SKB

# TECHNICAL REPORT

92-20

## SKB 91

**Final disposal of spent nuclear fuel.
Importance of the bedrock for safety.**

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# Final disposal of spent nuclear fuel

## SKB 91 – Importance of the bedrock for safety

# SUMMARY

*The safety of a deep repository for spent nuclear fuel has been assessed in this report. The spent fuel is assumed to be encapsulated in a copper canister and deposited at a depth of 600 m in the bedrock. The primary purpose has been to shed light on the importance of the geological features of the site for the safety of a final repository.*

*The assessment shows that the encapsulated fuel will, in all likelihood, be kept isolated from the groundwater for millions of years. This is considerably longer than the more than 100,000 years that are required in order for the toxicity of the waste to have declined to a level equivalent to that of rich uranium ores.*

*However, in order to be able to study the role of the rock as a barrier to the dispersal of radioactive materials, calculations have been carried out under the assumption that waste canisters leak. The results show that the safety of a carefully designed repository is only affected to a small extent by the ability of the rock to retain the escaping radionuclides. The primary role of the rock is to provide stable mechanical and chemical conditions in the repository over a long period of time so that the function of the engineered barriers is not jeopardized.*

## BACKGROUND

One of SKB's responsibilities is to come up with recommendations as to how and where the final disposal of Sweden's radioactive waste should be arranged. After review and approval by the regulatory authorities, SKB shall also design and build the necessary facilities and carry out final disposal of the waste.

Between 1977 and 1983, in keeping with the requirements in the Stipulations Act, subsequently superseded by the Act on Nuclear Activities, SKB published a series of reports examining the feasibility of final disposal of spent nuclear fuel in Swedish bedrock. After extensive circulation of the reports for review by Swedish and foreign experts, the Government found in 1984 that a method has been presented that could be accepted with regard to safety and radiation protection.

During the 1980s, SKB has continued its investigations of study sites in Sweden and examined alternative methods for final disposal. The body of knowledge has been expanded in terms of both an understanding of the processes that are important for long-term safety and data and models for being able to quantify them.

The experience gained from these studies has lent further support to the view that it is possible to isolate the fuel from the groundwater over a long period of time by encapsulating it in a copper canister. In a suitable environment, this isolation can be maintained for such a long period of time that the toxicity of the waste will decline to a level equivalent to that of uranium ores. The granitic bedrock in Sweden at a depth of a few hundred metres or more exhibits suitable chemical conditions for long-lasting canisters. The results of the studies have also strengthened the belief that the bedrock in Sweden offers many sites where the rock also has a high capacity to retain radionuclides should they escape from the repository's engineered barriers.

A fundamental principle of all planning for a final repository in Sweden is that its safety shall be based on the multi-barrier principle, i.e. that the safety of the repository shall not be dependent on a single safety barrier. Accordingly, even if the copper canister is capable of isolating the waste from the groundwater for a very long time, it is also important to define the safety-related requirements on the bedrock under the assumption that radionuclides nevertheless escape from the repository.

## PURPOSE AND DELIMITATIONS

According to existing plans, system selection and siting for a final repository will begin during the 1990s. The present report presents a safety assessment (SKB 91) that examines how the long-term safety in a final repository is affected by the geological characteristics of the repository site, i.e. how the rock barrier performs under the assumption that radionuclides leak out of the repository. The report is intended to form part of the background material that is required for the siting of a final repository for spent nuclear fuel.

The following questions are explored:

- What importance do the site-specific characteristics of the bedrock and the hydrological regime around the repository have for overall safety?
- What relative importance do different site-specific characteristics have for safety?
- How can the placement and design of the repository be adapted to conditions on the site in order to take advantage of the safety barriers offered by the bedrock?

The assessment deals with the safety of the repository during the post-closure phase. The possibility of achieving adequate safety during the operating phase – i.e. during treatment, transport and deposition of the waste – is in all essential respects independent of the geological conditions on the repository site.

SKB's continued work during the '90s will include selection of the schematic design, siting of the final repository and adaptation of the design and the barrier system to the chosen site. During this phase, SKB 91 will serve as a basis for systematic analyses where parameters that affect safety are varied. A secondary goal is therefore to test, in connection with SKB 91, a system of efficient procedures for carrying out safety assessments.

The report covers only final disposal of spent nuclear fuel, since this waste category contains the largest quantities of radiotoxic materials and thereby imposes the strictest demands on the protective function of the repository. Certain types of long-lived decommissioning waste, internal reactor parts and operational waste may be disposed of in the repository for spent fuel, but the different repository sections do not have to be situated in such a manner that they affect each other.

# MAIN FEATURES OF THE REPOSITORY

## Principles

The following principles have served as a basis for the design:

- Final disposal is done in crystalline Swedish bedrock at a depth that protects the repository against disturbances from the surface (i.e. 300 – 700 m) in one or more blocks of rock surrounded by structurally weak zones;
- The waste is encapsulated in canisters that are handled as separate units. Their fuel content, size and geometric placement pattern in the repository is chosen so that the temperature on the surface of the canister is limited to well under 100°C;
- The waste is surrounded by several different barriers to isolate the waste from surrounding groundwater and prevent or delay the dispersal of radionuclides from the deposited waste;
- The repository is arranged so that it is not dependent for its safe function on long-term surveillance and inspection. However, the placement of the repository in the crystalline rock will make it possible to access the waste as long as the existence and location of the repository are known.

## Repository site

The topography, geology and other site-specific characteristics of the repository site have been chosen in agreement with the conditions in the Finnsjön area in northern Uppland, see Figure 1. The area has been chosen as an example, since an extensive

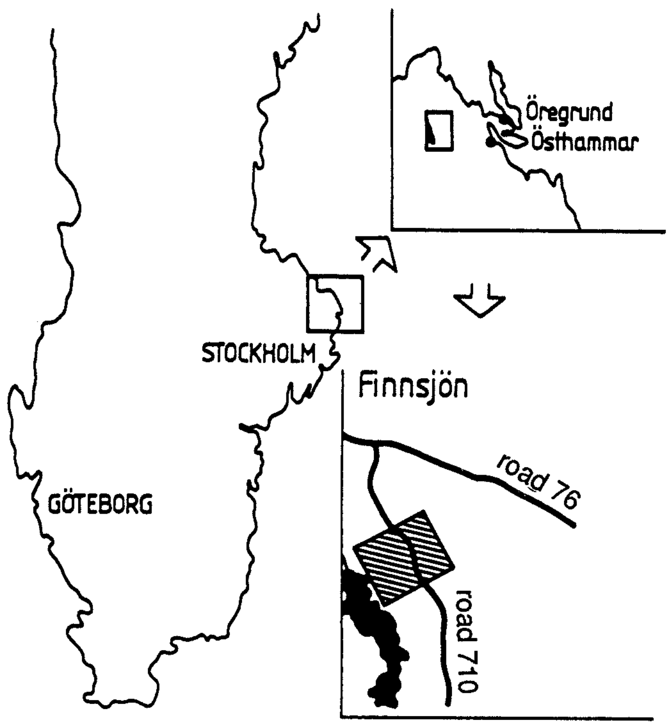



*Figure 1. The Finnsjön area in northern Uppland.*

body of data is available from the area. Finnsjön was judged in KBS-3 to be a possible site for locating a final repository, though less favourable than some of the other study sites. The present-day understanding of the geology of the site is strengthened by data from the Forsmark area and the repository for low- and intermediate-level waste, SFR, as well as data from Dannemora Mine.

## Design

Deposition is arranged largely as described in the KBS-3 report, see Figure 2. The spent fuel is placed in copper canisters, which are then filled with lead. The canisters are deposited one by one in holes drilled in the floor of a system of drifts in the rock. The space between canister and rock is filled with bentonite clay. The system of storage drifts is assumed to be regular with a distance of 25 m between the drifts. The distance between the deposition holes is 6 m. The quantity of fuel is equivalent to 7,800 tonnes of uranium, i.e. the quantity obtained from the Swedish nuclear power programme through the year 2010.

At closure of the repository, all cavities are backfilled. Drifts and shafts are provided with sealing plugs to block potential transport pathways for the groundwater.

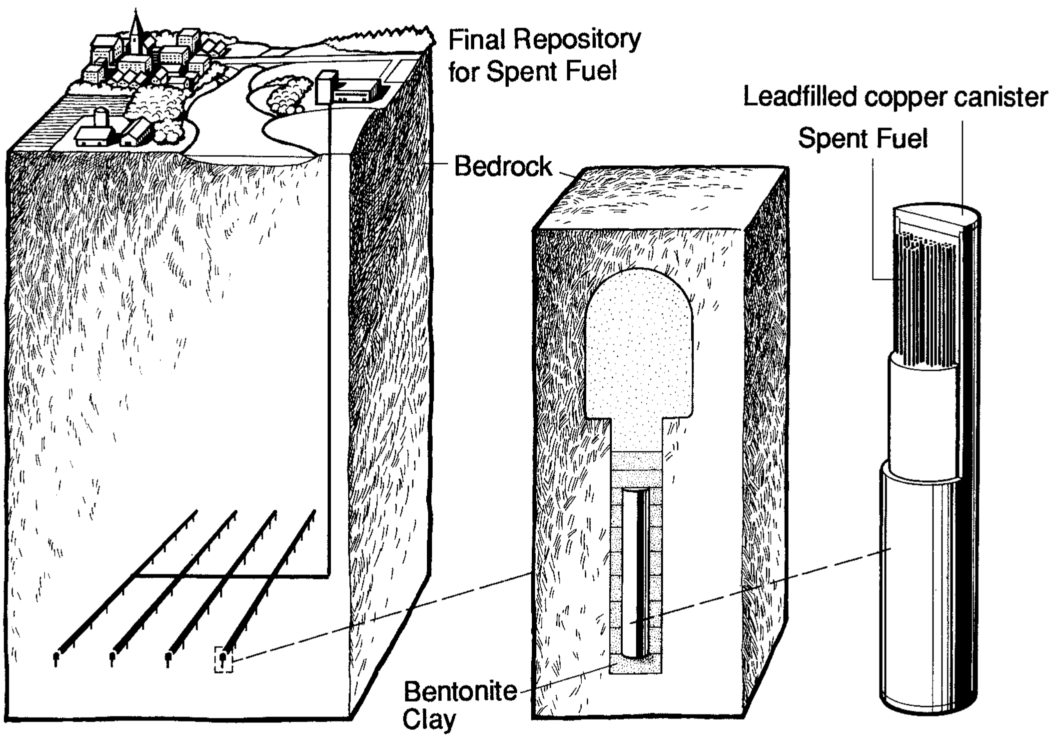



*Figure 2. Schematic design of a final repository for spent nuclear fuel in crystalline basement.*

## THE ASSESSMENT

### General

The time spans that have to be taken into account in the assessment of the safety of a final repository are long and the processes that can be of importance for safety are many and often slow. Safety assessments can therefore not be based solely on the results of experiments. The analyses must be based on models for known and possible interactions between the components in the repository. The external environment in which the repository has been placed and the environment that may exist in the future must also be taken into consideration.

Since long-term safety can be affected by changes in the repository's future environment, the analysis of future scenarios occupies a central place in the safety assessment. By a "scenario" is meant a description of a conceivable future situation or sequence of events that can be of importance for the safety of the repository. International efforts have been made to formalize the assessment and to establish appropriate procedures. One important question is how to show that no important phenomena have been overlooked.

In the safety assessment, an analysis is made of how the transport of radionuclides from the repository to the biosphere can take place. The factors and processes that can affect the transport are identified and evaluated. In order to avoid underestimating environmental impact, many data have been chosen pessimistically (in an unfavourable way). The calculation results should therefore not be viewed as a prediction of expected releases, but rather as upper limits.

### Reference scenario and variations

The reference scenario describes the repository to be assessed and defines the external environmental conditions that constitute the basis for the safety assessment.

Since the aim in siting a repository is to avoid areas with unusual minerals or ores, with regional zones of movement and with extreme topographical gradients, it can be foreseen that all potential repository sites will resemble each other in these respects. The biosphere description in the assessment has been simplified, since site-specific differences in the biosphere between the studied sites in Sweden are considerably less than the changes that can occur over time. Intrusion scenarios have not been discussed, since the probability or consequences of someone intentionally or unintentionally getting into the repository cannot be expected to differ considerably for the different candidate sites.

The analyses are carried out under the assumption that deposition takes place at an even pace, after which the excavated space will begin to be backfilled. Finally, it is assumed that the repository will be sealed some time in the 2050s.

The most likely situation is that all canisters fulfil the integrity requirements that have been established for encapsulation, i.e. that the groundwater will not come into contact with the fuel for a very long time. To evaluate the performance of the rock as a barrier to dispersal of radionuclides, however, certain releases must be assumed. The reference case has therefore not been based on the most likely state of the repository, but has been defined so that each canister that is deposited has a probability of 0.1% of having an initial manufacturing defect. For the entire repository, this means that 5-6 canisters will have defects. The defect is defined as a hole penetrating the canister's welded joint.

Climate changes will probably occur during the time the repository is supposed to function. A temperature increase is likely in the shorter perspective, but in the longer perspective, on the 10,000-year scale, new ice ages similar to the most recent one are expected.

A glaciation changes many of the premises for a safety assessment. The most important change from the safety viewpoint is, however, that the strong link between radioactive materials in the biosphere and doses to humans is broken when the intensive cultivation of soil for food production ceases. Therefore, a future ice age is not included in the reference scenario, even though many regard one as likely.

However, to shed light on how a future glaciation could develop and in what way it could affect a deep repository, the main report also describes a glaciation scenario.

Besides the reference case, the importance of certain variations in the properties of the site is also assessed in SKB 91. The purpose is to quantify the safety-related importance of various geological conditions. The variables have been selected because they are assumed to have a safety-related importance, contain large uncertainties, or constitute parameters that can be varied relatively freely in designing the repository. The calculations are carried out with the chain of models from the reference case or with models that are more directly associated with varied parameters.

The parameters that have been subjected to variations are listed below.

- The groundwater flow;
- The groundwater travel time from the canister to the surface;
- Dispersion conditions in the model block;
- The area of the rock surfaces in contact with the mobile groundwater;
- The chemical conditions in the immediate vicinity of the canister;
- The influence of salinity on groundwater circulation;
- The depth of the repository;
- The presence or absence of flat-lying fracture zones;
- The respect distance between the periphery of the repository and surrounding fracture zones;
- The conductivity contrast between fracture zones and rock mass;
- The size of the regional gradient;
- The perturbed zone in the rock caused by the excavation work, and its orientation;
- The various receiving bodies for the deep groundwater's outflow in the biosphere.

In addition, certain conditions have been discussed in a qualitative fashion, for example the importance of groundwater composition and temperature for the safety of the repository.

## Models and data

A number of pessimistic simplifications were made in KBS-3 where positive factors were disregarded if they could not be quantified. For example, it was assumed that the effectiveness of the canister in inhibiting the release of radioactive materials is completely lost when it is penetrated by the first hole, and that the radionuclides reach the biosphere at the same instant they reach a major fracture zone. Such simplifica-

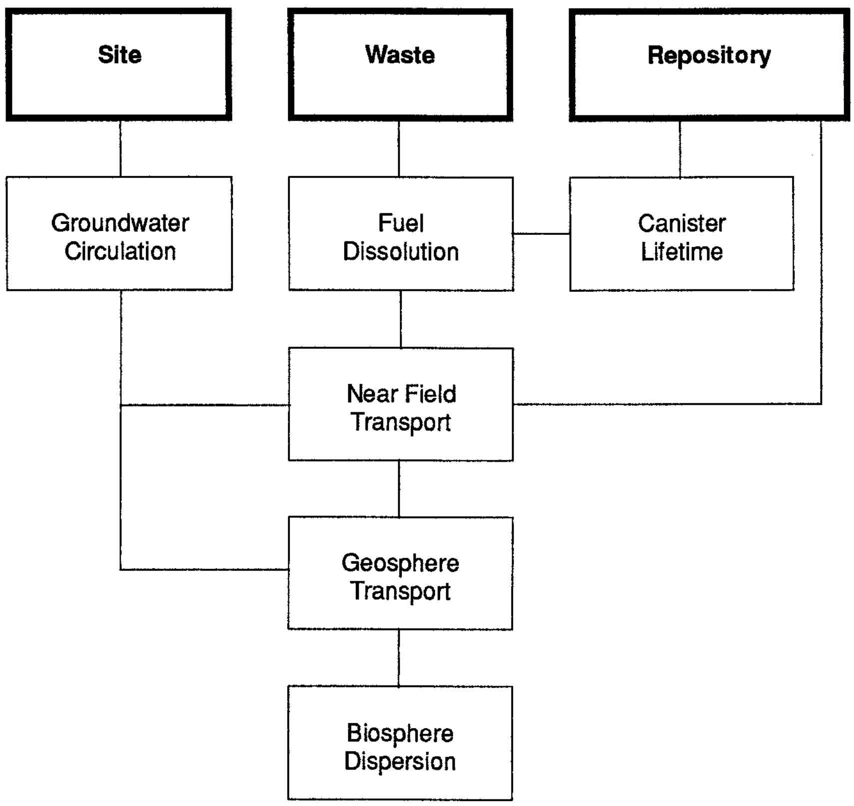



***Figure 3.*** *Schematic diagram of safety assessment in SKB 91 and its information flows.*

tions have been avoided wherever possible in SKB 91, but remain in certain cases where the process is so complicated that a detailed analysis does not appear meaningful today. The purpose has been to present a realistic and not overly pessimistic picture of the performance of the repository so that the effect of assumed variations in the characteristics of the site are not hidden behind exaggerated safety margins. Figure 3 shows a schematic diagram of the assessment procedure and the flow of information between the different sub-assessments.

The repository's far field has been analyzed with the aid of a stochastic hydrology model, i.e. a model that takes into account the fact that the characteristics of the rock can vary from point to point in an irregular fashion. Since the assessment is being performed for a site where the data base was originally gathered for other purposes than the siting of a final repository, the statistical material on the properties of the rock may be deficient in some respects. Such a situation with limited data availability closely resembles the one that exists at an early stage of a site investigation. Here again the initial assessments must be made on the basis of a few boreholes and the results must be viewed as possible outcomes. With a larger quantity of data available, the uncertainty is expected to decrease. The assessment can indicate the difference between favourable and unfavourable assumptions concerning groundwater conditions on the site, and also indicate places where a better database is essential or unimportant, as the case may be.

In contrast to the assessment of the hydraulic conditions in the far field, fuel dissolution and the radionuclide transport in the near field have been evaluated deterministically, partly so that uncertainties in the description of the near field will not conceal the effects of variations in the far field on the model results, and partly because the parameters in the near field can be quality-controlled to a higher degree than those in the far field.

The general premises and calculation sequence used in SKB 91 are presented below.

- The quantity of spent nuclear fuel is based on SKB's Plan reports and the assumption that the Swedish nuclear reactors will be operated up to the year 2010;
- The radionuclide inventory and residual heat in the fuel at different times are calculated on the basis of previous operating data and a forecast for the time up to shutdown;
- Temperature is calculated for a repository design similar to that in the KBS-3 report;
- The groundwater movements in the area are calculated regionally and locally. The modelling is based on topography, lineament interpretation and measurements of hydraulic conductivity;
- Canister performance is based on
  - thermodynamic stability in pure water, groundwater flux in the repository area, measured levels of corrosive substances in the groundwater and diffusive mass transport between groundwater and canister,
  - build-up of gas pressure from the radioactive decay process,
  - a probability of 1/1,000 that an individual canister is deposited with an initial defect;
- Dissolution of the fuel is calculated based on
  - the assumption that it will take at least 1,000 years before water comes into contact with the fuel,
  - a model where the transformation of the fuel matrix is controlled by oxidant production via $\alpha$-radiolysis;
- Nuclide transport in the near field is calculated using
  - a transient model for calculating the transient breakthrough of radionuclides to the far field,
  - a stationary model for diffusion through a canister hole via the buffer material up to the mobile groundwater in a fracture or in a disturbed zone around the drift;
- Nuclide transport in the far field is calculated on the basis of flow paths from different parts of the repository, generated by the groundwater model, and one-dimensional modelling of matrix diffusion and sorption;
- Dispersal of radioactive materials in the biosphere is calculated for a standard biosphere taking into account different pathways to man via well, cattle, grain cultivation and fishing;
- The dose conversion factors are based on the ICRP's recommendations.

