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**Radionuclide Transport Paths  
in the Nearfield – A KBS-3  
Concept Study**

Roland Pusch

Clay Technology AB and Lund University of Technology

July 1990

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RADIONUCLIDE TRANSPORT PATHS IN THE NEARFIELD -  
A KBS3 CONCEPT STUDY

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Clay Technology AB and Lund University of Technology

July 1990

This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the author(s) and do not necessarily coincide with those of the client.

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# **Radionuclide Transport Paths in the Nearfield - A KBS3 Concept Study**

**Lund 1990-07-20**

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and  
Lund University of Technology**

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## SUMMARY

The general scope of the study has been to identify and define major paths for radionuclide transport from KBS3 canisters, focussing on the nearfield rock.

A primary purpose was to document the hydraulic properties of the "disturbed zones" around blasted tunnels and it is concluded from compilation of theoretical data and field experiment recordings that stress relief and blasting effects combine to form a pervious zone that extends to about 1 m from the tunnel periphery. It has an average, isotropic hydraulic conductivity of no less than  $10^{-8}$  m/s.

A second major purpose of the study was to generalize the structure of granitic rock with respect to water-bearing fractures. Forsmark, Finnsjön, and Stripa data have been considered and found to support the idea of rather regular "orthogonal" fracture systems with relatively large spacings. The hydraulically active part of the fractures, which can be characterized by simple statistical distributions of persistence, spacing, and aperture, is formed by channels, which can be taken as plane, straight stripes with constant width and aperture. The width can be assumed on the basis of field observations while the aperture is estimated from the bulk conductivity and the geometry of the fracture network.

The major transport paths of the rock have been concretized and combined to form a general simplified model intended for calculation of radionuclide transport through water flow and through diffusion through continuous water passages. This model comprises of a circumscribing pervious zone of "wall disturbance" around the deposition holes in addition to the fracture channels.

## SCOPE OF STUDY

Quantitative determination of the rate and capacity of radionuclide migration through water flow and diffusion from HLW canisters requires geometrical and hydraulic modelling of the migration paths, which is the scope of the present study.

According to the KBS3 concept, deposition holes with a length of about 8 m and a diameter of 1.5 m will be drilled from the floor of tunnels excavated by blasting at 500 m depth or more. Blasting and stress relief create a disturbed zone with an increased hydraulic conductivity in the axial direction of the tunnels and this sets one condition for the hydraulic modelling, namely that a circumscribing zone of limited radial extension can be considered as a porous medium with an (isotropic) hydraulic conductivity that is significantly higher than that of the virgin rock. These effects are associated with the development of a stress-induced "skin zone" with reduced hydraulic conductivity in the radial direction immediately outside the disturbed zone with enhanced conductivity.

While it is reasonable to assume that these zones behave as porous media and can be described by use of average hydraulic conductivity values, the conditions around drilled deposition holes are different. Here, excavation damage is much less intense - although not negligible - and the influence of stress relief also less important, at least in the lower part of the holes. It is clear that for the immediate vicinity of the deposition holes, the major passages for radionuclide migration are represented by a small number of tortuous channels in a few long-extending fractures. Hence, quantification of these discrete components of the transport system requires specification of their location, frequency

and geometry.

The study has been focussed on all these matters and yields concrete data concerning the following issues:

1. Hydraulic conductivity data of the "disturbed" zone around blasted KBS3 tunnels
2. Model of channels in fractures intersecting KBS3 deposition holes, respecting frequency, aperture and width (breadth) of 2 characteristic types of granitic rock. One of them represents relatively strongly fractured rock, while the other is representative of common rock matrix at several hundred meters depth. The model is derived on the basis of characteristic fracture patterns derived from various studies of rock structures at Forsmark, Finnsjön, and Stripa

## INTRODUCTION

The major kinds of discontinuities that are usually present in crystalline rock are shown in Fig.1. Joints, which will be termed fractures in the present report, are the most common structural features and they tend to form sets of mutually parallel units. The drawing demonstrates this and also indicates that the fractures are discontinuous in their own planes and extend over relatively short distances, i.e. a few meters to a few tens of meters.

Naturally, the interconnection of fractures largely controls the hydraulic characteristics of a rock mass.

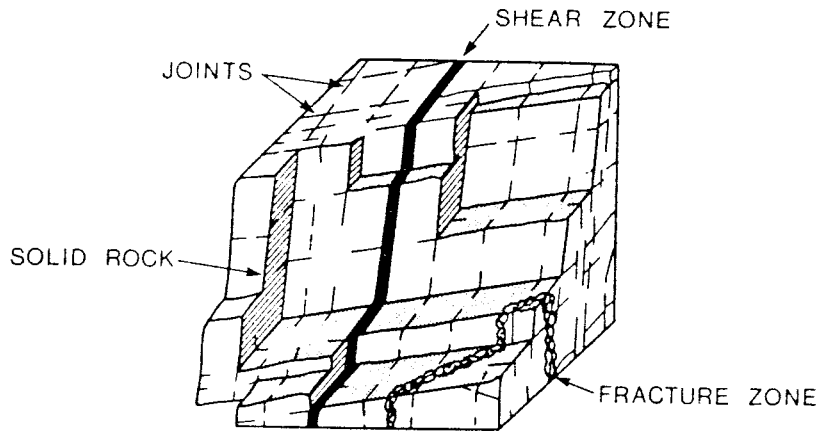


Fig.1. Discontinuities in a fractured rock mass (Gale & Witherspoon)

Fracture zones, being defined as zones of closely spaced and interconnected discrete breaks (Gale & Witherspoon), are tectonically induced disturbances of long extension and range in width from meters to tens of meters but need not to be continuous throughout the rock mass. Shear zones, finally, can extend for kilometers and result from large-scale shear that usually has resulted in intense crushing of the rock. They are of similar width as fracture zones and often contain clay formed from attack of hydrothermal solutions that flowed through these pervious zones. The hydraulic characteristics often vary very much from point to point.

In this report, which concerns the pathways of water in the nearfield of KBS3 canister deposition holes, we will focus on the first-mentioned type of discontinuities, i.e. fractures.



## FRACTURE SYSTEMS

## General aspects

Applying current concepts of strength of brittle substances, like those introduced by Gramberg (1) and Paul & Gangal (2), to macrostructurally isotropic brittle materials, it is concluded that failure planes will develop from microscopic discontinuities and form sets of plane fractures that are oriented more or less parallel to the plane containing the major and intermediate principal stresses at sufficiently high deviator stresses. Provided that rock behaves in this way, one can assume that the predominant stress orientation in many geographic areas would have led to major fracture sets that are oriented subhorizontally as well as steeply, generating the typical structure shown in Fig.1. This is actually the case as illustrated by Fig.2 which depicts the major structure of granite in southwestern Sweden.

Naturally, micro- and macroscopic variations in mineralogical composition and the influence of local stress fields caused by ancient thermal effects and tectonics have caused deviations from this regular pattern but we will see in the subsequent text that the concept of "orthogonal" fracture systems applies sufficiently well to be used in the present context.

As concerns the geometry and frequency of macroscopic fractures it is quite clear that their present length and frequency are primarily functions of the strain that the rock has undergone. The distribution of fracture lengths is logically due to the variations in art, initial orientation, and frequency of microstructural defects, i.e embryotic fractures, that characterized the rock mass prior to the strain that resulted in macroscopic fracturing. Variations

in mineralogical composition naturally gave a particularly large spread in fracture length, but even in very homogeneous rock there is a spectrum of lengths and spacings.

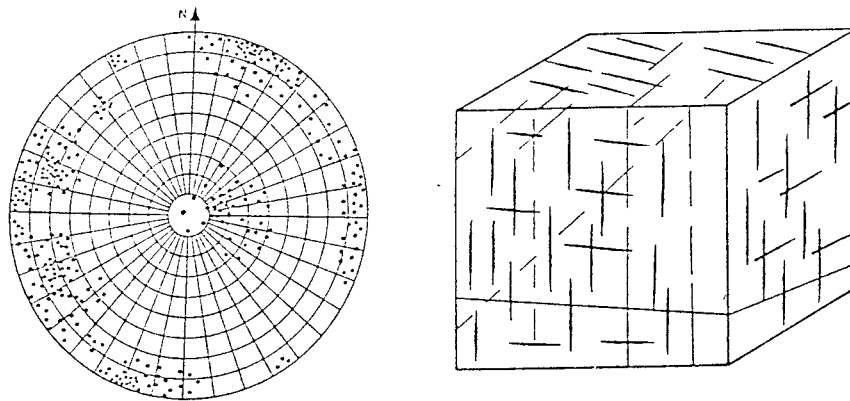


Fig.2. Typical fracture systems in granite. Left: Pole diagram in Schmidt net lower hemisphere projection, showing one subhorizontal fracture set, one striking more or less NW, and one striking NNE to NE. Right: generalized orthogonal fracture system

Although the tensile origin of many fractures implies that they may initially have been more or less ellipsoidal ("Griffith"), chemical processes like neoformation of minerals and creep under high compressive stresses have led to complete closure of the large majority of ancient fractures. Thus, it is probable that only relatively recently formed fractures are hydraulically active and that only part

of the fractures let water through. Many studies confirm this and demonstrate that the water passages have the form of channels.

