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Description of transport pathways in a KBS-3 type repository

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ABSTRACT

A descriptive model of the radionuclide transport pathways in the near-field of a KBS-3 type repository has been developed. The model is based on the buffer and backfill properties, a generalized discontinuity model of the undisturbed rock and the effects of drilling and blasting. A reference description of the near-field rock properties is given, with implications for transport modelling.

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1 INTRODUCTION

According to the general planning of SKB, presented in R&D-programme 1989, a new integrated safety evaluation of the final storage of spent nuclear fuel will be finalized during 1991 (SKB 91). The report will be one important part of the background material to the future site selection process in Sweden.

The primary objective of the assessment is to clarify the role and importance of site-specific factors for the total safety of the repository. Therefore, less effort is put into the studies of the near-field performance (spent fuel, engineered barriers and the part of the rock that has been altered by excavation) in the sense that no variations and alternatives in the near-field are studied. However, to get a good understanding of the importance of different geologic parameters for the overall safety of a repository, it necessary to have a realistic description of the radionuclide migration pathways in the near-field. The objective with the present study is to identify the major transport pathways and to quantify their importance.

2 BUFFER AND BACKFILLS

2.1 General

Highly compacted Na bentonite clay blocks placed below, around and above the canisters will take up water from the rock, swell and form a tight contact with the metal canisters and the surrounding rock. The bentonite becomes water saturated and homogeneous in a few years or tens of years and below the canister top it thereby forms a medium with an average bulk density of 2.0 g/cm^3 and a hydraulic conductivity of about 10^{-13} m/s (E in Fig.1). Higher up in the holes, the bentonite undergoes significant upward expansion which leads to a drop in bulk density and an associated rise in hydraulic conductivity (D in Fig.1). The density may drop to around 1.8 g/cm^3 corresponding to a hydraulic conductivity of 10^{-9} m/s (Pusch et al 1990).

The tunnel backfill consists of mixtures of Na bentonite powder and suitably graded ballast material, the proportions being 10% bentonite/90% ballast in the lower two thirds of the tunnel section, and 20% bentonite/80% ballast in the uppermost part (Fig.1). The hydraulic conductivity of the backfill is assumed to be 10^{-9} m/s, for which more effective compaction techniques are required than those applied in the Stripa field tests, which are otherwise most relevant to the subject (Pusch & Nilsson, 1982).

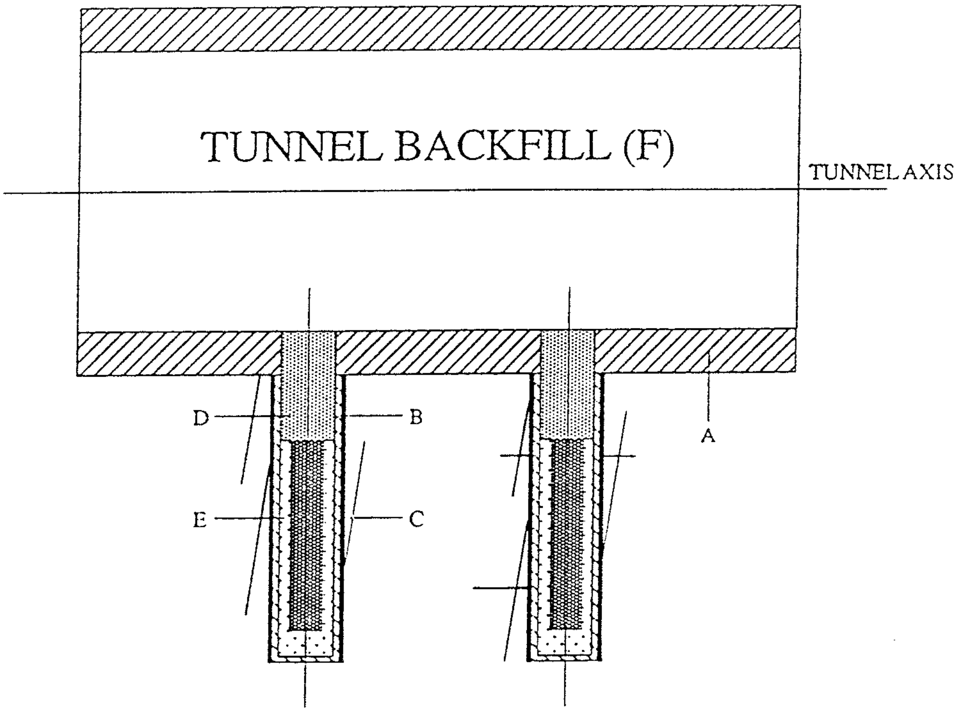

Fig. 1 Major transport paths in KBS3 near-field. A) Disturbed zone around tunnel, B) Wall disturbance around deposition holes, C) Channels in rock fractures, D) Expanded bentonite, E) Intact bentonite, F) Backfill

2.2 *Interaction with surroundings*

The dense bentonite in the deposition holes establishes a very intimate contact with the surrounding rock such that there will be no permeable clay/rock interface. It also exerts a swelling pressure on the rock which tends to compress fractures that are more or less parallel to the walls of the holes, and which makes the clay penetrate into fractures that have a geometrical aperture of more than around 150 μm. The penetration depth is usually very small, however, and should be neglected in a conservative analysis.

The bentonite/ballast backfills in tunnels and shafts are less effective in establishing tight contact with surrounding rock, especially at the upper end of the walls and at the roof. Still, one can assume that the backfill itself and the rock/backfill interface are less permeable than the shallow, mechanically disturbed zone of blasted tunnels.

A matter of considerable importance is the compressibility of bentonite/ballast backfills exposed to the swelling pressure of the dense canister-embedding clay in the deposition holes, and to rock blocks falling from the degrading roof in a long term perspective. The first-mentioned effect will have the character of upward movement of the backfill overlying the deposition holes by which the density of canister-embedding clay is reduced and its conductivity increased. The latter may be increased by several orders of magnitude but since the density changes are not significant below about 1 m depth in the holes, the net effect is not expected to be very dramatic.

The second effect, i.e. the compaction of backfill contacting the roof by falling rock, will lead to a somewhat reduced hydraulic conductivity, which is counteracted by a strong increase of the axial conductivity of the disintegrating shallow rock. The effect on the backfill can be neglected in the present context, while the increase of the permeability of the roof can be of significant importance. In order to moderate the effects of disintegrating tunnel roofs, the upper part of the backfill preferably consists of highly compacted bentonite in the form of blocks or pellets. The matter is further discussed later in the text.

2.3 Longevity

The isolating properties of buffer and ballast depend on changes in mineralogy and physico/chemical properties that result from heating and possible exposure to changes in groundwater composition. Transformation of smectite to hydrous mica by neoformation of the latter mineral is concluded to be a general probably dominant degradation process, while conversion to hydrous mica by passing through an intermediate "mixed-layer" state is also possible (Pusch & Karnland, 1990). Both mechanisms are controlled by the access to potassium and to temperature, and the latter process also requires replacement of lattice aluminum by magnesium or iron. At temperatures below 100° C, as implied by the KBS3 concept, the dense bentonite surrounding canisters will not undergo significant mineral transformation even in a 10^6 year perspective but processes associated with the saturation early after application of the clay blocks may cause some cementation by which the ability of the clay to expand may be reduced.

For tunnel backfills the situation is different and more critical although the temperature will be considerably lower than in the deposition holes. Thus, the low bentonite content will yield a very low "buffering capacity" and if the potassium content in the water is significant, a considerable part of the smectite may be transformed to hydrous mica which will increase the hydraulic conductivity of the backfill by orders of magnitude.

3 ROCK

3.1 Generalized discontinuity model of virgin, undisturbed and unweathered granitic rock

3.1.1 General

Various attempts have been made to integrate most of the commonly observed types of discontinuities into single models but most of them do not include fine rock structures, which actually control the properties of the near-field rock by undergoing changes related to the quickly altered stress field caused by excavation of tunnels and drilling of deposition holes. This chapter refers to a complete model being worked out in conjunction with an ongoing study of the near-field rock of several candidate repository concepts (Pusch & Hökmark, 1991). The model is based on comprehensive mapping, compilation and statistical treatment of structural features of all scales in crystalline rock, primarily from Finnsjön, SFR and Stripa, as well as on theoretical and experimental studies of fracture evolution in crystalline rock. The model, which implies that discontinuities of importance for water and gas flow and large strain can be generalized as orthogonal, "fractal"-like sub-systems, is useful for qualitative and quantitative estimation of hydraulic and rock mechanical behaviour as well as groutablity.

3.1.2 1st order discontinuities

1st order discontinuities correspond to regional fracture zones with a spacing of 1 to a few kilometres, ranging in width from meters to tens of meters. They have an extension of many tens of kilometres and usually form a more or less distorted orthogonal pattern. They contain closely spaced and interconnected breaks, yielding an average hydraulic conductivity of around 10^{-6} m/s. In the descriptive model presented in chapter 4 the spacing of the usually steeply oriented zones is set to 3 km.

3.1.3 2nd order discontinuities

2nd order discontinuities represent local, usually steeply oriented fracture zones that are commonly found with spacings of 100 to several hundred meters. They may extend for several thousand meters and have a width, character and an organization that are similar to those of the 1st order discontinuities. Their hydraulic conductivity is estimated at around 10^{-7} m/s. In the model the spacing is set to 500 m.

3.1.4 3rd order discontinuities

3rd order discontinuities, which serve as major transmissive fracture zones in repositories because of their frequency and conductivity, may extend for several hundred meters in their own plane. They often form an orthogonal-type subsystem conformous to the large-scale structures and usually consist of several discrete, not always interacting breaks. Their width is typically a few decimeters, and their spacing is taken to be 50 m in the model. The average hydraulic conductivity is set at 10^{-8} m/s.

3.1.5 4th order discontinuities

4th order discontinuities represent the hydraulically active members of the basic fracture pattern. Literature offers a huge supply of information concerning these fractures, and although there are different views respecting their spacing and character there seems to be some consensus. Putting together the information from extensive studies of granitic rock, it is concluded that the idea of virtually orthogonal systems of water-bearing fractures applies in principle. It is also concluded that the spacing of the fractures forming these sets is relatively large, i.e. on the order of 2 - 5 m, which is also their persistence. Looking closer at the connectivity of the fractures it seems probable that the average spacing of interacting members of the network in virgin granite is around 5 m, which is therefore applied in the model.

A very important fact is that the water-transmissive fractures in granitic rock do not act as plane parallel slots, but let water pass through channels. Although there are exceptions, many channels seem to be located where fractures intersect and this is taken to be a basic feature of a generalized model of transport paths. Also, a standard geometric measure is ascribed to the channels, namely 100 μm aperture, and a width of 1 cm. Applying this to rock characterized by only 4th order discontinuities one finds that a 25 m^2 section holds only one channel, which yields an average bulk hydraulic conductivity of around 10^{-11} m/s. This applies well to the Stripa rock.

Fig.2 illustrates 4th order fractures with channels applied to a KBS3 deposition hole without considering rock disturbances.

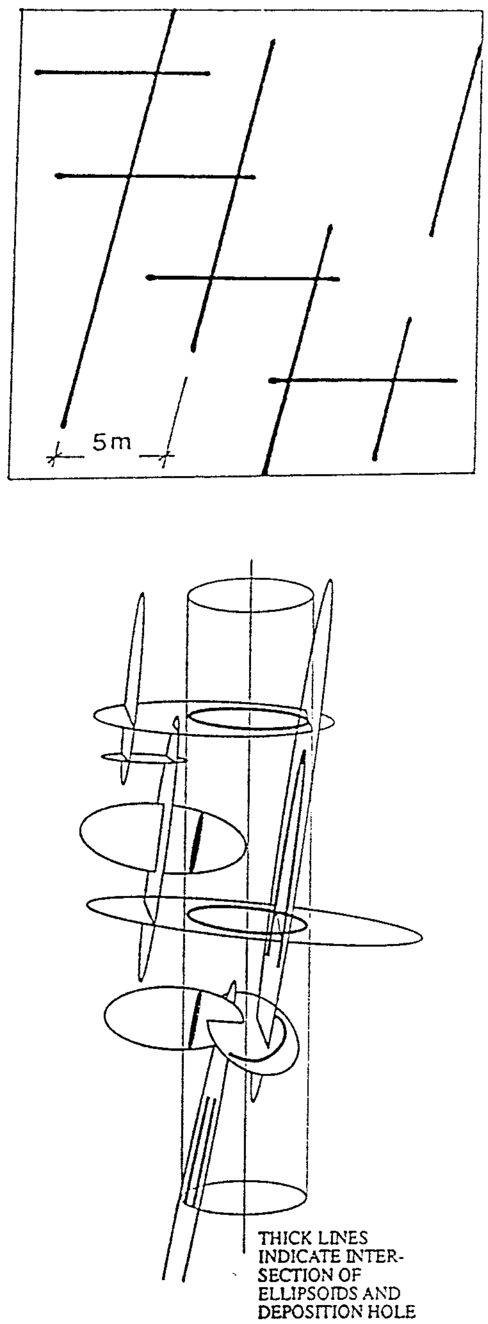

Fig.2 4th order discontinuities. Upper: 2D view of nearly orthogonal fracture system. Lower: Application to KBS3 deposition hole

3.1.6 5th order discontinuities

One can define a substructure of 5th order discontinuities that is largely conformous to the orthogonal-type network of fractures that constitute the 4th order discontinuities.

