is the rate of percolation to the groundwater and K is the hydraulic conductivity. I may be a function of the x coordinate. It is assumed that K is constant. As a simple example, a first order polynom will be considered:

$$\frac{d^2h^2}{dx^2} = -\frac{2a}{L}x - 2b$$

This equation can easily be integrated. Inserting the boundary conditions $h=h_0$ at $x=0$ and $h=h_L$ at $x=L$ gives:

$$\frac{h^2-h_0^2}{L^2} = \frac{ax}{3L}(1-\frac{x^2}{L^2}) + \frac{bx}{L}(1-\frac{x}{L}) + \frac{x}{L}\frac{h_L^2-h_0^2}{L^2} \tag{14}$$

Some special cases can be studied. The most trivial case is when no infiltration occurs and a and b are equal to zero. This case is not interesting and will not be studied further.

A more interesting case is when only a is equal to zero. This corresponds to a constant I. For this case equation (14) can be rewritten:

$$\frac{h^2-h_0^2}{L^2} = \frac{bx}{L}(1-\frac{x}{L}) + \frac{x}{L}\frac{h_L^2-h_0^2}{L^2} \tag{15}$$

The derivative can then be calculated in order to find the place where the hydraulic gradient is equal to zero. This point can be interpreted as a water divider for the groundwater. It is often assumed that the water divider for the groundwater is coinciding with the water divider for surface water, that is, it is dependent on the topography. It shall be remembered that no assumption about the topography have been made in this example. It shall be noticed that:

$$\frac{dh}{dx} = 0 \Leftrightarrow \frac{dh^2}{dx} = 0 \quad if\ h \neq 0 \tag{16}$$

It is found that the hydraulic gradient is zero ($x=x_0$) where:

$$\frac{x_0}{L} = \frac{1}{2} + \frac{1}{2b}\frac{h_L^2-h_0^2}{L^2} \tag{17}$$

It is reasonable to assume that the second term in the right member is small compared to the first one. The place for zero derivative is thus near the middle.

An other interesting case is when b is equal to zero. For this case equation (14) can be written if the last member is neglected:

$$\frac{h^2-h_0^2}{L^2} = \frac{ax}{3L}\left(1-\frac{x^2}{L^2}\right) \tag{18}$$

The derivative can be calculated and it's place for zero can be expressed:

$$\frac{x_0}{L} = \frac{1}{\sqrt{3}} = 0.58 \tag{19}$$

It can be seen from equations (17) and (19) that the point for zero derivative is found somewhere near the middle in case of rectilinear distribution of the quantity I.

One extreme example is when the quantity I is equal to zero, that is a zero infiltration, except when $x < x_1$:

$$\frac{d^2h^2}{dx^2} = -2b \quad 0 < x < x_1$$

$$\frac{d^2h^2}{dx^2} = 0 \quad x_1 < x < L \tag{20}$$

The solution can be written:

$$\frac{h^2-h_0^2}{L^2} = -\frac{b}{L^2}x^2 + \frac{bx_1(2L-x_1)}{L^3}x + \frac{h_L^2-h_0^2}{L^3}x \quad ; \; 0<x<x_1$$

$$\frac{h^2-h_0^2}{L^2} = \frac{bx_1^2}{L^3}(L-x) + \frac{h_L^2-h_0^2}{L^3}x \quad ; \; x_1<x<L \qquad (21)$$

The derivative can be written:

$$\frac{dh^2}{dx} = -2bx + 2bx_1 - \frac{bx_1^2}{L} + \frac{h_L^2-h_0^2}{L} \quad ; \; 0 < x < x_1$$

$$\frac{dh^2}{dx} = -\frac{bx_1^2}{L} + \frac{h_L^2-h_0^2}{L} \quad ; \; x_1 < x < L \qquad (22)$$

The value of the derivative will be zero where $x = x_o$:

$$\frac{x_0}{L} = \frac{x_1}{L} - \frac{1}{2}\left(\frac{x_1}{L}\right)^2 < \frac{x_1}{L} \qquad (23)$$

It can be seen that the point for zero derivative is found somewhere within the interval where the quantity I is not equal to zero. The example shows that large variations in percolation may have an impact on the place for the water divider.

From equation (15), describing the shape of the groundwater surface at constant infiltration rate, it can be seen that the level is increasing with the rate, that is the quantity h^2 is approximately proportional to I if h_0 is small and equal to h_L. At increasing infiltration rate the level will increase until un obstacle is encountered, as for example a ditch or a depression defining a new boundary condition. It can be assumed that the water level in surface waters has a smaller variation than a groundwater level. Figure 4.2 shows the principle. This suggests that the presence of depressions, and not the presence of hills, determines the shape of the groundwater surface. It can also be seen that the percolation rate has an influence on the gradients and the location of water dividers. A climate change with large increase in precipitation may thus have an impact on the flow pattern of the groundwater.

In this example it has been assumed that there is an impermeable horizontal surface below the flow domain. A solution for the case of a sloping surface and given water divider was given by Dahl (1969).

For the case of constant infiltration rate, I, and if $h_0 = h_L$ and $x/L = 1/2$, equation (15) can be rewritten:

$$\frac{h^2-h_0^2}{L^2} = \frac{I}{4K} \tag{24}$$

This equation is fulfilled by for example the cases in table 4.1. It shall be remembered, that the model is very simplified while it is one-dimensional and that no flow is supposed to take place below a certain level $h = 0$. In reality the flow is three-dimensional and the hydraulic conductivity tends to decrease with the depth. If h_0 is assumed to be the sea level, the last column in the table shows the maximum possible height of the groundwater level above the sea level. It can be noticed that the values of the conductivity are rather high compared to the values observed by for example Olsson (1979). According to those observations, the conductivity should have a value between 10^{-10} and 10^{-4} m/s. One explanation could be that the water flows practically only in fracture zones with high conductivity. The value for the percolation, I, corresponds to an annual percolation of 200 mm, which is about one third of the annual precipitation in northern Europe.

It can be concluded that:

- Low hydraulic gradients are found at large distances from coasts and surface waters.

- The hydraulic gradient is to a small extent influenced by spatial variations of percolation.

- It is difficult to find a representative value of the conductivity that can be used for a one-dimensional model. An explanation is that flow-paths may exist that can be represented in two or three dimensions but not in one dimension.

4.2.2 Two dimensional modelling

The examples above show that places with zero hydraulic gradient may exist at relatively large distance from the boundaries. The calculations were however performed in one dimension. Applications of two-dimensional models will show that the hydraulic gradient may also be dependent on the depth below the ground surface.

Provided that the porous medium is homogenous and isotropic, the flow can be described by the Laplace equation. Analytic solutions are found for some special cases. Solutions are often presented in form of stream lines and potential lines. In case of percolation to a groundwater surface, it can be shown that the groundwater surface is not a stream line. This case is thus rather complicated, and analytical solutions are not found. In general, numerical methods have to be applied. While simple examples with regular geometrical configuration will be studied, the finite element approach is not motivated and the finite difference method will be applied.

For two dimensions and steady state conditions, the hydraulic potential, or head h, shall fulfill the following differential equation, which can be derived from Darcy's law and mass conservation:

$$\frac{d}{dx}(K_x\frac{d}{dx}h) + \frac{d}{dz}(K_z\frac{d}{dz}h) = 0 \qquad (25)$$

According to equation (25) the porous medium may be non homogenous and anisotropic with respect to the hydraulic conductivity. The modelled area has been divided into a regular mesh, and the derivatives have been approximated by finite differences. The solution was carried out by means of iteration. The number of nodes was 21 in each direction and the number of iterations was 500. The distance between the nodes was chosen to 50 m in the vertical direction and 100 m in the horizontal direction, so that a cross section of 2000 m length and 1000 m depth was modelled. As boundary conditions, no flow was assumed across the left boundary as a symmetry axis consisting of a water divider. At the upper surface a prescribed flow was assumed corresponding to one third of the mean precipitation. Prescribed head was assumed at the lower and the right boundaries. An alternative would be to chose the no flow condition at the lower boundary. However, it is difficult to motivate the existence of an impermeable layer at a certain level.

The result of the calculations are shown in the figures 4.3 to 4.12. The hydraulic gradients are shown as arrows which lengths have been calculated as differences in hydraulic head divided by the distances between the nodes. The unit for the gradient is metres of water column per metre. The length of the arrows shows the relative magnitude of the hydraulic gradient.

A low hydraulic gradient alone does not guarantee a low flow velocity if the hydraulic gradient is high. Therefore examples of calculated flow velocities are shown. Also flow velocities are shown as arrows. Their length and direction have been obtained by multiplication of the hydraulic gradient by the hydraulic conductivity. It has been assumed that the main directions of the hydraulic conductivity coincides with the coordinate axes. In case of an isotropic medium the flow velocity will be straight opposite to the hydraulic gradient.

Figure 4.3 shows an example of calculated hydraulic gradients. The hydraulic conductivity is 10^{-6} m/s in both horizontal and vertical direction. The corresponding velocities are shown in figure 4.4.

Figure 4.5 shows an example of calculated hydraulic gradients for an anisotropic case. The hydraulic conductivity is 10^{-6} m/s in the horizontal and $0.2 \cdot 10^{-6}$ m/s in the vertical direction. The corresponding velocities are shown in figure 4.6. A comparison between the figures gives at hand that the direction of the flow velocity is not always straight opposite to the direction of the hydraulic gradient.

Absolute values of the hydraulic gradient at a level of 500 m below the ground surface for three anisotropic cases are shown in figure 4.7. They are plotted on a logarithmic scale. The hydraulic conductivity in horizontal direction is 10^{-6} m/s. It can be seen that the hydraulic gradient does not vary so much with the horizontal distance near the water divider.

Carlsson and Olsson (1977) investigated the variation of the hydraulic conductivity with the depth below the ground surface. Some different locations were investigated. It was reported that the hydraulic conductivity decreased with the depth with up to tree orders of magnitude for each one hundred metres, but also a case with invariable conductivity was reported.

Figure 4.8 shows an example of calculated hydraulic gradients for an isotropic case with a decreasing hydraulic conductivity with depth. At the surface, the hydraulic conductivity is 10^{-6} m/s in both horizontal and vertical direction, and decreases with a factor 0.7 for each 100 m of depth. The corresponding velocities are shown in figure 4.9. A comparison between this figure and figure 4.4 gives at hand that the water flow is forced towards the surface when the hydraulic conductivity decreases with depth below the ground surface.