The fact that only interconnected fractures contribute to the bulk conductivity means that one must apply 3D views of the fracture network, considering in particular the interaction of channels of intersecting fractures (Fig.3). Any attempt to model this must be based not only on realistic

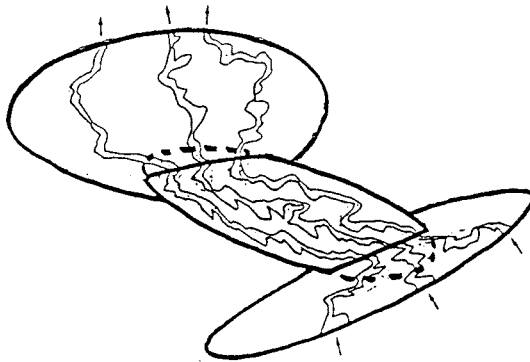


Fig.3. Interacting flow channels in fractures (Tsang)

parameter values respecting fracture lengths and spacings but also on the geometric character of the channels and here is where available data are very sparse or non-existent. A practical way of attacking the problem is to ascribe a certain "equivalent" shape and geometry of the fractures yielding the bulk conductivity that can be measured, and thus disregard, to begin with, from the actual channel configuration. Such considerations have led to a general phenomenological physical model that yields realistic hydraulic conductivity values as a function of rock stresses, provided that common distributions of fracture lengths, spacings, and apertures are applied (3). It is illustrated by Fig.4 and can be described as a generalized system of orthogonal, very

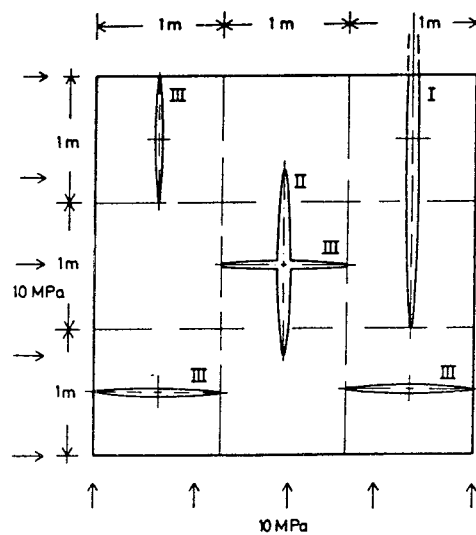
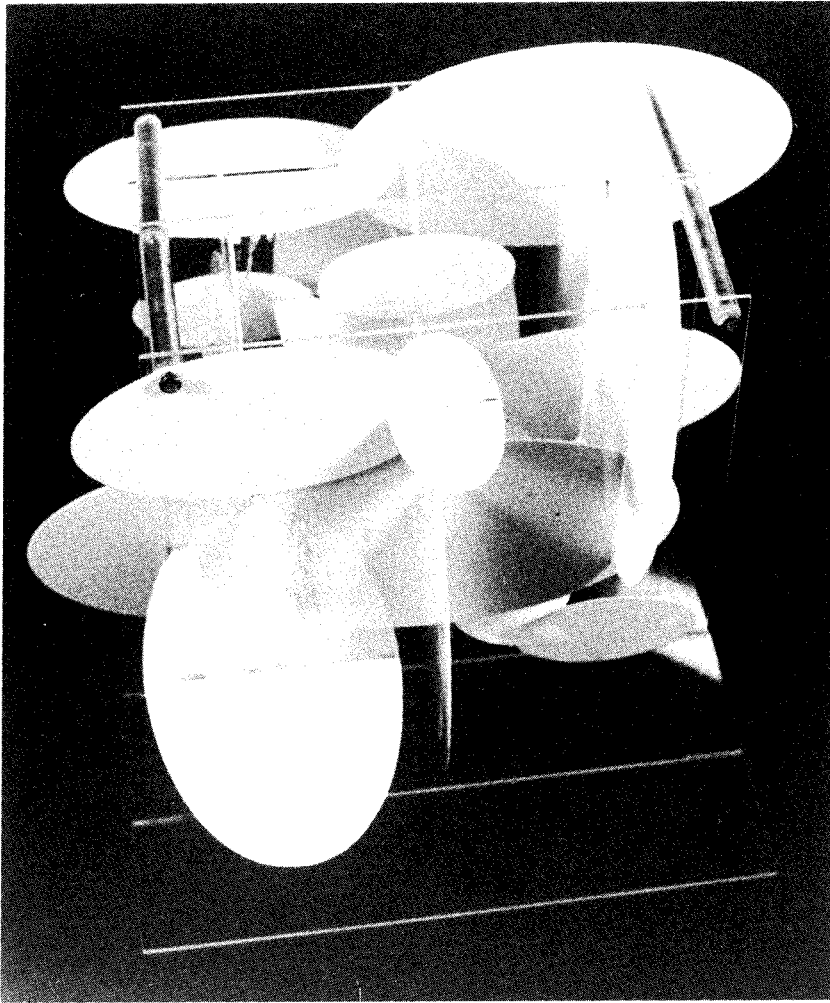


Fig.4. Physical model of ellipsoidal fractures appearing as white discs. Lower picture shows arbitrary cross section taken parallel to one basal surface of a cubical rock element

oblate ellipsoids with constant diameter ratio. Increase in normal stress on the surfaces containing the major and intermediate diameters thus yields shortening of all three dimensions of fractures with concomitant reduction of the interaction with neighboring fractures. This model will form the basis of the quantification of water passages in the nearfield, a necessary prerequisite being actual data of fracture lengths, spacings and apertures.

## DISTURBED ZONES

### General

For shafts and tunnels the number and physical state of the water passages and consequently of the hydraulic conductivity of the rock adjacent to the excavations is altered due to disturbances and there is both analytical assessment and laboratory and large-scale field test results to demonstrate this quantitatively.

### Influence by blasting

Empirical estimates have yielded an approximate relationship between the amount of explosives used for blasting and the radial extension of the zone of blasting-induced disturbance, and it shows that the range is 0.5 to 1 m when careful, smooth blasting is applied. Fig.5 illustrates the major effect of blasting, i.e. generation of new fractures and propagation of some of the original ones. Recently, a physical model has been proposed for estimation of the hydraulic conductivity of the disturbed zone (4). It is based on the finding that radial fractures of certain extension are formed along the major part of the blasting holes and on the assumption that they

are determinants of the longitudinal conductivity, which is estimated to be  $10^{-8}$  m/s or higher (Fig.6).