The 5th order breaks are not hydraulically active in undisturbed virgin granite since they are either not connected to waterbearing structures or closed either by creep or by "mechanico/chemical" processes. The distance between 5th order discontinuities seems to be around 1/10 of that of the 4th order breaks and their spacing is therefore taken as 0.5 m in the model. They are assumed to become hydraulically active by dilatancy or by fissuring of the fracture coatings when the stress situation is sufficiently altered by excavation or exposure to non-uniform heating. Fig.3 illustrates the general character of 5th order discontinuities.

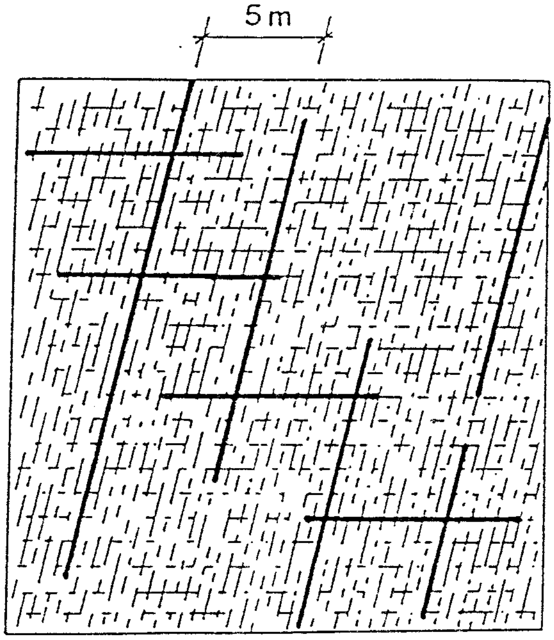

Fig. 3 5th order discontinuities integrated in a 4th order break network

3.1.7 6th order discontinuities

The 6th order discontinuities are naturally occurring fissures representing embryonic fractures grown from Griffith cracks. They are assumed to have been generated by the same stress fields that created the 4th and 5th order discontinuities and are therefore more or less aligned with these fractures in undisturbed rock, while they may be developed in other directions in rock that is overstressed in conjunction with excavation. In undisturbed granitic rock they have the form of plane fissures with a spacing and extension of 0.01 - 0.1 m and an aperture of 1 - 10 μm, yielding an average porosity and hydraulic conductivity of the rock matrix of 0.2 - 0.5 %, and 10^{-12} to 10^{-10} m/s, respectively.

3.1.8 7th order discontinuities

The smallest discontinuities of importance for the hydraulic conductivity of virtually homogeneous rock is concluded to be interconnected voids located at the junction points of several adjacent crystals and having the form of incomplete crystal contacts. They have the form of microscopic "Griffith"-type discontinuities of which the largest ones tend to merge into more or less aligned 6th order discontinuities.

The 7th order discontinuities do not make up for the porosity of the crystal matrix but they control its hydraulic conductivity, which is on the order of 10^{-13} m/s to 10^{-11} m/s. In the model 7th order breaks are assumed to have the form of channels with 0.1 - 1 μm aperture and 100 μm width (Fig.4).

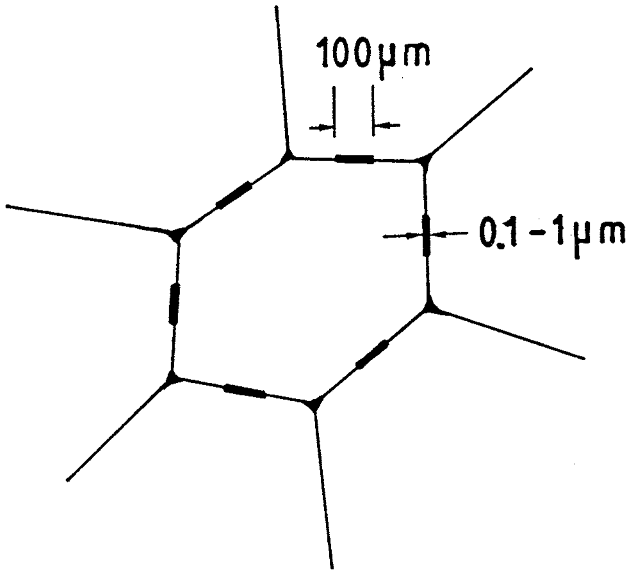

Fig.4 7th order discontinuities of the rock structure model

3.1.9 Summary

Putting together the spectrum of specified discontinuities we arrive at the condensed summary in Table 1.

Table 1. Structural features of virgin, unweathered granitic rock

Feature	Typical Spacing m	Typical Bulk conduct. m/s
1st order	3000	10^{-6}
2nd order	500	10^{-7}
3rd order	50	10^{-8}
4th order	5	10^{-11}
5th order	0.5	0
6th order	0.05	10^{-11}
7th order	Any	10^{-13}

3.2 Structural variations on a large scale

3.2.1 Orientation of discontinuities

3.2.1.1 General

The orientation of tunnels with respect to the strike of major, steep fracture sets is a determinant of the influence of blasting and stress redistribution in the near-field rock. Large-scale variations in orientation of the major sets of fractures are of vital importance since if one aims at orienting a straight deposition tunnel at a certain angle to one of the major fracture sets, which helps to reduce axial flow along it, it is possible only if this set has a constant strike and dip (Pusch & Hökmark, 1991).

3.2.1.2 Strike

Several studies of the strike of major discontinuities in granitic rock have been made by various investigators, the most comprehensive ones being conducted by LBL in the Stripa mine and reported in a number of papers. The granite intrusive at Stripa was found to be characterized by two major sets of 4th and 3rd order (differently termed by LBL) fractures, one striking W to NW (dipping steeply to N or S) and a second one strike N to NE (dipping 50-60° to W), i.e. approximately the same general pattern found in many other parts of Sweden. A third set of more or less flatlying 4th and 5th order breaks is also very common.

In conjunction with the ongoing study of the near-field of several candidate repository concepts, additional detailed investigations in the Stripa mine at 345 to 390 m depth, have demonstrated how the strike may vary over large distances in granitic rock. This study showed a rather systematic large-scale variation in strike, i.e. the data tend to indicate that the two steep sets exhibit an undulating, sinusoidal type pattern that may possibly be related to regional tectonics or variation in major stress fields. Assuming this pattern to be typical of granitic rock and to be repetitive over larger distances it can be generalized as shown in Fig.5, from which one reads that the wavelength is around 500 m, i.e. about the spacing of 2nd order discontinuities.

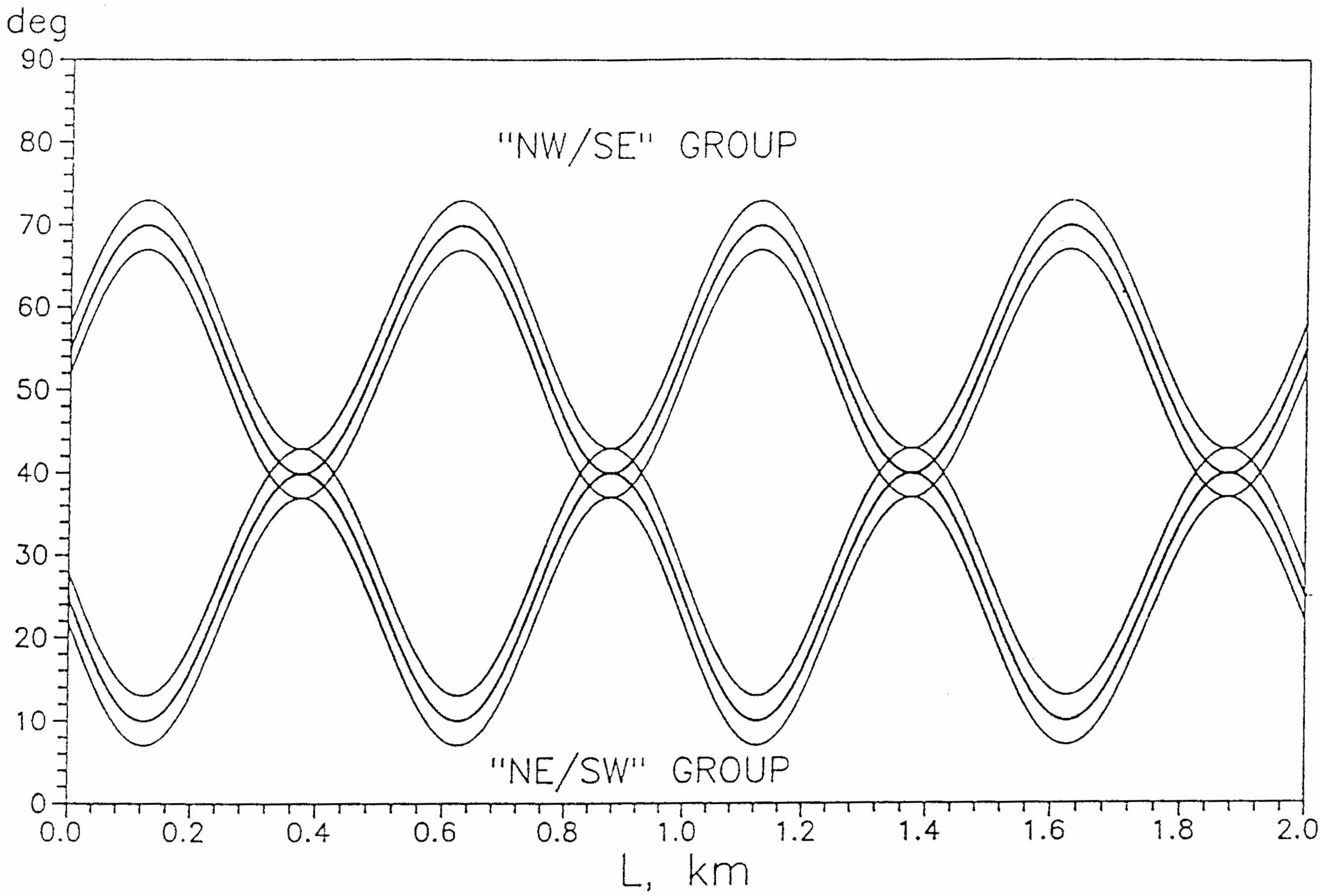

Fig.5 Generalized undulation pattern of major 4th order breaks in Stripa granite. α shows the deviation from the N/S direction

3.2.1.3 Dip

Commonly, the steeply oriented fracture sets of granite have a dip ranging between 70 and 90°. Measurements in Stripa have shown that the dip of such sets varies over large distances, the range being +/- 15° from the average inclination. This range can be assumed to be typical also of flatlying fracture sets.

3.3 Influence of mechanical disturbances on granite rock structure

3.3.1 Introduction

Taking the general model of undisturbed, virgin rock as a basis, due consideration of various disturbing effects yields a near-field rock model that accounts for the influence of excavation and heating. Although it is certainly very schematic it should be useful for the present purpose.

3.3.2 *Influence of excavation on rock structure*

3.3.2.1 *Blasting*

Blasting yields very high gas overpressures of short duration and this breaks up rock by brittle failure. Cracks are formed that extend radially from charged boreholes and prismatic blocks are loosened due to the tensile stresses that are set up by the reflection of the shock wave in the presence of free surfaces. The extension of radially oriented blasting induced fractures can be roughly estimated by assuming that the crack volume is equal to the reduction in volume of the adjacent rock by compression and such calculations yield penetration depths of a few decimeters if careful blasting is employed.

One finds that natural fractures of the III-type in Fig.6 get widened by at least 1 mm, part of the expansion being permanent if the hoop stress is not very high. In the floor, where the charge is higher and the hoop stress lower, a rather large part of the expansion is preserved. Rock debris that enters the latter type of fractures prevents effective closure and grouting of such fractures.