The importance of changes in certain premises has been evaluated by means of variation analyses with relevant models or with the entire model chain.

# CONCLUSIONS

## General

The SKB 91 safety assessment differs in certain respects from previous analyses. Greater knowledge has made it possible to take into account factors that were previously dealt with in a simplified fashion. One example is the limitation of the leakage from a damaged canister due to the transport resistance offered by the hole in the canister wall, another is the transport of radionuclides in fracture zones. The increased computing power of modern computers and new assessment models have also made it possible to take into account the variability in the hydraulic conductivity of the rock, as well as the actual geometry of the repository.

Aside from the fact that initially defective canisters are assumed to have been deposited, in order for there to be any releases at all to be calculated, the new models make the assessments more realistic than before. At the same time, the results are also affected more strongly by the features of the repository site, i.e. the results are more site-specific than before. This is necessary in order for it to be possible to examine the impact the rock barrier has on safety, but also means that a transfer of the results of this study to other sites must be done with caution.

## Repository safety

*Probable conditions*

The engineered barriers in the repository have been designed so that they provide a long-term isolation of the radioactive materials from the surrounding groundwater. The fuel is encapsulated and deposited in a carefully controlled manner so that in all likelihood the repository will not contain any defective canisters.

The canister and buffer materials have been chosen so that the barriers are not sensitive to reasonable changes in groundwater chemistry or temperatures. The chemical environment in deep granitic bedrock is such that the copper walls of the canisters will not be penetrated by corrosive substances until possibly after several tens of millions of years.

The lead-filled canisters will act as solid bodies in the rock and will withstand the prevailing pressures, including those that can arise in the event of a future glaciation. Possible rock movements caused by changes in rock stress after a glaciation will be released in the regional fracture zones that surround the repository and are structurally weak parts of the bedrock. Rock movements of such magnitude that the canister would be sheared off will only occur in fracture zones with a length of 10 km or more. Such structures can be identified during the construction of a repository and no canisters will be deposited there.

One possible reason for the canisters losing their integrity is that an inner helium pressure is built up in the canister by $\alpha$-decay in the fuel. This pressure will not reach the level of the yield limit of the copper canister until some 10 million years or so after encapsulation.

Thus, the copper canister will isolate the spent fuel for a very long time, considerably longer than the 100,000 years-plus that are required for the toxicity of the radioactive materials to decline to a level equivalent to that of rich uranium ores.

*Reference scenario*

To substantiate the safety assessment, the repository's impact on the environment has also been studied for less probable cases. One assumption is thereby that leaky canisters have been deposited owing to the fact that defects during manufacture have not been detected in the quality control. A reference scenario has been defined where 0.1% of the deposited canisters have initial defects. Fuel dissolution, transport of radionuclides from the barriers in the near field, through the bedrock and the biosphere, and dose to man are calculated for this scenario.

The release of radionuclides from a damaged canister is limited strongly by the slow dissolution of the fuel and by the maximum possible size of an initial defect. The calculations show that if the radionuclides escaping from a damaged canister travel directly up to the biosphere without being affected at all by their transport through the bedrock on top of the repository, the dose would be no more than 0.001 mSv/y for all nuclides except cesium-135, see Figure 4.

Part of the inventory of isotope cesium-135 is assumed to have been released from the fuel matrix and thus be available for outward transport as soon as the groundwater comes into contact with the fuel. With the above assumption that this amount of cesium from a damaged canister would reach the biosphere directly, it can give rise to a dose of about 0.03 mSv. In reality it takes about 10 years before the maximum release rate from the near field is reached, which reduces the annual dose from cesium to a few percent of the values given in Figure 4.

In other words, the barriers in the near field limit the releases to levels that lie below the suggested dose limit of 0.1 mSv/y.

Thus, the principal safety-related requirement on the rock around the repository is that it shall preserve a chemically and mechanically stable environment around the repository, so that the performance of the engineered barriers is ensured.

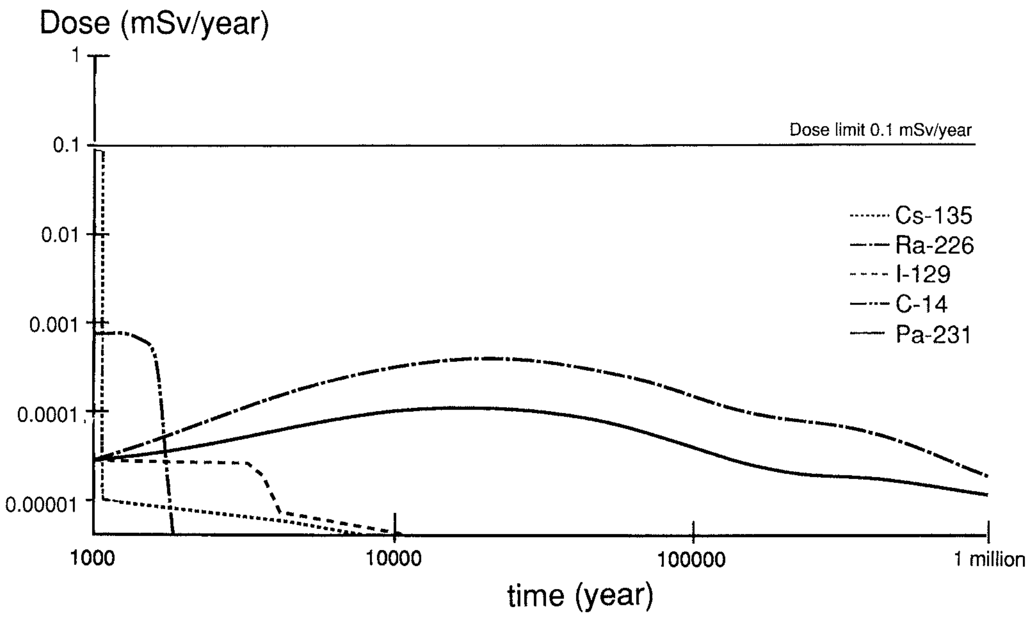



***Figure 4.*** *Dose rate to individual under the assumption that the release from an initially defective canister takes place directly to the biosphere.*

In order to determine the safety-related importance of the rock barrier at Finnsjön, a geohydrological modelling of the area has been performed. Water flow and travel times up to the biosphere in different parts of the repository have been calculated.

Sampling in the Finnsjön area has shown that water at repository depth has a higher salinity than shallower water. This stratification of the groundwater's density reduces the groundwater flux. Studies indicate a groundwater travel time between repository depth and ground surface that is between 10 and 100 times longer at existing salinities, compared with a pure fresh water case. The calculations in SKB 91 are based on the less favourable fresh water case, since the prevailing situation may change during the span of time that must be considered, and since the excavation work may disturb the balance. A release to salt water normally gives a considerably lower dose than one to potable water.

The analysis of the radionuclide release rates in the event of an initial canister defect shows that the release from the near field is only slightly affected by the water flow around the deposition hole.

The groundwater fluxes in the model block have been calculated with both stochastic and deterministic hydrology models. The flow patterns that are generated are in good agreement with each other. The results show that the flow is mainly determined by topographical conditions and a flat fracture zone above the repository. Other fracture zones only affect the flow pattern to a small extent. The principal discharge of groundwater from the repository area takes place to Lake Skålsjön, or to the surface water that runs down towards Lake Skålsjön along the Imundbo zone, see the fold-out map at the back of the report.

The travel times for water up to the ground surface have been calculated for flow paths that start in different parts of the repository. For nearly half of the flow paths, the transit time is so long that water from repository depth does not reach the ground surface until after 10,000 years, see Figure 5. For the flow paths that reach the ground surface before 10,000 years, the median value of the groundwater travel time in the reference case has been calculated to be 110 years.

The calculations show that the size of the release of nuclides to the biosphere is affected to some extent by the groundwater travel time. If the nuclides released from the near field reach the biosphere via a flow path with a groundwater travel time of less than 10 years, the calculations give a dose approximately 10 times higher than if the release had taken place via a flow path with a travel time of 100 years. At a groundwater travel time of 10,000 years the dose is about 10 times lower, see Figure 6.

The entire chain of calculations from release from the fuel to dose in the biosphere has been carried out for the reference case. The results show that the repository's impact on the environment is several powers of ten less than the dose limit suggested by the authorities. Compared to this margin, the effect on the results of the random variability in the hydraulic conditions is limited, see Figure 7.

The importance of the way in which radioactive materials enter the biosphere has been studied with a biosphere model. Compared to a leakage to potable water on land, the same release to the Baltic Sea gives doses that are about 100 times lower. If a well should be so extremely positioned that it manages to collect all the radionuclides that leak out from a repository, an individual who fills his entire water need with water from this well alone would receive a dose up to 100 times higher.

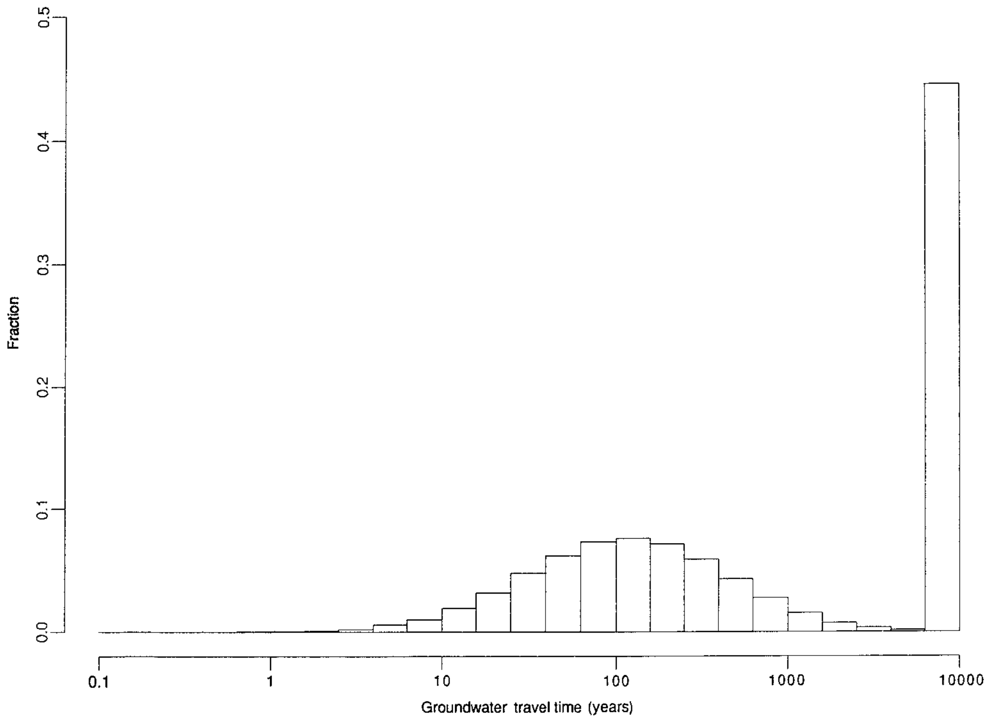



*Figure 5. Histogram of groundwater travel time for water from different parts of the repository to the ground surface for the reference case.*

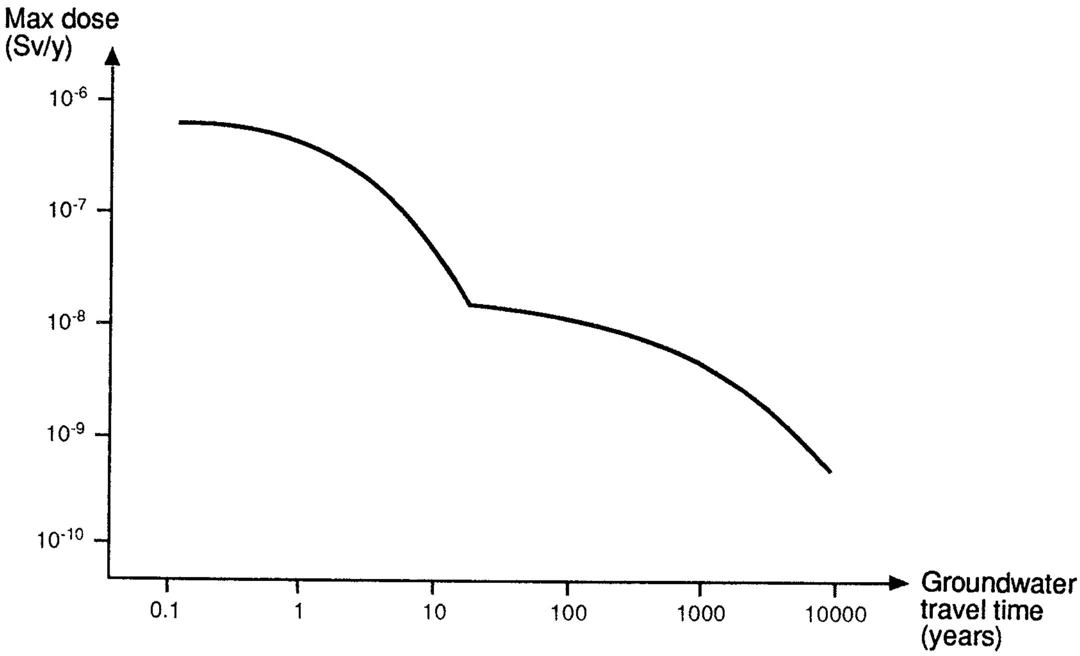



*Figure 6. Maximum annual dose commitment for release from an initially defective canister at different travel times for groundwater from canister to biosphere.*

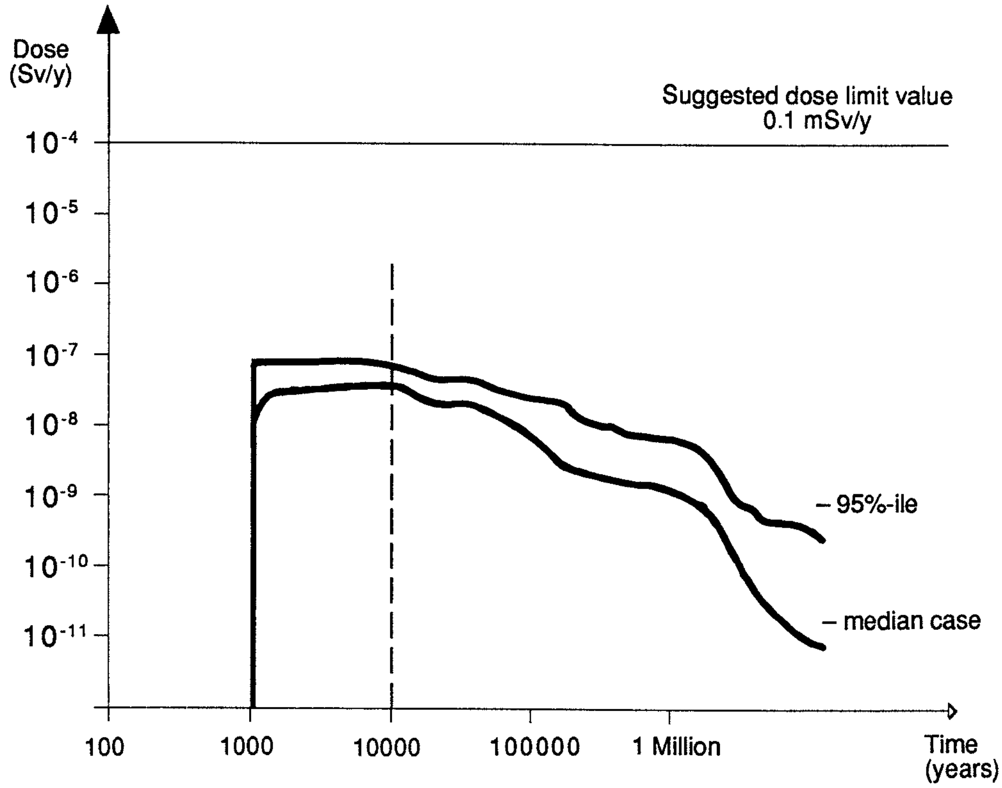



***Figure 7.*** *The reference case – Dose commitment for individuals at different times after closure of the repository. The curves show a typical case and an unfavourable case.*

**In summary**, the assessments show that the barriers in the near field isolate the radioactive materials in the spent fuel very effectively. Radioactive fission products and all actinides with high initial inventory and with the potential to give high individual doses are retained in the near field. Thus, cesium-137 and strontium-90 decay before the water comes into contact with the fuel in a defective canister. The solubility limits and sorption in the bentonite clay prevent other materials with high initial activity – such as the actinides plutonium, neptunium and americium and the long-lived fission products zirconium-93, palladium-107 and tin-126 – from escaping into the rock even if the canister has an initial defect.

In practice, only the highly soluble and long-lived nuclides carbon-14, iodine-129 and cesium-135, plus the long-lived uranium daughters radium-226 and protactinium-231, can escape from the near field. This limits the release (even with a damaged canister) to such a low level that the safety-related importance of the rock as a barrier to radionuclide transport is very limited. The principal safety-related requirement on the rock is therefore that it should provide a mechanically stable environment where canisters can be emplaced without landing in the middle of potential zones of movement, and that it should provide a chemically stable reducing environment for the near field.

**The rock as a barrier – variation calculations**

The safety requirements on a repository are intended to ensure that the safety of the final disposal system is based on several passive barriers. Thus, even if it is not necessary from a dose point of view to find the geologically absolutely most favourable site for a repository in Sweden, it is reasonable to attempt to utilize optimally the potential of the rock on the chosen site to act as a barrier against radionuclide migration.

The chemical environment in the Swedish bedrock, and the stability that rock blocks being considered for the repository can be credited with, differ very little from place to place. The factor that most readily summarizes the barrier potential of a given rock volume is the distribution of groundwater travel times from the repository to the biosphere.

To shed light on how this property, i.e. the distribution of travel times shorter than 10,000 years, is affected by different site-specific characteristics and parameters, some fifteen or so variations of the geohydrologic features of the site have been carried out in the reference case.

The variations cover

- properties of the rock mass in the repository area;
- properties of steeply dipping fracture zones;
- properties of near-horizontal fracture zones;
- the size of regional and local hydraulic gradients.

Other variations have been performed to demonstrate the importance of contact area between flowing groundwater and rock, dispersion and matrix diffusion, or the importance of salinity stratification in the groundwater.

A general observation is that streamline patterns and commonly occurring groundwater travel times in a bedrock such as in the Finnsjön area are relatively little affected by the locations of the steeply dipping fracture zones and their distance from the repository. In order for a clear effect to be apparent, the ratio between the hydraulic conductivity of the fracture zones and that of the rock must be increased from just over a factor of 10 to more than 100. Figure 8 shows how the distribution of travel times changes.

On the other hand, a clearer effect of changed conditions is obtained for fracture zones with a nearly horizontal orientation. If the flat-lying zone lying above the repository is replaced with "normal" rock, the flow pattern is changed and the flow paths become flatter. The effect is even clearer if a similar flat zone is assumed to lie below the repository. Figure 9 shows how the changes affect the groundwater travel times from the repository up to the ground surface.

**In summary,** the variations show that the flow pattern and groundwater travel time for water from the repository to the biosphere are changed to a relatively small extent by most of the variations of the hydrogeological characteristics on the site that have been performed. Significant changes are mainly caused by flat-lying, highly conductive zones, which can create both more and less favourable conditions than in the reference case by isolating the repository from groundwater gradients at the ground surface or by routing the water that passes the repository quickly up into a nearby discharge area. However, even in these cases, the effect of the repository's engineered barriers means that the dose is not affected by more than an order of magnitude or so, i.e. less than the margin to the recommended dose limit values.