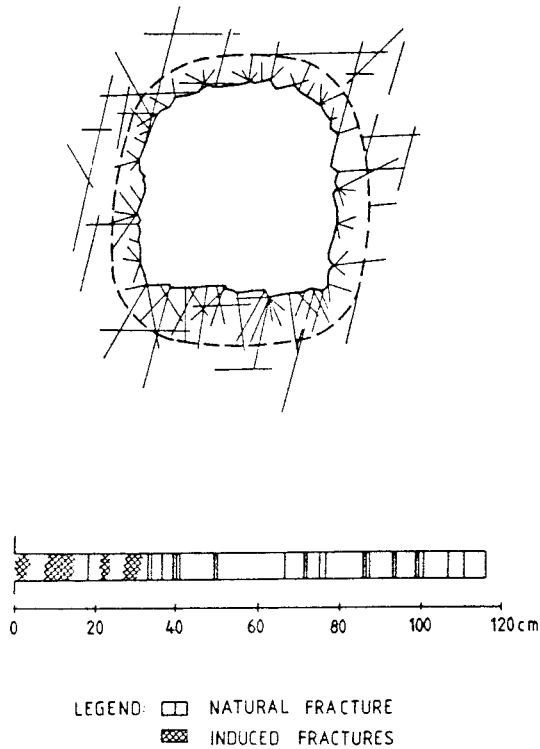


Fig.5. Upper: Schematic picture of fracturing around a tunnel induced by blasting. The broken curve represents the boundary of the blasting-disturbed zone. Lower: Core map showing typical rich fracturing at tunnel wall (Stripa)

#### Influence by drilling on the physical state of borehole walls

Mechanical damage by excavation of deposition holes has some impact on the hydraulic conductivity of the rock immediately adjacent to the walls of deposition holes. A preliminary study of this effect based on compilation of published data and taking the bulk conductivity of virgin rock to be  $10^{-11}$  to  $10^{-10}$  m/s, indicates that "wall disturbance" is significantly different for percussion hammering, coring, full-face

drilling, and very careful blasting (4). Thus, blasting, however carefully and cautiously performed, is concluded to increase the hydraulic conductivity to  $10^{-8}$  to  $10^{-6}$  m/s within 10 cm distance from the wall, while full-face drilling is expected to affect the rock to about the same distance but producing an increase in conductivity only to about  $10^{-9}$  m/s.

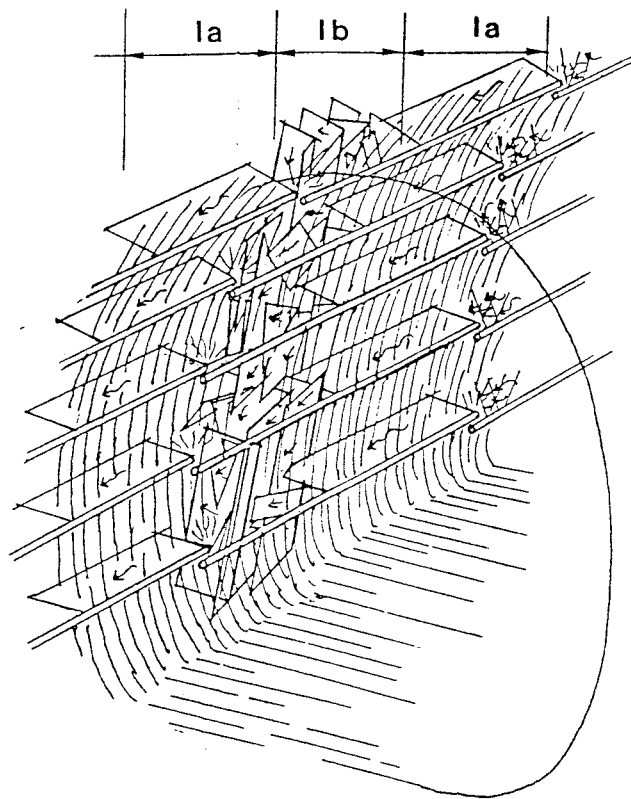


Fig.6. Schematic view of zones of blasting-induced defects in tunnel wall. Ia represent zones of regular sets of plane fractures extending radially from the 3 m long blasted holes, the depth and length being about 0.3 and 1.5 m, respectively (Stripa). Ib represents strongly fractured, intermediate zone

Percussion drilling is concluded to have two effects: generation of disc-shaped fractures perpendicular to the axis of the holes, and fine-fracturing to 1 - 2 cm distance from the wall giving this zone an estimated conductivity of  $10^{-9}$  m/s. Core-drilling, finally, is concluded to create much less damage but there will still be a 2 - 3 mm zone of enhanced hydraulic conductivity, presumably  $10^{-10}$  to  $10^{-9}$  m/s, along the entire periphery. Fig.7 illustrates probable modes of interaction of major fracture flow paths and the various zones of wall disturbance.

One concludes from this that regardless of the technique of producing deposition holes there will be a continuous zone of enhanced hydraulic conductivity along the entire periphery of the holes, extending from the base of the holes to the disturbed zone around the overlying tunnel. *This means, in turn, that radionuclides emanating from one single flaw or a number of flaws in a canister will have a minimum distance of migration through the embedding clay of around 38 cm before they reach a major conductive passage in the rock.*

Obviously, the technique selected for the preparation of deposition holes will be of significant importance. Thus, blasting will definitely create a major conductor that is of greater importance for nuclide migration than natural fractures intersecting the hole and this technique is therefore logically outruled.

#### Influence by stress relief

Pre-existing fractures will be widened, compressed, extended or shortened by stress relief depending on their orientation as well as on the primary stress field. For the simple case of isotropic initial



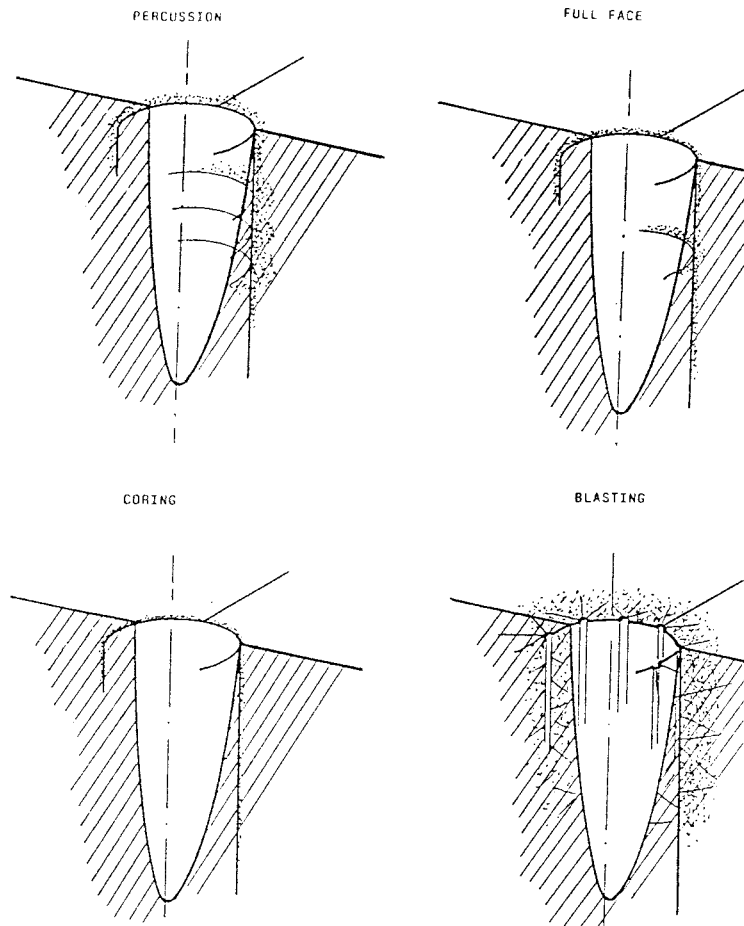


Fig.7. Modes of interaction between major flow paths along fractures forming rock wedges (cross-lined) and wall damage zones

stress conditions and cylindrical shape of the excavation, and assuming also ideally elastic behavior of the rock and no structural changes due to blasting, one finds that the longitudinal conductivity of "onionskin" fractures increases by 10 times while the conductivity of radially oriented fractures is slightly reduced. Considering the aforementioned

orthogonal-type fracture network one would find that, provided that the strike of one of the steep fracture sets is parallel to the tunnel or hole axis, the longitudinal conductivity of the floor and roof would decrease for high horizontal rock stresses, while it would increase in the walls.

A major effect of stress relief is produced where the fractures form wedges (Fig.8). UDEC-based calculations show that apart from the possible risk of formation of unstable rock blocks, the aperture of very steep fractures running close to large-diameter boreholes may be increased so that the longitudinal hydraulic conductivity becomes enhanced by tens or even hundreds of times. The present understanding is that the influence of stress relief on the conductivity of the rock adjacent to the periphery of tunnels and deposition holes may be of this order of magnitude but that the zone of influence is not more than about 1 meter around KBS3 tunnels and a few decimeters around KBS3 deposition holes.