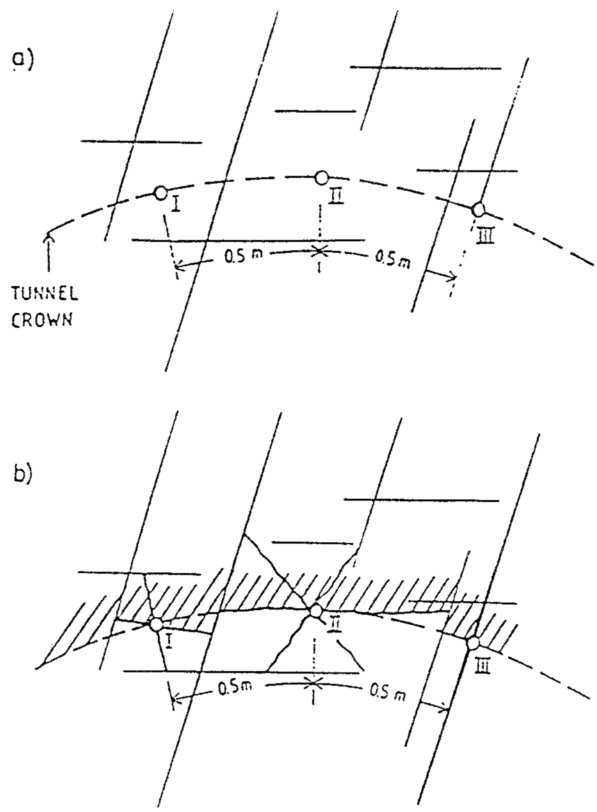

Fig.6 Natural pattern of 4th and 5th order fractures in virgin form (upper), and after blasting (lower)

Radially extending new fractures (I and II in Fig.6) are estimated to get a net hydraulic aperture of a few tens to a few hundreds of microns depending on the magnitude of the hoop stress. The actual shape of the open parts of the fractures is probably archipelago-like with wide channels.

In addition to the radially extending fractures, which actually only extend over part of the boreholes (cf. Fig.7), there is rather rich fracturing at the inner end of the boreholes caused by the higher amount of explosives at this end.

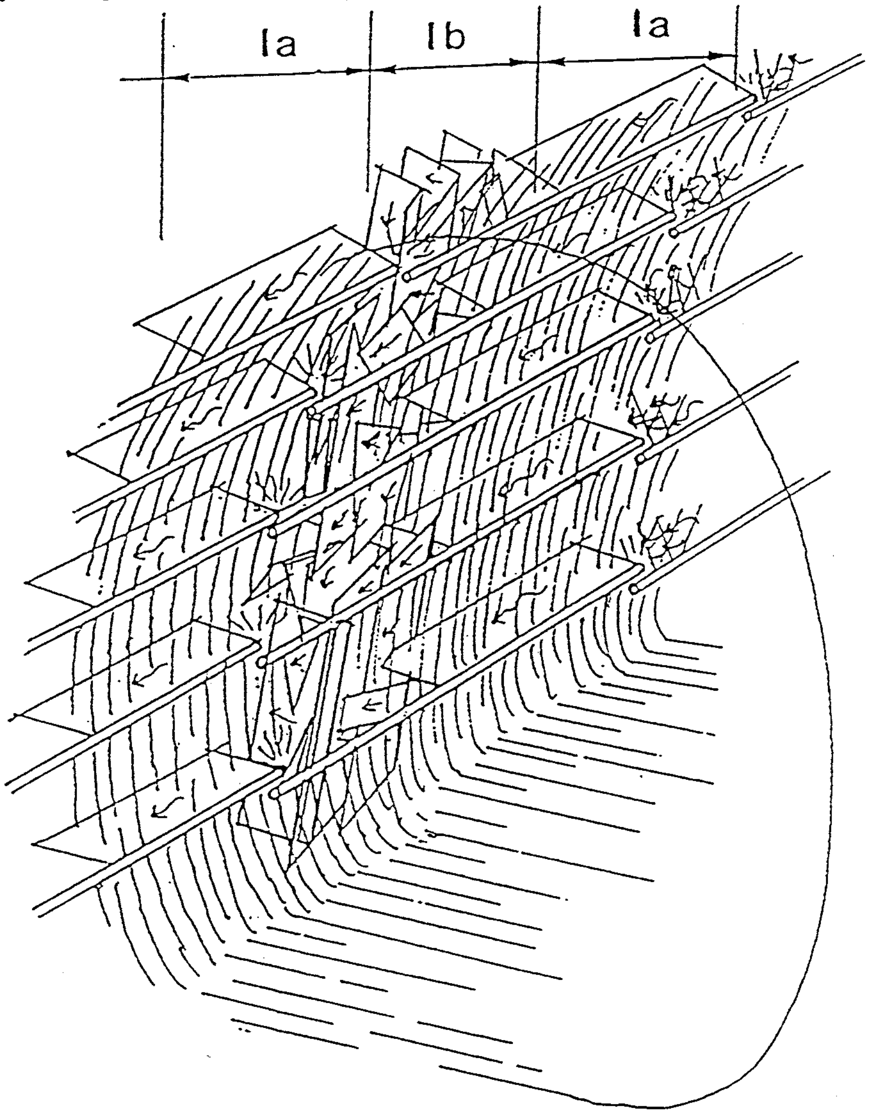

Fig.7 Schematic view of zones of blasting-induced defects. Ia: Zones of regular sets of plane fractures extending radially from blasted holes. Ib: Strongly fractured zone at the tip of the holes

In summary, it is clear that blasting will cause expansion and formation of fractures along a large part of the blasting holes, and that significant fracturing will take place at their tips and this is estimated to increase the axial bulk hydraulic conductivity within at least a few decimeters distance from the periphery of blasted tunnels to 10^{-9} to 10^{-6} m/s. This enhancement may not be effective over long distances, however, since the continuity of the disturbed zone is very much dependent on the natural rock structure as demonstrated later. Still, it can be assumed that the degree of continuity is high in the floor and that the net bulk hydraulic conductivity down to almost 1 meter depth in the central part of the floor is 10^{-8} to 10^{-7} m/s.

3.3.2.2 Stress redistribution

One can distinguish between two major types of stress influence on near-field rock that affect the porosity and thereby its hydraulic conductivity. The major one refers to strain-induced changes in aperture and extension of the hydraulically active part of existing, natural fractures, mainly of the 4th order type, while the other has the form of activation of 5th order, previously hydraulically inactive fractures, as well as of creating new fractures particularly of the 6th order.

Drilling of deposition holes and excavation of tunnels means that surrounding rock tends to move towards the empty space, the movement taking place in the form of rotational and translatory displacement of rock blocks by which the aperture of joints between them are changed (Fig.8). A second effect is that the hoop stress increases considerably, by which the rock close to the periphery becomes exposed to high uniaxial stresses leading to growth of 6th and 7th order discontinuities.

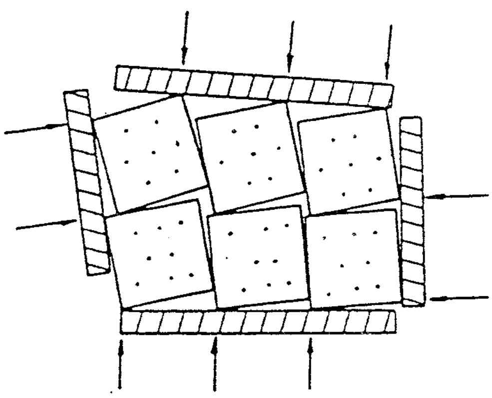

Fig.8 Rock block movement on changing the stress state

In the case of KBS3 repositories, which are not intended to be located much deeper than about 500 m, the primary rock stress conditions are characterized by a major principal stress of 15 to 25 MPa, operating horizontally, and a vertically operating minor principal stress of around 13 MPa. This can be taken as a basis for estimating the distance from tunnel and borehole peripheries within which there is significant influence on fracture apertures and hydraulic conductivity. The outcome of such calculations conducted by use of 2D and 3D codes, checked by backcalculation using experimental data, will be referred to here.

Tunnels

Various numerical analyses based on 2D and checked by 3D stress/strain calculations have been made for calculating changes in axial hydraulic conductivity due to stress redistribution. Applying representative fracture patterns and strength properties of the joints, qualitative and semiquantitative estimates of changes in conductivity have been obtained and they appear to be in reasonable agreement with experimental data. If due attention is paid to actual restraints to block movements as implied by the limited extension and undulation of axially oriented fractures, one finds that changes in aperture are negligible beyond a distance from the tunnel periphery of corresponding to 1 tunnel diameter.

Within 1 m distance from the periphery the net effect of stress redistribution on fracture apertures can be interpreted as an increase in axial conductivity by 2 to 3 orders of magnitude, while the increase is estimated at 1 - 2 orders of magnitude for the rock zone extending from this inner zone to 1 tunnel diameter distance from the periphery. The structural changes generated by stress redistribution can be assumed to have the form of activation of 5th order fractures in the outer disturbed zone. Using the simplified model of transport paths in the form of standardized channels along the lines of intersection of fractures, one finds that the number of channels is increased by 100 times by activation of all 5th order fractures, which would correspond to an increase in hydraulic conductivity of 2 orders of magnitude. The actual disturbance in the outer zone is naturally stronger within the first few meters from the tunnel periphery, and in the innermost zone additional, wider channels are expected to be formed.

The combined effect of dynamic loading by blasting and very high hoop stresses in the moment when the room is created, cause overstressing and formation of a shallow, fissured zone by growth of 6th order discontinuities. It contributes to the increased axial conductivity of the blasting-affected peripheral zone, but its practical importance depends very much on the orientation of the tunnel with respect to the strike of the major steep fracture sets.

In the roof, which is usually more or less aligned with the ubiquitous sets of flatlying fractures, the effect of high hoop stresses may yield a particularly strong increase in axial conductivity in the shallow rock due to rock disintegration by intergrowth and expansion of 6th and 7th order discontinuities. The disturbance depends on the shape of the tunnel and on the rock structure as indicated by the displacement vectors shown in the example given in Fig.9, which illustrates the special case of a flat roof and small radius of curvature of the upper corners. One finds by applying reasonable rock strength values that the roof may deflect by up to 2 mm over the central 2 m part and that the associated movements in the rock mass can extend to about 2 m from the periphery. These figures can be interpreted in the form of widening of 3 natural, flatlying 5th order fractures by 800 μm each, or by the growth and expansion of 20 6th order discontinuities to an aperture of 100 μm. The first example would yield a net hydraulic conductivity of a 2x2 m rock element at the crown of the tunnel of about 10^{-3} m/s, while the same element would have a conductivity of around 10^{-5} m/s in the second example. Similar effects may also appear in the upper parts of the walls.

A more suitable, arched shape of the crown would minimize the risk of instant development of a very conductive roof zone but it is estimated that the high stresses generated in the roof will then cause time-dependent displacements that will cause progressive failure and fall of blocks if the support of the tunnel backfill is not sufficient (Pusch, 1984). Hence, the net effect of stresses in the roof may range from the aforementioned increase in conductivity by 2 orders of magnitude within 1 m distance from the periphery, to a condition with an increase to as much as 10^{-3} m/s. As indicated in Chapter 2.2 an effective support of the roof by highly compacted bentonite in the upper part of the backfill can serve to moderate roof disintegration. Thus, applying bentonite in a form that yields a swelling pressure of a few MPa, time-dependent expansion of fractures resulting from downward movement of the roof can be at least partly prevented. However, fracture expansion that takes place before the backfilling is applied cannot be counteracted even by very high swelling pressures. Minimizing disintegration of the roof and upper parts of the walls can be achieved by selecting a cross section, usually more or less circular, that gives effective arching and minimum radial displacements of the upper part. By this, the averse axial conductivity of the disturbed zone can probably be less than 10^{-5} m/s.