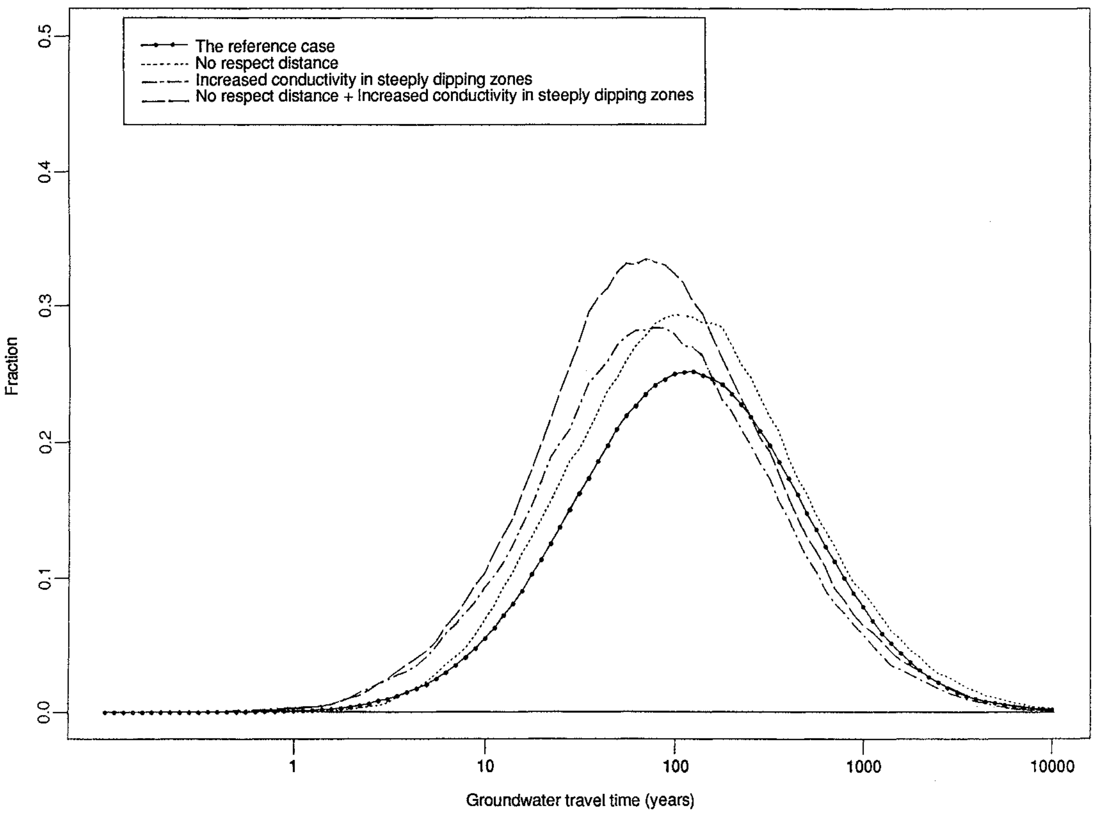



***Figure 8.*** *Dependence of groundwater travel times on the distance between repository and fracture zones and on the ratio between the hydraulic conductivity in fracture zones and rock.*

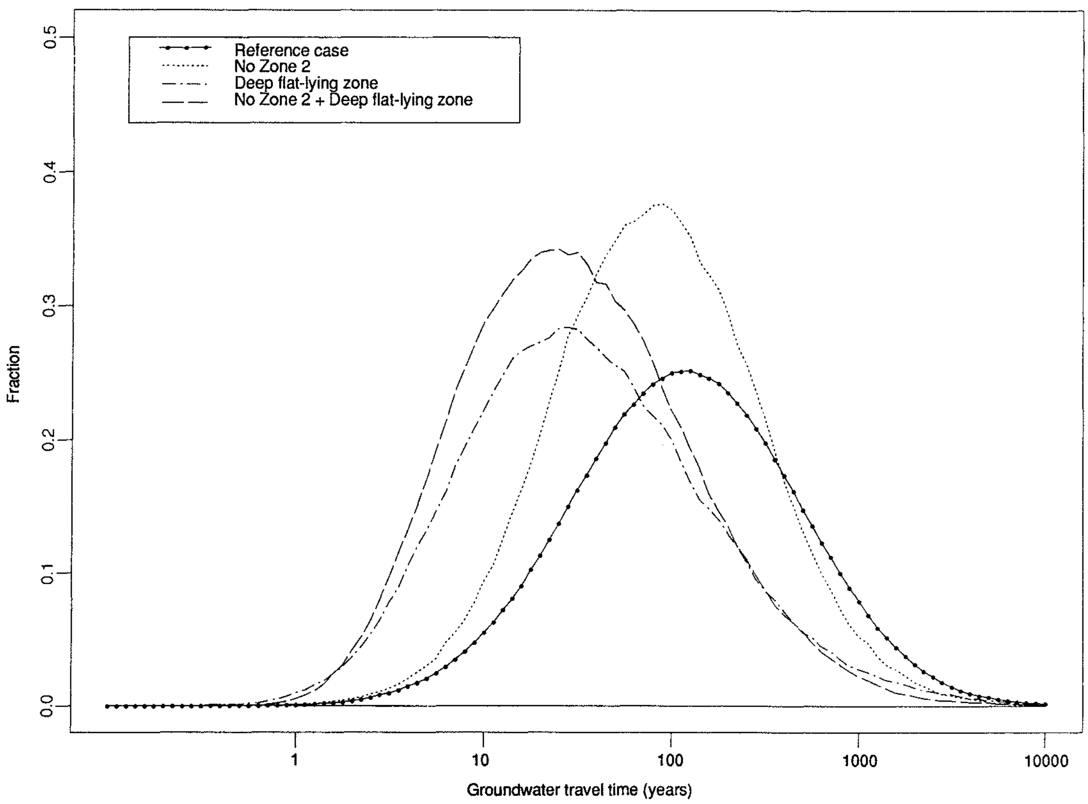



***Figure 9.*** *Dependence of groundwater travel times on flat-lying zones with high conductivity.*

If a high salinity in the groundwater around the repository persists for a long time, a lower groundwater flux will be obtained at the same time as wells with deep groundwater will become saline.

The effect of many of the variations discussed above is naturally dependent on the local conditions that have been chosen for the reference case. Even if there is a great similarity between future candidate sites, conclusions drawn from the results for one site may only be applied to other sites with caution.

## Repository configuration – adaptation to local conditions

The excavation of deposition drifts can create a zone with higher hydraulic conductivity parallel to the drift. If the direction of the drift is perpendicular to the hydraulic gradient, no appreciable effects will be obtained. Even when the drifts are oriented maximally unfavourably with respect to the fractures and the hydraulic gradient, the effects are small. Only when the above conditions are combined with large differences in hydraulic conductivity between the rock and nearby fracture zones will an increase in the short travel time fraction be noticeable, see Figure 10.

Provided that the rock block is sufficiently large, or that several adjacent blocks can be used for deposition, the repository layout utilized provides a good opportunity to adapt the positions of drifts and deposition holes to progressively obtained information on the local properties of the repository rock. The analyses show that the hydraulic conditions in the evaluated repository block are such that the shortest travel

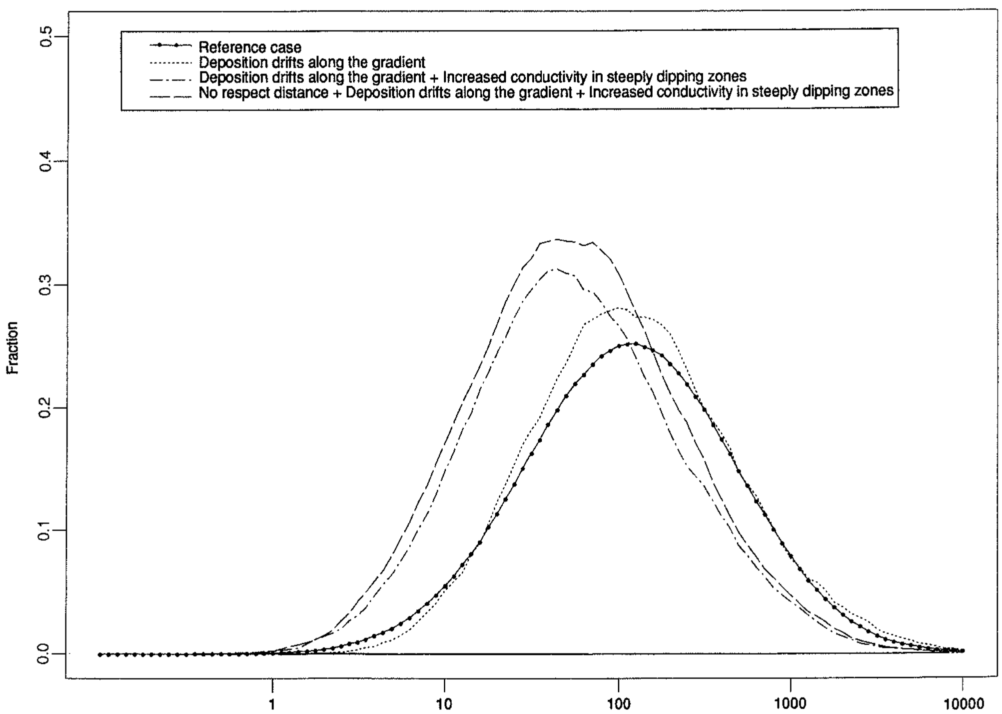



***Figure 10.*** *Dependence of groundwater travel times on increased conductivity around the repository drifts.*

times are always associated with a specific corner in the repository. For the Finnsjön area, the value of not depositing in this corner is greater than trying to avoid deposition positions that by chance have been located in unfavourable conditions.

The variations covering zones above and below the repository show that a respect distance between major flat-lying fracture zones and the nearest canister positions of around 100 m is well warranted. A change in the depth of the repository by 100 m up or down affects the travel times by a factor of two.

**In summary**, it can be concluded that some opportunity exists to exploit the potential of the local bedrock to act as a safety barrier by adapting the geometric configuration of the repository. However, the differences do not normally appear to be of such a magnitude that they would be decisive in determining whether a site is acceptable or not. One main reason for this is that the repository is extensive in space. Even if a certain placement of the repository were to bring a number of canister positions into a less favourable location, the safety of all the canisters in the repository would be affected only marginally.

Qualitative evaluations such as the above are deemed to be valid for all sites studied in Sweden. A quantification of the value of adapting the repository to local conditions is highly site-specific, however. Moreover, only part of the site-related information at Finnsjön has been obtained for the purpose of being used in a safety assessment.

Similar judgements of the importance of various parameters must nevertheless always be made when adapting a repository to a given site. There are great similarities as far as the limitations of the body of data are concerned between the premises for SKB 91 and the conditions that will prevail at an early stage of a site evaluation. The essential difference is that the geological investigations can be continuously focused on parameters and structures which are found to be important in the general analyses. In-depth analyses based on a larger body of data, interspersed with verifying investigations and a progressive refinement of the body of data, will permit a gradually improved understanding to be obtained of the safety-related performance of the site and a local adaptation of the repository design.

The assessment methodology that has been used for SKB 91 has therefore been built up so that it permits running assessments in parallel with ongoing site characterization and repository design. Models can be replaced to match the desired level of detail, and databases and most parameters can be changed in a simple manner, without requiring modifications in models and computer programs.

## SUMMARIZING CONCLUSIONS

The SKB 91 safety assessment shows that a repository constructed deep down in Swedish crystalline basement with engineered barriers possessing long-term stability fulfils the safety requirements suggested by the authorities with ample margin. The safety of such a repository is only slightly dependent on the ability of the surrounding rock to retard and sorb leaking radioactive materials. The primary function of the rock is to provide stable mechanical and chemical conditions over a long period of time so that the long-term performance of the engineered barriers is not jeopardized.

SKB 91 has shown that the safety-related requirements on a site where a final repository is to be built are such that they are probably met by most sites SKB has investigated in Sweden. The assessments also show that there are a number of factors that can strongly determine how the bedrock performs as an extra safety barrier. Examples are the presence and location of flat-lying structures and their hydraulic conductivity.

SKB 91 constitutes an example of how performance and safety assessments can be used to shed light on the importance of different geological structures in a potential repository area and to clarify factors that are essential from a safety point of view. The methodology can, in the continued siting work, be utilized to adapt the repository in such a way that the ability of the rock to contribute to the safety of the repository is effectively utilized. However, this requires access to site-specific data and an opportunity to augment these data continuously as the safety assessments progress.

# CONTENTS

# 1 GENERAL

*This chapter shows how the SKB 91 safety assessment fits in with SKB's overall activities, and describes the purpose of the assessment. An overview is then given of the repository system on which the safety assessment is based.*

## 1.1 HISTORY

One of SKB's functions is to come up with recommendations as to how and where the final disposal of Sweden's radioactive waste should be arranged. After review and approval by the regulatory authorities, SKB shall also design and build the necessary facilities and carry out final disposal of the waste.

Between 1977 and 1983, in keeping with the requirements in the Stipulations Act, subsequently superseded by the Act on Nuclear Activities, SKB published a series of reports that showed that it is possible to carry out a final disposal of spent nuclear fuel in the Swedish bedrock using available technology and in a manner that is acceptable in terms of safety and radiation protection. After extensive review by Swedish and foreign experts, this was approved by the Government in 1984. Through extensive investigations of study sites, SKB has also shown that there are several sites in Sweden that possess the geological properties required for this.

During the 1980s, SKB has continued its investigations of study sites in Sweden and examined alternative methods for final disposal. The body of knowledge has been expanded in terms of both an understanding of the processes that are important for long-term safety and data and models for being able to quantify them.

The experience gained from these studies has lent further support to the view that it is possible to isolate the fuel from the groundwater over a long period of time by encapsulating it in a copper canister. In a suitable environment, this isolation can be maintained for such a long period of time that the toxicity of the waste will decline to a level equivalent of that of rich uranium ores. The granitic bedrock in Sweden at a depth of a few hundred metres or more exhibits suitable chemical conditions for this. The results of the studies have also strengthened the belief that the rock in Sweden offers many sites where the bedrock also has a high capacity to retain radionuclides should they escape from the repository.

A fundamental principle of all planning for a final repository in Sweden is that its safety shall be based on multiple barriers, i.e. that the safety of the repository shall not be dependent on only one safety barrier. Accordingly, even if the canister is capable of completely protecting the waste from the groundwater for a very long time, it is also important to define the safety-related requirements that should be made on the bedrock under the assumption that radionuclides nevertheless escape from the repository's engineered barriers.

## 1.2 PURPOSE AND DELIMITATIONS

The present report presents a safety assessment (SKB 91) that examines how the long-term safety in a final repository is affected by the geological characteristics of the repository site, i.e. how the rock barrier performs under the assumption that radionuclides leak out of the repository. The report is intended to form part of the background material that is required for the siting of a final repository for spent nuclear fuel.

The following questions are explored:

- What importance do the site-specific characteristics of the bedrock and the hydrological regime around the repository have for overall safety?
- What relative importance do different site-specific characteristics have for safety?
- How can the placement and design of the repository be adapted to conditions on the site in order to take advantage of the safety barriers offered by the bedrock?

The report deals only with the safety of the repository during the passive storage phase, i.e. the time following its closure. The possibility of achieving adequate safety during the operating phase – i.e. during treatment, transport and deposition of the waste – is in all essential respects independent of the geological conditions on the repository site.

SKB's continued work during the '90s will include selection of the schematic design, siting of the final repository and adaptation of the design and the barrier system to the chosen site. During this phase, SKB 91 will serve as a basis for systematic analyses where parameters that affect safety are varied. A secondary goal is therefore to build up a system of efficient procedures for carrying out safety assessments. In other words, a system for handling of data, coupling of models, reporting of results etc. where models and databases can be exchanged in a practical fashion, depending on the purpose of the assessments.

The report covers only final disposal of spent nuclear fuel, since this waste category contains the largest quantities of radiotoxic materials and thereby imposes the strictest demands on the protective function of the repository. Certain types of long-lived decommissioning waste, internal reactor parts and operational waste may be disposed of in the repository for spent fuel, but the different repository sections do not have to be situated in such a manner that they affect each other.

## 1.3 MAIN FEATURES OF THE REPOSITORY

### 1.3.1 Principles

The following principles have served as a basis for the design:

- Final disposal shall be done in crystalline Swedish bedrock at a depth that protects the repository against disturbances from the surface (i.e. 300 – 700 m) in one or more blocks of rock surrounded by zones of weakness;
- The waste shall be encapsulated in canisters that are handled as separate units. Their fuel content, size and geometric placement in the repository shall be chosen so that the temperature on the surface of the canister is limited to well under 100°C;

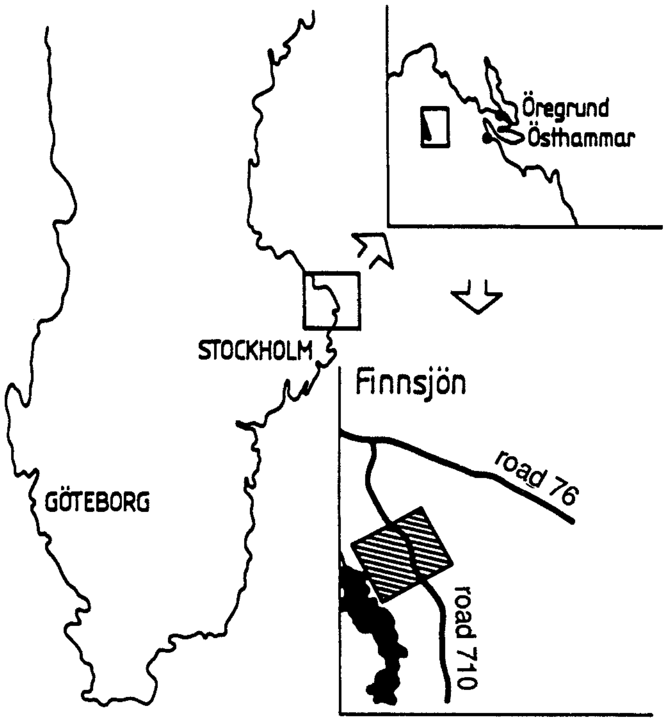



***Figure 1-1.*** *The Finnsjön area in northern Uppland.*

- The waste shall be surrounded by several different barriers to isolate the waste from surrounding groundwater and prevent or delay the dispersal of radionuclides from the deposited waste;
- The repository shall be arranged so that it is not dependent for its safe function on long-term surveillance and inspection. However, the placement of the repository in the bedrock will also make it possible to access the waste as long as the existence and location of the repository are known.

### 1.3.2 Repository site

The topography, geology and other site-specific characteristics of the proposed repository site have been chosen in agreement with the conditions in the Finnsjön area in northern Uppland, see Figure 1-1. Finnsjön has been chosen as an example, since an extensive body of data is available from the area. Finnsjön was judged in KBS-3 to be a possible site for locating a final repository, though less favourable than some of the other study sites. The present-day understanding of the geology of the site is strengthened by data from the Forsmark area and SFR as well as data from Dannemora Mine.

### 1.3.3 Design

Deposition is arranged largely as described in the KBS-3 report, see Figure 1-2. The spent fuel is placed in copper canisters, which are then filled with lead. The canisters are deposited one by one in holes drilled in the floor of a system of drifts in the rock. The space between canister and rock is filled with bentonite clay. The storage drifts are assumed to be regularly laid out at a centre-to-centre distance of 25 m. The distance between the deposition holes is 6 m. The quantity of fuel is assumed to be 7,800 tonnes (uranium weight), i.e. the quantity obtained from the Swedish nuclear power programme through the year 2010.

At closure of the repository, all cavities are backfilled. Drifts and shafts are provided with sealing plugs to block potential transport paths for the groundwater.