A heterogenous case is shown in the figure 4.10 through 4.12. The hydraulic conductivity in both horizontal and vertical direction has been set to 10^{-6} m/s for the whole area except for a part in the middle where it was set to 10^{-5} m/s. In that way an area with low hydraulic conductivity is surrounded by an area with high hydraulic conductivity which again is surrounded by an area with low hydraulic conductivity. The distribution of hydraulic conductivity is shown in figure 4.10. The figures 4.11 and 4.12 show the calculated hydraulic gradients and velocity distribution. A comparison with the homogenous case gives at hand that the hydraulic gradients and the flow velocities are smaller in the heterogenous case when an area with a high hydraulic conductivity can conduct a large part of the water.

It can be concluded that:

- The direction of the flow velocity is not straight opposite to the direction of the hydraulic gradient in case of an anisotropic medium.

- The hydraulic gradient does not vary so much with the horizontal distance near the water divider.

- The water flow is forced towards the surface when the hydraulic conductivity decreases with the depth below the ground surface.

- The hydraulic gradients and the flow velocities are smaller in an area with a low hydraulic conductivity that is surrounded by an area with high hydraulic conductivity.

5. CONCLUSIONS

A realistic modelling of contamination migration has to be based on a discrete approach if the migration shall be predicted reliably. The porous medium approach can however be used to calculate the flow pattern at large scale, but prediction of contaminant transport becomes uncertain.

Low hydraulic gradients are found at large distances from coasts and surface waters. The hydraulic gradient is to a small extent influenced by spatial variations of percolation.

It is difficult to find a representative value of the conductivity that can be used for a one-dimensional model. An explanation is that flow-paths may exist that can be represented in two or three dimensions but not in one dimension.

The direction of the flow velocity is not straight opposite to the direction of the hydraulic gradient in case of an anisotropic medium.

There is a tendency that the hydraulic conductivity decreases with depth. The explanation is that the upper parts of the bedrock have larger frequency of open fractures than the deeper parts. The water flow is forced towards the surface when the hydraulic conductivity decreases with the depth below the ground surface.

The hydraulic gradients and the flow velocities are smaller in an area with a low hydraulic conductivity that is surrounded by an area with high hydraulic conductivity.

6 ACKNOWLEDGEMENT

This work was performed at the Department of Water Resources Engineering, Lund University, and was supported by the Swedish National Board for Spent Nuclear Fuel.

REFERENCES

Abelin, H. (1986). Migration in a Single Fracture. An in Situ Experiment in a Natural Fracture. Royal Institute of Technology, Department of Chemical Engineering, Stockholm.

Abelin, H., J. Gidlund, L. Moreno and I. Neretnieks (1983). Migration in a Single Fracture in Granitic Rock. International Symposium on the Scientific Basis for Nuclear Waste Management VII, Boston. Materials Researh Society Symposia Proceedings 26, 239-246.

Abelin, H. and J. Gidlund (1985). Migration in a Single Fracture Instrumentation and Site Description. Stripa Project Internal Report 85-02, Swedish Nuclear Fuel and Waste Management Co, Stockholm.

Abelin, H., I. Neretnieks, S. Tunbrant and L. Moreno (1985a). Final Report of the Migration in a Single Fracture - Experimental results and evaluation. Stripa Project Internal Report 85-03, Swedish Nuclear Fuel and Waste Management Co, Stockholm.

Abelin, H., L. Moreno, S. Tunbrant, J. Gidlund and I. Neretnieks (1985b). Flow and tracer movement in some natural fractures in the Stripa granite. Symp. Radioactive waste disposal, In situ experiments in granite, Proc. 2nd NEA/Stripa proj. symp. 67 - 81.

Andersson, J., A. M. Shapiro and J. Bear (1984). A stochastic model of a fractured rock conditioned by measured information. Water Resour. Res. 20(1), 79-88.

Andersson, J. and R. Thunvik (1986). Predicting mass transport in discrete fracture networks with the aid of geometrical field data. Water Resour. Res. 22(13), 1941-1950.

Andersson, J. and B. Dverstorp (1987). Conditional simulations of fluid flow in three-dimensional networks of discrete fractures. Water Resour. Res. 23(10), 1876-1886.

Aris, R. (1956). On the dispersion of a solute in a fluid flowing through a tube. Proc. R. Soc. London, Ser. A, 235, 67-77.

Atkinson, R., A. W. Herbert, C. P. Jackson and P. C. Robinson (1985). NAMSOL User Guide. United Kingdom Atomic Energy Authority Report AERE-R 11365.

Barbreau, A., Y. Sousselier, M. Bonnet, J. Margat, P. Peaudecerf, P. Goblet, E. Ledoux, G. de Marsily (1980). Premières évaluations des possibilités d'évacuation des déchets radioactifs dans les roches christallines. Underground Disposal of Radioactive Wastes, Vol. 1, International Atomic Energy Agency, Vienna, IAEA-SM-243/68, 387-411.

Bear, J. (1961). On the tensor form of dispersion in porous media. J. Geoph. Res. 66(4), 1185-1197.

Bhatacharya, R. N. and V. K. Gupta (1983). A theoretical explanation of solute dispersion in saturated porous media at the Darcy scale. Water Resour. Res. 19(4), 938-944.

Birgersson, L., H. Abelin, J. Gidlund and I. Neretnieks (1985), Water flowrates and tracer transport to the 3D drift in Stripa. Symp. Radioactive waste disposal, In situ experiments in granite, Proc. 2nd NEA/Stripa proj. symp. 82-94.

Calhoun, J. C. (1949). Porosity-permeability relationships. Oil and Gas Journal 47(43), 185.

Carlsson, L. and A. Carlstedt (1976). Estimation of transmissivity and permeability in Swedish bedrocks. Nordic Hydrological Conference, Reykjavik August 29th - September 1st, III 27-39.

Carlsson, A. and T. Olsson (1976). Bestämning av berggrundens permeabilitet genom vattenförlustmätning. Vannet i Norden No 3, 29-35.

Carlsson, A. and T. Olsson (1977). Hydraulic properties of Swedish crystalline rocks. Hydraulic conductivity and its relation to depth. Bull. Geol. Inst. Univ. Uppsala. N.S. 7, 71-84.

Carlsson, L., A. Winberg and B. Grundfelt (1983). Model calculations of the groundwater flow at Finnsjön, Fjällveden, Gideå and Kamlunge. KBS Technical Report 83-45.

Carman, P. C. (1939). Permeability of saturated sands, soils and clays. Jour. Agri. Sci 29, 262-273.

Crank, J. (1975). The Mathematics of Diffusion. Second edition, Clarendon Press, Oxford

Dahl, N. J. (1969). Grundvandsbevægelse. Teknisk Forlag, Copenhagen.

Dahlblom, P. (1985). Groundwater flow and dispersion processes in fractured rock. Research in Progress 1985, 10-11, Institutionen för Teknisk Vattenresurslära, Lunds Tekniska Högskola/ Lunds Universitet, Rapport nr 3096.

Dahlblom, P (1990). The ability of a model based on capillary tubes to reproduce the migration in fractured rock. "Fundamentals of Fluid Transport in Porous Media", Arles, France May 14-18, 1990. Poster sessions 65-68. Institut Français du Pétrole.

Dahlblom, P (1991). Hydrodynamic dispersion in rock fractures. "European Geophysical Society XVI General Assembly" Wiesbaden. Annales Geophysicae, supplement to volume 9, C

Dahlblom, P. and P. Hjorth (1986). Dérivation stochastique du coefficient de dispersion. Hydrogéologie 2, 207-214.

Dahlblom, P. and L. Jönsson (1990). Modelling of flow and Contaminant Migration in Single Rock Fractures. SKN Report 37, Statens Kärnbränslenämnd, Stockholm.

Darcy, H. (1856). Les Fontaines Publiques de la Ville de Dijon. Dalmont, Paris.

Day, P. R. (1956). Dispersion of a moving salt-water boundary advancing through saturated sand. Trans. Amer. Geophys. Union 37(5), 595-601.

Ebach, E. A. and R. R. White (1958). Mixing of fluids flowing through beds of packed solids. A.I.Ch.E. Journal 4(2), 161-169.

Erbe, F. (1933). Die Bestimmung der Porenverteilung nach ihrer Größe in Filtern und Ultrafiltern. Kolloid-Zeitschrift 63, 277-285.

Fick, A. (1855). Ueber Diffusion. Annalen der Physik, 170, 59-86.

Fried, J. J. and M. A. Combarnous (1971). Dispersion in porous media. Adv. Hydrosci., 7, 169-282.

Gidlund, G., K. Hansson and U. Thoregren (1979). Kompletterande permeabilitetsmätningar i Karlshamnsområdet. Svensk Kärnbränsleförsörjning, Stockholm, TR 79-06.

Goblet, P., E. Ledoux, G. de Marsily, P. Peaudecerf, P. Calmels and R. Guizerix (1983). Processes of solute transfer in fissured aquifers. Rep. Inst. Geol. Sci., No 82/6, 6-14.

Gupta, V. K., R. N. Bhattacharya and G. Sposito (1981). A molecular approach to the foundations of the theory of solute transport in porous media. J. Hydrol., 50, 355-370.

Harleman, D. R. F. and R. R. Rumer (1963). Longitudinal and lateral dispersion in an isotropic porous medium. J. Fluid Mech. 16(3), 385-394.

Heath, M. (1985). Deep digging for nuclear waste disposal. New Scientist 31 Oct. 30-32.

Herbert, A. W., D. P. Hodgkinson and J. Rae (1985). A pictorial view of radionuclide migration from a deep underground repository for cemented intermediate-level waste. United Kingdom Atomic Energy Authority, Oxfordshire. AERE M 3496.

Hult, A., G. Gidlund and U. Thoregren (1978). Permeabilitetsbestämningar. Kärnbränslesäkerhet, Stockholm, TR-61.

Irmay, S. (1965). Modèles théoriques d'écoulement dans les corps poreux. RILEM Bulletin N.S. 29, 37-43.

de Josselin de Jong, G. (1958). Longitudinal and transverse diffusion in granular deposits. Trans. Amer. Geophys. Union, 39(1), 67-74.

Klinkenberg, L. J. (1957). Pore size distribution of porous media and displacement experiments with miscible liquids. Jour. Petr. Techn., Apr. 1957, 63-66.

Klockars, C. E. and O. Persson (1982). The hydraulic properties of fracture zones and tracer tests with non-reactive elements in Studsvik. KBS, Stockholm, Teknisk Rapport 82-10.

Lenda, A. and A. Zuber (1979). Tracer dispersion in groundwater experiments. Isotope Hydrology, Proceedings of a Symposium arranged by IAEA, Vienna, 619 - 641.