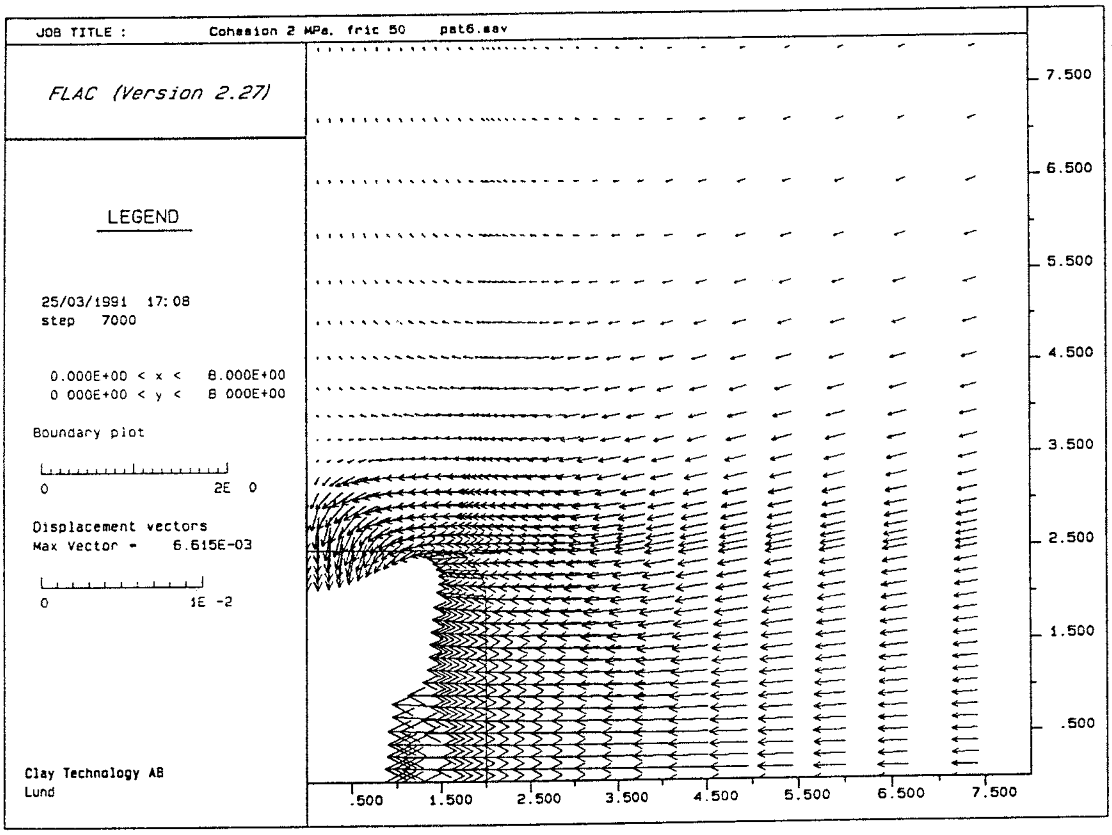

Fig.9 Possible displacement pattern in the upper part of KBS3 tunnels

Deposition holes

There are two sorts of influence on the rock structure around deposition holes: shear and compression or tension of natural fractures, and influence of fragmentation by the drilling.

Using characteristic fracture patterns, 2D analyses of rock movements around drilled holes one concludes that shear displacements along natural fractures will probably not exceed a few hundred microns, meaning that the system will behave almost completely elastically. The apertures of natural fractures of the 4th order type are insignificantly altered and although some 5th order fractures may be activated they will probably not contribute much to the conductivity of the rock mass. However, it is clear that since the radius of influence of the stress redistribution caused by the tunnel excavation reaches down to about half the depth of the deposition holes, their upper half will be located in structurally altered rock with an enhanced conductivity in the axial direction of the tunnels. The influence of the up to 10 MPa high swelling pressure on the walls of the holes has an insignificant influence on the hydraulic conductivity of the surrounding rock.

The hoop stresses will be less than 100 MPa, which means that the rock crystal matrix will stay intact, except for the close vicinity of the hole peripheries, where some microstructural breakdown will take place in the course of the drilling.

The mechanical impact when the drillbits of a rotating cutting-head shear off and break up the crystal matrix is known to cause fissuring by activating 6th and 7th order discontinuities. Assuming that full-face-type drilling is applied, mechanically induced defects are expected to appear within 10 cm distance from the borehole wall, yielding an average hydraulic conductivity of about 10^{-10} m/s. Some more intense microfracturing is expected within the first 2 - 5 cm distance, where the conductivity may be raised to 10^{-9} m/s.

A special effect of stress redistribution is caused when the holes are located so that rock wedges are formed (Fig.10). Since the spacing of 4th order fractures is almost the same as that of the deposition holes it is realized that wedges will appear in a large fraction of the holes in a repository although there is a reasonable chance of minimizing it by proper location of the individual holes. The change in aperture of the fractures forming the boundaries of such wedges can only be roughly estimated by use of numerical methods since their separation from the rock mass yields unstable conditions, but it is likely that the fractures expand to form slots with an aperture of several hundred microns. This means that bentonite clay may enter the slots and help to isolate them and they will also tend to be compressed and partly closed by the swelling pressure exerted by the canister-embedding dense clay.

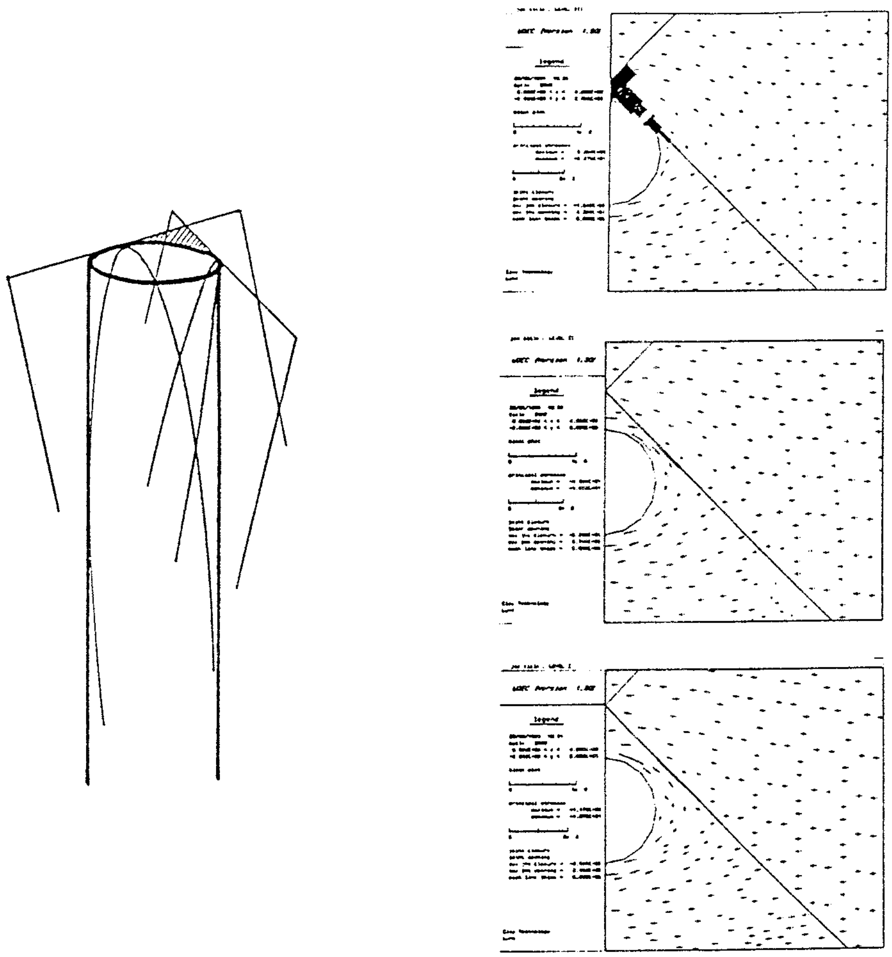

Fig.10 Rock wedge formed adjacent to deposition hole. The graph illustrates fracture widening at the interface of the wedge and the rock mass

3.3.2.3 Thermomechanical effects

Propagation of a heat front from the deposition holes will induce successive expansion of rock blocks by which strain is caused that alters the aperture and extension of hydraulically active fractures and activates previously sealed ones. The influence on fracture apertures can be calculated by use of the aforementioned computer codes and there is also some experimental evidence of the effect of heating on rock structure.

Tunnels

Calculations using the aforementioned 2D computer codes indicate that the displacements in the rock around a KBS3 tunnel may be on the same order of magnitude as those caused by excavation. As a rough estimate one can assume that during the larger part of the heating period, the net effect of thermally induced changes in aperture may be a doubling of the average hydraulic conductivity. The subsequent cooling will generate additional strain that may even further increase the conductivity.

Still, it can be assumed that the net effect of heating and subsequent cooling is taken into consideration by assuming that the net change in average hydraulic conductivity in the axial direction by all sorts of disturbances is increased by two to three orders of magnitude within 1 m distance from the periphery and by one to two orders of magnitude within the distance of the tunnel diameter.

The heating yields significant upward movement of the rock around the upper half of the deposition holes, which suggests that associated activation of 5th order breaks causes an increase also in radial and tangential conductivity in the outer disturbed zone below the tunnel floor. Here, the conductivity can therefore be assumed to be isotropic.

Deposition holes

Using the aforementioned codes for 2D stress/strain analysis it is concluded that heating to a level that corresponds to the basic KBS3 concept, i.e. to a maximum temperature of the walls of the deposition holes of around 80° C, the surrounding rock will not undergo significantly more strain than in the unheated case. The only practically important effect is that the aperture of most fractures will tend to be reduced on heating while they will be reopened to approximately the original shape on subsequent cooling. The heating is concluded to increase the hoop stresses considerably, i.e. by almost 100 % which corresponds to more than 100 MPa, but this is still only about 50 % of the figure that would yield spalling. The swelling pressure of at least a few MPa exerted on the walls by the maturing canister-embedding clay helps to stabilize the rock.

4 Suggested model for water and radionuclide migration paths in the near-field

4.1 General

Putting together the data derived from various sources, a general conservative model of the water and radionuclide transport paths can be formed. It is expressed here in terms of average hydraulic conductivity values for the respective zones for direct use in numerical calculations, and it also has the form of a strongly generalized system of channels in the rock.

A very important factor will be taken into consideration, namely the orientation of the tunnels with respect to the strike of the major NW/SE and NE/SW 3rd and 4th order fracture sets.

4.2 *Main features of the model*

4.2.1 *Basic pattern of 4th, 5th and 6th order discontinuities*

The basic pattern of conductive passages is that of an orthogonal system of cubical symmetry consisting of 4th order fractures with an average spacing of 5 m[1]. Integrated in a "fractal"-type manner in this system is a corresponding network of 5th order fractures with an average spacing of 0.5 m but this subsystem is not active in transferring water in undisturbed granite. In the near-field rock that has undergone sufficient strain by stress redistribution or heating, the 5th order fractures are assumed to have been activated. *In a very generalized model, the transport paths are taken to be channels formed along the lines of intersection of the fractures, which are assumed to have a very long extension in their own plane. Assuming the channels to be of a standard type, i.e. forming crosses of 1 cm wide slots with an aperture of 100 μm, the bulk hydraulic conductivity is approximately the same as that deduced for the various individual rock zones.*

Close to the tunnel periphery, the effect of blasting and high hoop stresses is manifested by a shallow zone of expanded, intergrown 6th order fissures. It is assumed to extend by 0.2 to 0.4 m from the periphery as indicated by the fracture spacing in cores drilled from the periphery.

Figs. 11, 12 and 13 demonstrate the influence of orientation of KBS3 tunnels with respect to the strike of the two steeply oriented fracture sets of the model. The major conclusions that can be drawn with respect to the zone of disturbance are:

1. If the strike of the tunnel axis deviates by more than about 10 - 15° from the strike of one of the steeply oriented fracture sets, there is a low degree of inter connectivity of the blasting-induced zone of disturbance close to the walls

2. The interconnectivity of the blasting-induced zones in the floor and roof is very high independently of the strike of the tunnel axis

3. If the strike of the tunnel axis deviates by more than about 10 - 15° from that of one of the steeply oriented fracture sets, the aperture changes due to stress redistribution are limited and the transport paths very tortuous, thus causing only a moderately increased axial conductivity

Based on all the assumed features of the model, one can identify two typical cases for KBS3 tunnels, one of them being very conservative and the other representing an average, reasonably achievable condition.

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[1] This distance may vary by 50% depending on the origin and stress history of the rock

4.3 *"Standard" reference case*

A sort of standard, normally achievable case is assumed to be one where the tunnel axis deviates by more than 15° from the strike of one of the major, steeply oriented fracture sets. This case implies different properties of both the blasting-disturbed zone and the outer zone affected by stress redistribution and temperature. The first-mentioned one will not comprise a continuous zone of intense fissuring close to the periphery and it is therefore assumed that the average axial conductivity may not exceed 10^{-8} m/s within 1 m distance from the periphery. The axial hydraulic conductivity of the outer zone that extends 1 tunnel diameter from the inner blasting affected zone, is estimated to be only one order of magnitude higher than that of the undisturbed virgin rock, i.e. 10^{-9} m/s for the assumed value 10^{-10} m/s for the undisturbed rock. However, also in this case the roof zone may reach a very high conductivity depending on how effectively the rock is supported from below.