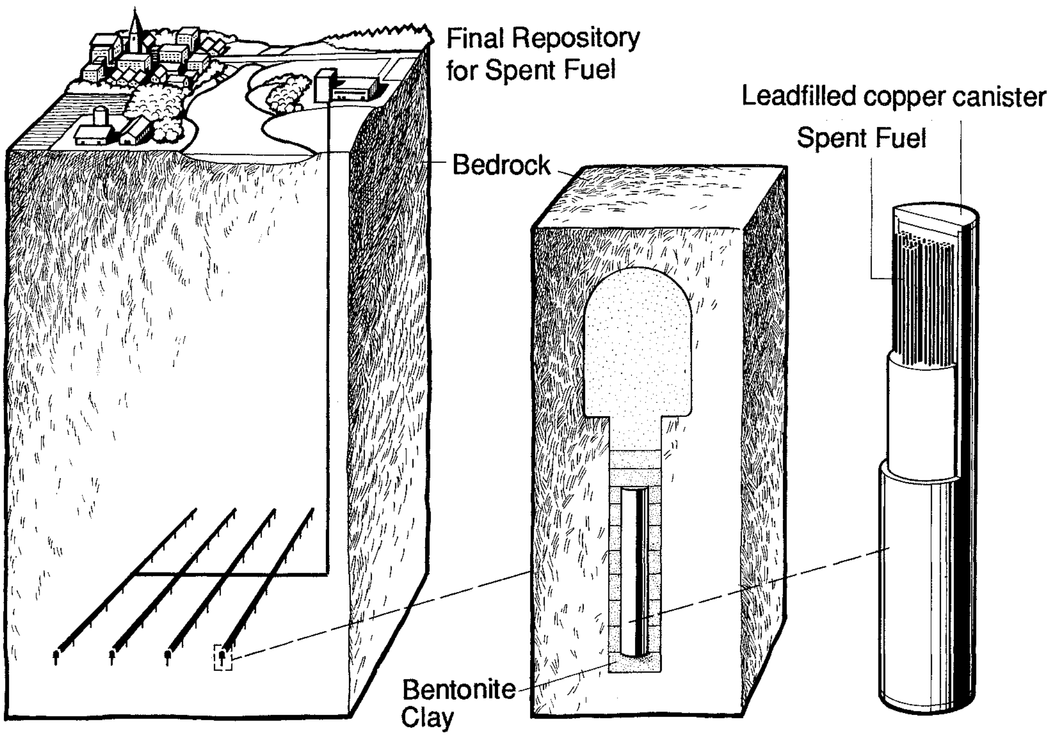



***Figure 1-2.*** *Schematic design of a final repository for spent nuclear fuel in crystalline basement.*

# 2 SAFETY ASSESSMENT METHODOLOGY

*The chapter provides an overview of the premises for and execution of SKB 91. The reference scenario is discussed and the sequence of model calculations is presented. The choice of performance index for the repository is described against the background of the acceptance criteria that have been discussed for the final disposal. Quality assurance in conjunction with the assessment is commented on.*

## 2.1 GENERAL

The time span that should be taken into account in the assessment of the safety of a final repository is long and the processes that can be of importance for safety are many and often slow. Safety assessments can therefore not be based solely on the results of experiments. The analyses must be based on models for known and possible interactions between the components in the repository. The external environment in which the repository has been placed and the environment that may exist in the future must also be taken into consideration.

In recent years, the methods for safety assessments of final disposal of radioactive waste have been discussed internationally, for example within OECD/NEA /2-1/. A collective opinion issued by IAEA and OECD/NEA and supported by CEC states that a satisfactory methodology for evaluating long-term safety is available /2-2/.

A reliable assessment of the performance of the repository system and the impact this performance has on safety requires the assessment to be carried out in a structured manner. The structure in SKB 91 is described below with references to the sections where the questions are dealt with:

- Acceptance criteria are established for the repository system to be assessed (section 2.4);
- The radioactive waste to be deposited is defined both chemically and physically. Its residual heat and content of radionuclides are calculated (Chap. 3);
- The manufacturing of engineered barriers and the materials used in them are described (Chap. 4);
- The conditions in the repository area are evaluated and summarized (Chap. 5) and the placement and excavation of the repository are described (Chap. 6);
- The relationships between nuclide releases to the biosphere and consequences for man and his environment are established (Chap. 7);
- Processes whereby different materials in the repository or its surroundings can interact with each other are identified and modelled (Chap. 8);
- Essential processes for the interaction in the repository and between the repository and its external environment are compiled in a reference scenario (section 9.3). Reasonable changes of these conditions that can be of importance for the long-term performance of the repository are evaluated in alternative scenarios or variation cases (see e.g. sections 7.5 and 9.6);
- The results of the assessments for reference cases and variations, alternative scenarios etc. are compared with the acceptance criteria and the conclusions are presented (Chap. 9 and 10).

## 2.2 SCENARIOS

Since long-term safety can be affected by various changes in the repository's future environment, the analysis of future scenarios occupies a central place in the safety assessment. International efforts have been made to formalize the assessment and establish a purpose-suited procedure /see e.g. 2-3/. One important question is how to show that no important phenomena or environmental premises have been overlooked.

Since SKB's aim in siting a repository is to avoid areas with unusual minerals and ores, regional zones of movement and extreme topographical gradients, it can be foreseen that all potential repository sites will resemble each other with regard to these environmental premises. The biosphere description has also been simplified, since site-specific differences in the biosphere between the studied sites in Sweden are considerably less than the changes that can occur over time. Intrusion scenarios have not been discussed, since the probability or consequences of someone intentionally or unintentionally getting into the repository is not expected to differ appreciably for the different candidate sites.

In SKB 91, the emphasis is placed on the performance of the repository area and on how differences in geological conditions would affect this performance.

### 2.2.1 Features, events and processes

The long-term safety of a final repository must be assessed with the aid of models. These models shall clarify the performance of the repository in connection with all the features, events and processes (FEPs) that can affect the repository. The methodology for identifying and defining these FEPs is divided into three stages:

1) Identification of features, events and processes (FEPs) that may affect a final repository in the future;
2) Sorting/screening of identified FEPs and definition of the FEPs that are included in the regular analysis sequence for the reference scenario (the Process System);
3) Combination of other FEPs to scenarios plus subsequent sorting/screening of them.

A methodical review of FEPs in accordance with the above was carried out in 1988-89 in a joint study by SKI and SKB /2-4/. A large number of processes and events were defined as feasible and systematically analyzed to arrive at the most probable combinations – the scenarios. In connection with this review, it was realized that the number of combinations, and thereby the number of calculation cases in a systematic review, will be far too great. However, the systematic review serves the purpose of documenting all identified FEPs in a database and presenting the reasons for including or excluding a given FEP in the calculation cases.

In a licensing phase, different site- and system-specific conditions (Features) are assumed to be well-known and documented. The main interest in this phase is in how different events or special processes can affect the performance of the repository. In a site selection phase, on the other hand, interest is focused on the possible safety-related importance of differences between available sites.

In SKB 91, the list of FEPs given in /2-4/ is used in its original condition. A division has been made into site-related FEPs (primarily Features) and others (Processes and Events, P/E). Site-specific features are generally studied as variations in the far-field model. For others, an updating of definitions and reasons for inclusion/exclusion of P/Es in existing models has been carried out, i.e. stage 2 above /2-5/.

This work has been done for all P/Es in the so-called Process System as described in /2-4/. The Process System, PS, is the total quantity of processes and events that will affect the repository with some level of certainty. After appropriate simplifications, the PS therefore serves as the basis for how the performance of the repository is modelled in the reference case.

To avoid a situation where the importance of site-specific factors is concealed by uncertainties in source terms or in near-field performance, or by changes in the biosphere, the number of variations or scenarios for these sub-systems has been limited. To further avoid a situation where variations in different parameters merely reflect the effect of applying safety margins, the parameters of the reference case have been selected in a reasonably realistic manner. This means that some of the pessimistic assumptions and simplified models that have been used in previous safety assessments have been replaced with greater realism in SKB 91.

To clarify the importance of the inhomogeneity of the rock and the uncertainty associated with the fact that the hydraulic properties of the rock have only been measured in a limited number of points, a stochastic model has been used to describe the groundwater movements in the rock. For each model realization, values for rock conductivity are randomly chosen between the measurement points in such a manner that the statistical picture of the conductivity of the area has the same correlation and variance as the statistics of the measurement results. In this way, the uncertainty in the modelling stemming from the natural variability of the rock and our imperfect knowledge of it will be reflected in the results of the different realizations with the stochastic model.

The variations performed beyond this reflect the effects of changed parameters such as mean conductivity, hydraulic gradient, locations of fracture zones in relation to the repository, repository depth etc.

A more complete status report on scenario development is intended to be given during 1992 in connection with the presentation of R&D Programme 92.

### 2.2.2 Reference scenario and variations

Data regarding waste characteristics, the sizing of the barrier system, site-specific premises, repository design and conditions in the surrounding biosphere can be found in the following chapters 3 to 7. The analyses are carried out under the assumption that deposition takes place at an even pace, after which the spaces are backfilled /2-6/. Finally, it is assumed that the repository will be sealed some time in the 2050s.

The most likely situation is that all canisters will fulfil the integrity requirements that have been established for encapsulation, i.e. that the groundwater will not come into contact with the fuel for a very long time, when the integrity of the copper casing has been violated by corrosion or internal pressure. However, the risk that a defect may have arisen in conjunction with canister fabrication cannot be entirely neglected. The reference case has therefore not been based on the most likely state of the repository, but has been defined so that each canister that is deposited has a probability of 0.1% of having an initial manufacturing defect. For the entire repository, this means that 5-6 canisters will have defects. The defect is defined as a through hole in the canister's welded joint.

Calculation models and premises for the calculations carried out are presented in Chapter 8.

Climate changes will occur during the time the repository is supposed to function. A temperature increase is likely in the shorter perspective, but in the longer perspective, on the 10,000-year scale, new ice ages are expected.

A glaciation changes many of the premises for a safety assessment. The decisive change from the safety viewpoint is, however, that the strong link between radioactive materials in the biosphere and doses to humans is broken when the intensive cultivation of soil for food production ceases. Therefore, a future ice age is not included in the reference scenario, even though many regard one as likely. However, to shed light on how a future glaciation could develop and in what way it could affect a deep repository, section 7.5 describes a glaciation scenario. Certain general assessments of its impact on the groundwater and on the risk of rock movements in the repository are presented in Chapter 9.

Besides the reference case, the importance of certain variations is also assessed in SKB 91. The purpose is to quantify the safety-related importance of various geological conditions. The variables have been selected in the expectation that they could be of safety-related importance, contain large uncertainties, or constitute parameters that can be varied relatively freely in designing the repository. The calculations are carried out with the model set from the reference case or with models that are more directly associated with varied parameters.

The variations that have been evaluated are listed below. A more detailed examination of the premises is made in Chapter 9.

- The groundwater flow;
- The water travel time from the canister to the surface;
- Dispersion conditions in the model block;
- The area of the rock surfaces that are in contact with the mobile groundwater;
- Propagation of the redox front;
- The influence of salinity on groundwater circulation;
- The depth of the repository;
- The presence or absence of flat fracture zones;
- Exclusion zone between repository and fracture zones;
- The conductivity contrast between fracture zones and rock mass;
- The size of the regional gradient;
- The disturbed zone in the rock caused by the excavation work, and its orientation;
- The various receiving bodies for the deep groundwater's outflow in the biosphere.

In addition, certain conditions have been discussed in a qualitative fashion, for example the importance of variations in groundwater chemistry and canister temperature for the safety of the repository.

## 2.3 MODELS AND DATA

A number of pessimistic simplifications were made in KBS-3 where positive factors were disregarded if they could not be quantified. For example, it was assumed that the effectiveness of the canister in inhibiting the leakage of radioactive materials is completely lost when it is penetrated by the first hole, and that the radionuclides reach the biosphere at the same instant they reach a major fracture zone. Such simplifications have been avoided wherever possible in SKB 91, but remain in certain cases where the process is so complicated that a detailed analysis does not appear meaningful today. The purpose has been to present a realistic, but not overly pessimistic, picture of the performance of the repository so that the effect of assumed variations in the characteristics of the site are not hidden behind exaggerated safety margins. Figure 2-1 shows a schematic diagram of the assessment procedure and the flow of information between the different sub-assessments.

Since the assessment is being performed for a site where the database was in part gathered for other purposes than the siting of a final repository, the statistical material may be deficient in some respects. However, by choosing a stochastic model to describe the repository's far field, the consequences of different random outcomes can be studied on the basis of statistics from existing investigations. Such a situation with limited data availability closely resembles the one that exists at an early stage of a site investigation. There as well the initial assessments must be made on the basis of a few boreholes and the results must be viewed primarily as possible outcomes. With a larger quantity of data available, the uncertainty in the modelling is expected to decrease. The calculations can shed light on the differences between different as-

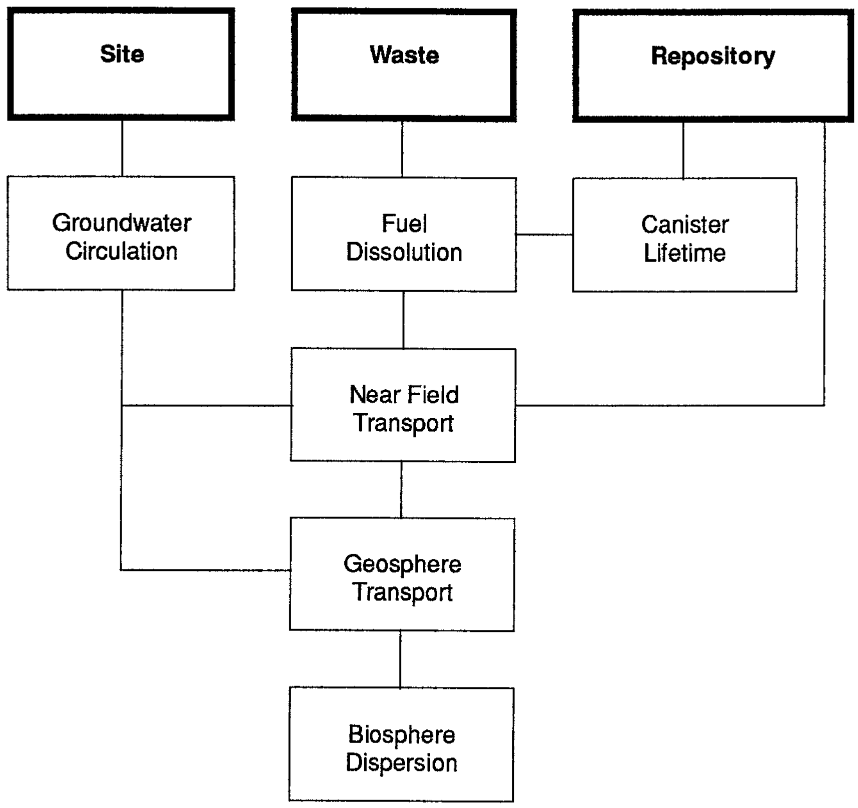



***Figure 2-1.*** *Schematic diagram of safety assessment in SKB 91 and its information flows.*

sumptions regarding groundwater conditions on the site, and also clarify what further investigations may be essential or unimportant, as the case may be, in establishing the suitability of the site for constructing a final repository.

In contrast to the assessment of the hydraulic conditions in the far field, fuel dissolution and the radionuclide transport in the near field are evaluated deterministically, partly so that uncertainties in the description of the near field will not conceal the effects of variations in the far field on the model results, and partly because the parameters in the near field can be quality-controlled to a higher degree than those in the far field.

The general premises and calculation sequence used in SKB 91 are presented below. Particulars regarding input data and models are given in Chapter 8.

- The quantity of spent nuclear fuel is based on the assumption that the Swedish nuclear reactors will be operated up to the year 2010;
- The nuclide content and residual heat in the fuel at different times are calculated on the basis of previous operating data for the time up to shutdown;
- The temperatures in the repository are calculated for a repository design similar to KBS-3;
- The groundwater movements in the area are calculated regionally and locally. The regional area gives boundary conditions to the local area. The modelling is based on topography, lineament interpretation and measurements of hydraulic conductivity;
- Canister performance is based on
  - thermodynamic stability in pure water, groundwater flux in the repository area, measured levels of corrosive substances in the groundwater and diffusive mass transport between groundwater and canister,
  - the porosity in a lead-filled canister and the build-up of gas pressure from the radioactive decay process,
  - a probability of 1/1,000 that an individual canister is deposited with an initial damage;
- Dissolution of the fuel is calculated based on
  - the assumption that it will take at least 1,000 years before water comes into contact with the fuel,
  - a new model where the conversion of the fuel matrix is controlled by oxidant production via $\alpha$-radiolysis,
  - pessimistically estimated gap inventories for cesium, chlorine, iodine and carbon;
- Nuclide transport in the near field is calculated using
  - a transient model for calculating the time of the first penetration,
  - a stationary model for diffusion through a canister hole via the buffer material up to the mobile groundwater in a fracture or in a disturbed zone around the drift;
- Nuclide transport in the far field is calculated on the basis of pathlines from different parts of the repository, generated by the groundwater model, and one-dimensional modelling of matrix diffusion and sorption;
- Dispersal of radioactive materials in the biosphere is calculated for a standard biosphere taking into account different transport pathways to man via well, cattle, grain cultivation and fishing;
- The dose conversion factors are based on the ICRP's recommendations.

The importance of changes in certain premises has been evaluated by means of variation analyses with relevant submodels or with the entire model chain.

## 2.4 RULE SYSTEM AND ACCEPTANCE CRITERIA

### 2.4.1 General

The disposal of spent nuclear fuel shall be carried out so that it meets the requirements on radiation protection and safety laid down in the Radiation Protection Act and the Act on Nuclear Activities. The licensing authorities are the Swedish Radiation Protection Institute, SSI, and the Swedish Nuclear Power Inspectorate, SKI.

Specific guidelines for the long-term aspects of disposal have not been established in Sweden. However, an ongoing cooperation between the Nordic authorities for nuclear safety and radiation protection is aimed at formulating recommendations. The proposed guidelines are expected to be common for the Nordic countries. A draft was published in 1989 /2-7/.

The document, which has been discussed both within the Nordic Region and internationally, appears to be in good agreement with today's view of acceptance matters in Europe and with the international recommendations discussed within, for example, the IAEA /2-8/. Since this Nordic work reflects the current thinking of the Swedish nuclear regulatory authorities, the account in the SKB 91 report has been expressed in terms that conform to the performance measures discussed in the aforementioned document.

### 2.4.2 Objective and principles

The goals and principles of the document are given below, accompanied by comments on their applicability to SKB 91.

**Objective** – The goal of final disposal is to protect human health and the environment and to limit the burdens on future generations.

The implications of this goal are summed up in seven principles:

**Principle 1** – Health risks and effects on the environment from waste disposal, at any time in the future, shall be low and not greater than would be acceptable today. The judgement of the acceptability of a disposal option shall be based on radiological impacts irrespective of any national boundaries.

A number of different safety indexes are used in SKB 91 in the consequence calculations for the assessment's reference case and in the variations. These measures are retained regardless of whether the variations lead to consequences that occur at different times. Moreover, the assessments compare consequences in typical biospheres, regardless of where they are.

**Principle 2** – The burden on future generations shall be limited by implementing "at an appropriate time" a final disposal option which does not rely for its safety on long-term institutional controls or remedial actions.

SKB 91 analyzes a passive multibarrier system, which is planned to be put into operation around the year 2020.

**Principle 3** – The individual radiation dose, excluding doses from unlikely disruptive events, shall be less than 0.1 mSv/y. In addition, the probabilities and consequences for unlikely disruptive events shall be studied, discussed and presented in qualitative terms and, wherever practicable, assessed in quantitative terms in relation to the risk of death entailed by a dose of 0.1 mSv/y.

SKB 91 reports the individual doses that could be obtained in the reference case and selected variations, under the assumption of a stylized and static biosphere. For times up to a few thousand years, the individual dose to groups living nearby is calculated. For times after this, the dose shall, in agreement with the discussion in the document, be regarded as a performance index for the repository. The time perspectives are discussed in greater detail in section 2.4.3.

**Principle 4** – The radionuclides that are released from the repository shall not lead to a significant change in the radiological environment on the repository site. This means that the flow of radionuclides from the repository to the biosphere shall be low compared with the inflow of natural-emitting nuclides, or quantitatively not more than

a) $10^5$ Bq/y of long-lived fission products;
b) $10^4$ Bq/y of long-lived actinides;

per tonne of natural uranium used to produce the waste.

Both activity flows to the biosphere and individual doses resulting from them are calculated for the reference case. The importance of certain variations is elucidated by examining how the probability of rapid transport pathways from the repository up to the biosphere changes.

**Principle 5** – The radiation protection for a final repository shall be optimized. Towards this end, radiation doses and risk shall be compared and balanced against many other factors that could influence the outcome.

SKB 91 aims at clarifying the safety-related importance of a number of parameters (e.g. repository depth, exclusion zone to fracture zones etc.) that can be chosen more or less freely. This constitutes a part of the body of information which is needed to be able to adapt the design of the repository to a selected site. The principle is not applicable to SKB 91.

**Principle 6** – Compliance of the overall disposal system with the radiation protection criteria shall be convincingly demonstrated by means of safety assessments based on qualitative judgements and quantitative results from models that have been validated as far as is reasonable.