Levenspiel, O. and W. K. Smith (1957). Notes on the diffusion-type model for the longitudinal mixing of fluids in flow. Chem. Engng. Sci. 6, 227-233.

Lindblom, U. (1977). Groundwater movements around a repository. Phase 1, State of the art and detailed study plan. KBS TR 6.

Lindh, G., P. Hjorth, L. Anderberg, L. Jönsson and P. Dahlblom (1984). Hydrological aspects on the final deposition of spent nuclear fuel including future research needs. NAK rap 12, Kärnbränslenämndens forskningsinventering del II, 26-56.

Long, J. C. S., P. Gilmour, and P. A. Witherspoon (1985). A model for steady fluid flow in random three-dimensional networks of disc-shaped fractures. Water Resour. Res. 21(8), 1105-1115.

Louis, C. (1967). Strömungsvorgänge in klüftigen Medien und ihre Wirkung auf die Standsicherheit von Bauwerken un Böschungen im Fels. Veröffentlichungen des Institutes für Bodenmechanik und Felsmechanik der Universität Fridericiana in Karlsruhe, Heft 30.

Magnusson, K-Å. and O. Duran (1978). Geofysisk Borrhålsmätning. Kärnbränslesäkerhet, Stockholm, TR-61.

Martel, S. J. and J. E. Peterson Jr. (1990). Use of Integrated Geologic and Geophysical Information for Characterizing the Structure of Fracture Systems at the US/BK Site, Grimsel Laboratory, Switzerland. Earth Sciences Division, Lawrence Berkeley Laboratory, University of California, LBL-27912 NDC-16, Berkeley.

Neretnieks, I. and A. Rasmuson (1983). An approach to modelling radionuclide migration in a medium with strongly varying velocity and block sizes along the flow path. KBS Teknisk Rapport 83-69.

Novakowski, C. and A. Lindberg (1984). Hydrogeological Conditions in the Costal Zone of Southwestern Finland with Respect to the Disposal of Radioactive Waste. Geological Survey of Finland, Report of Investigation 66, Espoo.

Novakowski, K. S., G. V. Evans, D. A. Lever and K. G. Raven (1985). A Field Example of Measuring Hydrodynamic Dispersion in a Single Fracture. Water Resour. Res., 21(8), 1165-1174.

Ogata, A. and R. B. Banks (1961). A Solution of the Differential Equation of Longitudinal Dispersion in Porous Media. Geological Survey Prof. Paper 411-A, Washington.

Olsson, T. (1979). Hydraulic Properties and Groundwater Balance in a Soil-Rock Aquifer System in the Juktan Area, Northern Sweden. Sos. Upsal. Pro Geol.Quater. 12, Uppsala.

Perkins, T. K. and O. C. Johnston (1963). A review of diffusion and dispersion in porous media. J. Soc. Petrol. Eng. 3, 70-84.

Persson, A. P-G. (1985). The Temperature Log as an Indicator of Permeable Zones and Fractures in Wells. Lund University, Department of Engineering Geology, Lund.

Pfannkuch, H. O. (1963). Contribution à l'étude des déplacements de fluides miscibles dans un milieu poreux. Rev. Inst. Fr. Petr. 18(2), 215-270.

Robinson, P. C. (1984). Connectivity, Flow and Transport in Network Models of Fractured Media. Theoretical Physics Division, A.E.R.E. Harwell, Oxfordshire.

Saffman, P. G. (1959). A theory of dispersion in a porous medium. J. Fluid Mech., part 3, 6, 321-349.

Saffman, P. G. (1960). Dispersion due to molecular diffusion and macroscopic mixing in flow through a network of capillaries. J. Fluid Mech., part 2, 7, 194-208.

Scheidegger, A. E. (1953). Theoretical models of porous matter. Producers Monthly 10, 17-23.

Scheidegger, A. E. (1954). Statistical Hydrodynamics in Porous Media. J. Appl. Phys. 25(8), 994-1001.

Scheidegger, A. E. (1957). On the theory of flow of miscible phases in porous media. Compt. Rend. Int. Ass. Sci. Hydr., Toronto, 236-242.

Scheidegger, A. E. (1959). Statistical approach to miscible displacement in porous media. Canadian Min. Metal. Bull. 52(561), 26-30.

Scheidegger, A. E. (1961). General theory of dispersion in porous media. J. Geoph. Res. 66(10), 3273-3278.

SKBF (1983). Kärnbränslecykels slutsteg. Använt Kärnbränsle - KBS-3, Del I-IV. Svensk Kärnbränsleförsörjning AB, Stockholm.

Snow, D. T. (1968). Rock fracture spacings, openings, and porosities. J. Soil Mech. Found. Div. Proc. ASCE 94(SM1) 73-91.

Stokes, J. (1980). On the description of the properties of fractured rock using the concept of a porous medium. KBS Teknisk Rapport 80-05.

Stokes, J. and R. Thunvik (1978). Investigations of groundwater flow in rock around repositories for nuclear waste. KBS Teknisk Rapport 47.

Taylor, G. (1953). Dispersion of soluble matter in solvent flowing slowly through a tube. Proc. R. Soc. London, Ser. A, 219, 186-203.

Thunvik, R. and C. Braester (1980). Hydrothermal conditions around a radioactive waste repository. KBS Teknisk Rapport 80-19.

Wei, H. F., E. Ledoux and G. de Marsily (1990). Regional modelling of groundwater flow and salt and environmental tracer transport in deep aquifers in the Paris Basin. J. Hydrol., 120, 341-358.

Wilson, C. R. and P. A. Witherspoon (1970). An Investigation of Laminar Flow in Fractured Porous Rocks. Department of Civil Engineering, Institute of Transportation and Traffic Engineering, Publication No 70-6. University of California, Berkeley.

FIGURES

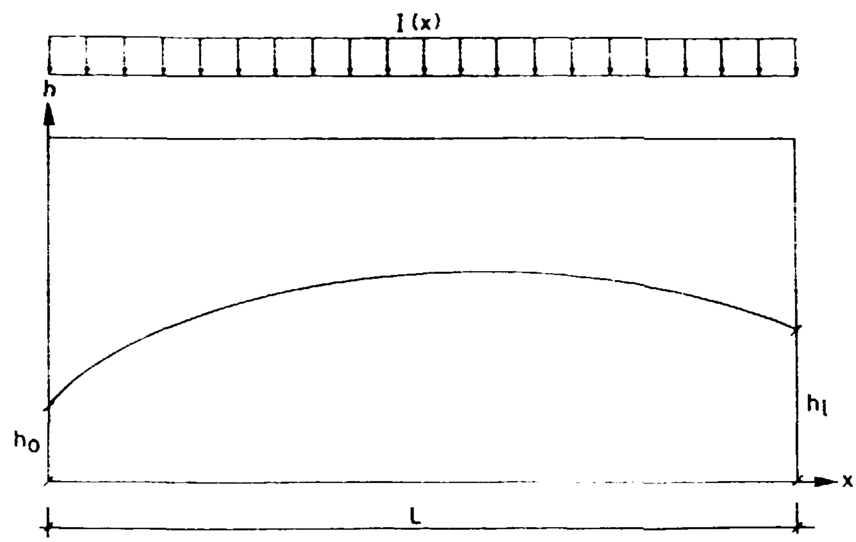

Figure 4.1 *An unconfined aquifer is recharged with a* constant (in time) rate I(x) which may be dependent of the space. The total distance between the boundaries is called L. The boundary conditions are the level of the groundwater surface above impermeable medium, denoted h_0 and h_L respectively.

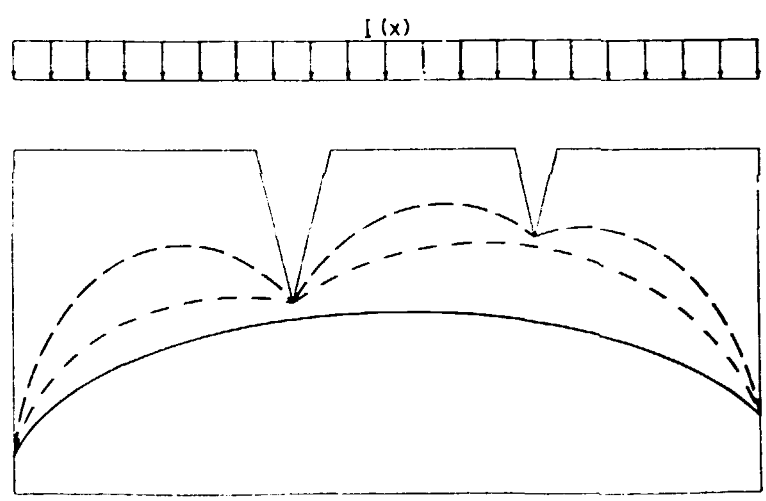

Figure 4.2 The impact of depressions on the shape of the groundwater surface.

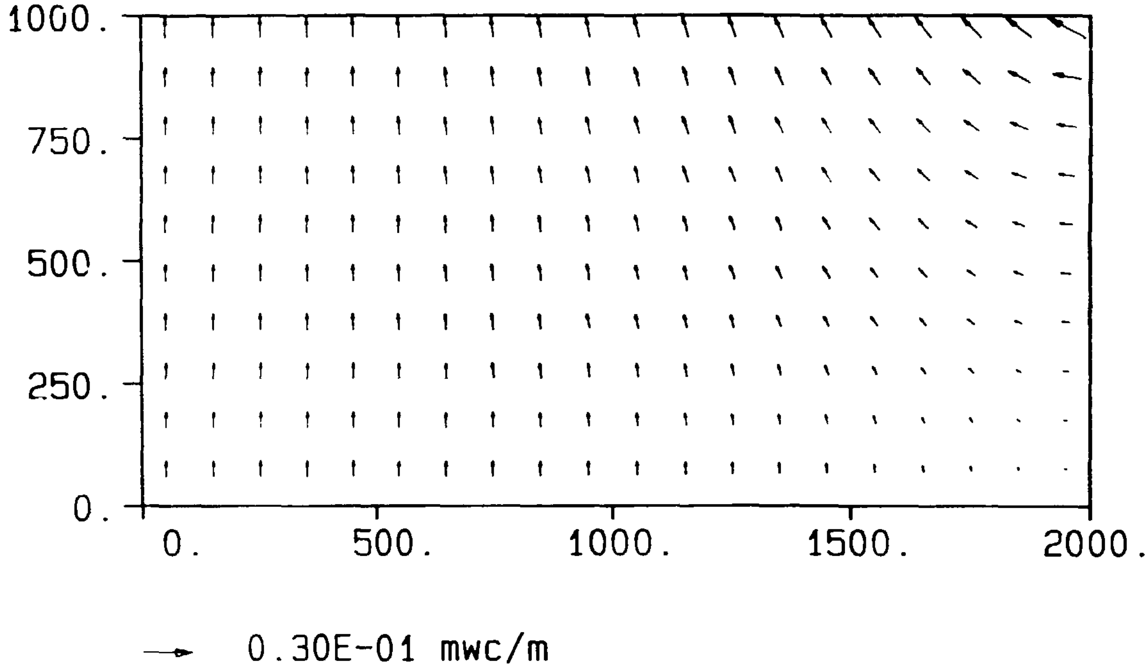

Figure 4.3 Example of calculated hydraulic gradients. The hydraulic conductivity is 10^{-6} m/s in both horizontal and vertical direction.