The water and radionuclide paths can be visualized in schematic form also for this case. Thus, in granitic rock with 4th order fractures, the moderate disturbance implied by the "standard" case would correspond to the activation only of every tenth 5th order fracture, i.e. formation of only 10 % of the total number of channels. This would correspond to 1 channel per 2.25 m^2 cross section, instead of 1 per 0.25 m^2 in the "conservative" case, and 1 per 25 m^2 in undisturbed, virgin granite.

4.4 *Conservative case*

The most conservative case corresponds to the 2D plane strain version that has been investigated in most of the computer analyses. In this case, which is illustrated in Fig.11, the tunnel is almost parallel to one of the steeply oriented fracture sets. With some generalization and approximating the tunnel section to be circular, one finds the distribution of the hydraulic conductivity in the axial direction to be the one in Fig.14, provided that the average hydraulic conductivity of the undisturbed, virgin granite is 10^{-10} m/s. Hence, one can expect that except for the roof, where the average hydraulic conductivity can be up to 10^{-3} m/s, the hydraulic conductivity within 1 m from the periphery may be 10^{-7} m/s. Close to the deposition holes, the most shallow 2 - 4 decimeter part of this zone, where strong fissuring is known to take place, may be even more pervious, a probable maximum hydraulic conductivity being 10^{-6} m/s.

The circumscribing disturbed zone, which extends to about 1 diameter distance from the periphery and which is affected by stress redistribution and heating, may have a hydraulic conductivity of 10^{-8} m/s. Fig.14 shows the schematic channel network corresponding to the average axial hydraulic conductivity of the respective zones.

The uppermost 1 meter length of the deposition holes is located in the blasting-disturbed rock zone with an average hydraulic conductivity of $k=10^{-6}$ m/s (Fig.15. From this level and 3.5 m further down, the holes are located in rock affected by stress re- distribution caused by the tunnel excavation and by heating and here the hydraulic conductivity is around 10^{-8} m/s. In the lowest 3 m part of the holes the rock is practically undisturbed and maintains its original, virgin hydraulic conductivity, i.e.

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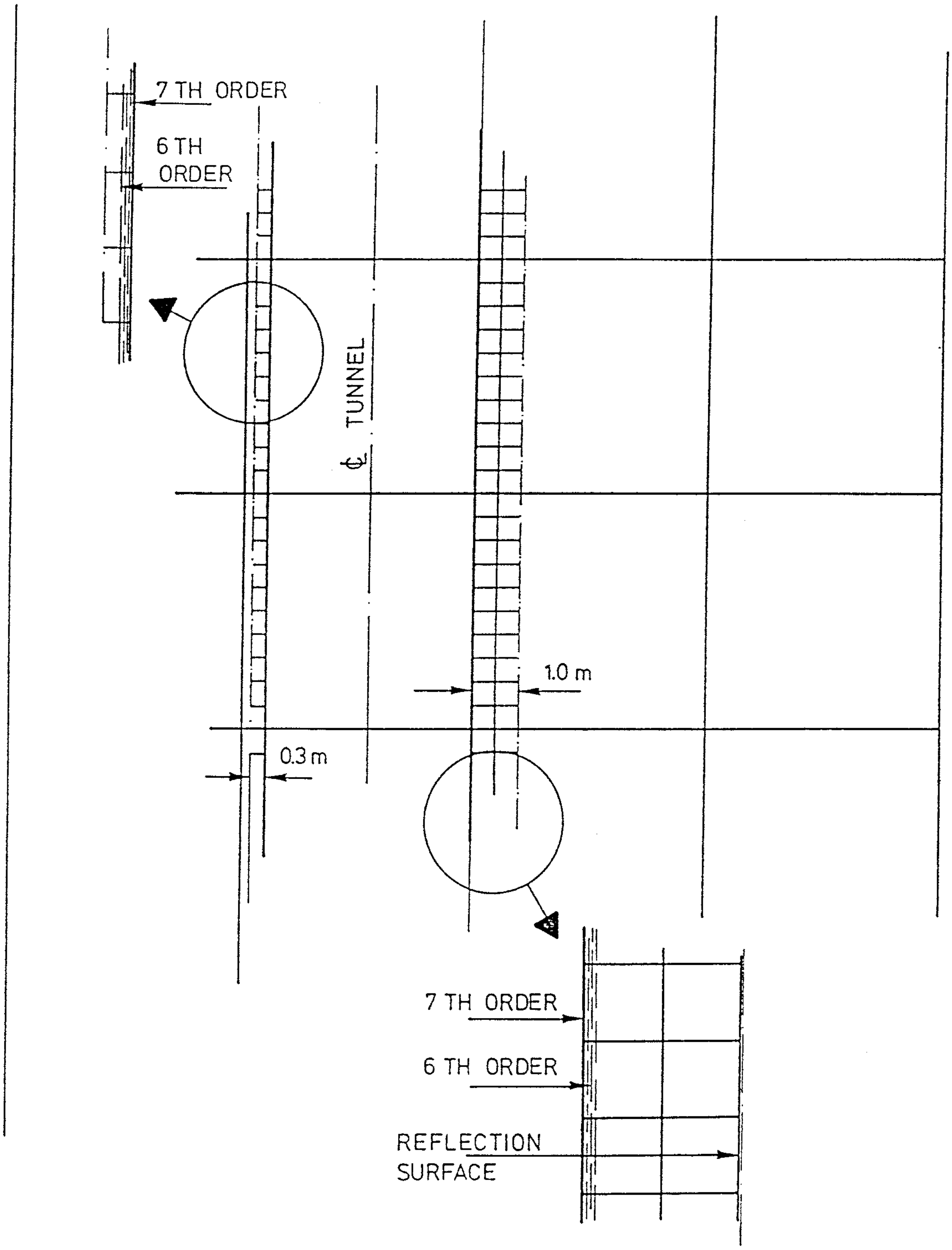

Fig.11 Schematic picture of KBS3 tunnel with its axis parallel to the strike of one major steep fracture set

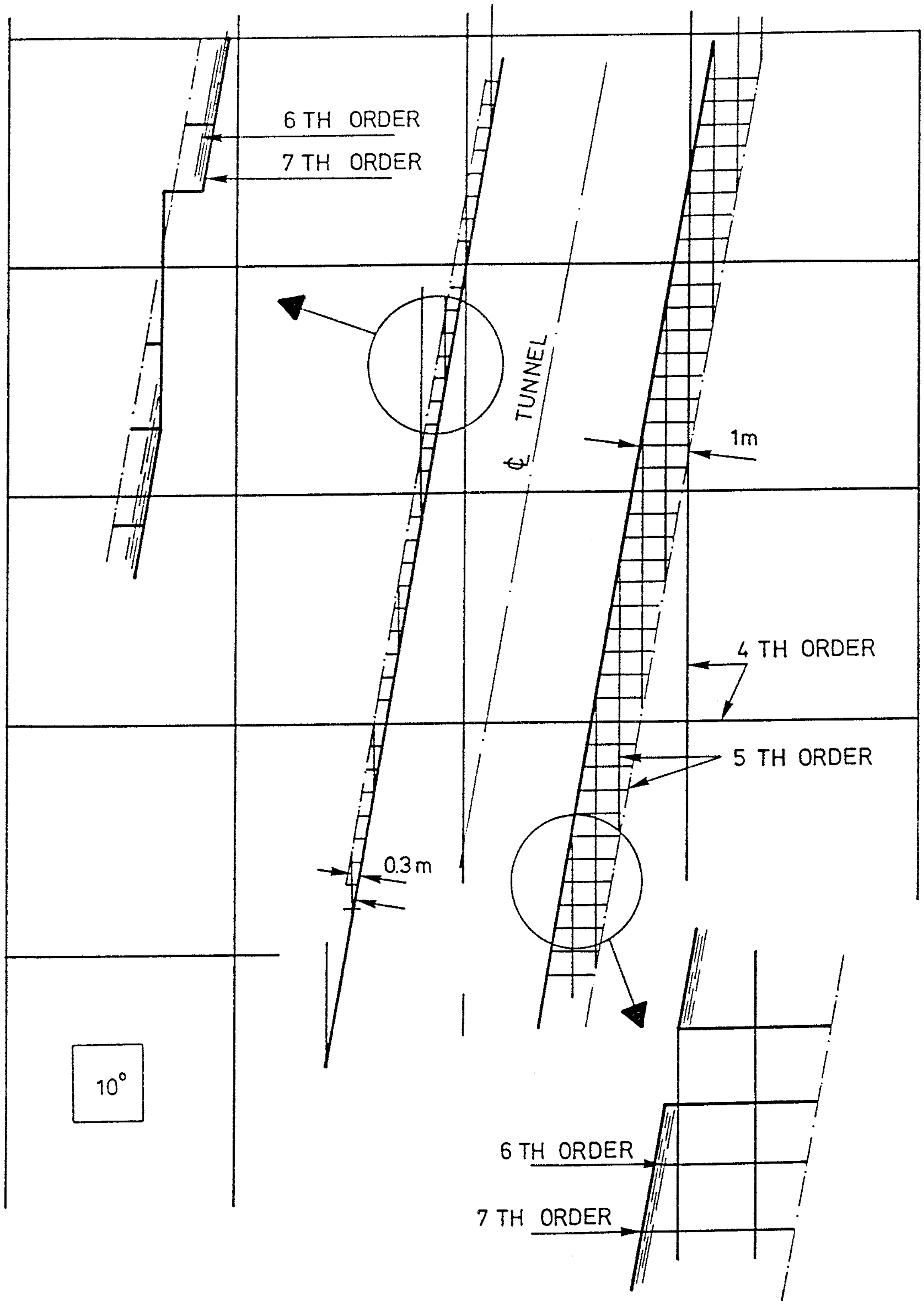

Fig.12 Schematic picture of KBS3 tunnel with its axis deviating 10° from the strike of one major steep fracture set

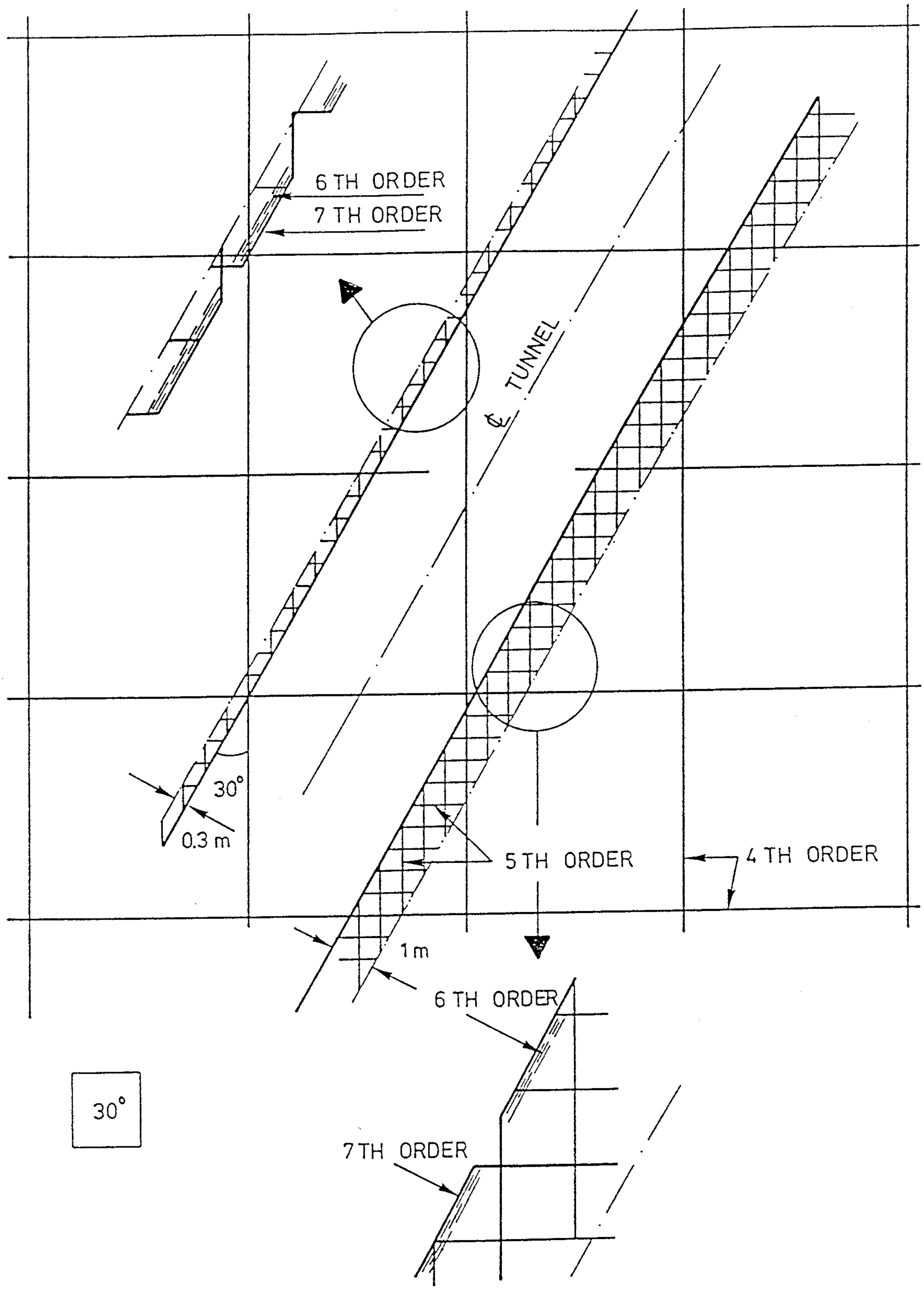

Fig.13 Schematic picture of KBS3 tunnel with its axis deviating 30° from the strike of one major steep fracture set