The method for carrying out the safety assessment that has been developed in conjunction with SKB 91 will also serve as a basis for how future assessments in connection with siting and system design will be carried out.

**Principle 7** – A quality assurance programme for the components of the disposal system and for all activities from site confirmation through construction and operation to the closure of the disposal facility shall be established to achieve compliance with the design bases and pertinent regulations.

In the execution of SKB 91, certain rules for quality assurance have been established, chiefly in order to facilitate the traceability of data and of program versions. The purpose has been to test such procedures and the practical labor input they require in preparation for the impending start of the siting process.

**Other technical criteria**

The draft Nordic document contains a number of recommendations regarding the properties of the site and the design of the repository and the safety barriers. The purpose of the variations in SKB 91 is in fact to illuminate the safety-related value of many of these factors.

### 2.4.3 Time perspective and performance index

As is evident from the above principles, different indexes can be used to quantify the performance of the repository from the viewpoint of safety. The choice of such a performance index is influenced by the period of time or the phenomena to be considered, and by how the result is intended to be used.

The calculation results for the reference case are presented in the form of a probability distribution of individual dose to a farming group of people who are assumed to live adjacent to the discharge area for the groundwater that has passed through the repository area (Chap. 7). These individual doses are regarded as typical for a group of people who live in an environment that can be affected by the final repository. An extremely high degree of local self-sufficiency, in comparison with conditions in Sweden today, has hereby been assumed. It has further been assumed that the climate does not deviate significantly from the present-day climate. The dose is judged to be a reasonable index of the performance of the repository during the next few thousand years. This index has also been used as a comparison index to show how the performance of the repository is affected over longer periods of time. This analysis extends from the present to a point in time 1 million years in the future.

For the reference case and a number of variations, the calculated releases are also reported as release to the biosphere of radionuclides that dominate the releases in terms of dose. This analysis also applies to the period of time from the present up to 1 million years hence.

The performance of the repository after 1 million years is only discussed against the background of those processes that affect the repository's barriers.

The assessments in SKB 91 show that the ability of the near field to limit the releases is only slightly affected by water flux and rock quality. The safety role of the site can therefore be directly related to the barrier effect of the surrounding bedrock. In other words, the role of the site in determining safety depends on how site-specific properties affect the travel time between the repository and the biosphere. The frequency of stream tubes with different water travel times constitutes the most direct index for the safety-related performance of the site, and is therefore used as a comparison index for certain variations.

## 2.5 QUALITYASSURANCE

The work with SKB 91 has been subjected to a quality assurance plan. The purpose, aside from ensuring high and documented quality of the assessment, has been to provide a practical test of quality assurance procedures in preparation for the coming performance and safety assessments in conjunction with the selection of the design and site for the final repository for spent fuel. The emphasis has been placed on the accuracy and traceability of data and records.

SKB 91 has been divided into a number of analysis areas with delimitations and information flows between the areas as follows:

- A: Near-field analyses
- B: Analysis of radionuclide transport in the near field
- C: Geohydrological analyses
- D: Biosphere analyses
- E: Analyses of fuel composition
- F: Scenario analyses.

A leader has been appointed for each analysis area. This has also included the quality work. The project manager has had overall QA responsibility.

# 3 SPENT NUCLEAR FUEL

*This chapter presents the mechanisms for how radionuclides can be released from the spent fuel after the fuel matrix has come into contact with water. The calculation model is described. An account is given of the radionuclide content and residual heat of the fuel.*

## 3.1 FUNCTION OF THE FUEL IN THE FINAL REPOSITORY

### 3.1.1 General

The spent fuel that makes up the high-level waste also acts as an engineered barrier in the repository owing to its low solubility in water and its low corrosion rate. On canister penetration, release from the repository will be limited due to the slow dissolution of the fuel.

### 3.1.2 Mechanisms for release

The release of radionuclides from irradiated fuel in contact with groundwater is the result of two mechanisms:

- release of radionuclides in the gap in the fuel rods between the fuel pellets and the cladding tube, and from grain boundaries in the uranium oxide fuel;
- release of radionuclides due to dissolution or conversion of the uranium oxide matrix.

These mechanisms are in turn dependent on a number of different factors such as burnup, groundwater composition, local redox conditions, temperature etc. For repositories in Swedish bedrock, redox conditions have by far the greatest influence.

**Release from gap and grain boundaries**

The conditions under which irradiation takes place in the reactor are of importance for the release of volatile fission products during operation, for the microstructure of the fuel and for the segregation of fission products in the $UO_2$ grains. A number of studies have verified that these factors are of importance for how certain fission products are leached out on contact with water. Of particular importance is the release of cesium and iodine from the fuel matrix to the fuel-clad gap and to cracks in the fuel, since these nuclides can dominate the release at an early stage after a canister damage. The fraction of released cesium and iodine is comparable with the fission gas release during reactor operation /3-1, 2/. This nuclide fraction is leached out relatively quickly when the fuel comes into contact with water. This is illustrated for cesium in Figure 3-1, where it can be seen for both BWR and PWR fuel that the fraction released can be up to 1% of the cesium content in typical cases.

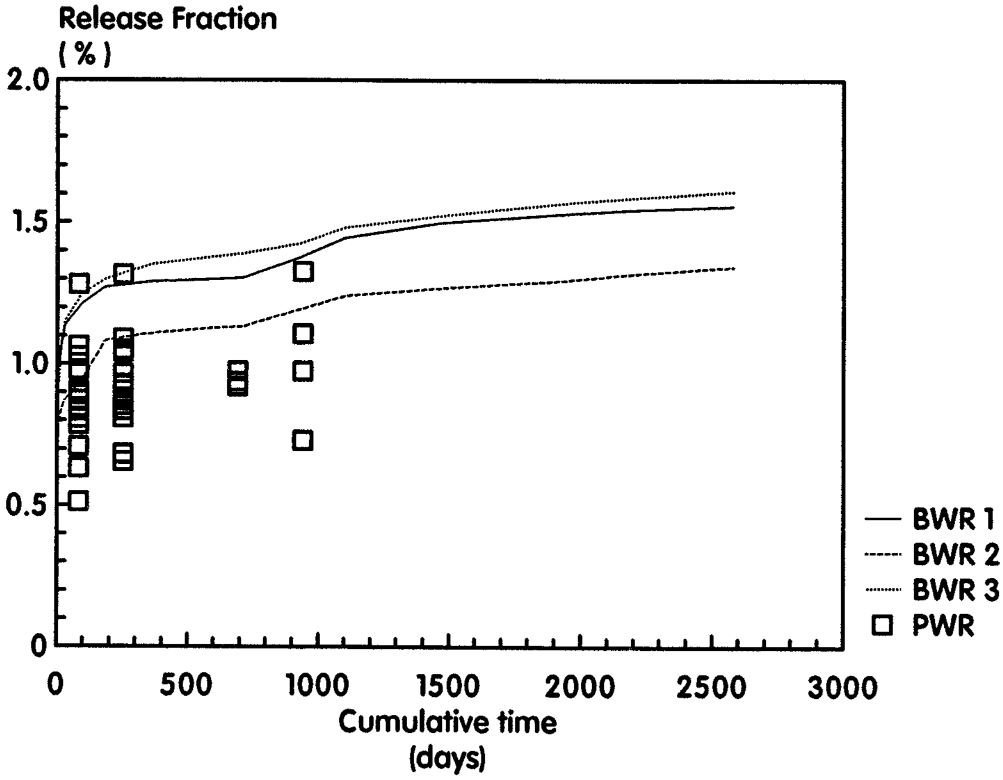



*Figure 3-1. Fraction of released cesium as a function of the contact time.*

The release from the grain boundaries in the fuel is more difficult to estimate, since the grain boundary inventory in the fuel is largely unknown. The attempts that have been made to determine a grain boundary inventory of fission products have without exception given negative results, i.e. it has not been possible to exactly determine any inventory. Auger analysis of intergranular fracture surfaces has not revealed any segregation of fission products to the grain boundaries of fuel with low fission gas release, with the exception of metallic inclusions containing the metals Mo, Ru, Pd, Tc and Rh, which can also occur in the grain boundaries /3-3/.

An attempt to determine the grain boundary inventories of Cs, Tc and Sr in light-water reactor fuel by chemical means revealed very small, if any, grain boundary inventory for strontium and technetium. The upper limit was set at 0.2%, but the analysis results were close to the detection limits, and negative values were even determined in a few cases. The inventory of cesium could be up to 1% of the total cesium content of the fuel /3-4/. This value is so low that it is covered by the conservatively set value for immediately released cesium in the safety assessment.

Nor do experiments performed within SKB's research programme indicate that there are grain boundary enrichments of fission products on any significant scale. New data show, however, that technetium, after prolonged contact with water under oxidizing conditions, leaches differently than cesium and strontium. This may suggest that technetium is leached from other parts of the fuel or from separate phases in the fuel. Under reducing conditions, however, this is of no importance, since the release of technetium is solubility-limited to very low levels.

## Release due to matrix dissolution

Fission products and actinides that are released due to matrix dissolution constitute the predominant portion of the fuel's radioactivity. Nuclides that lie embedded in the fuel grains are protected against direct dissolution in groundwater. They can only be released if the fuel matrix is dissolved or converted. In an environment in which $UO_2$ is oxidized to $U_4O_9$ or $U_3O_7$, the quantity of dissolved uranium will be limiting because oxidation to these oxides does not lead to breakup of the crystal lattice.

If the oxidation proceeds further, e.g. to $U_3O_8$, $UO_3$ or to some other U(VI) compound, the radionuclides can be released as matrix conversion proceeds, despite the fact that the uranium concentration in solution may still be low.

## Factors that affect matrix dissolution

*Groundwater composition*

The most important of the groundwater components that could affect the dissolution of irradiated $UO_2$ are carbonate and phosphate ions. Phosphate contents of any importance are unlikely in most groundwaters, while carbonate contents in the millimolar range are relatively common.

The effect of carbonate content on fuel dissolution under oxidizing conditions has been studied in the concentration range $1 \cdot 10^{-5}$ M to $3 \cdot 10^{-2}$ M. Although the concentration of dissolved uranium increases with increasing carbonate concentration, it has been found that the release of fission products does not increase to a corresponding degree /3-1, 6, 7, 8/.

*Radiolysis*

One effect of ionizing radiation from the fuel is a production of oxidants through radiolytic decomposition of water. Radiolysis produces equivalent amounts of oxidative and reducing species, but it is the greater reactivity of the oxidative species that is feared to give rise to local oxidizing conditions.

After only a few hundred years the $\gamma$- and $\beta$-radiation has decayed to levels that are negligible compared with the $\alpha$-radiation /3-9/. The $\alpha$-radiation will remain sufficiently high to be of potential importance for long periods of time. However, more recent studies in Canada indicate that there may be a threshold value of the dose rate below which no radiolytic oxidation to $UO_{2.33}$ occurs /3-10,11/. For oxidation degrees below $UO_{2.33}$, no oxidative dissolution of the fuel occurs. For CANDU™ fuel, this takes place after 500 to 1,000 years. For light-water reactor fuel, the dose rate would fall below the threshold value after about 20,000 years /3-9, 12/.

A summary of the entire experimental background for an electrochemical model for oxidative dissolution of $UO_2$ has been published by Shoesmith et al. /3-13/.

*Redox potential*

Studies have shown that in the oxidative dissolution of $UO_2$, the oxygen concentration and the redox potential are of great importance. The dissolution rate appears to be proportional to the partial pressure of the oxygen. Roughly speaking, a decrease in oxygen concentration by one order of magnitude also corresponds to a decrease in dissolution rate by one order of magnitude /3-14/. Under reducing conditions, i.e. redox potentials below about -100 mV on the hydrogen scale, $UO_2$ is the stable solid phase. Under mildly reducing conditions, one of the phases $UO_2$, $U_4O_9$ or $U_3O_7$ will therefore be stable /3-15/. Under these conditions, the release of radionuclides will be limited by the dissolution of uranium, since these uranium oxides have the same structure as $UO_2$ and no rearrangement of the crystal lattice takes place.

*Temperature*

Experiments with fuel dissolution show that the temperature dependence is relatively weak. In the temperature range 25 to 150°C, the dissolution rate increases by approximately a factor of ten /3-16/. For temperatures up to 85°C, the dissolution rate seems to increase by a factor of three to five /3-17/. The concentrations of actinides in solution decline by one or two orders of magnitude, however.

*Other engineered barriers*

Several studies have been carried out to study the effect of the engineered barriers on fuel dissolution and on the behaviour of fission products and actinides in solution. A study carried out by SKB shows that the presence of a dilute bentonite suspension does not increase the dissolution rate for the fuel, but that most of the actinides and fission products are sorbed strongly on the bentonite /3-18/. Similar observations have been made in the presence of iron and iron corrosion products /3-19/.

### 3.1.3 Model for fuel dissolution

**General**

A fuel dissolution model must have a term that describes the release of activity from the gap between the fuel pellets and the cladding tube (and in cracks in the fuel), and a term that describes the release due to matrix dissolution. It is also desirable to model the dissolution of any grain boundary activity. The release of gap activity can vary considerably, depending on the irradiation history of the fuel. It takes place very rapidly and can be regarded as instantaneous compared to the very slow matrix dissolution. After this phase, release of grain boundary activity may be dominant in a second phase, before matrix dissolution takes over in the final phase as a rate-limiting process.

The modelling of the first phase is relatively straightforward, providing the distribution of fuel with different fission gas releases is known. Typical values are about 1% of the total inventory of cesium and iodine, but can be higher in extreme cases.

Without detailed knowledge of the fuel, 5% cesium and 10% iodine can be set as conservative values for released gap activity.

Modelling of the kinetics in the second phase is considerably more difficult and requires further research, both to determine the grain boundary inventory and to determine its rate of release.

The modelling of matrix dissolution will be guided by whether the near-field conditions are such that $UO_2$ is thermodynamically stable or not. The stability of uranium dioxide under reducing conditions is largely dependent upon the fact that it has an extremely low solubility over a wide range of temperature and pH. If such reducing conditions are maintained in the repository that $UO_2$ is stable, the fuel dissolution can be described with a very simple model where the release rate is equal to the saturation concentration of uranium times the equivalent volume of groundwater that passes the fuel canister per unit time. Even though the simplicity of the model is appealing, it can only be applied if it can be shown that the radiation field at the fuel surface – particularly the $\alpha$-radiation – does not create local oxidizing conditions, where $UO_2$ is no longer stable. If this is the case, a model for radiolytic oxidative dissolution of the fuel must be applied.

**Radiolytic dissolution of fuel**

The variation of the $\alpha$-dose rate with time for spent fuel can be calculated accurately. The difficulty in the modelling lies in translating dose rate to oxidation rate for $UO_2$. To do this several assumptions must be made /3-7/.

In the first place, it is assumed that the oxidation rate is proportional to the dose rate. It has been shown that in an irradiated system that contains $Fe^{2+}$, the production of Fe(III) is proportional to the $\alpha$-dose rate /3-20/. It may therefore be reasonable to assume that this is also true for the $UO_2$ system.

In the second place, a value must be assigned to the proportionality constant. Not very much is known about radiolysis in the heterogeneous system $UO_2$-groundwater, but it is reasonable to assume that the reactions with the solid phase are slower than is the case for the homogeneous system with dissolved $Fe^{2+}$. If data from the $Fe^{2+}$ system is applied in the calculations, this results in radiolytic oxidation rates that are 3 to 4 times higher than what has been measured in the laboratory in systems where atmospheric oxygen has been present, and 30 to 40 times higher than what has been measured in systems where an attempt has been made to achieve oxygen-free conditions by adding hydrogen in the presence of a palladium catalyst. It is therefore reasonable to assume that the calculations give a pessimistic upper limit for the influence of the $\alpha$-radiolysis on the fuel dissolution rate. More realistic data is obtained if the experimentally measured values are applied to derive the proportionality constant. An application of the fuel dissolution rates that are measured in the laboratory under formally reducing conditions probably gives the most realistic description of the oxidation process under repository conditions, and the data measured under oxidizing conditions are also to be regarded as pessimistic. The fuel conversion as a function of time for different input data is illustrated in Figure 3-2.

It is worth pointing out that electrochemical experiments with $UO_2$ and $\alpha$-sources that have been carried out in Canada suggest that a linear relationship does not exist between $\alpha$-dose rate and the oxidation rate for $UO_2$ /3-21/. For high dose rates, models calculations give oxidation rates that are 3 to 4 times higher than the ex-

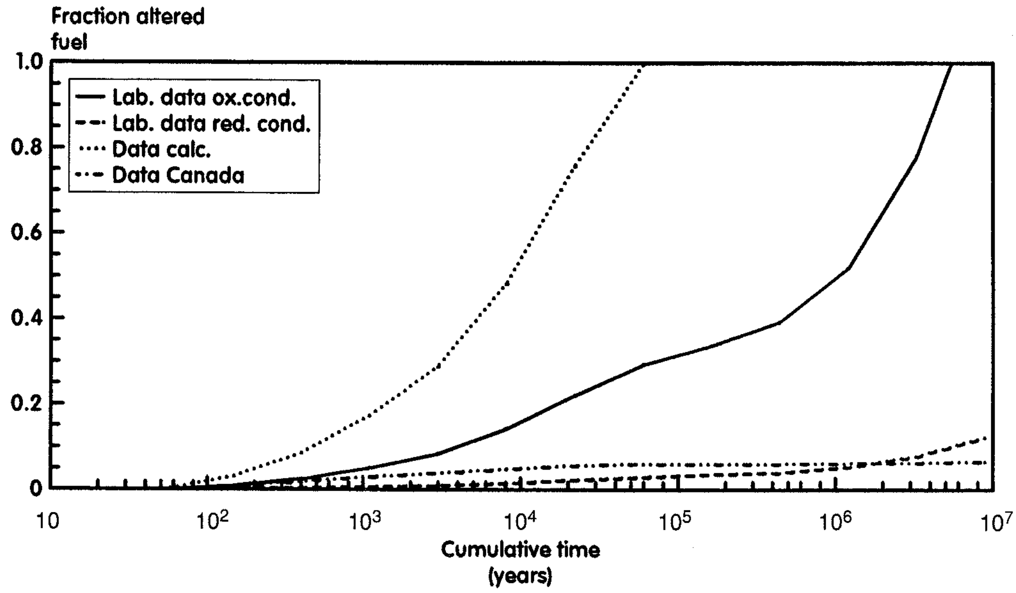



***Figure 3-2.*** *Fraction of converted fuel as a function of time. The oxidation is assumed to start 40 years after discharge from the reactor.*

perimental results. For low dose rates the calculations appear to overestimate the oxidation rate by several orders of magnitude. The reason for this is probably that the radiolysis model overestimates the effects of both $O_2$ and $H_2O_2$ on the oxidation of $UO_2$ /3-22/. A result of a calculation based on the results of the Canadian experiments is also illustrated in Figure 3-2. As can be seen in the figure, a fuel conversion takes place initially, but after about 10,000 years it has virtually ceased.

If there is – as previously discussed – a threshold value below which the radiolysis does not lead to oxidative dissolution of the fuel, a model for solubility-limited dissolution must be used. Current information indicates that this could be the case after several tens of thousands of years. In this case, the fuel dissolution rate would be several orders of magnitude lower than the value used in the calculations for SKB 91 for the water flux that applies in the repository.

### Comparison with naturally occurring uraninite

A qualitative idea of the degree of conservatism in the various calculation cases can be obtained from a comparison with natural uraninite deposits. Cigar Lake in Canada is one such deposit, which has survived one billion years in an open water-saturated system without any appreciable secondary dispersal of the nuclides in the ore /3-23/. An application of calculated values for the radiolytically induced oxidation, as discussed in the preceding paragraph, shows that a total conversion of the orebody would have occurred within an interval of 18-170 million years, depending on the choice of input data. If, on the other hand, the model is based on the Canadian experiments, it is found that in one billion years only a few percent of the ore would be converted. Although the model cannot be directly applied to uranium ore, since the latter can differ considerably from spent nuclear fuel in terms of morphology etc., the comparison nevertheless shows that the more pessimistic calculation cases must be regarded as unrealistic.

**Discussion of the model**

The model alternative based on laboratory data from oxidizing conditions has been chosen as a reference model for SKB 91. As is evident from the preceding discussions, this must be regarded as a pessimistic choice.