#### Field data

The Buffer Mass Test conducted in the Stripa mine comprised backfilling of a 12 m long drift and this gave an opportunity of estimating the longitudinal conductivity of the rock adjacent to the blasted drift (5). The major purpose of the test was to investigate the rate of water uptake and development of swelling pressures in 6 large holes with highly compacted bentonite embedding electrical heaters, and in the 12 m long inner part of the 35 m long drift that was backfilled with bentonite/sand mixtures. This backfilling absorbed water that flowed in from the surrounding rock and the prediction was that the pore pressures, as measured by piezometers at the rock/backfill interface and in the rock, would rise

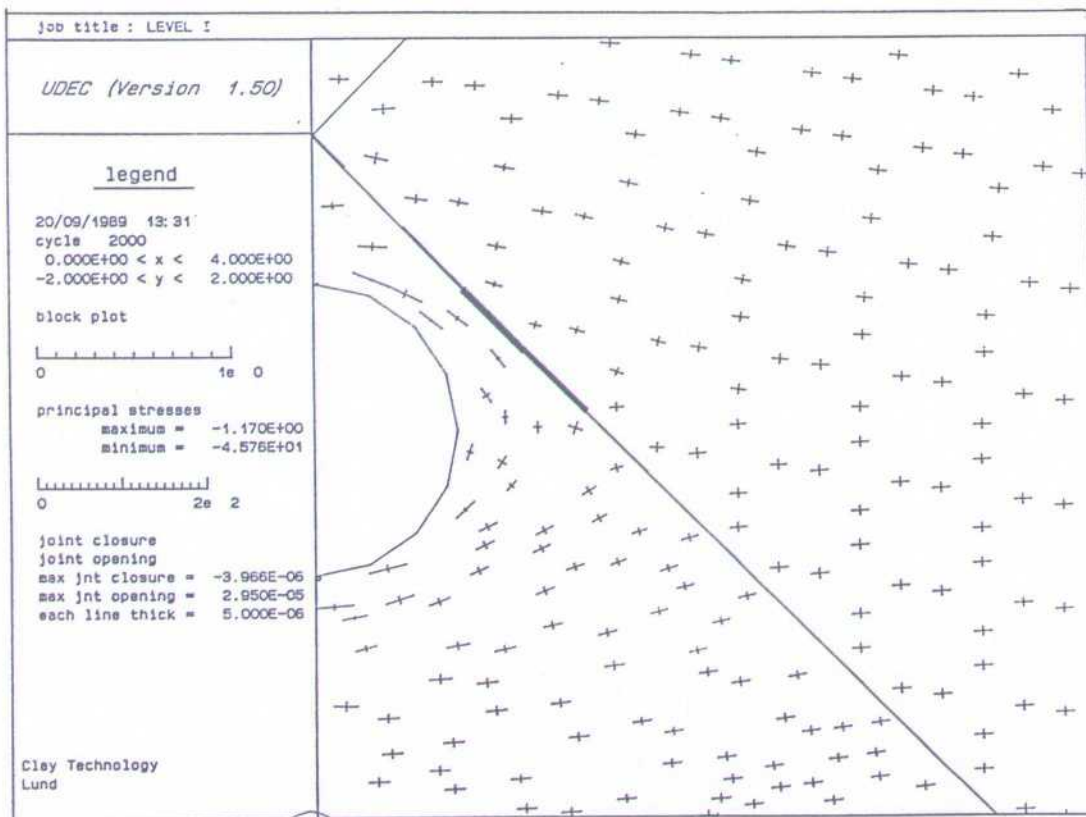
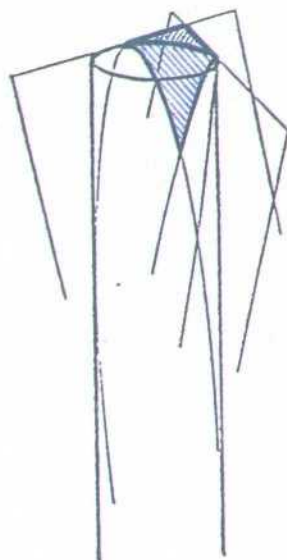


Fig.8. Rock wedge in deposition hole. Upper: wedge formed by intersecting long-extending plane fractures. Lower: UDEC-calculated stress pattern and changes in aperture of fractures

in the course of the saturation of the backfill. Surprisingly, the water head in the rock adjacent to the filling never rose to more than 30 to 50 kPa, while the measured outflow along the rock/backfill interface increased substantially. Using pressure data indicating the approximate longitudinal hydraulic gradient, and the recorded discharge of water, the average longitudinal conductivity of the disturbed zone, within 0.5 to 1.0 m from the periphery, turned out to be  $10^{-8}$  to  $10^{-6}$  m/s. Ongoing tests with more sophisticated systems for pressurizing and collection of percolated water tend to validate these figures, which represent the combined disturbing effect of blasting and stress relief.

#### Conclusion

It is firmly believed that the net effect of stress relief and blasting, however carefully performed, result in a zone of disturbance of 1 m radial extension from KBS3 tunnels and that its longitudinal conductivity is no less than  $10^{-8}$  m/s and probably much higher than that. Such zones therefore form major hydraulic conductors in blasted repositories.

#### NEARFIELD OF DEPOSITION HOLES

##### General

The rock surrounding deposition holes and extending from just below the holes up to the lower boundary of the disturbed zone around the overlying tunnel, controls the rate by which radionuclides move after having penetrated the canister-embedding clay. Its

potential as barrier primarily depends on the transport capacity of the water-bearing passages with special respect to possible changes in capacity due to the afore-mentioned mechanical disturbances, thermal effects, creep, and dissolution of fracture coatings. We will confine ourselves here to consider rock characterized by natural, simple fracture networks disregarding from all the effects mentioned apart from those caused by drilling and stress release. As necessary basis of such considerations one needs relevant empirical data of natural fracture systems in granite and some published information on this issue will be compiled and discussed in the subsequent chapter.

#### FRACTURE DATA FROM FIELD STUDIES

*FORSMARK, SFR (6,7,8,9)*

##### Fracture zones

The major constituent of the SFR rock mass is granite (45 - 65 %), with gneiss-granite as second most important type (30 - 50 %). Eight major fracture zones have been identified in the SFR area of which seven, including the dominant Singö fault, are vertical or very steeply oriented and one (H2) almost horizontal. This number is obtained by applying the definition that fracture zones are rock structures with a fracture frequency exceeding 10 - 20 fractures per meter (line scanning).

The average strike of the major fracture zones is about N40W and N25E. The latter is also characteristic of a hydraulically active schistose zone close to the silo.

## Fractures

The orientation of the fracture zones appears to be characteristic also of the system of fractures in the rest of the central granitic part of the SFR area, and one finds that, in principle, the basic orthogonal structure in Figs.1 and 2 applies. Thus, two of the major fracture sets are steeply oriented and striking N40W and N25E, while one is almost horizontal.

Unlike most fracture mapping efforts, the SFR survey was focussed on identifying *conductive fractures*. A general conclusion is that the average number of conductive fractures is one tenth of the total number of identified fractures and that there are about 0.3 conductive fractures per meter length (line scanning) in the SFR rock mass excepting the fracture zones (8). Different recording techniques gave a surprisingly small spread, i.e. 0.20 - 0.32 fractures per meter, i.e. an average fracture spacing of 3 - 5 meters. A large number of conductivity measurements in boreholes as well as by large-scale inflow measurements were made, the latter giving average bulk permeabilities of  $10^{-9}$  to  $10^{-8}$  m/s and even higher values of certain parts of the fracture zones. Wide variations were found in the borehole loggings which were made down to 200 m depth and which tended to give higher values than the bulk determinations. However, the fact that most of the measurements did not allow for evaluating conductivities lower than  $10^{-9}$  m/s must have yielded skew distributions and too high average values. Applying the figure 3 - 5 m for the spacing of conductive fractures, the relatively high permeability of the rock mass located between the fracture zones, implies that the fracture apertures are improbably high. Actually, primary borehole loggings show an average fracture spacing

- excepting the shear and fracture zones - of about 0.23 m (Ref.9, Table 4.4) and if the ratio of the numbers of conductive and total fractures still holds, one arrives at the more probable average distance 2.3 meters between conductive fractures.

Attempts have also been made to determine the number of clearly identified leaking spots per conductive fracture, a parameter of great practical importance in the present context (8). However, in tunnels such recording tends to be uncertain since the local conditions with respect to RH and ventilation etc, determine how many wet spots that can be seen. The reported characteristic frequency 1 spot per conductive fracture probably only represents the largest channel in the respective fracture.