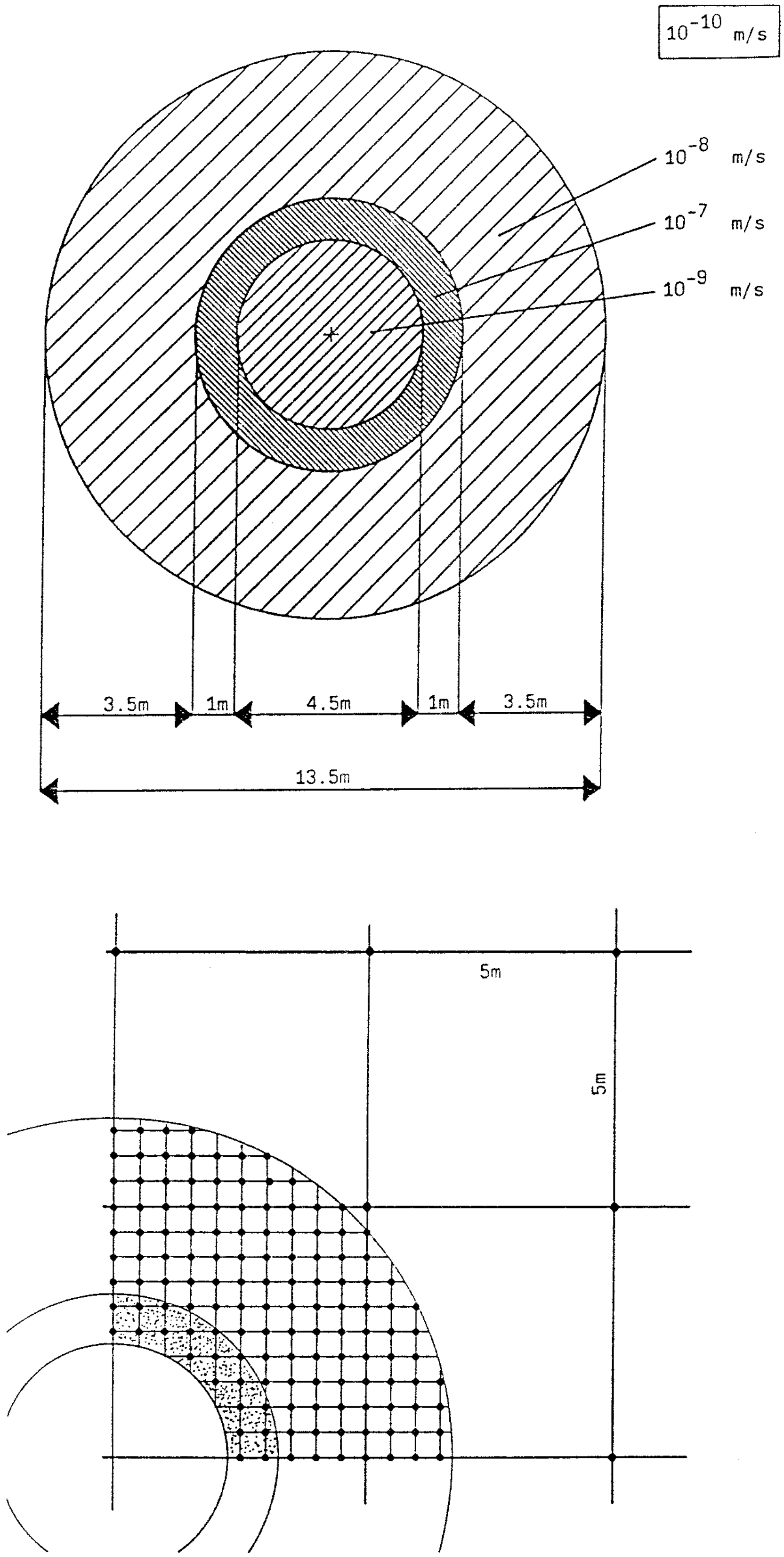

Fig.14 Cross section of KBS3 tunnel, "conservative" case

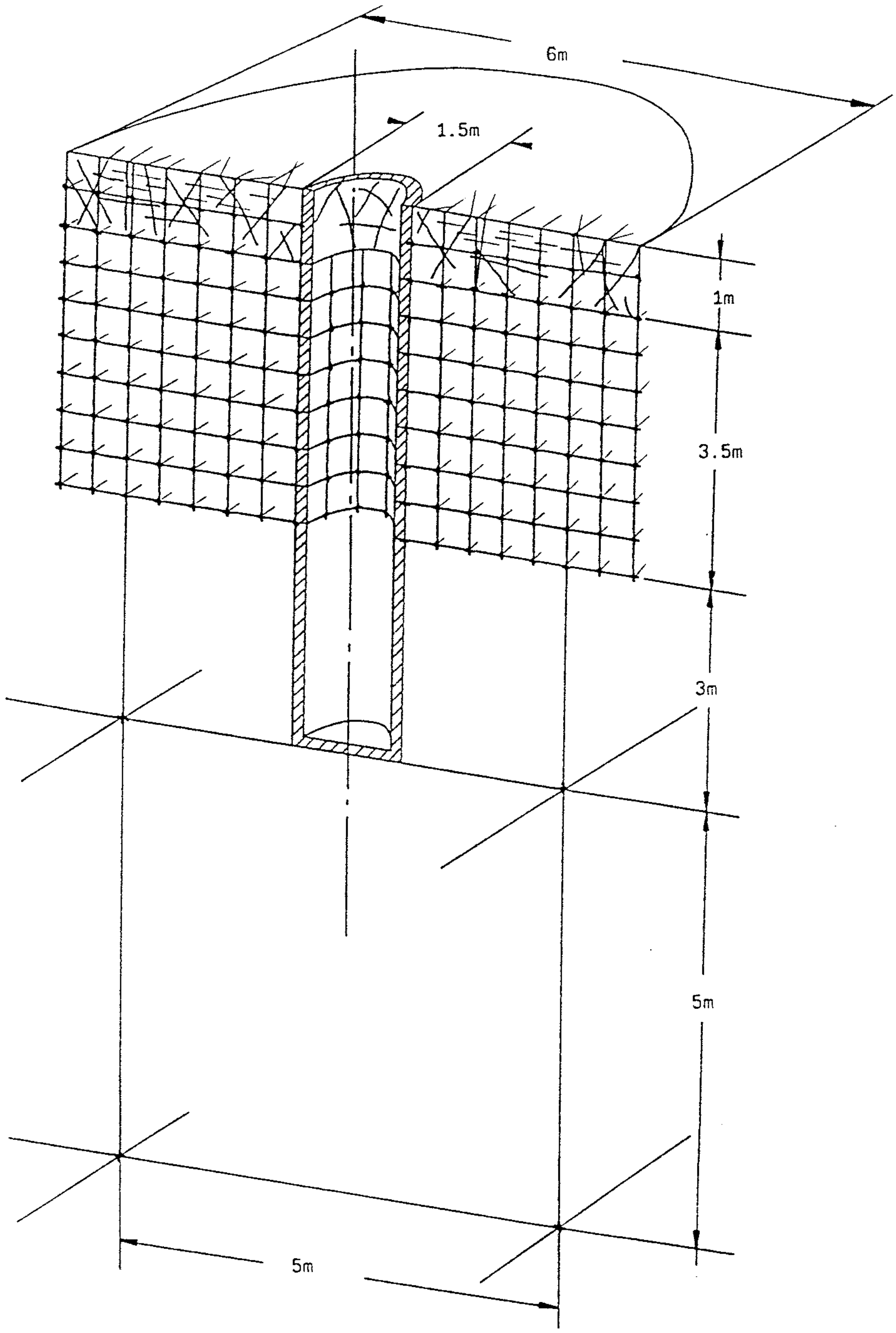

Fig.15 Deposition hole in the "conservative" case. The hole is surrounded by disturbed rock with the conductivity $k=10^{-6}$ m/s to 1 m depth, under which the stress and heat affected rock has $k=10^{-8}$ m/s due to activated 5th order breaks. Lower down the rock has $k=10^{-10}$ m/s except for the shallow 10^{-9} m/s skin zone (hatched)

4.5 *Aspects on the applicability of the models*

The choice of the hydraulic conductivity 10^{-10} m/s of the virgin, undisturbed granite is not critical to the use of the model. Thus, assuming this figure to be 10^{-9} m/s, which is in fact an unusually high figure, the "conservative" and "standard" cases would yield 10^{-7} m/s and 10^{-8} m/s, respectively, for the axial conductivity of the outer disturbed zone, while the figure 10^{-11} m/s for undisturbed rock would yield the figures 10^{-9} and 10^{-10} m/s, which is more or less what one finds for the Stripa granite.

A matter of practical importance is the natural undulation of the strike of the fracture sets discussed earlier in the chapter. Using the diagram in Fig.5, which is based on actual measurements in the Stripa mine, one finds that deviation of the main tunnel strike from the ideal N/S direction by less than about 7° means that no part of a several hundred meter long tunnel will yield the "conservative" case, i.e. when the tunnel walls become parallel to the strike of one major steep fracture set. If the deviation is +/15° from the N/S direction about 35 % of the tunnel length will correspond to the "conservative" case, while the percentage drops to 15 to 20 when the deviation is in the range of +/- 20 - 40° from the N/S direction.

4.6 *SKB 91 Reference description of tunnels and deposition holes*

Based on the model presented earlier in this chapter a reference description of the near-field environment to be used in the SKB 91 analysis is chosen.

Tunnels

* The repository will not be intersected by any 1st order fracture zones.
* The tunnel orientation will be according to the "Standard" reference case in chapter 4.4 i.e. the orientation will be > 15° from the principle fracture orientation of 4th - 6th order fractures.
* The blast damaged zone will extend 1 m radially out from the tunnel periphery a has a hydraulic conductivity two orders of magnitude higher than the undisturbed rock. The outer stress-redistributed zone will stretch one tunnel diameter out from the periphery, with an increased axial hydraulic conductivity of one order of magnitude.
* The cross-section of the upper part of the tunnel will be given effective arching and a minimum of radial displacement to avoid distubances of the tunnel roof and the effect of a cave-in in the tunnel roof will therefore be treated as a variation.

Deposition holes

* All deposition holes will be intersected by at least one (1-3) 4th order natural fracture.
* A number of opened 5th order fractures will intersect all deposition holes.
* The deposition holes will be drilled with TBM-technique, which gives a disturbed zone around the hole that stretches 3 cm out from the periphery and

has a hydraulic conductivity one order of magnitude higher than the surrounding intact rock.

* In 20% of the holes, "wedges" will be formed from stress relief. The opened fracture have an aperture of 500 μm. The fracture is a "short-cut" from the deposition hole wall to the disturbed zone under the tunnel.

5 IMPLICATIONS FOR TRANSPORT MODELLING

5.1 General

In section 3 and 4 a conceptual model of fractures and channels in rock has been described. The channels which form the conductive paths in the rock have a very wide range of transmissivities. Typically they span a range of many orders of magnitude (Moreno and Neretnieks 1991) and form an irregular stochastic network. The network in the undisturbed rock is modified by the excavation and by presence of the drift. The very sparse network in undisturbed rock becomes less sparse near the drift. It has been estimated that a repository hole, if located in undisturbed rock, would only have a small chance to be intersected by a water conducting channel. In the region of rock nearest to the drift the repository hole would be intersected by several channels. The fractures opened by the blast damages may even be so frequent that this region is best described by a porous medium from the flow and transport point of view. This is the approach taken in the near field model developed by Romero et al (1991).