The choice of input data is most critical for an early canister damage. The relatively high radiolysis then leads to initially elevated oxidation rates. In the case of canister penetration after times longer than one million years, which is of the same order of magnitude as the life of the copper canister under normal conditions, the choice of input data for the model is less critical. Naturally the relative differences remain, as is illustrated in Figure 3-2, but the much lower $\alpha$-dose rate after such a long time leads to a considerably longer time for fuel dissolution. Thus, for example, the most pessimistic alternative, i.e. the case based on radiolysis calculations, gives a time of over two million years for complete conversion of the fuel. The corresponding time for the model used in SKB 91 is about 11 million years. It must also be regarded as pessimistic, however, since it is based on laboratory measurements under oxidizing conditions.

## 3.2 RADIONUCLIDE INVENTORIES AND RESIDUAL HEAT

### 3.2.1 General

Every year, SKB prepares an account of obtained and expected production of energy and waste in the Swedish nuclear power programme. The account is based on a number of fundamental data and assumptions regarding the operating time and availability of the reactors. The data on fuel quantities and fuel burnup in SKB 91 are taken from PLAN 90 /3-24/, or from the background material on which it is based.

As regards the fuel's general physical properties, the appearance and dimensions of the fuel assemblies etc., the reader is referred to PLAN 90 and KBS-3.

### 3.2.2 Quantities, burnups and residual heat at deposition

The spent fuel assemblies that are deposited in the repository will have different designs, burnups and decay times. For SKB 91, in agreement with the material on which the cost calculations are based, the total quantity has been divided into two roughly equal parts:

- typical fuel discharged in 1985 and deposited in 2025;
- typical fuel discharged in 2000 and deposited in 2035.

For "typical fuel discharged in 1985", the burnups have been chosen on the basis of the operating data used for the cost calculations. All burnups are given in Megawatt-days per tonne of uranium:

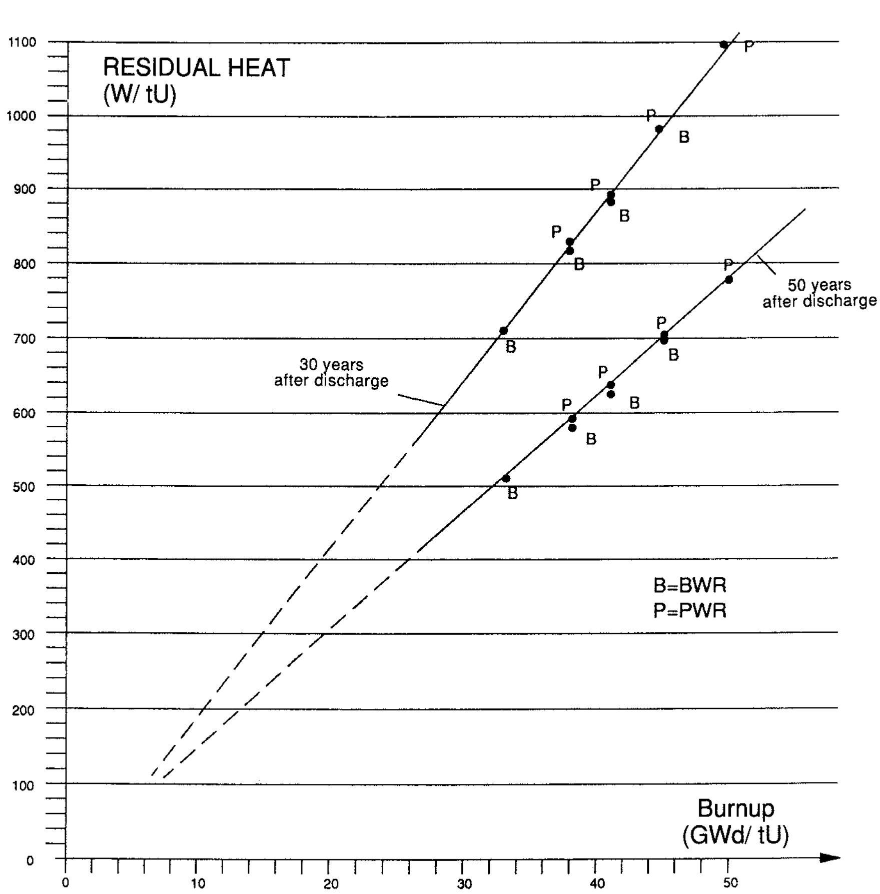



***Figure 3-3.*** *Residual heat of fuel assemblies as a function of burnup for two different periods of time after discharge from the reactor.*

| TYPE[1] | BURNUP | Quantity of U per assembly |
|---|---|---|
| BWR1 | 33,000 MWd/tU | 174.9 kg |
| PWR1 | 38,000 MWd/tU | 419.4 kg |

[1]The type designations are used only for SKB 91.

Calculations of residual heat and radionuclide content have been carried out for these fuel types.

For "typical fuel discharged in 2000", the burnup has been chosen so that it agrees with the assumptions in the cost calculations.

| TYPE | BURNUP | Quantity of U per assembly |
|---|---|---|
| BWR2 | 38,000 MWd/tU | 177.3 kg |
| PWR2 | 41,000 MWd/tU | 454.8 kg |

In view of the fact that future burnups may turn out to be higher, calculations have also been carried out for a number of other burnups. As is evident from Figure 3-3, the residual heat during the most interesting periods of time is roughly proportional to the burnup. The same is true of the radionuclide content. At a given nuclear power programme, expressed in total quantity of energy produced, the total quantity of spent fuel produced is inversely proportional to the fuel's average burnup. The repository's total residual heat is thus the same, regardless of what burnups are obtained in the future.

At a given residual heat per canister at the time of deposition, the surface area of the repository area and the number of canisters are not affected either. On the other hand, the easily leached fraction of certain assemblies can increase with increasing burnup, see section 3.1.2.

The outside diameter of the canister has, as in KBS-3, been chosen to be 800 mm, but the wall thickness has been reduced to 60 mm, see section 4.1. This allows the option, in a practical implementation, of emplacing more fuel in each canister than the eight assemblies assumed in KBS-3, up to a maximum of twelve BWR assemblies, or of depositing the fuel channels together with the BWR fuel. Such options will be further evaluated in SKB's continued work /3-25/.

In view of current and expected burnup levels and out of temperature considerations, a suitable residual heat for a canister at deposition has been set at 1,050 W. It has been deemed possible to combine both already discharged and future fuel assemblies with reference to their burnups so that most canisters end up at around 1,050 W ± 10%. For example:

- 9 BWR1 assemblies, 950 W at deposition;
- 4 BWR 1 + 2 PWR1, 1,014 W at deposition;
- 8 BWR2 assemblies, 1,066 W at deposition;
- 3 BWR2 + 2 PWR2, 1,148 W at deposition;
  etc.

A canister containing 8 BWR2 assemblies with a burnup of 38,000 MWd/tU has been chosen as a reference canister. This gives the canister a residual heat at deposition of 1,066 W and a content of 1.4 tonnes of uranium.

The quantity of spent fuel assumed in the cost accountings is equivalent to 7,800 tonnes of uranium. At a mean residual heat in the canister at the time of deposition of 1,050 W, the total number of canisters is about 5,300.

### 3.2.3 Radionuclide content and residual heat

The calculations of nuclide content and residual heat in the spent fuel have been done using the well-known computer programs CASMO and ORIGEN2. Details concerning the calculations are presented in /3-26, 27/. The decay chains of the heavy nuclides are shown in Figure 3-4.

Radionuclide content and residual heat in the chosen reference fuel at closure and different times thereafter are presented below. Parts made of Zircaloy, stainless steel and Inconel/Incoloy are included, but not the channels of Zircaloy that surround the BWR assemblies. Tables 3-1 to 3-3 show the content of important fission products, actinides and activation products in the spent fuel as a function of time. Figures 3-5 and 3-6 show the decline of residual heat and radionuclide content in the reference canister.

**4 N**

Pu 240 (6 570)
↓
U 236 (23.4 · $10^6$)
↓
Th 232 (14 100 · $10^6$)
Ra 228
Ac 228
↓
Th 228 (1.91)
Ra 224
Rn 220
Po 216
Pb 212
Bi 212
Po 212 (64.0%), T l 208 (36.0%)
↓
Pb 208 (stable)

**4 N + 1**

Am 241 (433)
↓
Np 237 (2.14 · $10^6$)
Pa 233
↓
U 233 (159 000)
↓
Th 229 (7 300)
Ra 225
Ac 225
Fr 221
At 217
Bi 213
Po 213 (97.8%), T l 209 (2.2%)
Pb 209
↓
Pb 209 (stable)

**4 N + 2**

Pu 242 (376 000)
↓
U 238 (4470 · $10^6$)
Th 234
Pa 234m (99.9%), Pa 234 (0.1%)
Pu 238 (88)
↓
U 234 (245 000)
↓
Th 230 (80 000)
↓
Ra 226 (1 600)
Rn 222
Po 218
Pb 214
Bi 214
Po 214
Pb 214 (22.3)
Bi 210
Po 210
↓
Pb 206 (stable)

**4 N + 3**

Am 243 (7 370)
Np 239
↓
Pu 239 (24 100)
↓
U 235 (704 · $10^6$)
Th 231
↓
Pa 231 (32 800)
Ac 227 (21.8)
Th 227 (98.6%), Fr 223 (1.4%)
Ra 223
Rn 219
Po 215
Pb 211
Bi 211
Tl 207 (99.7%), Po 111 (0.3%)
↓
Pb 207 (stable)

***Figure 3-4.*** *The radioactive decay chains of the heavy nuclides. The half lives in years are given in parentheses. Half lives shorter than 20 years have generally not been included. N is an integer. Nuclides in chain 4N have atomic weights that are evenly divisible by 4. All heavy nuclides are found in these decay chains. There is no coupling between them.*

**Table 3-1. Fission products (some can also occur as activation products) in Bq per tonne of uranium (+X = $10^X$, -X = $10^{-X}$).**

| | Half-life in years | 2050* | 10 years | 100 years | 1 K years | 10 K years | 100 K years | 1 M years | 10 M years | 100 M years |
|---|---|---|---|---|---|---|---|---|---|---|
| Se-79 | 65+3 | 1.7+10 | 1.7+10 | 1.7+10 | 1.7+10 | 1.5+10 | 5.9+09 | 4.0+05 | - | - |
| Sr-90 | 28,8 | 9.1+14 | 7.1+14 | 8.4+13 | 4.2+04 | - | - | - | - | - |
| Zr-93 | 1.5+6 | 7.6+10 | 7.6+10 | 7.6+10 | 7.6+10 | 7.5+10 | 7.2+10 | 4.8+10 | 8.1+08 | 1.6-09 |
| Tc-99 | 214+3 | 5.4+11 | 5.4+11 | 5.4+11 | 5.4+11 | 5.3+11 | 3.9+11 | 2.1+10 | 4.0-03 | - |
| Pd-107 | 6.5+6 | 4.9+09 | 4.9+09 | 4.9+09 | 4.9+09 | 4.9+09 | 4.8+09 | 4.4+09 | 1.7+09 | 1.1+05 |
| Sn-126 | 100+3 | 3.3+10 | 3.3+10 | 3.3+10 | 3.3+10 | 3.1+10 | 1.7+10 | 3.2+07 | 2.6-20 | - |
| I-129 | 15.7+6 | 1.3+09 | 1.3+09 | 1.3+09 | 1.3+09 | 1.3+09 | 1.3+09 | 1.3+09 | 8.5+08 | 1.6+07 |
| Cs-135 | 2.95+6 | 1.8+10 | 1.8+10 | 1.8+10 | 1.8+10 | 1.8+10 | 1.8+10 | 1.4+10 | 9.1+08 | 1.5-03 |
| Cs-137 | 30.1 | 1.4+15 | 1.1+15 | 1.3+14 | 1.3+05 | - | - | - | - | - |
| Sm-151 | 90 | 9.2+12 | 8.5+12 | 4.3+12 | 4.2+09 | - | - | - | - | - |

**Table 3-2. Actinides and actinide daughters in Bq per tonne of uranium arranged in decay chains (+X = $10^X$, -X = $10^{-X}$).**

| | Half-life in years | 2050* | 10 years | 100 years | 1 K years | 10 K years | 100 K years | 1 M years | 10 M years | 100 M years |
|---|---|---|---|---|---|---|---|---|---|---|
| Pu -240 | 6570 | 2.1+13 | 2.1+13 | 2.1+13 | 1.9+13 | 7.3+12 | 5.3+08 | 2.2+04 | 2.0+04 | 9.4+03 |
| U-236 | 23.4+6 | 1.1+10 | 1.1+10 | 1.1+10 | 1.1+10 | 1.4+10 | 1.6+10 | 1.6+10 | 1.2+10 | 8.5+08 |
| Th-232 | 14.1+9 | 2.7+01 | 3.3+01 | 7.9+01 | 5.6+02 | 6.3+03 | 7.8+04 | 8.0+05 | 7.0+06 | 2.6+07 |
| Am-241 | 433 | 1.4+14 | 1.4+14 | 1.3+14 | 3.1+13 | 4.5+09 | 2.9+06 | - | - | - |
| Np-237 | 2.14+6 | 1.4+10 | 1.4+10 | 1.8+10 | 3.9+10 | 4.5+10 | 4.3+10 | 3.5+10 | 1.8+09 | 4.2-04 |
| U-233 | 159+3 | 3.2+06 | 3.8+06 | 1.0+07 | 1.3+08 | 1.8+09 | 1.6+10 | 3.5+10 | 1.8+09 | 4.2-04 |
| Th-229 | 7300 | 1.8+04 | 2.1+04 | 7.9+04 | 5.4+06 | 6.3+08 | 1.4+10 | 3.5+10 | 1.8+09 | 4.2-04 |
| Pu-242 | 376+3 | 8.0+10 | 8.0+10 | 8.0+10 | 8.0+10 | 7.9+10 | 6.7+10 | 1.3+10 | 1.3+03 | |
| Pu-238 | 88 | 8.3+13 | 7.7+13 | 3.8+13 | 3.7+10 | 9.2-09 | - | - | - | - |
| U-238 | 4.47+9 | 1.2+10 | 1.2+10 | 1.2+10 | 1.2+10 | 1.2+10 | 1.2+10 | 1.2+10 | 1.2+10 | 1.2+10 |
| U-234 | 245+3 | 4.7+10 | 5.0+10 | 6.4+10 | 7.7+10 | 7.6+10 | 6.1+10 | 1.7+10 | 1.2+10 | 1.2+10 |
| Th-230 | 80+3 | 2.0+07 | 2.4+07 | 7.1+07 | 6.8+08 | 6.6+09 | 4.0+10 | 1.7+10 | 1.2+10 | 1.2+10 |
| Ra-226 | 1600 | 2.1+05 | 3.1+05 | 2.1+06 | 1.3+08 | 5.1+09 | 4.0+10 | 1.7+10 | 1.2+10 | 1.2+10 |
| Pb-210 | 22.3 | 8.0+04 | 1.3+05 | 1.3+06 | 1.3+08 | 5.1+09 | 4.0+10 | 1.7+10 | 1.2+10 | 1.2+10 |
| Am-243 | 7370 | 9.2+11 | 9.2+11 | 9.1+11 | 8.4+11 | 3.6+11 | 7.7+07 | 7.1+03 | 4.8+03 | 8.7+01 |
| Pu-239 | 24.1+3 | 1.1+13 | 1.1+13 | 1.1+13 | 1.1+13 | 8.3+12 | 6.3+11 | 7.1+03 | 4.8+03 | 8.7+01 |
| U-235 | 704+6 | 5.3+08 | 5.3+08 | 5.3+08 | 5.4+08 | 6.3+08 | 8.9+08 | 9.1+08 | 9.1+08 | 8.3+08 |
| Pa-231 | 32.8+3 | 1.3+06 | 1.4+06 | 2.4+06 | 1.3+07 | 1.1+08 | 7.4+08 | 9.1+08 | 9.1+08 | 8.3+08 |

**Table 3-3. Activation products from structural material and impurities in the fuel (some can also occur as fission products) in Bq per tonne of uranium (+X = $10^X$, -X = $10^{-X}$).**

| | Half-life in years | 2050* | 10 years | 100 years | 1 K years | 10 K years | 100 K years | 1 M years | 10 M years | 100 M years |
|---|---|---|---|---|---|---|---|---|---|---|
| C-14 | 5730 | 3.9+10 | 3.9+10 | 3.8+10 | 3.4+10 | 1.2+10 | 2.2+05 | - | - | - |
| Cl-36 | 300+3 | 1.1+09 | 1.1+09 | 1.1+09 | 1.1+09 | 1.1+09 | 8.6+08 | 1.1+08 | 1.1-01 | - |
| Ni-59 | 80+3 | 1.1+11 | 1.1+11 | 1.1+11 | 1.1+11 | 9.8+10 | 4.5+10 | 1.9+07 | - | - |
| Ni-63 | 100 | 1.2+13 | 1.1+13 | 5.5+12 | 6.2+09 | - | - | - | - | - |
| Nb-94 | 20+3 | 4.7+09 | 4.7+09 | 4.7+09 | 4.6+09 | 3.4+09 | 1.6+08 | 7.0-06 | - | - |

*2050 indicates the assumed date when the repository will be sealed.