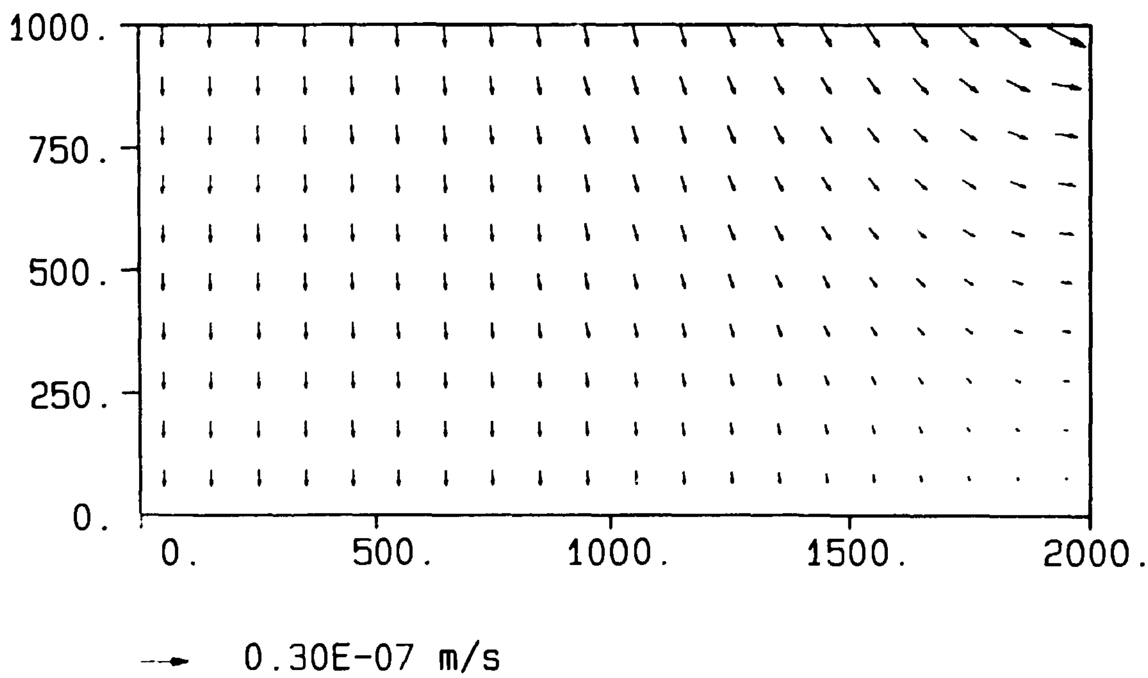

Figure 4.4 Example of calculated velocities. The hydraulic conductivity is 10^{-6} m/s in both horizontal and vertical direction. Same example as in figure 4.3.

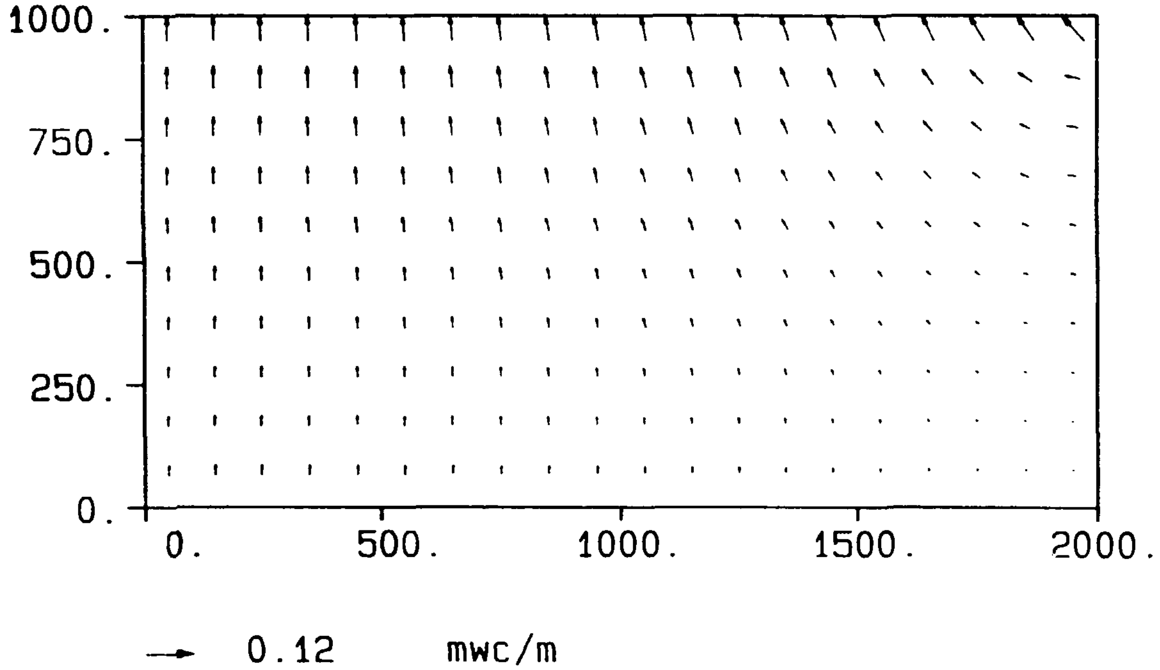

Figure 4.5 Example of calculated hydraulic gradients for an anisotropic case. The hydraulic conductivity is 10^{-6} m/s in the horizontal and $0.2 \cdot 10^{-6}$ m/s in the vertical direction.

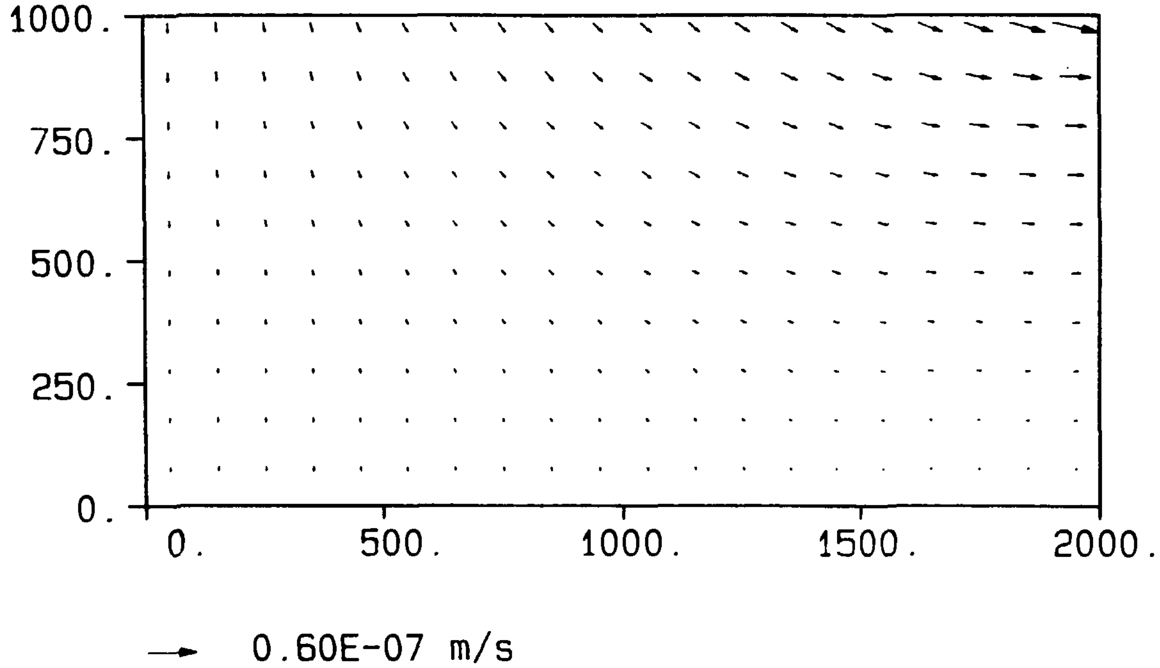

Figure 4.6 Example of calculated velocities for an anisotropic case. The hydraulic conductivity is 10^{-6} m/s in the horizontal and $0.2 \cdot 10^{-6}$ m/s in the vertical direction. Same example as in figure 4.5.

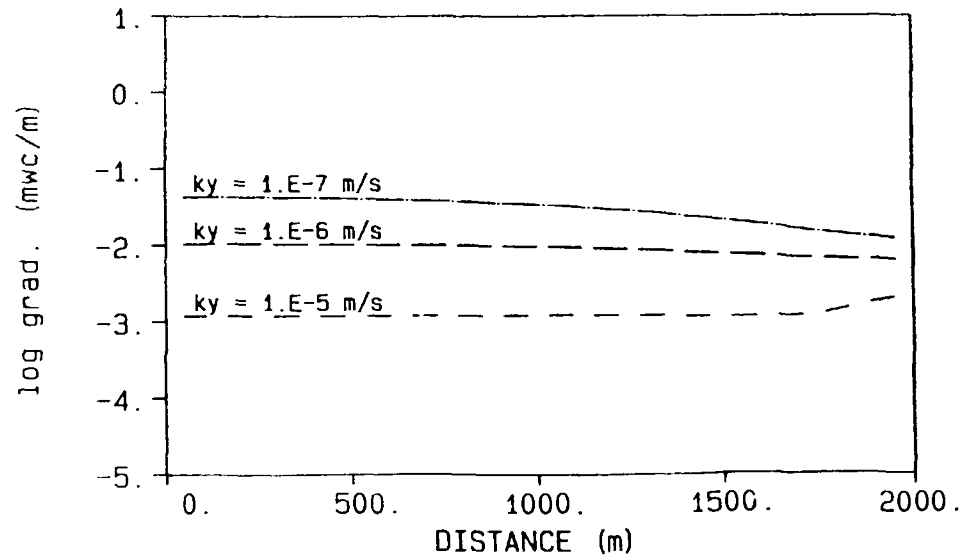

Figure 4.7 Absolute values of the hydraulic gradient at a level of 500 m below the ground surface for three anisotropic cases. They are plotted on a logaritmic scale. The hydraulic conductivity in horizontal direction is 10^{-6} m/s.