Transport of nuclides may take place by advective flow as well as by molecular diffusion. In regions where the hydraulic conductivity is low, eg in the compacted bentonite in the deposition hole and in the rock matrix, the transport may be faster by molecular diffusion than by flow. There are many potential pathways through which the nuclides may migrate from a damaged canister to mobile water which may reach the biosphere. Figure 5.1 summarizes the main paths. The nuclide released through a hole "A" in the canister wall will spread out by diffusion through the bentonite. One path leads to fractures (channels) in the undisturbed rock "B". This path is connected to the channel network in the rock. It may thus be connected to the disturbed zone around the drift as illustrated in the figure. The nuclide may also move by molecular diffusion (transport by flow is negligible) upward through the bentonite and the thin disturbed zone of the deposition hole and come into contact with the mobile water in the disturbed zone "Q2". Some of the nuclide may move into the backfill in the drift where it spreads out by diffusion and to some extent by flow. Fractures with flowing water intersecting the drift will pick up some of the nuclide as illustrated by "Q3". Water in fracture zones near the deposition hole may also get some nuclide by molecular diffusion through the rock matrix "Q4".

The relative importance of the different pathways can be very different depending on the location of the channels, the flowrates in the channels and in the disturbed zone etc. Once a specific case is defined, however, the release rates can be obtained in a rather straightforward manner by the near field model (Romero et al 1991)

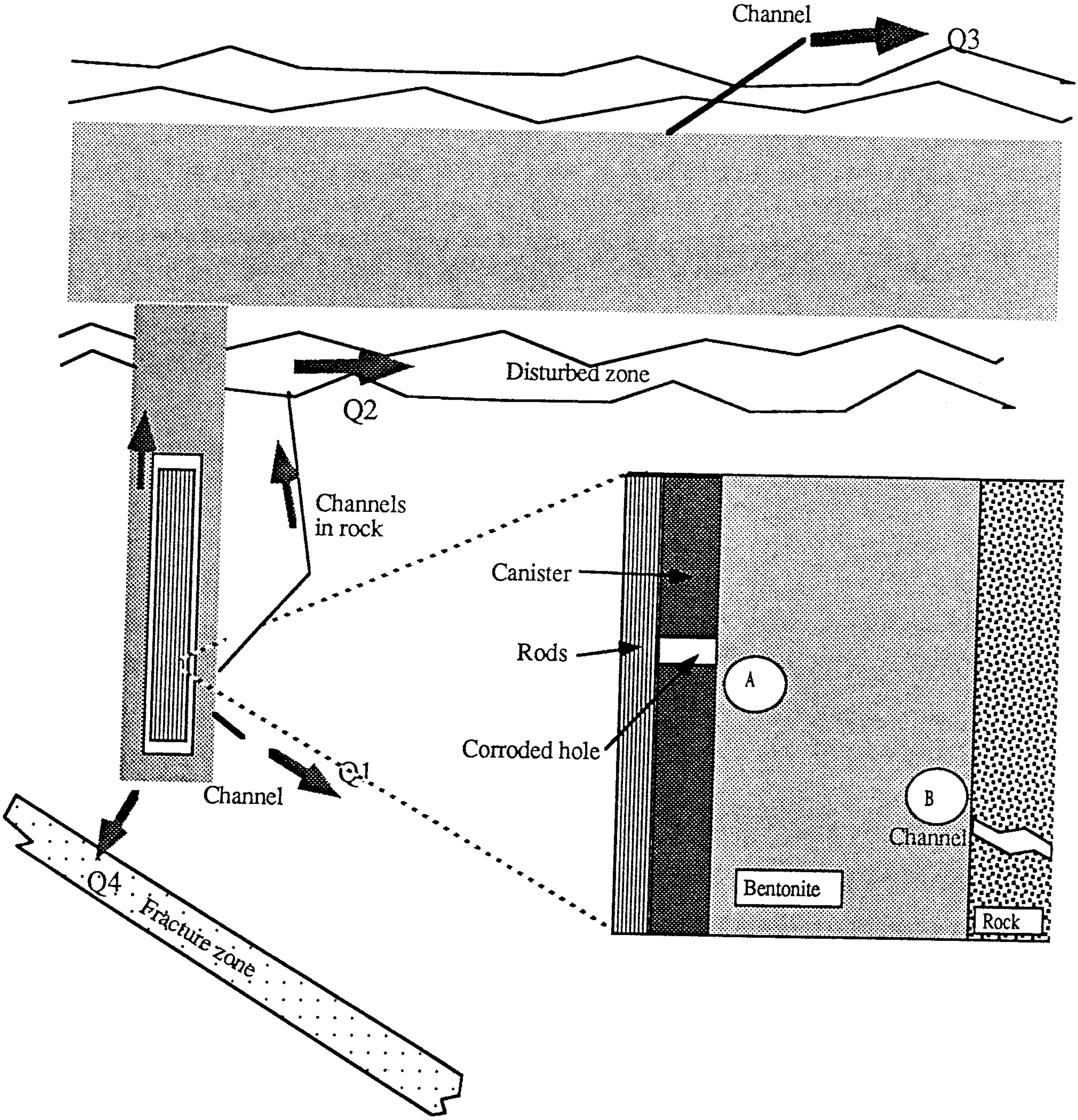

Figure 5.1 Main pathways for nuclide transport around a deposition hole

5.2 Channelling effects

The network of channels is sparse and only a few channels would be intersected by channels carrying water with significant flowrates. It has been estimated that typically only one canister in 10 will have contact with such channels (Moreno and Neretnieks 1991) For the majority of the canisters the other pathways leading to the disturbed zone may be more important for the release. Because of the extent of the disturbed zone this will most probably be well connected to the channel network in the undisturbed rock. Pathways "Q2" and "Q3" may then become the important paths at least for the nonsorbing and weakly sorbing nuclides. The strongly sorbing nuclides will be considerably retarded due to sorption in the bentonite and in the backfill in the tunnel.

5.3 Disturbed zone around tunnels

The disturbed zone around the drift will have a much higher conductivity then the intact rock and may form one of the main paths for nuclide transport as discussed above. The flowrate in this region will be large and will go mainly along the drift. The drift will intersect fractures zones which will supply the water and which will lead it off. The fracture zones will be potential paths to the biosphere.

This section sets out to estimate the flowrate under certain idealized conditions which are chosen in such a way that the results can be generalized. Also it is attempted to assess which factors and mechanisms are important in determining the flowrate.

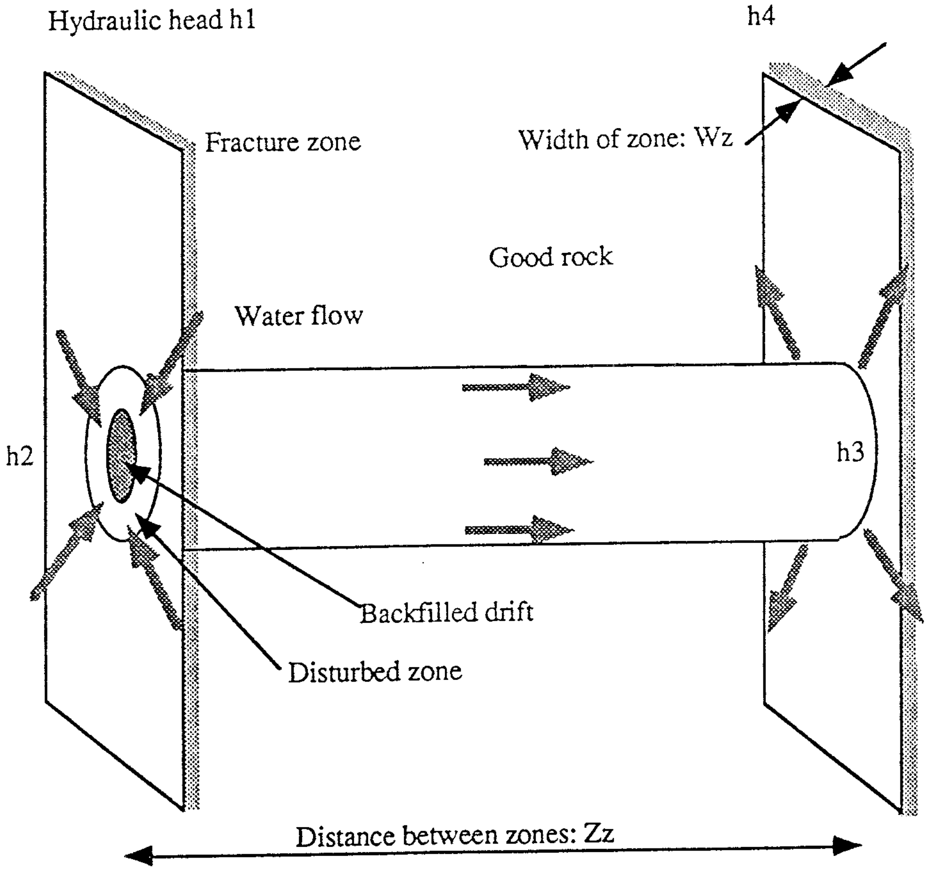

Figure 5.2 Drift intersected by two zones of 2nd order.

Referring to the previous description of the rock and its fracture systems the following generalized concept can be formed of the hydraulic system influencing the flow around a tunnel. Figure 5.2 shows how the drift intersected by fracture zones may look. The drift is modelled with a circular cross section. The fracture zones have a much higher hydraulic conductivity than the "good" rock as has the disturbed zone around the drift. In a simplified system as depicted in Figure 5.2, water will flow radially in the zone towards the intersection with the drift. along the drift and radially out into the next zone with a lower hydraulic head. The flowrate along the drift will be determined by the relative resistances in the zones and the drift and by the hydraulic heads.

Figure 5.3 shows a cross section of the drift and also indicates which hydraulic conductivities are expected. These rather idealized conditions will be used in the sample calculations below.

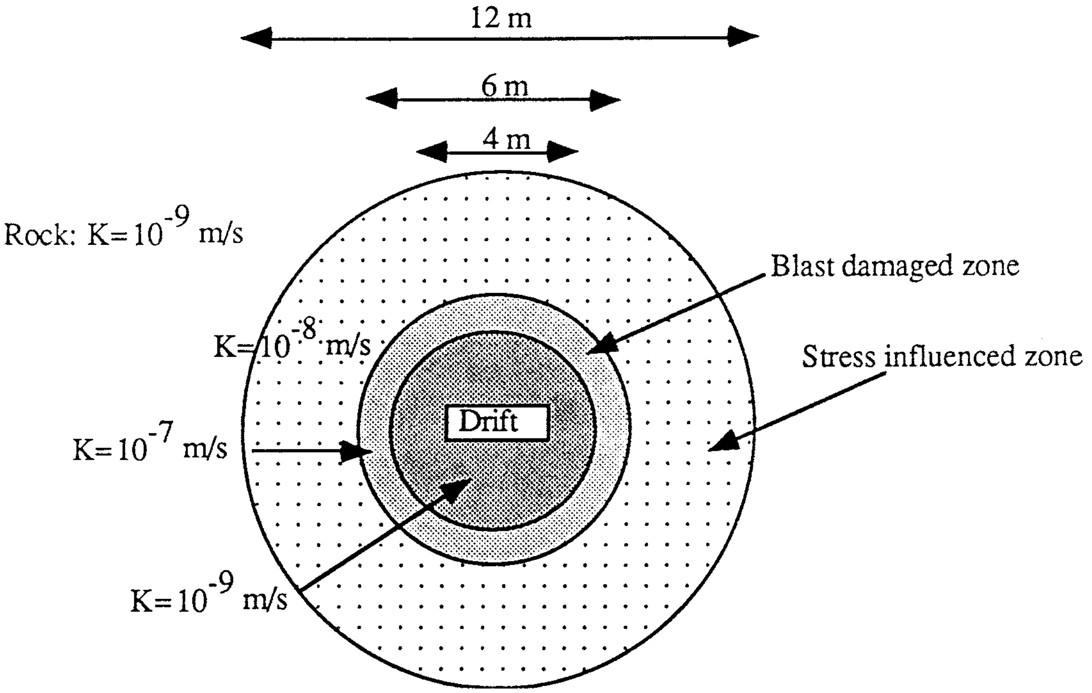

Figure 5.3 Cross section of the drift and the altered zones around it used in the sample calculations.

If the head, h_1, in the zone at a point far away and at the intersection with the drift, h_2, is known then the flowrate Q can be obtained from Darcy's law for radial flow if we assume that the zone behaves like a homogeneous porous medium. The expression is

$$Q=K_z\frac{2\pi W_z(h_1-h_2)}{\ln(r_1/r_2)} \qquad (1)$$

r_2 is the radius of the disturbed zone where the head is h_2 and r_1 is the radial distance to a point in the zone where the hydraulic head is h_1. It is assumed that the "good" rock is impervious and that there are no other drifts nearby which act as sinks or sources.