#### *FINNSJÖN (BRÄNDAN)*

##### Fracture and shear zones

The area has been investigated by use of geophysical methods including borehole logging, as well as by surface mapping (10). The dominant rock type is gneissous granodiorite and the area characterized by fracture and shear zones that are predominantly oriented subvertically to vertically with a spacing of 50 to 500 m and a trace length of several hundred meters. These zones display moderate to wide spacing of the fractures (0.2 - 2 m) with local lenses of more intense fracturing.

##### Fractures

Fractures were mapped by different methods which all showed that three largely orthogonal fracture sets

dominate:

- \* NW dipping  $60 - 90^{\circ}$
- \* NE steeply dipping
- \* Flatlying set (dip less than  $20^{\circ}$ )

This system resembles the configuration found at Forsmark, which demonstrates that a large part of the county of Uppland is characterized by a rather uniform fracture pattern. A further similarity between the Forsmark and Finnsjön areas is that the fracture sets of the rock mass located between the shear and fracture zones are oriented in approximately the same fashion as these zones.

Fig.9 gives a general picture of the pattern of all fractures derived from mapping of a 1m x 48 m "cell" on a typical rock surface from which soil had been removed. The map clearly shows two of the three major fracture sets, and line scanning of the cell gave a frequency of 1 - 3 fractures per meter. Open fractures were recorded separately and were found to be 33 of the total number 272, i.e. about 1/8 of all fractures were found to contain visible open space, the main reason being weathering of fracture fillings. Applying this ratio to the figure 1 - 3 fractures per meter, one arrives at an average spacing of conductive fractures at line scanning of 2.6 to 8 meters, i.e. not far from the SFR data.

An important fact is that the orientation of the open fractures coincides rather well with that of the shear and fracture zones (Fig.10).



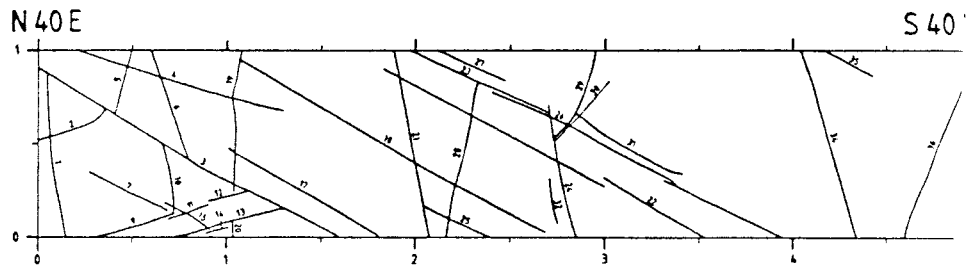


Fig.9. Example of fracture mapping within 1m x 48 m  
"cell" (10)

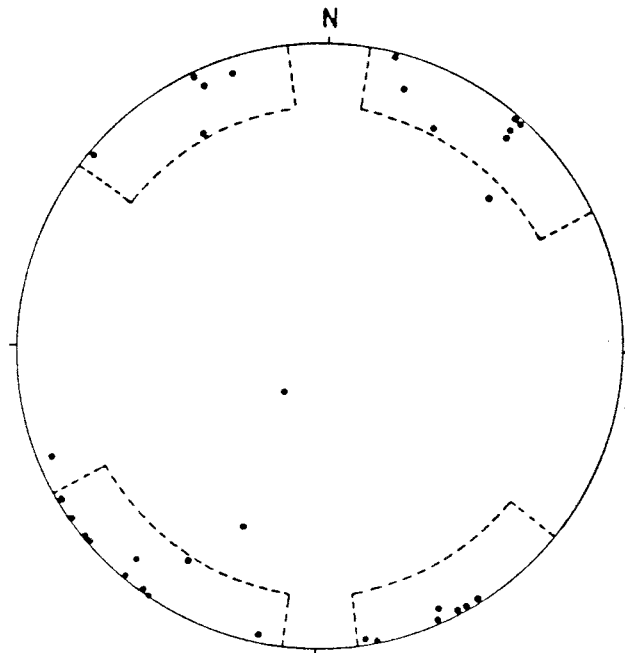


Fig.10. Orientation of open fractures within the 1m x  
48 m cell. Schmidt net lower hemisphere  
projection. The dotted lines represent shear  
and fracture zones (10)

The mapped trace length of the fractures turned out to be significantly larger of one of the fracture sets (NE) but as an average about 50 % of all fractures were less than 1 m long, 25 % were 1 - 3 m long, and 3 % were longer than 7 m (10). This is well correlated with the frequency of conductive fractures since their spacing requires a length of at least 3 m to cause effective connectivity.

A more reliable picture of the fracture frequency is offered by comprehensive borehole investigations (10). Thus, fracture mapping showed that, except for a very dominant 120 - 210 m thick flatlying zone (Zone 2), the average frequency of potentially conductive fractures is 0.3 - 0.7 per meter with an average value of 0.4, which corresponds to a spacing of such fractures of about 2.5 meters. The corresponding average hydraulic conductivity evaluated from packer tests at larger depths than 100 m varied between  $10^{-8}$  to  $10^{-7}$  m/s down to 200 m, and between  $10^{-9}$  and  $10^{-8}$  m/s deeper than about 330 m. Hence, both the geometrical features of the fracture sets and the hydraulic conductivity appears to be similar of the SFR rock mass and that at Finnsjön.

#### *STRIPA*

The Stripa granite is by far the most thoroughly investigated and characterized granitic rock in Sweden. It is an intrusive in leptite and has an apparent homogeneity and relative lack of foliation. A comprehensive study performed by Lawrence Berkeley Laboratories (LBL) showed that this rock mass is characterized by certain main fracture sets with a spacing of 0.3 - 0.7 m at line scanning. Also, the persistence of the fractures was investigated by LBL and this study showed that about 15 % of the total

fracture number have a trace length of more than 4 m and only 2 % more than 7 m. Furthermore, the equivalent hydraulic aperture (assuming slot-shaped fractures) was evaluated from 169 packer-sealed borehole tests at depths of up to 500 m and these tests showed that about 80 % of the fractures had an aperture smaller than 10  $\mu\text{m}$ , while about 14 % had an aperture in the range of 10 - 50  $\mu\text{m}$ , and 8 % were wider than 50  $\mu\text{m}$ . 1.2 % had an aperture of 100 - 200  $\mu\text{m}$ , while no fractures were wider than that. No particular emphasis was put to the identification of hydraulically active fractures and one can therefore assume that only a fraction of the identified fractures contribute effectively to the gross permeability.

This is clearly demonstrated by the conditions in the so-called heater holes in the Buffer Mass Test area. These holes have a diameter of 0.76 m and a depth of slightly more than 3 m, and careful mapping has shown that each of them is intersected by no more than 3 - 5 water-bearing fractures, disregarding from some occasional bifurcation. Actually, only 1 or 2 of these fractures contribute effectively to the bulk conductivity, which has been found to be in the interval  $10^{-11}$  m/s to  $5 \times 10^{-9}$  m/s at more than 1 m distance from the tunnel floor. The network of the major, hydraulically active fractures in the drift is illustrated by Fig.11, which demonstrates that the average spacing is around 2 meters.

A "rectified" 2D version in which the major fractures have been somewhat twisted and forced to strike parallel to the tunnel axis is shown in Fig.12. We see from these two figures that the most important fracture sets are the following:

1. NW to WNW,  $70^\circ$  NE -  $70^\circ$  SW (III in Fig.12)
2. N to NE, steep

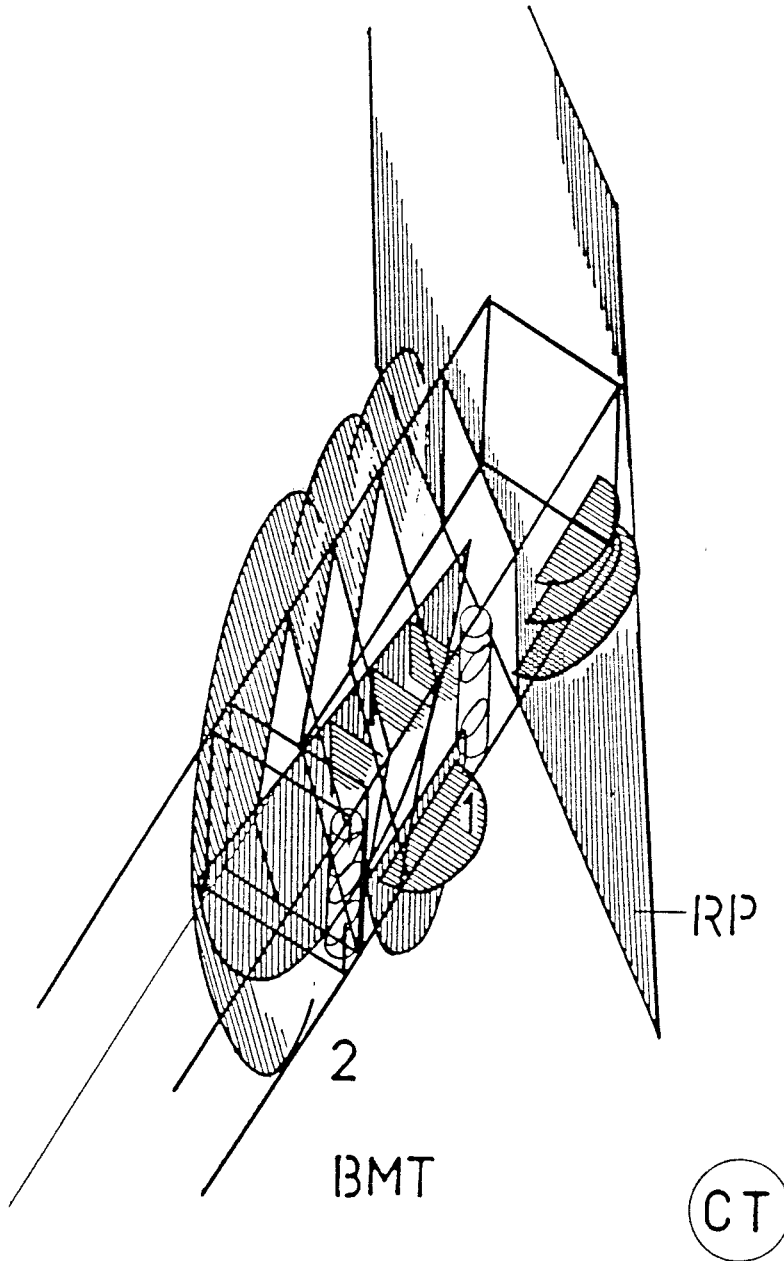
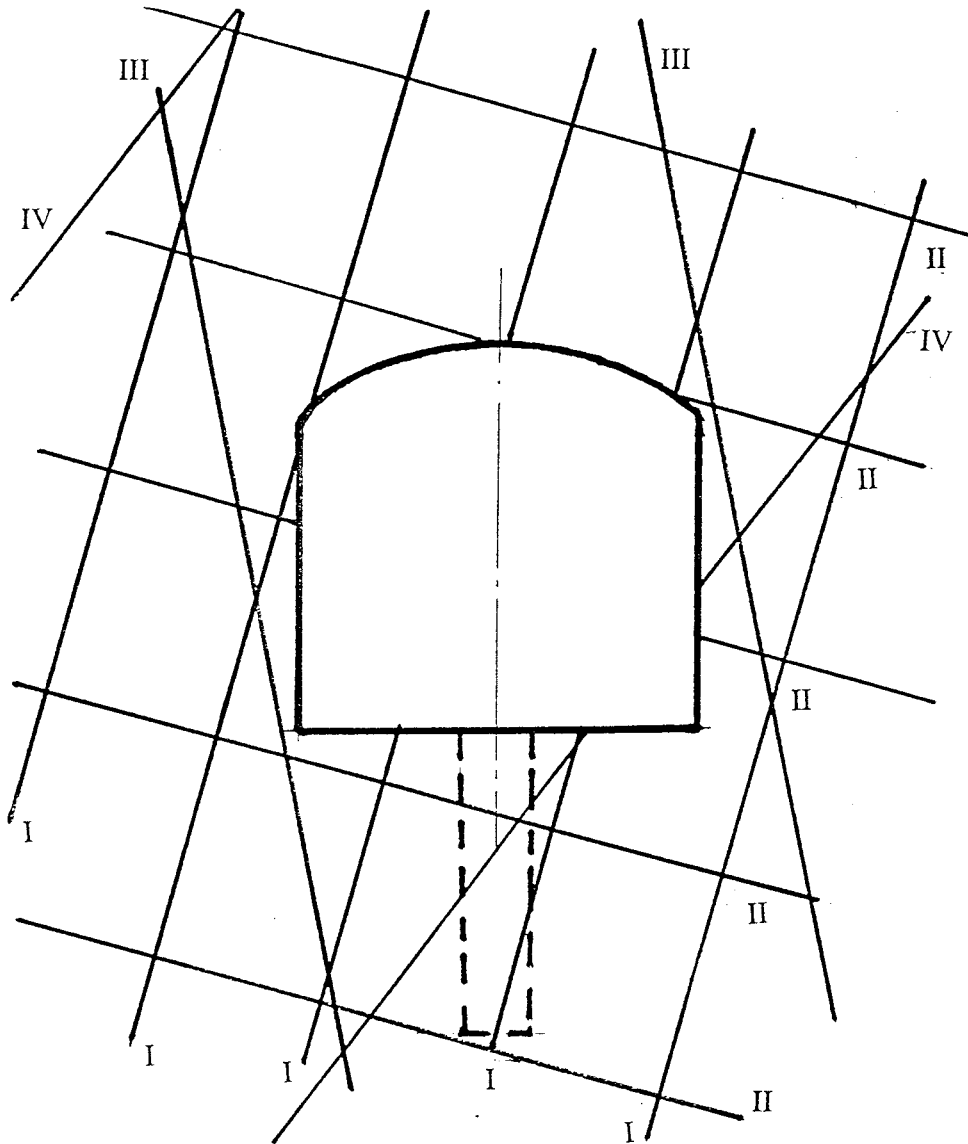
3. Flatlying (dip less than  $20^{\circ}$ , II in Fig.12)

Fig.11. Major long-extending fractures exposed in the inner, 12 m long part of the BMT drift. The RP zone is the largest water-bearing structure in the drift. The axis of the tunnel, which is about 4 m wide and high, is oriented almost N/S



- I SMOOTH, CHLORITE - COATED  $\theta=10^\circ$
- II SMOOTH, EPIDOTE - COATED  $\theta=40^\circ$
- III SMOOTH, CALCITE - COATED  $\theta=30^\circ$
- IV SMOOTH, CHLORITE - COATED  $\theta=10^\circ$

Fig.12. "Rectified" 2D version of the major fracture sets in Fig.11

## TENTATIVE MODEL OF MIGRATION PATHS IN NEARFIELD ROCK

## Fracture system

*General*

Putting together the information from SFR, Finnsjön, and Stripa it is concluded that the idea of virtually orthogonal systems of major water-bearing fractures, being responsible for the bulk conductivity of granitic rock, 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 m, while their persistence is in the range of 2 - 5 m. The average bulk conductivity of the rock due to these fractures is concluded to be  $10^{-10}$  to  $10^{-8}$  m/s.

Applying the simple model of orthogonally grouped ellipsoidal fractures mentioned previously in the report, one finds it to be realistic. Thus, using the fracture parameter spectra of Fig.13, and considering rock volumes of about  $30 \text{ m}^3$ , an earlier study showed that the total number of *hydraulically active* fractures is around 20 and the average bulk conductivity about  $10^{-8}$  to  $10^{-6}$  m/s for common rock stress situations (11).

This application would correspond to rather strongly fractured rock, such as the disturbed zone of the tunnel floors, while for rock deeper down one would have to displace the spectra in Fig.13 to yield a maximum value of  $0.05 \mu\text{m}$ , a minimum spacing of 1.5 m, and a minimum long diameter of about 2 m.

Now, considering a somewhat larger rock volume, namely the annular body surrounding a KBS3 deposition hole, i.e. with a length of 8 m and an outer diameter of 6 m, we arrive at the data given in Table 1 for two reference types of rock.