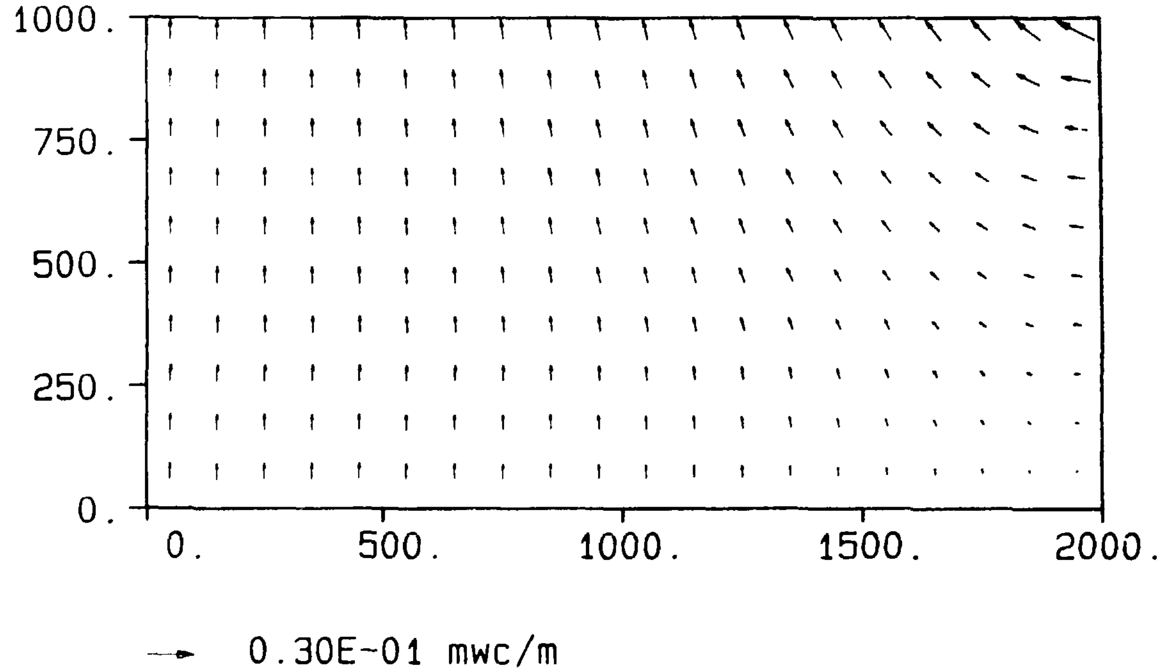

Figure 4.8 Example of calculated hydraulic gradients for an isotropic case with a decreasing hydraulic conductivity with depth. At the surface, the hydraulic conductivity is 10^{-6} m/s in both *horizontal and vertical direction,* and decreases with a factor 0.7 for each 100 m of depth.

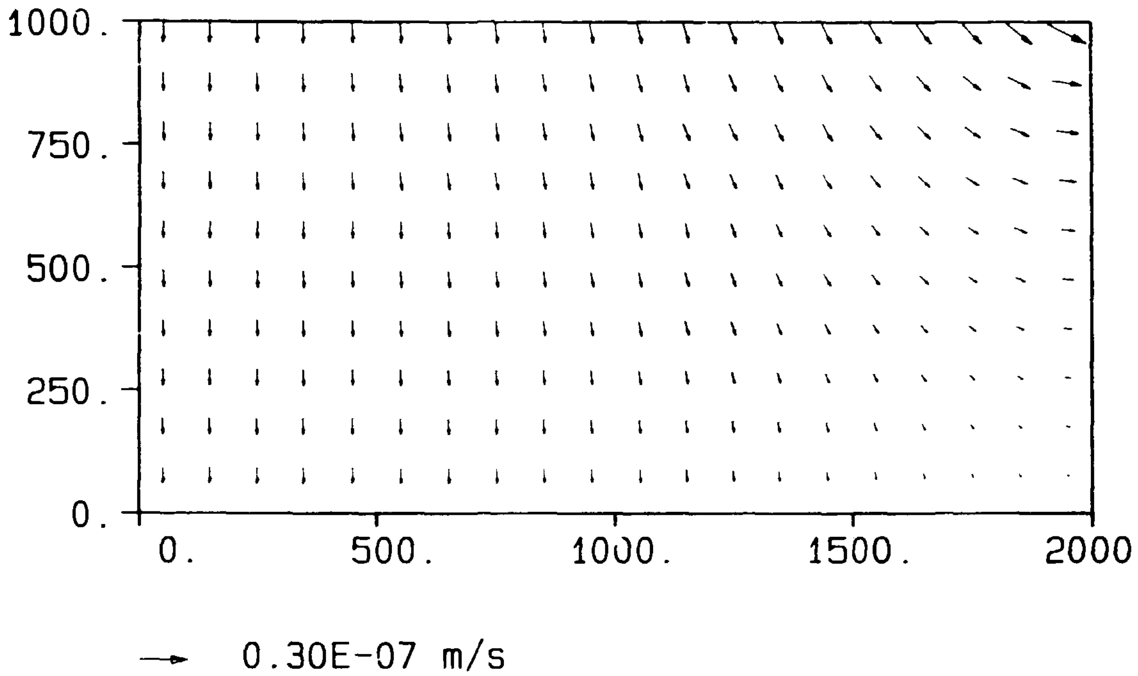

Figure 4.9 Example of calculated velocities for an isotropic case with a decreasing hydraulic conductivity with depth. At the surface, the hydraulic conductivity is 10^{-6} m/s in both horizontal and vertical direction, and decreases with a factor 0.7 for each 100 m of depth. Same example as in figure 4.8.

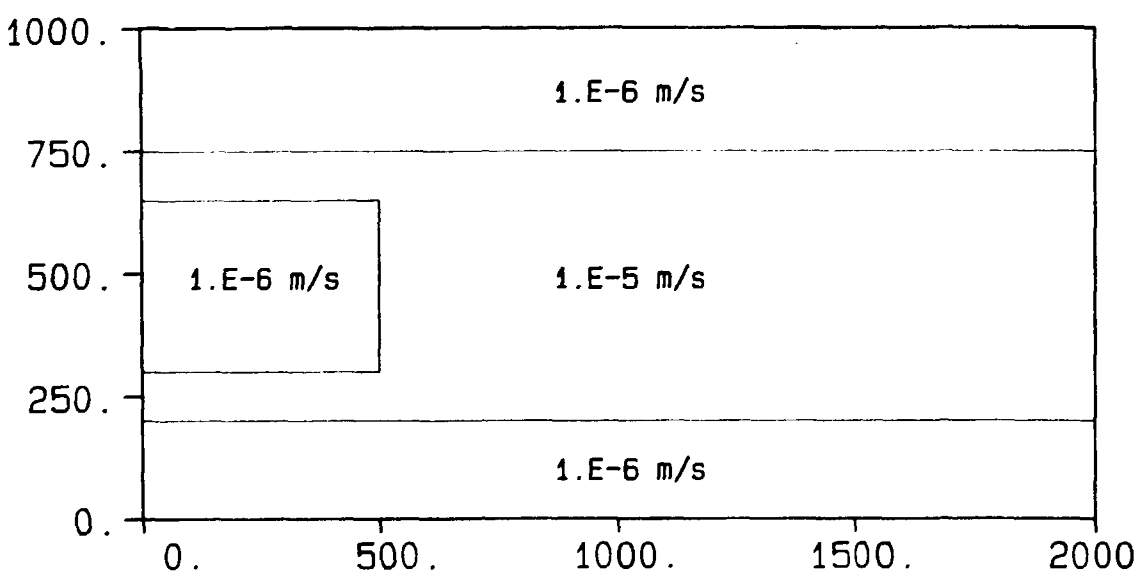

Figure 4.10 Definition of a heterogenous case according to the nydraulic conductivity. There is a difference of one order of magnitude in hydraulic conductivity within the area. The example is the same as in the figures 4.11 and 4.12.

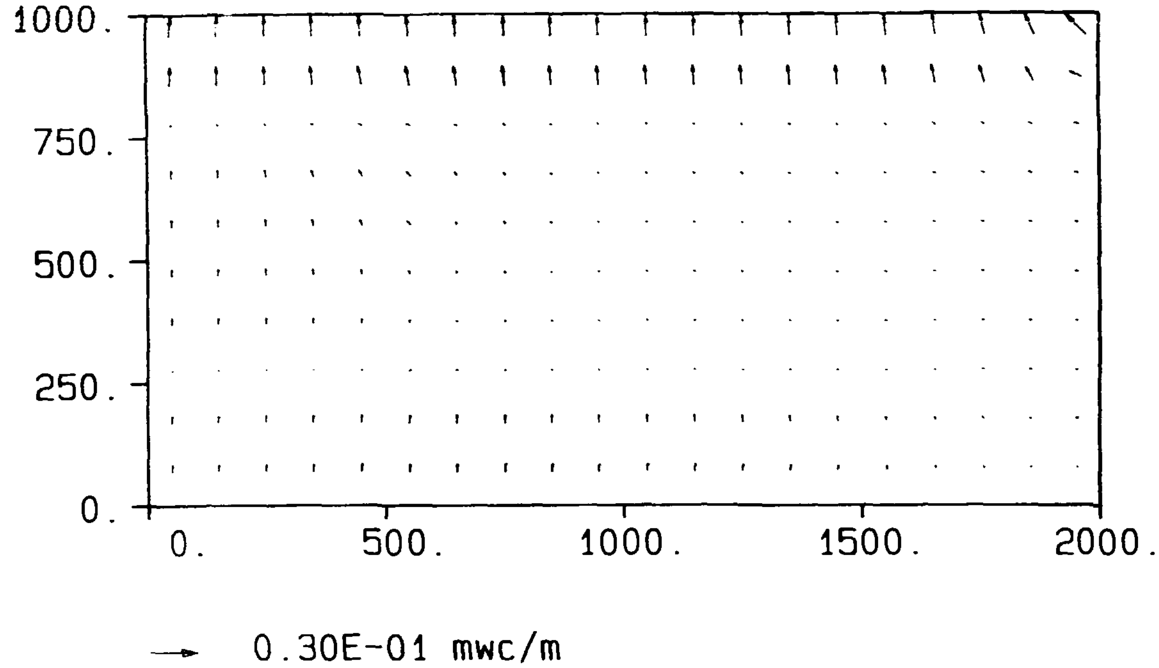

Figure 4.11 Example of calculated hydraulic gradients for a heterogenous case. The hydraulic conductivity varies between 10^{-6} and 10^{-5} m/s according to figure 4.10.