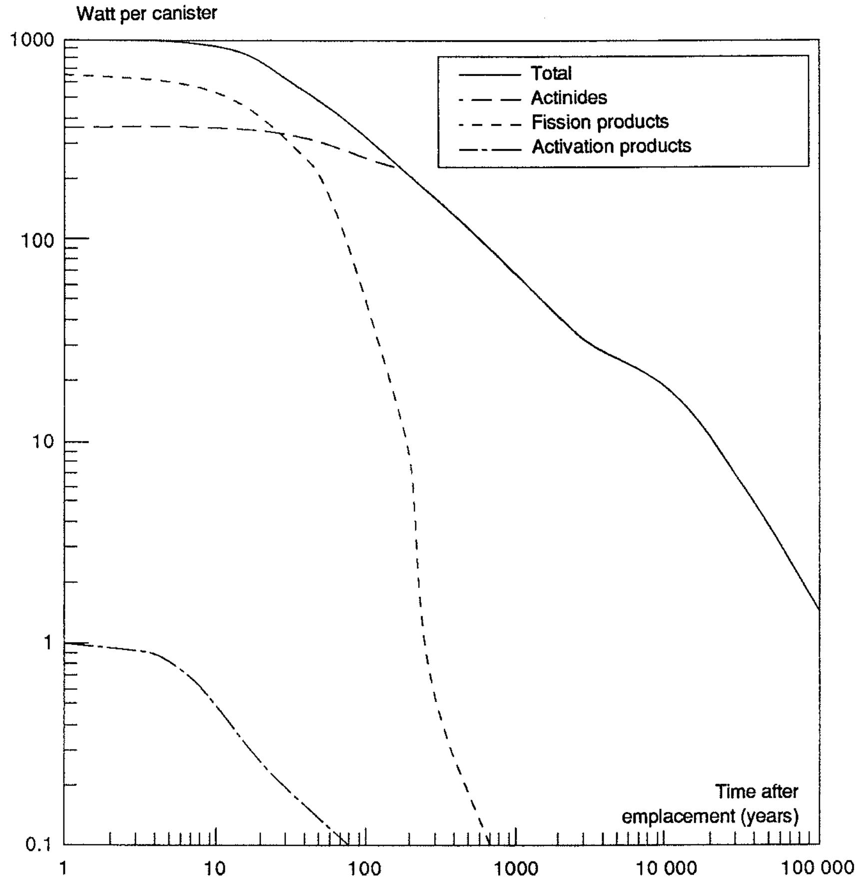



***Figure 3-5.*** *Residual heat in the reference canister as a function of the time after deposition.*

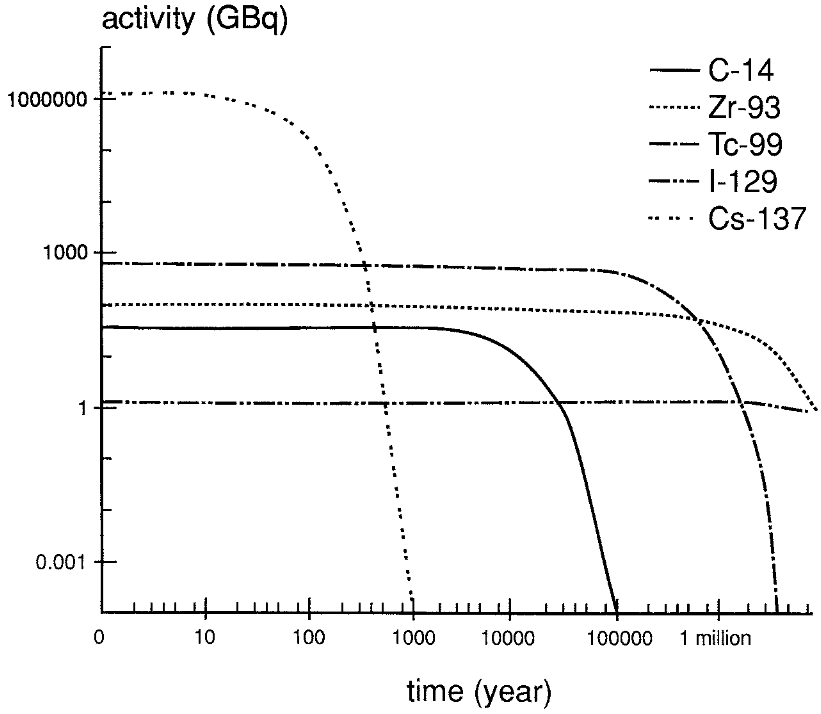



***Figure 3-6 a.*** *Content of important fission and activation products in one tonne of reference fuel as a function of the time after closure.*

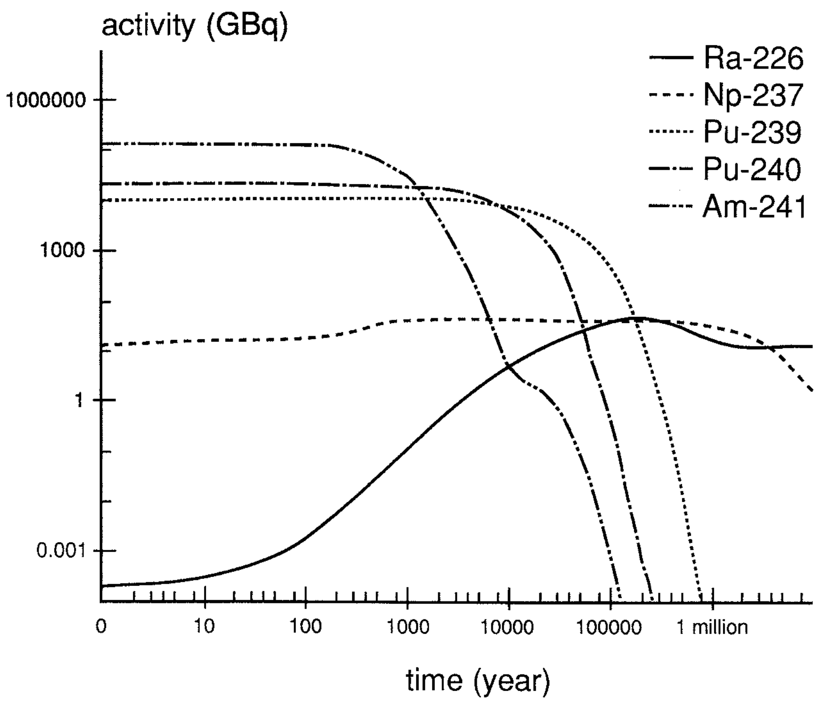



***Figure 3-6 b.*** *Content of important actinides in one tonne of reference fuel as a function of the time after closure.*

# 4 ENGINEERED BARRIERS

*This chapter presents material selection and design for the engineered barriers – canister and clay buffer. The durability of the barriers is discussed.*

## 4.1 CANISTER

### 4.1.1 Role of the canister

Before deposition, the spent fuel will be encapsulated in a canister. The canister is supposed to serve as protection during handling in the repository and, its most important function, as a barrier to release of radionuclides from the nuclear fuel. In view of the fact that both the residual heat of the fuel and its ability to radiolytically decompose water decline with time at the same time as the radionuclide content diminishes, the function of the canister is most important at an early stage. However, the longer the canister's isolating function lasts, the lower the requirements on the repository's other barriers will be.

### 4.1.2 Design and alternatives

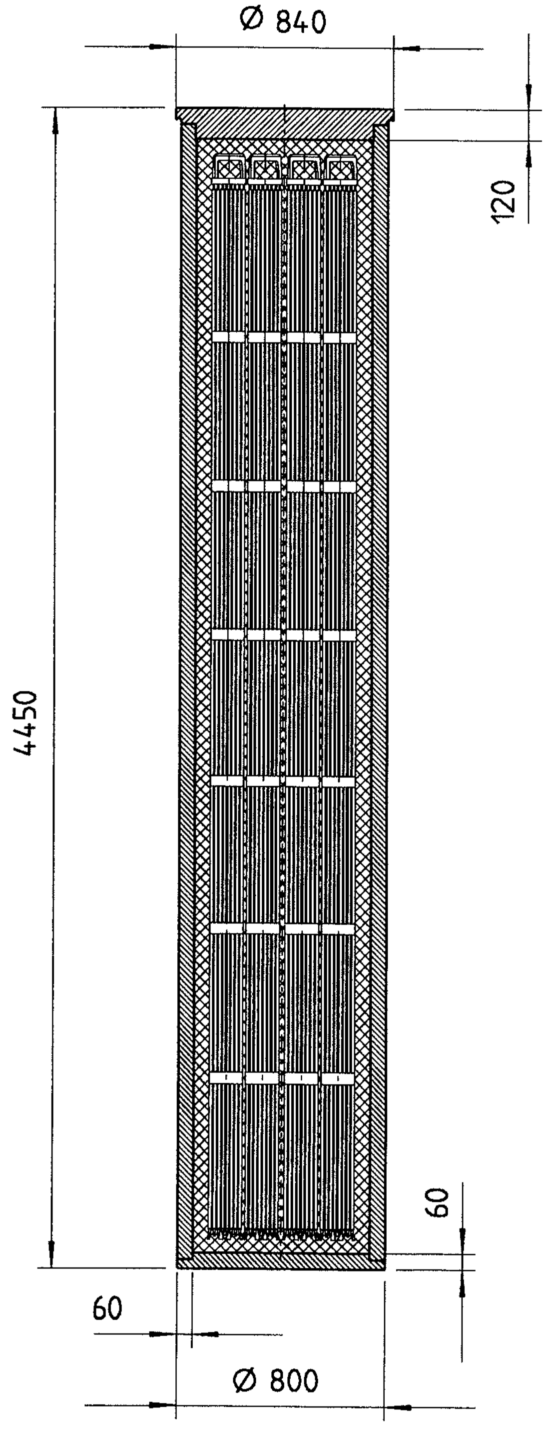
#### Material

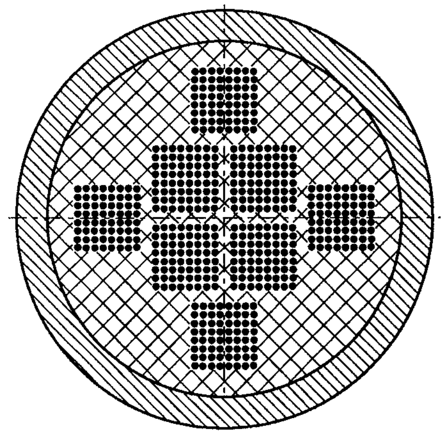
In order to obtain high corrosion resistance for the canister in the expected repository environment, the canister is fabricated of copper. There are several different copper grades that give a high corrosion resistance, for example oxygen-free pure copper, oxygen-free copper alloyed with 0.15% silver and oxygen-free copper with small additives of e.g. phosphorus or magnesium. The phosphorus-containing copper and the pure copper possess the same resistance to stress corrosion cracking /4-1/, but the pure copper possesses slightly better weldability /4-2/. On the other hand, creep tests have shown that at elevated temperatures (>200°C), pure copper has lower creep ductility than the other copper grades /4-3/. The final choice of copper grade will be based on an evaluation of the optimum combination of mechanical properties of the different materials.

#### Dimensions

The design of the canister is based on the KBS-3 canister. This canister is a thick-walled copper canister whose mechanical strength has been increased by filling it with lead. Alternative designs have not been discussed within SKB 91, since they are dealt with in a separate project called PASS, Project Alternative Systems Studies.

Based on the KBS-3 canister, certain modifications have been made. The reference canister is illustrated in Figure 4-1. In order to avoid unnecessary deviations from the near-field geometry in KBS-3, the outside dimensions of the canister have been kept



Section of canister

| | |
|---|---|
| Canister surface ($m^2$) | 11.18 |
| Estimated weight (kg) | |
| Canister | 5370 |
| Fuel assemblies | 2100 |
| Cast lead | 14630 |
| Total | 22100 |

***Figure 4-1.*** *Reference canister for SKB 91.*

the same. The outer shell of copper has, however, been reduced in thickness from 100 mm to 60 mm.

### Fabrication

The outer copper casing can be fabricated in a number of different ways /4-4/. In addition to the method described in KBS-3, fabrication of a forged and turned canister, other methods may also be considered, such as hot pressing of a whole canister or tube for the canister's shell, or rolling and forming of copper sheet. The first method has the advantage that only one weld at the lid is required to seal the canister. The other methods require more welds, both along the bottom and at the lid, and in the case of rolling and forming also a weld along the shell. However, these extra welds are done before fuel is placed in the canister, which facilitates both welding and subsequent quality control. Owing to the wall thickness of the canister, electron-beam welding appears to be the most suitable closure method, although friction welding may be considered as an alternative method.

### Quality inspection

There are two practical methods for quality inspection of the welds in the copper canister: ultrasonic testing and radiography. For the fabrication methods that require several welded joints, radiography can be well-suited to check them. Radiography is a sensitive method that enables several kinds of defects to be detected, with the exception of cracks perpendicular to the examination direction. Since all welds are expected to be performed by means of electron-beam welding, which gives a narrow joint, the method will be very revealing if the examination takes place in the direction of the electron beam. Ultrasonic testing is best suited for the welded joint in the lid /4-5/.

## 4.1.3 Chemical stresses

The canister's chemical stability was evaluated in conjunction with the assessment for KBS-3 /4-6/. Despite extensive research, no new facts have emerged that would occasion a reevaluation of the assessment of the corrosion attacks that was made then. However, more realistic assumptions have been made in connection with the corrosion evaluation for SKB 91.

In KBS-3, a pitting factor (the ratio between pit depth and average material loss) of 5 was assumed as the most realistic. The new assessment is based on a less pessimistic evaluation of the background data that was collected for KBS-3 as well as on an analysis of the same data done by AECL of Canada with the aid of extreme value statistics. The background data for KBS-3 show that the most probable value of the pitting factor is 2, even though there is some probability of greater pitting. The Canadian analysis shows that there is a very low probability that deep pits (pitting factor >2) will form on copper /4-7/.

In KBS-3 it was assumed that after reducing conditions had been established in the repository, sulphide in the buffer mass causes corrosion of the copper and that this depot of sulphide is exhausted over the course of 1,000 years. After this period, copper corrosion is dominated by corrodants that are transported to the canister through the groundwater. However, since the solubility of sulphide in the bentonite pore water is limited and the transport to the canister of dissolved sulphide takes place by diffusion, this will take considerably longer time. Calculations show that it will take more than 100,000 years to deplete the bentonite of sulphide. During this time no corrosion caused by sulphides can take place, since the sulphide content of the bentonite pore water is higher than in the surrounding groundwater /4-8/. Taking into account this and expected groundwater flows in the repository, no corrosion penetrations will take place on the canister at a pitting factor of 2 before more than 100 million years have passed.

The conclusion of the corrosion assessment must therefore be that it is highly unlikely that corrosion will decisively limit the life of the canister.

### 4.1.4 Mechanical stresses

The integrity of the canister can be violated by external forces. In the repository the canister will be exposed to a total external isostatic pressure of 16 MPa. This pressure is composed of the hydrostatic pressure at a depth of 600 m (6 MPa) and the bentonite's swelling pressure of maximum 10 MPa. To withstand this pressure the canister is filled with lead. However, 100% filling of the canister cannot be guaranteed, in part due to the differences in coefficient of thermal expansion between lead and copper. The resulting porosity in the lead of about 2% may be reduced by creep deformation of the outer copper shell, which can thereby undergo a creep strain of up to a few percent. With the possible exception of copper grades where low creep ductility has been demonstrated at elevated temperatures (>200$^{o}$C) /4-3/, creep strains of that magnitude are not a threat to the canister's isolating capacity.

A rock movement on the scale of a metre straight across a canister could damage the canister. The choice of repository site shall, however, ensure that it is protected by distinct regional zones of weakness in which any large-scale rock movements would tend to be released (see section 5.2.1). At the same time, the locations of the deposition holes shall be chosen in such a manner that fracture zones and areas with unsuitable rock stresses are avoided to further reduce the risk of large local movements across the canister positions (see section 6.3.3). Together with the capacity of the bentonite buffer for plastic deformation, this means that rock movements across a canister position of such magnitude that the canister would be damaged are deemed to be so unlikely that they are of no importance for the choice of repository site, other than in the ways indicated above.

Besides external mechanical stress, the canister will be subjected to internal pressure due to the formation of helium by $\alpha$-decay. If the generated helium is released from the fuel matrix it can accumulate in the empty volume inside the canister. The resultant pressure build-up is illustrated in Figure 4-2. The point in time at which the helium build-up results in canister penetration depends on the creep ductility of the copper material. As is evident from the figure, which applies to a completely rigid canister, this will probably not take place until after several million years, but long before corrosion has led to canister penetration. In other words, internal pressure build-up is the most probable process limiting the life of the canister in the repository.

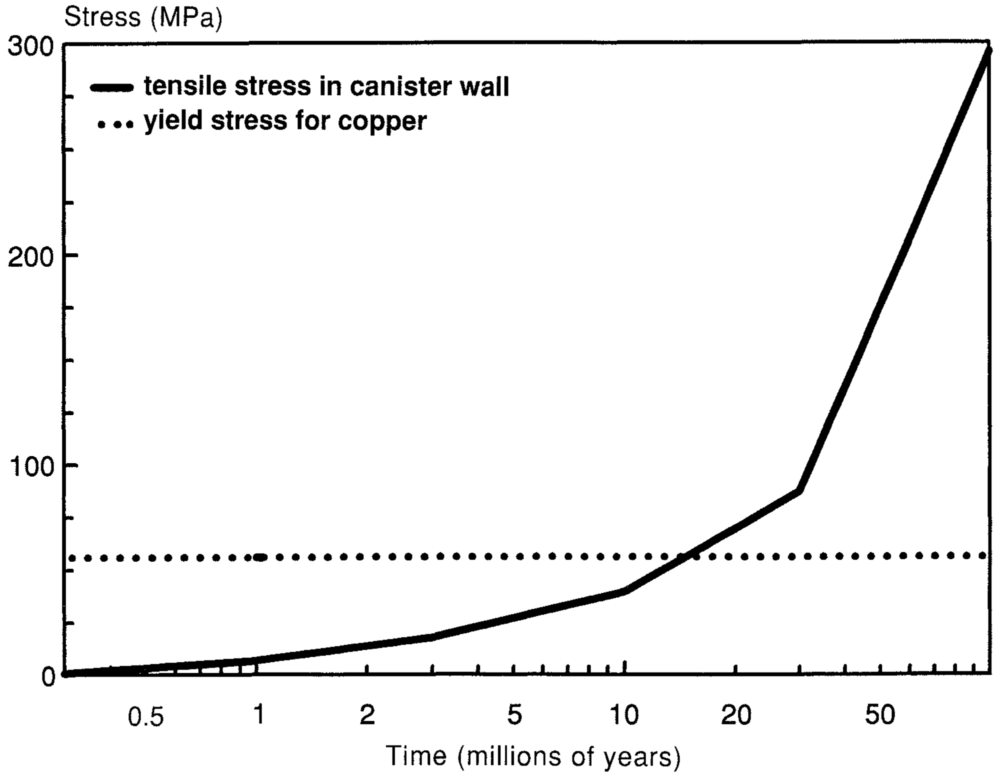



***Figure 4-2.*** *Calculated pressure build-up in the reference canister as a function of time.*

In the short time perspective, initial canister damage is therefore the only realistic mechanism for the groundwater to come into contact with the fuel in the repository. With a rigorously executed quality control programme, the probability that defective canisters will be deposited is very low. The extreme case for initial canister damage is judged to be a canister where sealing by means of electron-beam welding has failed due to operational problems with the welding equipment. The defect can be assumed to arise at a momentary interruption in the welding and result in an approximately 5 $mm^2$ large hole through the copper shell. An investigation of the corrosion effects of a small hole in the canister has shown that there is no process that would lead to greater corrosion in the hole than on other parts of the canister /4-9/.

## 4.2 BUFFER

### 4.2.1 Role of the buffer

The buffer material surrounds the canister in the deposition hole. On closure of the repository, the overlying disposal drifts are backfilled, see Figure 4-3.

The function of the buffer material is, in combination with the rock, to comprise a protective zone with a suitable environment around the canister.

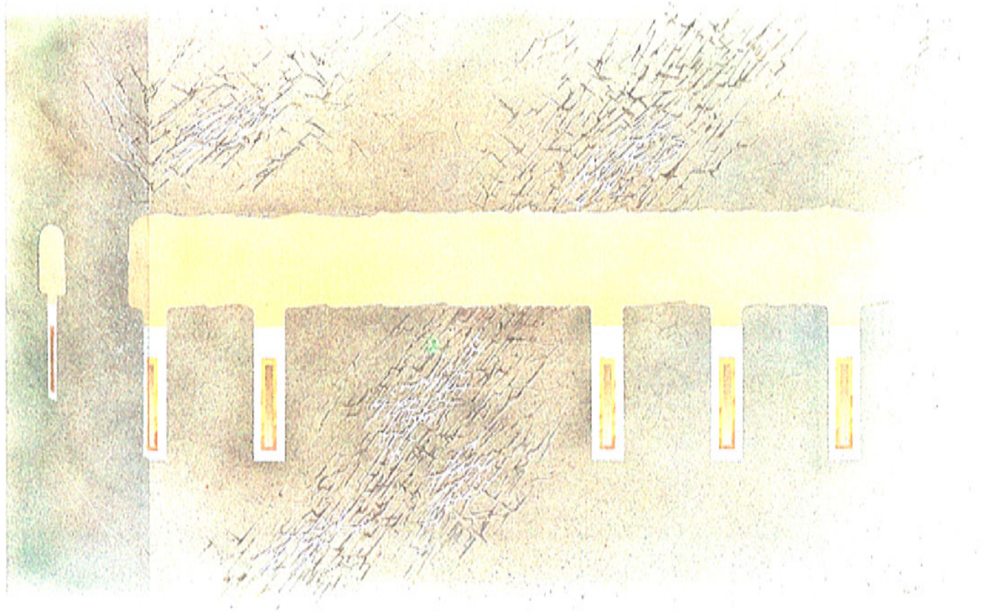


***Figure 4-3.*** *Final repository according to the KBS-3 method allows good opportunities for adaptation to varying rock conditions.*

Essential properties for the buffer material are:

- low hydraulic conductivity;
- good bearing capacity so that the canister is held in position in the deposition hole;
- suitable plasticity to prevent damage to the canister in the event of rock deformation;
- good thermal conductivity, so that the heat emitted by the fuel is transferred to the rock without the temperature of the canister or the buffer material becoming too high;
- long-term stability so that the material retains its properties.

On absorbing water, high-density bentonite swells and its plasticity increases. If the swelling is prevented mechanically, a high swelling pressure arises. This leads to self-sealing and homogenization and prevents water-bearing passages from lasting long in the material. The microstructure of high-density bentonite is characterized by the fact that only a small portion of the pore system is continuously open with mobile water.

### 4.2.2 Buffer material

The buffer material consists of compact bentonite that is applied in the form of highly compacted blocks. The bentonite grade can be chosen with different standards of purity. Natural sodium bentonites are found in the USA, among other places. In SKB 91, MX-80 Volclay has been chosen as reference bentonite /4-10/. Bentonite from Sardinia is used in SFR. It was originally a calcium bentonite that has been treated with soda to form sodium bentonite, so-called "activated bentonite".