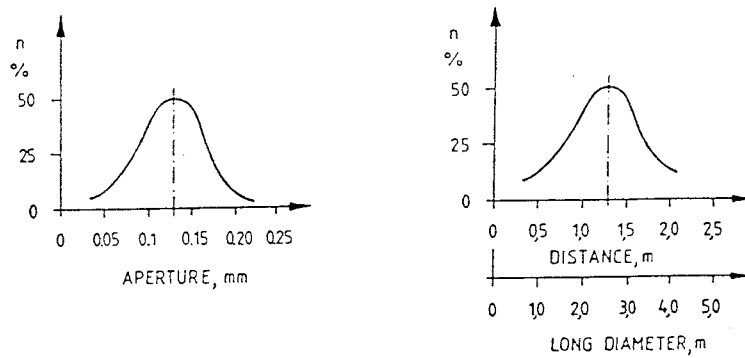


Fig.13 Example of distribution curves of aperture, persistence (length), and spacing (distance) of water-bearing fractures in granite (11)

Table 1. Major data of *hydraulically active* fractures of the rock annulus around KBS3 deposition holes using the orthogonal model of thin ellipsoids. (Note: only *hydraulically interacting* fractures included)

Rock type	Number of fractures	Long	Small	Average bulk
		diam.	diam.	conductivity
		m	m	m/s
A. "Fracture-rich rock"	18	3	$1.5 \times 10^{-4}$	$10^{-8} - 10^{-6}$
	18	2	$5 \times 10^{-5}$	
	18	1	$10^{-5}$	
B. "Normally fractured rock"	7	5	$5 \times 10^{-5}$	$10^{-10} - 10^{-8}$
	7	3	$2 \times 10^{-5}$	
	7	2	$5 \times 10^{-6}$	

The bulk conductivity values given in Table 1 are estimated from the calculated flow through some arbitrarily selected cross sections. One actually finds that, as an average for any horizontal cross section, only very few fractures, i.e. about 6 for type A and 3 for type B, carry water in the axial direction of the considered nearfield rock annulus.

The average hydraulically equivalent cross section at any level of the annulus is on the order of  $5 \times 10^{-4} \text{ m}^2$  for type A and around  $5 \times 10^{-5} \text{ m}^2$  for type B, and although these figures are general measures of the open space they are not directly related to the cross section of the channels that actually constitute the water-bearing parts of the fractures. The channel geometry can be estimated if the number of channels per meter fracture length is known and such data, obtained from systematic studies, do not seem to be available. However, applying the channel frequency that has been documented in the Stripa Rock Sealing Project, i.e. 2.5 channels with 1 cm width per meter sectioned fracture being a rather constant value, one finds for rock of type A with an average hydraulic conductivity of  $10^{-7} \text{ m/s}$ , that there are 5 channels with a (hydraulic) cross section of 1 cm width and  $70 \mu\text{m}$  aperture in each of the 6 steeply oriented active fractures. For rock of type B there are 7 channels with a (hydraulic) cross section of 1 cm width and  $35 \mu\text{m}$  in each of the 3 fractures that are responsible for the average axial hydraulic conductivity  $5 \times 10^{-10} \text{ m/s}$  according to the model.

#### *Simplified geometrical model of migration paths in rock fractures*

It does seem reasonable from considerations of the sort described in the preceding chapter to define the



channel system of the relatively small nearfield rock volume of KBS3 canister holes as sets of straight channels of constant cross section although it is actually very complex and tortuous. From the point of safety assessment the most critical constitution would be the case of vertically oriented channels running very close to the periphery of the deposition holes from their base up to the disturbed zone of the overlying tunnel floor, because it would imply minimum channel length and effective hydraulic interaction with the holes. The interaction would be through the subhorizontal sets of fractures spaced about 1.5 to 3 meters, and above all, through the zone of wall disturbance around the holes.

Hence, a tentative model of primary migration paths in the nearfield rock is the one shown in Fig.14, the parameters  $e$  (aperture) and spacing ( $c$ ) being related to the structure and average conductivity of the rock.

*Integrated model of migration paths in clay and rock from leaking KBS3 canisters*

The major hydraulic conductor of the nearfield is the disturbed zone of the tunnel floor, the channels along the deposition holes, and the pervious zone of wall disturbance around the holes. They combine to form the first-order transport system of the nearfield, while second- and third-order systems are represented by fine fissures and interconnected micropores in the rock, and by the voids of the canister-embedding dense bentonite clay. The latter systems are characterized by largely stagnant water and strong physico/chemical interaction between mineral surfaces and water as well as radionuclides.

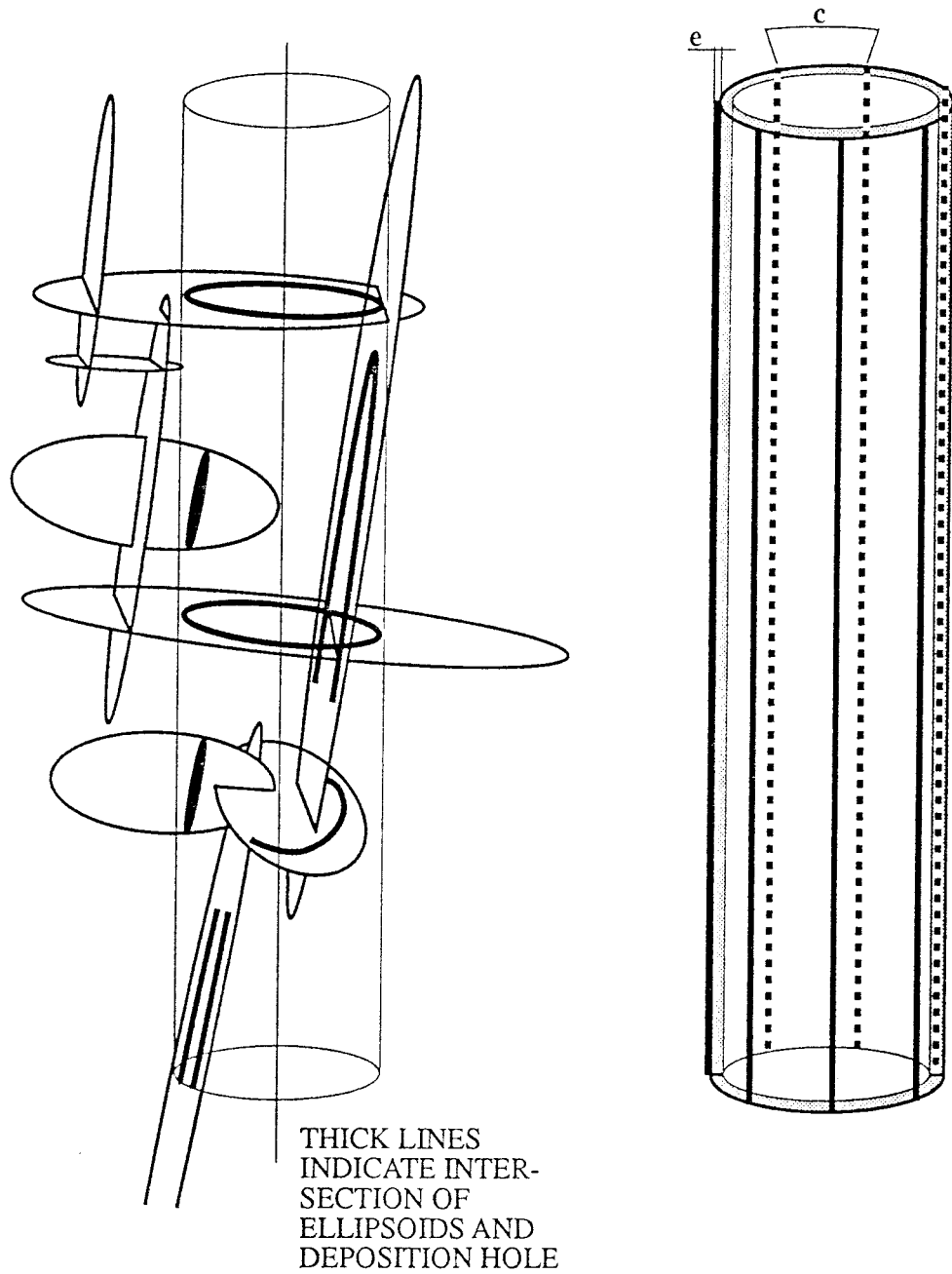


Fig.14. Schematic picture of rock characterized by an orthogonal system of fracture ellipsoids and hosting a KBS3 deposition hole

Schematically, the first-order system can be depicted as in Fig.15, in which 6 major components are specified, i.e. the disturbed zone around the tunnel (A), zone of wall disturbance around holes (B), fracture channels (C), bentonite clay with lower density above the canister (D) and intact, high density (E) below this level, and bentonitic tunnel backfill (F). They can be characterized with respect to their geometrical features and transport properties as compiled in Table 2. It should be noted that components A,B,D,E, and F can be regarded as porous media, characterized by their bulk conductivity, while C can be interpreted both as *discrete channels of the rock annulus with 6 m outer diameter surrounding deposition holes*, or representing a *porous medium of the same size*.