The flow along the drift in the disturbed zone is obtained from the linear flow expression

$$Q=K_{dz}A_{dz}\frac{(h_2-h_3)}{Z_z} \quad (2)$$

For the outflow into the other zone Equation (1) is used with the appropriate radii and hydraulic heads.

$$Q=K_z\frac{2\pi W_z(h_3-h_4)}{\ln(r_4/r_3)} \quad (3)$$

As a first illustration assume that the regional gradient is 0.003 m/m in the direction of the drift, that the distance between the fracture zones of 2nd order is 500 m and the flow resistances along the drift and in the outflow zone are negligible. Then the hydraulic head h_4 is equal to h_2. As the regional gradient is 0.003 and the distance between the zones is 500 m the head difference h_1-h_4=h_1-h_2 is $0.003 \cdot 500 = 1.5$ m. The hydraulic conductivity $K_z=10^{-7}$ m/s for a zone of 2nd order. The zone of this order has a width W_z=2 m. The radius r_2= 3 m and the radius r_1 is taken to be 300 m. This is an arbitrary choice of distance but makes little impact on the results because the ratio of the radii enter the expression in the logarithm. Equation 1 gives the flowrate Q= $4 \cdot 10^{-7}$ m^3/s or 13 m^3/year.

It may be argued that zones of 2nd order will be detected and that grouting may be made both in the fracture zone and in the disturbed zone near the fractured zone. If this is successful then the zones of 3rd order may become important in supplying the drift with water. Zones of 3rd order are found at a distance of 50 m. Their hydraulic conductivity is $K_z=10^{-8}$ m/s and their width W_z=0.2 m. Equation (1) gives a flowrate Q =0.13 m^3/year for every zone of 3rd order which the drift intersects. These figures are additive if the resistance along the drift is negligible. Figure 3 illustrates how the first half of the intersecting zones feed the drift and the second half act as outflow zones. For a drift 1000 m long there would be 20 zones and the flowrate at the middle of the drift where it is largest will be Q =1.3 m^3/year. This would be the flowrate along the drift if the zone around it had a very high conductivity and the zones of 2nd order were successfully grouted.

If it is instead assumed that all the head loss takes place along the drift then Equation (2) is used with h_2-h_3 =1.5 m. With a hydraulic conductivity K_{dz}=1·10-7 m/s and a cross section of the disturbed zone of $\Pi(3^2-2^2)$ m^2 the flowrate is obtained from Equation (2) to be Q = $4.8 \cdot 10^{-9}$ m^3/s or 0.16 m^3/year. Obviously the resistance in the zone around the drift is the largest and the resistance in the fracture zones has little influence on the flowrate in this example. In addition to the flow in the blast damaged zone there will be flow in the stress influenced zone. This can be assessed in the same way as was done above. Because we assume that the resistance to flow in this case is along the drift the heads h_2 and h_3 are known. The area is $\Pi(6^2-3^2)$ = 85 m^2 and with a hydraulic conductivity of 10^{-8} m/s the flowrate Q = $2.6 \cdot 10^{-9}$ m^3/s or 0.080 m^3/year.

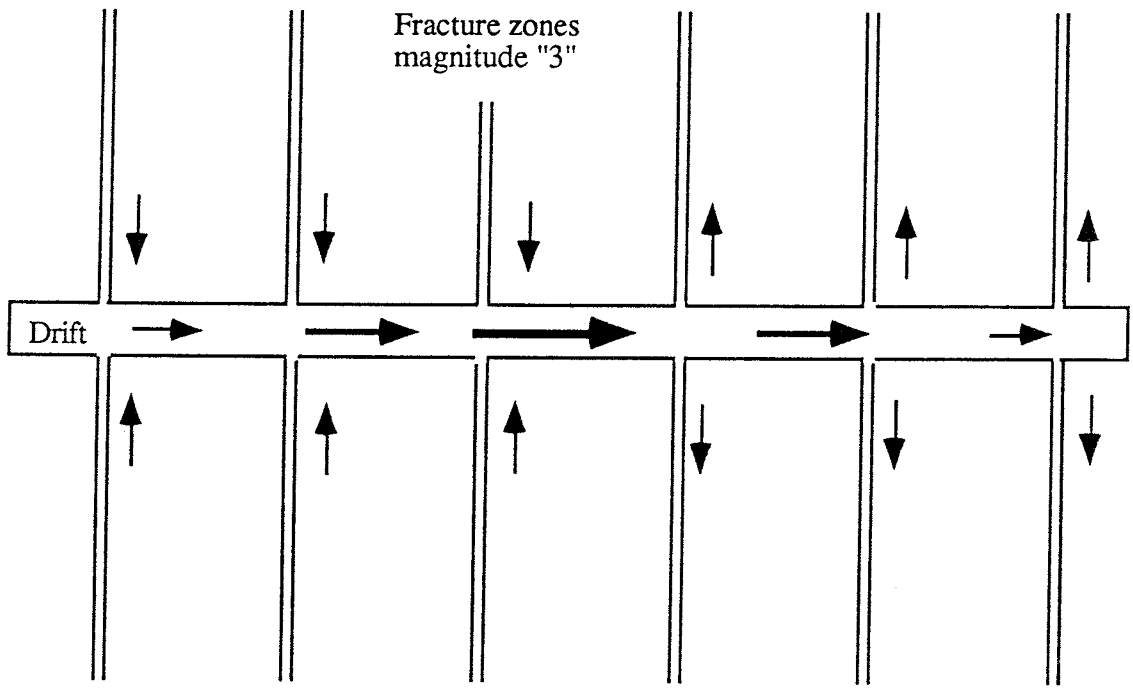

Figure 5.4 A set of fracture zones of 3rd order intersect the drift.

The flowrate will distribute itself between the blast damaged zone and the stress influenced zone proportionally to the hydraulic transmissivity T=A·K in these regions. From Figure 5.3 it is found that the blast damaged zone has a cross section area of 16 m^2 and the stress influenced zone has an area of 85 m^3. As the hydraulic conductivity is 10 times larger in the blast damaged zone the flowrate will divide itself in 2/3 rds in the blast damaged zone and 1/3 rd in the stress influenced zone. Table 1 shows the flowrates in the various zones

Table 1 Flowrates and fluxes in the blast damaged and stress influenced zones.

	Flowrate m^3/year		Flux $m^3/m^2 \cdot$year	
	Blast zone	Stress zone	Blast zone	Stress zone
Zone "2" case[1]	4.7	2.3	0.29	0.027
Zone "3" case[2]	0.87	0.43	0.054	0.0051
Zone along drift[3] limits flow	0.16	0.08	0.010	0.00094

[1]High conductivity along drift
[2]Zone "2" grouted and high conductivity along drift
[3]Conductivity in zones along drift as in example in text above

5.4 *Disturbed zone around deposition holes*

In section 3.3 the disturbed zone around the deposition holes has been estimated to have a thickness of 2-5 cm with a conductivity of 10^{-9} m^3/s. The disturbed zone may form a pathway for upward movement of water. The cross section for flow in the vertical direction in this region is 0.23 m^2 if the higher value, 5 cm, is assumed for the thickness. The vertical flowrate for a gradient of 0.003 is $6.9 \cdot 10^{-13}$ m^3/s or 0.02 l/a. This is about one order of magnitude less than the equivalent flowrates due to other pathways (Nilson et al 1991).

5.5 *Effects of cave-in*

If the tunnel is not backfilled to withstand the collapse of the rock above the roof then the hydraulic conductivity will increase very much and the water will flow in the collapsed region above the drift. The caved in zone is estimated to be a few m^2 in cross section. This is illustrated in Figure 5.5. The flow along the drift in the region below the drift will be very small. For a hydraulic conductivity of $K=10^{-3}$ m/s in the roof region the water will divide itself by about 1 part in the lower region and 10 000 parts in the roof region. The canisters will be located in a region with very low flux along the drift. The flow component in the direction along the drift may thus be expected to be small. It is likely that the direction of the hydraulic gradient near the drift also has a vertical component. If this is directed upward then the flow in the channels which intersect the repository hole may lead contaminated water to the caved in zone. If on the other hand the repository is located in an inflow region the vertical component will be directed downward and the contaminated water will not move into the high conductivity zone around the tunnel.

The disturbed zone of a few cm width and a hydraulic conductivity of $K=10^{-9}$ m/s around the deposition hole will have no additional impact on the transport of nuclides. Nor will a wedge in the upper part of the hole change the transport rates significantly because the water flowrates will not be influenced significantly in comparison to those discussed above. Nor will new significant diffusion paths be generated.

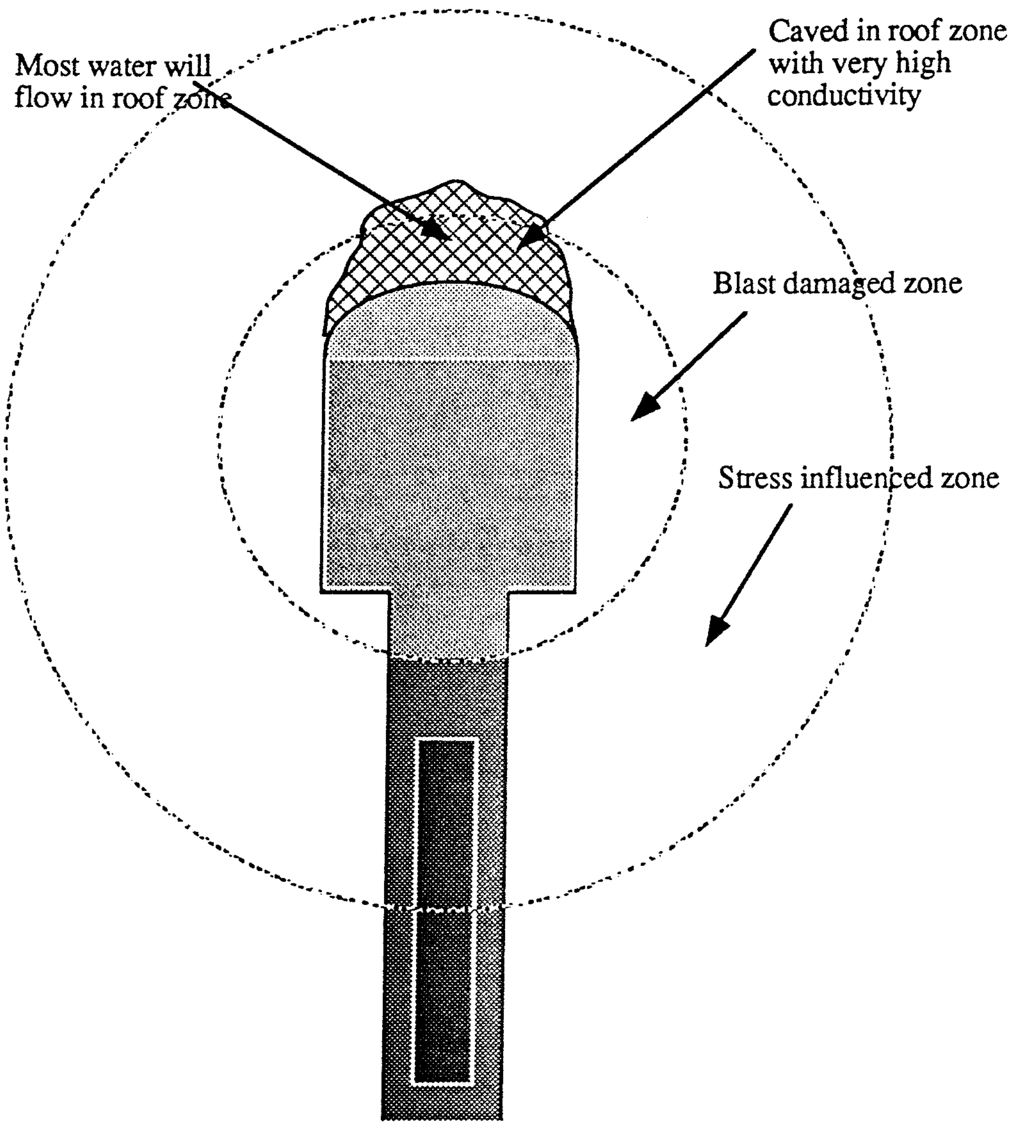

Figure 5.5 Cross section of the drift with a repository hole, the blast damaged zone, the stress influenced zone and the roof zone.

It may be concluded that a collapse of the roof zone may be very beneficial because it will divert the flow to the region above the drift and the top part of the deposition holes will have a much smaller flowrate around them. The flux around the canister may be expected to be significantly lower than the values shown in the first two rows of Table 1. If this cannot be ensured then the conductivity of the zones will be the limiting factors and the flow rate may be expected to be as shown in the lower row of Table 1.

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