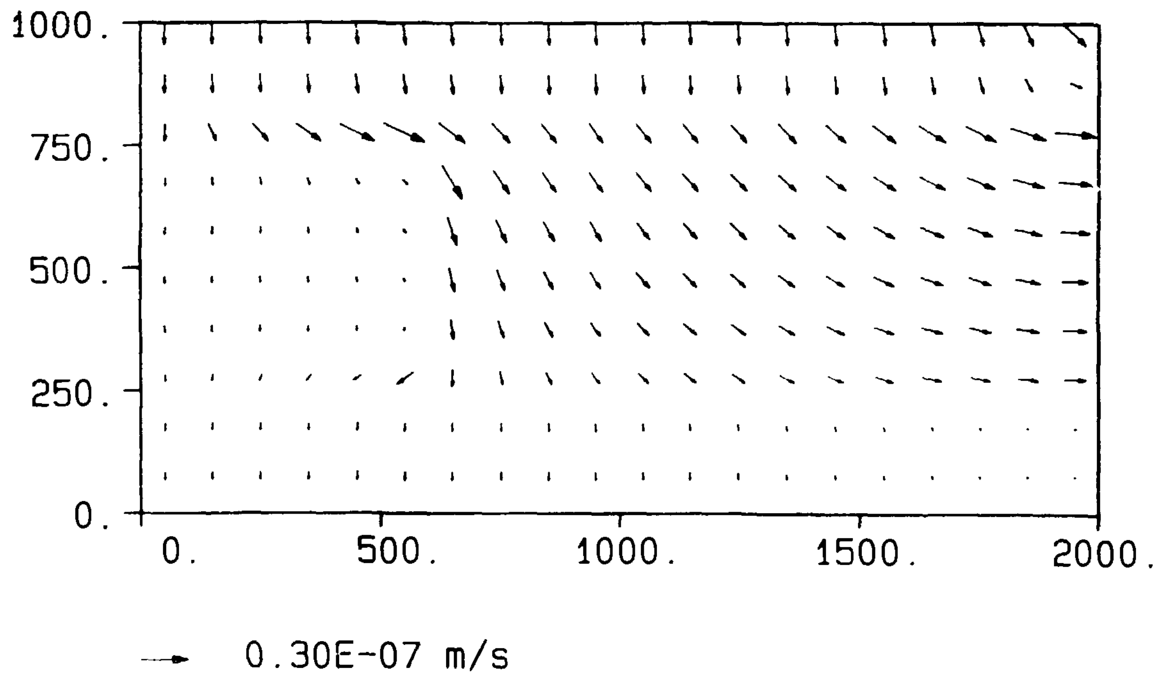

Figure 4.12 Example of calculated flow velocities for a heterogenous case. The hydraulic conductivity varies between 10^{-6} and 10^{-5} m/s according to figure 4.10.

TABLES

Table 4.1 Examples of cases that fulfil equation (24).

k(m/s)	I(m/s)	L(km)	h_0(km)	h(km)	$h-h_0$(km)
10^{-4}	$0.6\cdot 10^{-8}$	50	0.500	0.536	0.036
10^{-4}	$0.6\cdot 10^{-8}$	50	0.250	0.316	0.066
10^{-4}	$0.6\cdot 10^{-8}$	50	0.125	0.230	0.105
10^{-4}	$0.6\cdot 10^{-8}$	100	1.000	1.072	0.072
10^{-4}	$0.6\cdot 10^{-8}$	100	0.500	0.632	0.132
10^{-4}	$0.6\cdot 10^{-8}$	100	0.250	0.461	0.211
10^{-4}	$0.6\cdot 10^{-8}$	200	1.500	1.688	0.188
10^{-4}	$0.6\cdot 10^{-8}$	200	1.000	1.265	0.265
10^{-4}	$0.6\cdot 10^{-8}$	200	0.500	0.922	0.422
10^{-4}	$0.6\cdot 10^{-8}$	500.	2.000	2.784	0.784
10^{-4}	$0.6\cdot 10^{-8}$	500.	1.500	2.449	0.949
10^{-3}	$0.6\cdot 10^{-8}$	50	1.000	1.002	0.002
10^{-3}	$0.6\cdot 10^{-8}$	50	0.500	0.504	0.004
10^{-3}	$0.6\cdot 10^{-8}$	50	0.250	0.257	0.007
10^{-3}	$0.6\cdot 10^{-8}$	50	0.125	0.139	0.014
10^{-3}	$0.6\cdot 10^{-8}$	100	1.000	1.007	0.007
10^{-3}	$0.6\cdot 10^{-8}$	100	0.500	0.515	0.015
10^{-3}	$0.6\cdot 10^{-8}$	100	0.250	0.278	0.028
10^{-3}	$0.6\cdot 10^{-8}$	100	0.125	0.175	0.050
10^{-3}	$0.6\cdot 10^{-8}$	200	1.000	1.030	0.030
10^{-3}	$0.6\cdot 10^{-8}$	200	0.500	0.557	0.057
10^{-3}	$0.6\cdot 10^{-8}$	200	0.250	0.350	0.100
10^{-3}	$0.6\cdot 10^{-8}$	200	0.125	0.275	0.150
10^{-3}	$0.6\cdot 10^{-8}$	500	1.500	1.620	0.120
10^{-3}	$0.6\cdot 10^{-8}$	500	1.000	1.173	0.173
10^{-3}	$0.6\cdot 10^{-8}$	500	0.500	0.791	0.291
10^{-3}	$0.6\cdot 10^{-8}$	500	0.250	0.661	0.411
10^{-3}	$0.6\cdot 10^{-8}$	500	0.125	0.625	0.500

Reports published by the National Board for Spent Nuclear Fuel, SKN

NAK RAPPORT 1	**SAMMANSTÄLLNING AV NUKLEÄRA KÄLLDATA FÖR ANVÄNT KÄRNBRÄNSLE** *(Compilation of Nuclear Source Data for Spent Nuclear Fuel)* Göran Olsson Studsvik Energiteknik AB, april 1983 (19 pages of tables and diagrams, Swedish text)
NAK RAPPORT 2	**MATERIAL OCH PROCESSUTVECKLING FÖR DIREKT SLUTFÖRVARING AV ANVÄNT KÄRNBRÄNSLE** *(Material and Process Development of Ceramic Encapsulation of Spent Nuclear Fuel for Disposal)* Caj Airola Studsvik Energiteknik AB, november 1983 (119 pages mainly on engineering aspects of ceramic encapsulation, in Swedish)
NAK REPORT 3	**ENCAPSULATION OF SPENT NUCLEAR FUEL IN CERAMIC MATERIALS. AN INTRODUCTORY STUDY** S Forsberg, T Westermark Department of Nuclear Chemistry, The Royal Institute of Technology, Stockholm, Sweden, March 1983 (37 pages mainly on material properties, in English)
NAK RAPPORT 4	**INTERNATIONELL UTVECKLING FÖR KOMMERSIELL UPPARBETNING AV KÄRNBRÄNSLE, BEHANDLING AV UPPARBETNINGSAVFALL OCH ÅTERANVÄNDNING AV PLUTONIUM** *(International Development of Commercial Reprocessing of Spent Nuclear Fuel, Treatment of Reprocessing Wastes and Recycling of Plutonium)* Göran Carleson, Åke Hultgren Studsvik Energiteknik AB, mars 1983 (44 pages in Swedish)

NAK RAPPORT 5

SAMMANSTÄLLNING OCH VÄRDERING AV UTLÄNDSKA SÄKERHETSSTUDIER ÖVER SLUTFÖRVARING AV KÄRNBRÄNSLEAVFALL

(Review of Foreign Safety Studies on Disposal of Spent Nuclear Fuel Waste)

Ragnar Gelin
Studsvik Energiteknik AB, april 1983

(109 pages in Swedish)

NAK RAPPORT 6

NÅGRA HUVUDINRIKTNINGAR INOM MODERN RISKTEORI

(Some Main Trends in Recent Development of Risk Theory)

Nils-Eric Sahlin
AB Episteme, Lund, juli 1983

(23 pages in Swedish)

NAK RAPPORT 7

RISK PÅ LÅNG SIKT OCH DISKONTERING AV RISK

(Risk in the Long Term and Discounting of Risk)

Bengt Hansson
AB Episteme, juli 1983

(17 pages in Swedish)

NAK RAPPORT 8

RISK PÅ LÅNG SIKT OCH DISKONTERING AV RISK I SAMBAND MED FÖRVARING AV RADIOAKTIVT MATERIAL

(Long Term Risk and Discounting of Risk in Relation to Disposal of Radioactive Materials)

Ola Svenson, Gunnar Karlsson
Stockholms universitet, september 1983

(43 pages in Swedish)

NAK RAPPORT 9

UPPFÖLJNING AV UTLÄNDSKA SÄKERHETSSTUDIER ÖVER SLUTFÖRVARING AV KÄRNBRÄNSLEAVFALL

(Review of Foreign Safety Studies on Disposal of Spent Nuclear Fuel Waste)

Ragnar Gelin
Studsvik Energiteknik AB, juni 1984

(40 pages in Swedish)

NAK RAPPORT 10

INTERNATIONELL UTVECKLING AV MELLANLAGRING OCH UPPARBETNING AV ANVÄNT KÄRNBRÄNSLE SAMT PLUTONIUMÅTERFÖRING

(International Development of Intermediate Storage and Reprocessing of Spent Nuclear Fuel and on Recycling of Plutonium)

G Carleson, Å Hultgren
Studsvik Energiteknik AB, augusti 1984

(56 pages in Swedish)

NAK REPORT 11

THE DISPOSAL OF HIGH-LEVEL RADIOACTIVE WASTE 1984, Vol. I and II

Frank L Parker, Robert E Broshears, Janos Pasztor
The Beijer Institute of the Royal Swedish Academy of Sciences
October 1984

(Vol I 116 pages, Vol II 209 pages, in English)

NAK RAPPORT 12

KÄRNBRÄNSLENÄMNDENS FORSKNINGSINVENTERING 1983 - 1984
DEL I SLUTRAPPORT
DEL II FORSKARUTLÅTANDEN

(An inventory of research needs
Vol I Summary and Conclusions, 30 pages
Vol II Research proposals, 196 pages)