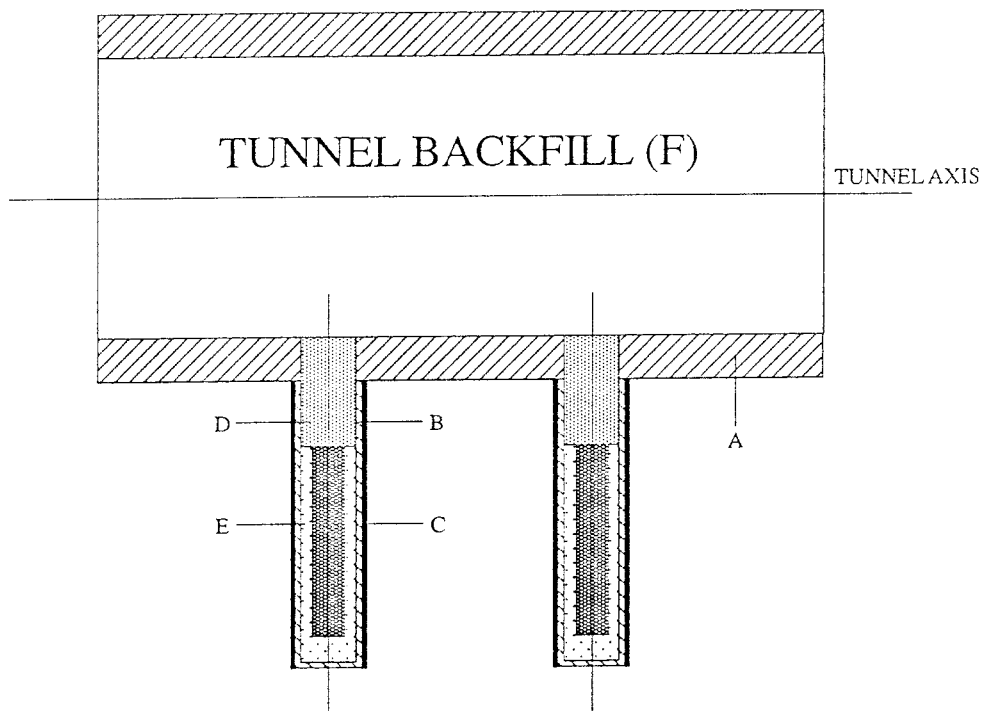


Fig.15. Schematic section of major transport components of the nearfield of KBS3 canisters. A) Disturbed zone around tunnel, B) Wall disturbance around deposition holes, C) Fracture channels, D) Expanded bentonite, E) Intact bentonite, F) Tunnel backfill

Table 2. Approximate data of the nearfield transport system of a KBS3 deposition hole

Component	Geometry	Hydraulic conduct. m/s	Remark
A "Disturbed zone of tunnel	1 m radially from periphery	$10^{-8}$	Isotrop. conduct.
B "Wall dist. zone of holes	a) Full-face 0.1 m, b) Percuss. 0.02 m c) Coring 0.003 m	$10^{-9}$	---
C "Fracture channels" (1 cm wide)	Rock A: Number: 30 Apert. 70 $\mu\text{m}$  Rock B: Number: 21 Apert. 35 $\mu\text{m}$	$10^{-8}$ - $10^{-6}$  $10^{-11}$ - $10^{-9}$	
D "Expanded bentonite"	3 m high cylinder with $\rho=1.8 \text{ g/cm}^3$	$10^{-11}$	
E "Intact bentonite"	5 m high cylinder annulus with 0.38m thickness and $\rho=2.1 \text{ g/cm}^3$	$10^{-13}$	
F "Tunnel backfill"	20 m <sup>2</sup> cross section	$10^{-9}$	

*Thermomechanically induced changes in transport paths*

The proposed model represents the rock state under prevailing temperature and rock stress conditions. Both can change and the influence of altered stress can be roughly estimated by applying UDEC or 3DEC

analysis of the nearfield, taking the orthogonal fracture pattern or simple wedge structures as a basis. It is reasonable to believe that future changes in regional and local stress fields will be moderate, at least in the next ten thousand years, and that their impact on the transport paths is less important than that of the temperature increase that will take place in the repository rock mass.

The heat dissipation from the canisters warms up the surrounding clay and rock, creating a temperature gradient that is associated with non-uniform expansion of the rock block system that constitutes the nearfield rock. This generates rotational and translatory, shear displacement of the rock blocks, resulting in permanent widening of the fractures due to the dilatant shear behavior. In practice, this is assumed to correspond to an altered shape of the channels and this change may in fact be substantial and lead to complete blocking of some channels and activation or neoformation of others. The matter has been dealt with in various laboratory and field tests (12, 13, 14), which indicate that the performance is strongly influenced by the presence of mineral coatings and fillings. A finding of great practical importance is that the hydraulic conductivity of sheared chlorite-coated fractures drops with time, a possible explanation being creep-induced microfracturing and blocking by chlorite debris that may hydrate and expand, or by neoformation of smectite minerals (4).

Disregarding from the possible sealing effect of fracture channels, it is concluded that their transport capacity is enhanced by the heating/cooling cycle that the nearfield will undergo in the first few thousand years after closing a KBS3 repository. The Stripa Rock Sealing Test, which involved hydraulic testing and grouting of simulated

deposition holes with 0.76 m diameter and 3 m depth by use of megapackers (15), gave evidence of the net increase in hydraulic conductivity of the nearfield rock following heating and cooling after grouting.

Tests were made by uniform heating of the walls of the holes to a constant temperature of around 70 - 90°C for about 3 months and subsequent cooling for a couple of months. In the heating period the temperature rose to about 40 - 50°C 60 cm off from the walls. A double "megapacker" with a height of 0.5 m and a distance of 0.5 m between the packers was used for "Lugeon" testing of each 0.5 m interval with some slight overlap of the packer positions. It was concluded from the tests that the heating/cooling reduced the sealing effect produced by the grouting, essentially by opening new channels. A conservative estimate was that the thermomechanical impact gave a net increase in hydraulic conductivity of ungrouted rock by about one order of magnitude (cf. 15).

Sticking to the generalized model of straight rock fracture channels with rectangular cross section along the zone of wall disturbance, an increase in bulk hydraulic conductivity by 10 times would yield a change in (hydraulically equivalent) dimensions corresponding to a doubling of their aperture, provided that their width, 1 cm, remains unchanged. Thus, for Rock A type, the aperture of the 30 channels would be increased from about 70 to 140  $\mu\text{m}$ , and for the 21 channels of Rock B type, from 35 to 70  $\mu\text{m}$ .

## CONCLUSIONS

The present study is an attempt to concretize the geometrical and transport characteristics of major radionuclide transport paths from KBS3 canisters

through the nearfield. The major conclusions respecting the nearfield rock are the following:

1. The water-bearing structural features of granitic rock appears to be similar for Forsmark, Finnsjön and Stripa. They are compatible with the concept of "orthogonal" fracture sets with rather large spacings
2. Very few fractures contribute significantly to the bulk hydraulic conductivity of nearfield granitic rock and their location, orientation and grouping are relatively easily recognized and visualized by applying the model of orthogonal ellipsoidal fractures
3. The hydraulically active part of interacting fractures is formed by a complex system of tortuous channels of varying shape and cross section. By applying generalized values of channel widths and assuming the channels to be straight and stripe-shaped with rectangular cross section, one arrives at an average aperture of hydraulically equivalent channels, the number of which is a function of the rock volume, fracture network, and bulk conductivity
4. Disturbed zones around tunnels and deposition holes are effective conductors
5. A simple, potentially useful model of transport paths in the nearfield rock is obtained by combining the concepts of "rectified", straight channels and wall disturbance of the deposition holes. In its most conservative form, the channels are all located along and contacting the zone of wall disturbance

## COMMENTS

No attempt has been made in this report to evaluate the relative importance of the various transport components but it is clear that since equivalent conductivity coefficients can be ascribed to each of them, simple FEM or similar analyses will reveal this and yield information on the average annual groundwater flux along the holes. As to radionuclide migration by diffusion, it is believed that the concept of discrete channels offers a basis for easy calculation of such transport as well.

A final comment is that further refinement and updating of the channel model should be made when additional information becomes available from ongoing migration and rock sealing tests at Stripa.

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