The report identifies knowledge gaps and presents proposals on items which ought to be addressed in the on-going Swedish research programme on disposal of spent nuclear fuel
(in Swedish)

Clas-Otto Wene et al, december 1984

NAK RAPPORT 13

RISKFORSKNING OCH BESLUT OM RISKER

(Risk Research and Decisions about Risks)

Sven Ove Hansson, februari 1985

(14 pages in Swedish)

NAK RAPPORT 14

UPPFÖLJNING AV UTLÄNDSKA SÄKERHETSSTUDIER ÖVER SLUTFÖRVARING AV KÄRNBRÄNSLEAVFALL

(Review of Foreign Safety Studies on Disposal of Spent Nuclear Fuel Waste)

Ragnar Gelin
Studsvik Energiteknik AB, april 1985

(37 pages in Swedish)

NAK RAPPORT 15	**UPPFÖLJNING AV DEN INTERNATIONELLA UTVECKLINGEN AV MELLANLAGRING OCH UPPARBETNING AV ANVÄNT KÄRNBRÄNSLE**

(International Development of Intermediate Storage and Reprocessing of Spent Nuclear Fuel and on Recycling of Plutonium)

Göran Carleson
Studsvik Energiteknik AB, juni 1985

(39 pages in Swedish)

SKN REPORT 16	**NAK WP-CAVE PROJECT - REPORT ON THE RESEARCH AND DEVELOPMENT STAGE, MAY 1984 TO OCTOBER 1985**

Boliden WP-Contech AB, November 1985

(129 pages in English)

SKN REPORT 17	**TECHNICAL AND SOCIO-POLITICAL ISSUES IN RADIOACTIVE WASTE DISPOSAL 1986**

Vol I	Safety, Siting and Interim Storage (184 pages)
Vol IA	Appendices (197 pages)
Vol II	Subseabed Disposal (95 pages)

Frank L Parker, Roger E Kasperson, Tor Leif Andersson, Stephan A Parker
The Beijer Institute of the Royal Swedish Academy of Sciences, November 1987

SKN RAPPORT 18	**INTERNATIONELL UTVECKLING INOM KÄRNBRÄNSLE-CYKELN MED TYNGDPUNKT PÅ TRANSPORTER OCH SAFEGUARDS**

(International Development within the Spent Nuclear Fuel Cycle with Emphasis on Transports and Safeguards)

Karin Brodén, Göran Carleson, Åke Hultgren
Studsvik Energiteknik AB, november 1987

(52 pages in Swedish)

SKN REPORT 19	**RISK DECISIONS AND NUCLEAR WASTE**

Sven Ove Hansson
The National Board for Spent Nuclear Fuel, November 1987

(38 pages in English)

SKN REPORT 20	**TIME ORIENTATION, PLANNING HORIZONS AND RESPONSIBILITY INTO THE FUTURE**

Ola Svenson, Göran Nilsson
University of Stockholm, January 1988

(40 pages in English)

SKN REPORT 21 **PSYCHOLOGICAL ASPECTS OF NUCLEAR WASTE DISPOSAL: Long time perception and the question of discounting of risks**

Gunnar Karlsson, Ola Svenson
University of Stockholm, January 1988

(40 pages in English)

SKN RAPPORT 22 **KÄRNKRAFT OCH RADIOAKTIVT AVFALL: Riskperception och attityder hos gymnasieelever i Stockholm**

(Nuclear Power and Radioactive Waste: Risk Perceptions and Attitudes of High-school Students in Stockholm, Sweden)

Britt-Marie Drottz, Lennart Sjöberg
Psykologisk Metod AB, Stockholm, januari 1988

(150 pages in Swedish)

SKN RAPPORT 23 **ATTITYDER TILL RADIOAKTIVT AVFALL**

(Attitudes to Radioactive Waste)

Lennart Sjöberg, Britt-Marie Drottz
Psykologisk Metod AB, Stockholm, januari 1988

(160 pages in Swedish)

SKN RAPPORT 24 **OPINIONSBILDNING I KÄRNKRAFTENS AVFALLSFRÅGA: Mediestudierna - teoretiska utgångspunkter och empiriska undersökningar**

(Formation of Public Opinion on the Question of Nuclear Waste: Media Studies - Theoretical Premisses and Empirical Investigations)

Kent Asp, Per Hedberg
Göteborgs Universitet, juni 1988

(12 pages in Swedish)

SKN RAPPORT 25 **SAMHÄLLSDEBATT I ENERGI- OCH KÄRNKRAFTSFRÅGOR: Utbudet av skrifter och tidskriftsartiklar om kärnavfall, kärnkraft och energiförsörjning under åren 1971-1987**

(Public Debate on Questions of Energy and Nuclear Power: Books and Articles on Nuclear Waste, Nuclear Power and Power Supply during the Years 1971-1987)

Monica Djerf
Göteborgs universitet, juni 1988

(46 pages in Swedish)

SKN RAPPORT 26

BIBLIOGRAFI: Utbudet av skrifter och tidskriftsartiklar om kärnavfall, kärnkraft och energiförsörjning under åren 1971-1987

(BIBLIOGRAPHY: Books and Articles on Nuclear Waste, Nuclear Power and Power Supply during the Years 1971-1987)

Monika Djerf, Per Hedberg
Göteborgs universitet, juni 1988

(44 pages in Swedish)

SKN RAPPORT 27

INTERNATIONELL UTVECKLING INOM KÄRNBRÄNSLE-CYKELN

(International Development within the Spent Nuclear Fuel Cycle)

Karin Brodén, Åke Hultgren
Studsvik Nuclear, mars 1988

(80 pages in Swedish)

SKN RAPPORT 28

ETIK OCH KÄRNAVFALL: Rapport från ett seminarium om ETISKT HANDLANDE UNDER OSÄKERHET i Stockholm den 8-9 september 1987

(Ethics and Nuclear Waste: A report from a seminar on Ethical Action in the Face of Uncertainty in Stockholm, Sweden, September 8-9, 1987)

Mars 1988

(210 pages in Swedish)

SKN REPORT 29

ETHICAL ASPECTS ON NUCLEAR WASTE: Some points discussed at a seminar on Ethical Action in the Face of Uncertainty in Stockholm, Sweden, September 8-9, 1987

April 1988

(14 pages in English)

SKN RAPPORT 30

SVENSKA FOLKETS ÅSIKTER OM KÄRNKRAFT OCH SLUTFÖRVARING EFTER TJERNOBYL

(Opinions of the Swedish People on Nuclear Power and Final Disposal of Nuclear Waste after Chernobyl)

Sören Holmberg
Göteborgs universitet, oktober 1988

(41 pages in Swedish)

SKN RAPPORT 31 **INTERNATIONELL UTVECKLING INOM KÄRNBRÄNSLE-CYKELN**

(International Development within the Nuclear Fuel Cycle)

Karin Brodén, Ragnar Gelin
Studsvik Nuclear, februari 1989

(60 pages in Swedish)

SKN RAPPORT 32 **TEKNIK OCH POLITIK KRING FÖRVARING AV RADIO-AKTIVT AVFALL. EN INTERNATIONELL JÄMFÖRELSE**

(Short version in Swedish of SKN Report 17)

Tor Leif Andersson
Mars 1989

(24 pages in Swedish)

SKN RAPPORT 33 **INTERNATIONELL UTVECKLING INOM KÄRNBRÄNSLE-CYKELN**

(International Development within the Nuclear Fuel Cycle)

Ingrid Aggeryd, Karin Brodén, Ragnar Gelin
Studsvik Nuclear, januari 1990

(63 pages in Swedish)

SKN RAPPORT 34 **FINNS DET SÄKRA SVAR? Rapport från ett seminarium om DEN NATURVETENSKAPLIGA KUNSKAPSBASEN FÖR SLUTFÖRVARINGEN AV DET ANVÄNDA KÄRNBRÄNSLET i Saltsjöbaden den 5 - 7 september 1989**

(Are there Safe Answers? A Report from a Seminar on the Scientific Basis for the Disposal of Spent Nuclear Fuel in Sweden, Saltsjöbaden 5 - 7 September 1989.)

Tor Leif Andersson (ed.)
Tellus Energi AB, mars 1990

(296 pages in Swedish)

SKN REPORT 35 **VIEWS ON THE CALCULATION OF FLOW AND DISPERSION PROCESSES IN FRACTURED ROCK**

Lennart Jönsson
University of Lund, March 1990

(57 pages in English)

SKN REPORT 36 **WATER FLOW CHARACTERISTICS OF ROCK FRACTURES**

Lennart Jönsson
University of Lund, March 1990

(54 pages in Swedish)

SKN REPORT 37	**MODELLING OF FLOW AND CONTAMINANT MIGRATION IN SINGLE ROCK FRACTURES** Peter Dahlblom, Lennart Jönsson University of Lund, March 1990 (54 pages in Swedish)
SKN REPORT 38	**REPROCESSING IN SWEDEN: HISTORY AND PERSPECTIVE** Å Hultgren, C-G Österlundh Studsvik Nuclear, August 1990 (32 pages in English)
SKN RAPPORT 39	**SEDIMENTÄR BERGGRUND SOM HYDRAULISK BARRIÄR, FÖRSTUDIE** *(Sedimentary Rocks as Hydraulic Barrier)* Kaj Ahlbom, Jan-Erik Andersson, Leif Carlsson, Sven Tirén, Anders Winberg Sveriges Geologiska AB, december 1990 (110 pages in Swedish)
SKN RAPPORT 40	**EN KVALITATIV STUDIE I LEKMÄNS UPPLEVELSE AV RISK I SAMBAND MED OMHÄNDERTAGANDE AV KÄRNAVFALL** *(A Qualitative Study of Laymens' Experiences of Risk in Connection With Storage of Nuclear Waste)* Gunnar Karlsson, Anneli Ljungberg Stockholms universitet, december 1990 (36 pages in Swedish)
SKN REPORT 41	**AN OVERVIEW OF DECISION THEORY** Sven Ove Hansson Uppsala University, January 1991 (60 pages in English)
SKN RAPPORT 42	**SKNS GRANSKNING AV FÖRUNDERSÖKNINGARNA INFÖR BYGGANDET AV ÄSPÖLABORATORIET** *(SKN's review of the preinvestigations for the Äspö Hard Rock Laboratory)* Kai Palmqvist, BERGAB Tommy Olsson, Golder Geosystem AB Januari 1991 (108 pages in Swedish)

SKN RAPPORT 43 **GEOGASTRANSPORT I BERG, FÖRSTUDIE**

(Geogas – a carrier or a tracer?)

Hans-Peter Hermansson, Jan Chyssler, Studsvik AB
Gustav Åkerblom, Anders Lindén, Sveriges Geologiska AB
Januari 1991

(43 pages in Swedish)

SKN RAPPORT 44 **INTERNATIONELL UTVECKLING INOM KÄRNBRÄNSLE-CYKELN**

(International Development within the Nuclear Fuel Cycle)

Ingrid Aggeryd, Åke Hultgren, Karin Brodén
Studsvik Nuclear, februari 1990

(44 pages in Swedish)

SKN RAPPORT 45 **OSÄKERHET OCH BESLUT, RAPPORT FRÅN ETT SEMINARIUM OM BESLUT UNDER OSÄKERHET I ANKNYTNING TILL KÄRNAVFALLSFRÅGAN PÅ HÄSSELBY SLOTT, DEN 4-6 APRIL 1990**

(Decisions in the Face of Uncertainty. A report from a seminar on decisions in the face of uncertainty in connection with nuclear waste in Stockholm, Sweden, April 4-6, 1990)

Redaktörer: Christian Munthe och Folke Tersman
Statens kärnbränslenämnd, februari 1991

(100 pages in Swedish)

SKN RAPPORT 46 **RISKUPPLEVELSER I SAMBAND MED LOKALISERING AV ETT SLUTFÖRVAR FÖR ANVÄNT KÄRNBRÄNSLE**

(Experiences of Risk in Connection with Site Selection for a Repository for Spent Nuclear Fuel)

Anders Biel och Ulf Dahlstrand
Göteborgs universitet, mars 1991

(57 pages in Swedish)

SKN RAPPORT 47 **KÄRNAVFALLSFRÅGAN I SVENSKA MASSMEDIER**

(The Nuclear Waste Issue in Swedish Mass Media)

Per Hedberg
Göteborgs universitet, april 1991

(74 pages in Swedish)

SKN REPORT 48	**THE IMPACT OF PARTY ON NUCLEAR POWER ATTITUDES IN SWEDEN** Sören Holmberg Göteborg University, April 1991 (38 pages in English)
SKN RAPPORT 49	**KÄRNAVFALL OCH SAMHÄLLSFORSKNING** *(Nuclear Waste and Social Science Research)* Christian Munthe och Folke Tersman Statens kärnbränslenämnd, april 1991 (70 pages in Swedish)
SKN RAPPORT 50	**KVINNOR, MÄN OCH KÄRNKRAFT** *(Women, Men and Nuclear Power)* Maria Oskarson Göteborgs universitet, augusti 1991 (60 pages in Swedish)
SKN REPORT 51	**GEOGAS - A CARRIER OR A TRACER?** Hans-Peter Hermansson, Jan Chyssler, Studsvik AB Gustav Åkerblom, Anders Lindén, Sveriges Geologiska AB October 1991 (66 pages in English)
SKN REPORT 52	**GEOGAS IN CRYSTALLINE BEDROCK** Hans-Peter Hermansson, Studsvik AB Rolf Sjöblom, Statens kärnbränslenämnd Gustav Åkerblom, Sveriges Geologiska AB, nu på SSI October 1991 (32 pages in English)
SKN REPORT 53	**IS THERE A DEFINITIVE ANSWER? The Scientific Base for the Final Disposal of Spent Nuclear Fuel. A condensed summary based on a report (SKN 34) of a seminar held at Saltsjöbaden, Sweden on September 5-7th, 1989.** J. A. T. Smellie Conterra AB, October 1991 (43 pages in English)

SKN REPORT 54

SPECIALIST MEETING ON ACCELERATOR-DRIVEN TRANSMUTATION TECHNOLOGY FOR RADWASTE AND OTHER APPLICATIONS
24-28 June 1991, Saltsjöbaden, Stockholm Sweden

Compiled by: R. A. Jameson
Los Alamos National Laboratory, USA, November 1991

(798 pages in English)

SKN REPORT 55

NUCLEAR WASTE MANAGEMENT REVIEW WORK
- Part of the Decision Making Process
Proceedings from a symposium in connection with the 10 year anniversary of the Swedish National Board for Spent Nuclear Fuel Stockholm, Sweden, September 25-26, 1991.

Statens kärnbränslenämnd, February 1992

(145 pages in English)

SKN RAPPORT 56

INTERNATIONELL UTVECKLING INOM KÄRNBRÄNSLECYKELN

(International Development within the Nuclear Fuel Cycle)

Ingrid Aggeryd och Karin Brodén
Studsvik Nuclear, december 1991

(71 pages in Swedish)

SKN REPORT 57

STABILITY OF METALLIC COPPER IN THE NEAR SURFACE ENVIRONMENT

Örjan Amcoff and Katalin Holényi
Uppsala University, December 1991

(77 pages in English)

SKN RAPPORT 58

UTREDNING OM UNDERLAG FÖR LOKALISERING AV ETT SLUTFÖRVAR FÖR ANVÄNT KÄRNBRÄNSLE
Del 1: Geologiskt underlag i översiktsskala

Thomas Lundqvist, Lennart Samuelsson och Sören Scherman
Svensk ingenjörstjänst SINTAB AB, mars 1992

(37 pages in Swedish)

SKN REPORT 59

SURVEY OF IN SITU TESTING AT UNDERGROUND LABORATORIES
with Application to Geological Disposal of Spent Fuel Waste in Crystalline Rock

Ernest Hardin
Reptec Corporation/Swedish Engineering Services (SINTAB), September 1991

(195 pages in English)

SKN REPORT 60	**SURVEY OF SITING PRACTICES FOR SELECTED MANAGEMENT PROJECTS IN SEVEN COUNTRIES** Ernest Hardin Reptec Corporation/Swedish Engineering Services (SINTAB), and Harald Åhagen, SINTAB
SKN RAPPORT 61	**SKNs FORTSATTA GRANSKNING AV FÖRUNDERSÖKNINGAR OCH PROGNOSER AVSEENDE ÄSPÖLABORATORIET** BERGAB/SINTAB
SKN REPORT 62	**SIMULATION OF THE MIGRATION IN FRACTURED ROCK BY A MODEL BASED ON CAPILLARY TUBES** Peter Dahlblom, Lund University, Department of Water Resources Engineering, April 1992 (43 pages in English)
SKN REPORT 63	**HYDRAULIC GRADIENTS IN ROCK AQUIFERS** Peter Dahlblom, Lund University, Department of Water Resources Engineering, April 1992 (67 pages in English)

The Swedish nuclear power programme

After the 1980 referendum on nuclear power, the Riksdag decided that nuclear power in Sweden would be phased out no later than the year 2010 and that the number of reactors would be limited to twelve. Since 1985, these reactors have all been in operation at the nuclear power plants in Barsebäck, Forsmark, Oskarshamn and Ringhals.

Different kinds of radioactive waste

Different kinds of radioactive waste are generated during the operation of a nuclear power plant - low-level waste, intermediate-level waste and high-level waste.

LOW- AND INTERMEDIATE-LEVEL WASTE

Low- and intermediate-level waste arising from the continuous operation of a nuclear power plant are known by the common name of **reactor waste**. Reactor waste consists of scrap material and metal, protective matting, clothing and suchlike which are used within the controlled areas of the nuclear power plants. This waste also consists of filter material which is used to trap radioactive substances in the reactor coolant. The radiation level of low-level waste is so low that it can be handled without any particular safety measures and so it is packed in plastic bags or sheet metal drums. However, certain protective measures are required when handling intermediate-level waste. This waste is cast in concrete or asphalt.

In the spring of 1988, SFR (the final repository for reactor waste) was taken into service. SFR is located under the seabed near to Forsmark nuclear power plant. The utilities plan to deposit all reactor waste as well as low- and intermediate-level waste from decommissioning in SFR.

HIGH-LEVEL WASTE

High-level waste mainly consists of spent nuclear fuel, i.e. fuel elements in which so many of the fissile atoms are spent that the elements can no longer be used. However, the spent fuel still generates heat on account of its radioactivity and must be cooled. The fuel is, therefore, stored in special pools filled with water in the reactor building for at least one year. The fuel is then transported by a specially built ship, called Sigyn, to CLAB (the central interim storage facility for spent nuclear fuel), located close to Oskarshamn nuclear power plant. CLAB was taken into service 1986. Since the radiation level is very high, the fuel is transported in specially built containers. The walls of the containers are made of thick steel so as to shield the personnel and surroundings from harmful radiation and to protect the fuel from damage.

The fuel is then placed in storage pools in an underground room at CLAB where it will be stored for at least forty years. During this time, the radioactivity and the heat generated by the fuel will decline thereby facilitating handling and disposal of the fuel.

The National Board for Spent Nuclear Fuel

One of the main tasks of the National Board for Spent Nuclear Fuel (SKN) is to review the utilities' research and development programme for the management of spent nuclear fuel and for the decommissioning of the nuclear power plants. The Board also supervises the way in which the utilities carry out the programme. In order to accomplish this task, The Board keeps abreast with international research and development work within the area and initiates such research that is important to its own supervisory functions. The research conducted by the Board is both scientific/technical and sociological in nature. The results from this research are published in the SKN Reports series. A list of published reports is available at the end of each publication.

Another of the Board's main tasks is to handle issues concerning the financing of costs within the area of nuclear waste. Each year, the Board estimates the size of the fee to be paid by the utilities to cover the current and future costs of waste management. The proposal on fees for the coming year is reported in SKN PLAN, which is submitted to the government before the end of October.

The Board is also responsible for seeing that the public is granted insight into the work on the safe disposal of spent nuclear fuel. The Board will continually issue short publications on this matter in the series, DISPOSAL OF SPENT NUCLEAR FUEL. The following publications have so far been issued:

1. Comments on the research programme for 1986. (In Swedish)
2. (Now replaced by number 5)
3. How do we choose a suitable site for a final repository? (In Swedish)
4. Radioactive waste: technology and politics in six countries. (In Swedish)
5. This is how nuclear waste management is financed. (In Swedish and English)
6. Evaluation of SKB's research programme 89. (In Swedish)
7. 100 questions and answers concerning spent nuclear fuel. (In Swedish)

STATENS
KÄRNBRÄNSLE
NÄMND

POSTAL ADDRESS	STREET ADDRESS	TELEPHONE	TELEFAX
Box 27824	Sehlstedtgatan 9	Nat 08-667 98 20	Nat 08-661 67 35
S-115 93 STOCKHOLM	STOCKHOLM	Int + 46 8 667 98 20	Int + 46 8 661 67 35
SWEDEN			

ALLMÄNNA FÖRLAGET

ISBN 91-38-12756-3