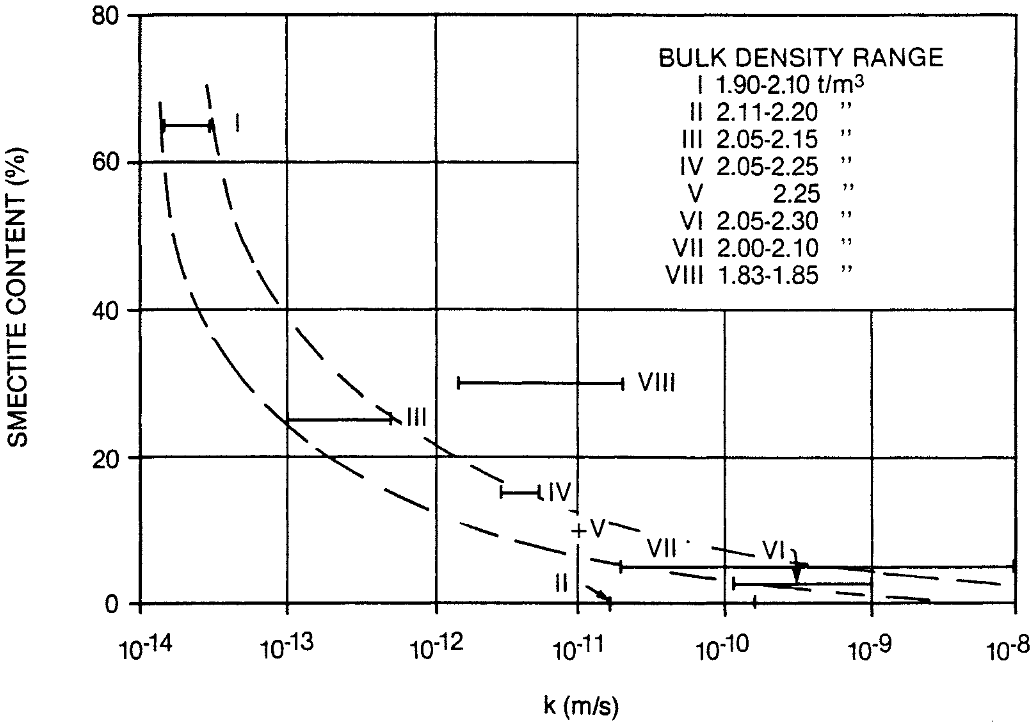



***Figure 4-4.*** *Hydraulic conductivity versus smectite content for eight clays. Smectite content is given as a percentage of the total quantity. The width of the area marked in the figure represents the range of variation of hydraulic conductivity of smectite clays with a density of at least 2.0 t/m$^3$ when water-saturated.*

The density of the bentonite in the deposition hole can be chosen at deposition by taking advantage of the material's swelling capacity in water and leaving more or less space in the deposition hole with open gaps or looser fill. On absorbing water, the material becomes homogenized to the density that corresponds to the swelling pressure and deformability of the surrounding material, i.e. chiefly the overlying fill.

A higher density and higher smectite content of the clay gives lower permeability and better isolation through lower diffusivity, see Figure 4-4 /4-11/. In SKB 91, the density of the water-saturated buffer material has been set at 2.0 t/m$^3$. The material has a smectite content of 65-80% and hydraulic conductivity has therefore been assigned a value of $10^{-13}$ m/s. Under these conditions, transport through the buffer is controlled by the diffusivity of the different nuclides and their sorption (see section 8.3.3).

Lower density gives the buffer greater plasticity and thereby the canister better protection against any deformations in the rock.

For practical reasons the maximum density is about 2.2 t/m$^3$. Good plastic conditions are obtained with a density of about 1.9 t/m$^3$, which is also quite sufficient to bear the canister /4-12/.

It is assumed that it will be possible to avoid potentially mobile zones in the rock as positions for deposition holes by identifying them before or after excavation of the disposal drifts.

The thermal conductivity of highly compacted bentonite is about 1 W/m°C. In the deposition hole, this value will be lower, 0.75 W/m°C (before water saturation has occurred), owing to moisture migration.

The properties of the bentonite are not affected below 70°C. Above that temperature, changes have been observed in a laboratory setting under special conditions at more than 100°C in the Finnsjön environment. However, in no case can these results be interpreted as indicating that the properties of the bentonite buffer will be jeopardized. In the range 100°C to about 130°C, knowledge of bentonite degradation is too uncertain to allow an exact temperature figure to be linked to the kinetics of degradation. A cautious judgement that can be made is that a temperature of about 130°C for several thousand years does not affect the desirable long-term performance of the bentonite. The critical factor is the availability of potassium, and at Finnsjön a concentration that is low in this context (6.5 mg/l) has been measured in the groundwater. The degradation process consists of montmorillonite being converted to illite, which has a slightly higher hydraulic conductivity and no swelling capacity.

Above 130°C, mineral alterations can occur that result in serious deteriorations of properties. In the laboratory, however, the reactions proceed very slowly even at a temperature of 200°C. The process is that montmorillonite is dissolved and beidellite (an aluminium-rich smectite clay) is formed. This, like montmorillonite, has good buffer properties. However, dissolved silicon is not consumed in this process, instead being precipitated in colder parts of the buffer and giving rise to cementation. Without any deeper knowledge of these process kinetics, 130°C is therefore regarded today as an upper limit for the stability of the bentonite, even with an insignificant potassium supply.

The good long-term stability of the bentonite is verified by investigations of bentonite from a depth of about 500 m at Hamra on the island of Gotland. This bentonite is about 450 million years old and has been heated to a temperature of 110°C to 120°C for at least 10 million years without any signs of cementation or significantly deteriorated isolating properties.

The fracture frequency along the deposition holes only affects the buffer if fracture widths significantly greater than 0.1 mm are common. The bentonite can then swell out into the fractures. The same applies at the boundary with the backfill, which can consist of 10% bentonite with aggregate of a suitable grade for compaction.

# 5 THE BEDROCK AT FINNSJÖN

*This chapter describes the geological, geohydrological and chemical conditions in the area at Finnsjön that has been chosen as a calculation example for the safety assessment. The general validity and long-term stability of features that may have safety-related importance are discussed.*

The Finnsjön area is situated in northern Uppland County about 140 km north of Stockholm, see Figure 5-1. The area was investigated during the years 1977-1978 as a part of the KBS project for the purpose of demonstrating geologically suitable sites for the final disposal of radioactive waste /5-1, 5-2/. During this period an extensive measurement programme was carried out in seven cored holes down to a depth of about 700 m. The area was subsequently used for various research purposes up to 1983 /5-3/, /5-4/.

A detailed study of a flat-lying fracture zone, Zone 2, in the northern part of the area started during 1985. The purpose was to obtain detailed knowledge of the importance of the fracture zone for the transport of groundwater and substances dissolved in the groundwater. The fracture zone project has included, among other things, the drilling of six new holes and detailed borehole measurements and cross-hole tracer tests. The fracture zone project has been completed and a summary and presentation of the principal results are provided in /5-5/. In recent years the area has also been used to test new borehole instruments and for various research projects, such as studies of fallout from Chernobyl /5-6/. So far the investigations have included 11 cored holes, with a depth of between 200 and 700 m, and 19 percussion boreholes, 100-460 m deep. The locations of these boreholes are indicated in Figure 5-1.

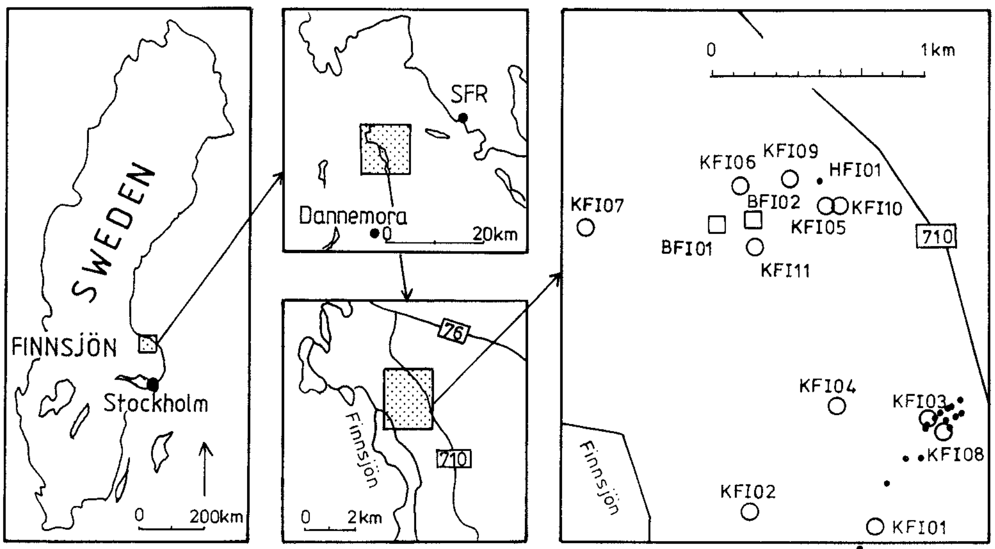



*Figure 5-1. Orientation map showing the location of the Finnsjön area on different scales. The detailed scale also shows all borehole positions.*

# 5.1 REGIONAL DESCRIPTION

Northern Uppland is a very flat region with large areas where the elevation differences are less than 10 m. The soil cover is thin, as a rule, and there are large areas rich in outcrops. Soils consist mainly of moraine (till) and clay, often overlain by peat bogs.

## 5.1.1 Geological evolution

The bedrock of northern Uppland consists of rock types that were formed 2,200 – 1,700 million years ago /5-7/. The oldest rock types are of volcanic or sedimentary origin. As a result of metamorphosis deep down in the earth's crust, they are hard crystalline rock types today. The metamorphosis occurred during a period of orogeny known as the Svecokarelian orogeny 1,850 million years ago, when a suite of magmatic rocks, from gabbro to granite, intruded into the bedrock. This suite also includes the granodiorite that comprises the principal rock type in the Finnsjön area.

During this period, an extensive deformation of the bedrock took place which resulted in a regional northwesterly foliation and the formation of regional shear zones /5-7/. In the final phase of the orogeny, dolerites (diabases) intruded and formed persistent northerly and easterly dykes. The youngest rock types in northern Uppland are the so-called younger granites with associated pegmatites and aplites. These rock types intruded into the bedrock 1,700 million years ago. The orogenic processes had then ceased. From this time up until today, the basement rock has primarily behaved as a brittle crystalline medium.

During the period 1,700 – 600 million years ago, the mountain chain was eroded down to a flat basement surface, known as the sub-Cambrian peneplain, on which Cambro-Silurian sedimentary rocks were deposited. These rock types are now eroded away and the Precambrian basement which we see today coincides largely with the peneplain.

Scandinavia and the Baltic Shield have been a coherent unit with all of Northern Europe for more than 900 million years and have been affected by the plate-tectonic movements. About 570 million years ago, for example, the region was located on the southern hemisphere and was headed toward the South Pole. About 400 million years ago the region was located on the equator. Other continents were also moving, and at this point in time Northern Europe collided with North America and Greenland, forming our mountain chain /5-16/.

A period of recurring ice ages began about 750,000 years ago /5-8/. Their exact number and extent is not yet known, but Scandinavia has probably been covered by many more inland ice sheets than has previously been assumed. The most recent ice age began 100,000 years ago. At its maximum extent 18,000 years ago, the inland ice sheet covered all of Scandinavia and northern Germany. It is estimated that the ice sheet was then between 2,000 and 2,500 m thick over northern Uppland. The weight of the ice pressed down the bedrock about 500 m /5-9/. The subsequent retreat of the ice sheet proceeded relatively rapidly, and 10,000 years ago the inland ice sheet withdrew from northern Uppland. Due to the previous depression, this region was then covered by the sea. The region has since been covered alternately by sea water and fresh water up to about 5,000 – 3,000 years ago, when the isostatic uplift once again made the Finnsjön area dry land. The current rate of uplift is 5.5-6.0 mm/year /5-10/.

### 5.1.2 Groundwater conditions

The fact that northern Uppland has been covered by sea in geologically recent time is one of the explanations why saline groundwater is often encountered in wells drilled in rock /5-11/. A review has been performed of the wells in the Finnsjön area and their salinities /5-12/. This report also discusses present-day practice in well drilling and dilution conditions in wells. Groundwater with a salinity in excess of that in the Baltic Sea off the coast of northern Uppland is also found in the Dannemora Mine and in SFR (final repository for low- and intermediate-level waste). The abundance of saline groundwater suggests that there are many areas where the groundwater movements are so small, and that are so isolated, that fresh water has not yet displaced the saline groundwater that remained after the area rose above sea level.

### 5.1.3 Stability on a regional scale

The Baltic Shield is an area of the earth with low seismic activity. Seismic disturbances seldom exceed a magnitude of ML=4 on the Richter scale. The Nation Defence Research Establishment's network of regional seismic stations in central and southern Sweden show that epicentres for earthquakes in the area covered by the network is concentrated to the region west of the so-called Protogine Zone. This zone constitutes a north-south boundary in the central part of southern Sweden which separates the Svecokarelian rock types in the east from the more recently formed west Swedish gneisses in the west. Earthquakes are therefore very rare on the coast of Uppland.

To the extent earthquakes occur in Sweden, they are most common at a depth of 10-20 km and the movements most often take the form of strike-slip faulting in vertical planes of weakness /5-14/. The amounts of movement are usually less than a millimetre and limited to areas within a radius of 100 m from the earthquake centre.

Based on the network of seismic stations, a general picture of the maximum horizontal stress (compression) has been calculated with the aid of stress releases in conjunction with registered earthquakes /5-14/. A northwesterly principal stress direction has thereby been obtained, which coincides with the general picture in Europe that has been obtained by means of rock stress measurements in boreholes. The results support the view that stresses in the northern European crust are mainly due to plate-tectonic movements. Studies of plate movements show that no essential changes in the current plate-tectonic regime, with compression from the Mid-Atlantic Ridge, can be expected during the next 100,000 years at least /5-15/.

Over the course of millions of years, however, the plate-tectonic forces have varied in size and direction, depending on the varying location of our continent in relation to the centres of spreading. In addition to these forces, sedimentary deposits and recurrent glaciations have placed vertical loads on the bedrock. Taken together, these loads have resulted in a network of fractures and fracture zones which, in the Finnsjön area, look roughly the same on different scales of resolution /5-17/.

As far as the stability of the bedrock is concerned, the aseismic movements – i.e. movements that do not give rise to earthquakes – are probably of greater importance than the seismically released movements /5-14/. Geodetic measurements in Finland and Estonia indicate horizontal movements on the order of a few millimetres per year in large-scale weakness structures /5-18/. Such conclusions cannot be drawn at present in Sweden on the basis of the network of geodetic stations.

In summary, the following can be assumed regarding the stability of the bedrock in northern Uppland: Ongoing aseismic movements may occur in the large zones of weakness with a regional extent. However, present-day stress conditions are not expected to release movements in smaller fracture zones or fractures. Future conditions that could release movements in these smaller structures as well are large vertical loads from inland ice sheets.

## 5.2 THE REPOSITORY SITE

### 5.2.1 Topographical conditions

The Finnsjön area, as a study area, is defined by a 6 $km^2$ rock block which is delimited by fracture zones of a regional extent, see Figure 5-2. The regional fracture zones constitute weak parts of the bedrock and protect the rock block against external rock movements. The rock block is one of several topographically similar blocks in northern Uppland that are slightly elevated above surrounding clay plains. The maximum difference in elevation between the highest point within the Finnsjön block and its surroundings is 15 m. In general the elevation difference is less, 5-10 m.

### 5.2.2 Soil and rock types

The Finnsjön area is characterized by frequent rock outcrops alternating with peat bogs. The soil cover is thin, often less than one metre, and consists mainly of moraine (till). Outside the boundaries of the area in the east are clay strata with a thickness of 2-5 m.

The bedrock consists of a medium-grain granodiorite with a northwesterly and steeply dipping foliation /5-7/. Decimetre-wide dykes of dolerite, aplite and pegmatite occur sporadically. The reddish colouration of the bedrock around fractures is characteristic, having been interpreted as a hydrothermal alteration. Normally, this alteration reaches a centimetre or two from the fracture, but in connection with fracture zones the bedrock can be reddish coloured at a distance of several metres from the fracture zone.

The temperature in the rock increases with depth by 1.3°C per 100 m /5-7/. At 600 m the temperature is 13.2°C.

### 5.2.3 Fracture zones

Figure 5-2 shows an interpretation of the occurrence of regional fracture zones around the Finnsjön area. The fracture zones “Gräsbo” and “Giboda” are interpreted here as

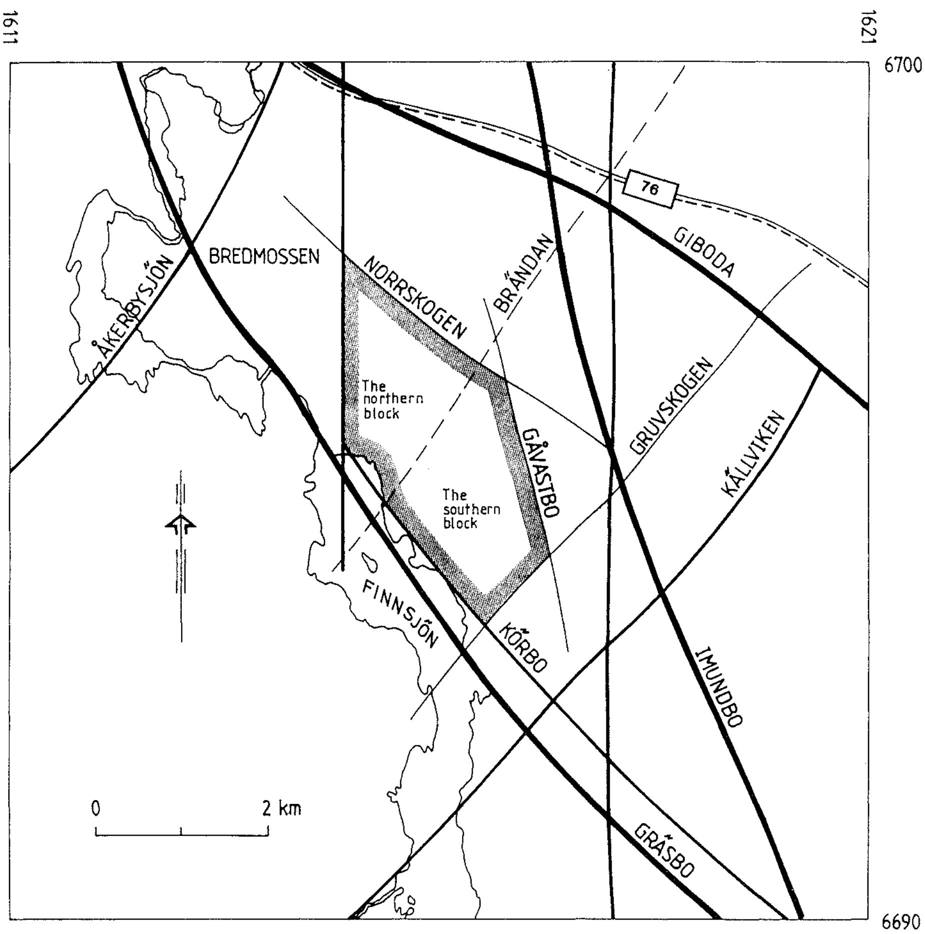



***Figure 5-2.*** *The Finnsjön rock block (shaded-in area). The Brändan zone (Zone 1) divides this block into a northern and a southern block. /5-7/.*

steeply dipping regional shear zones. The width, dip and character of these zones are not known, but since they are interpreted as being related to the Singö zone at SFR /5-7/, their features can also be preliminarily assumed to be similar, i.e. the zones are assumed to be steeply dipping, 100 m wide and water-bearing.

One of these regional fracture zones, Gräsbo, is situated adjacent to the southwestern boundary of the Finnsjön block. This fracture zone can be followed topographically for more than 50 km. Other limited fracture zones are judged to be of a lower dignity, although boreholes only exist through Gåvastbo (Zone 3) and Norrskogen (Zone 5). The results obtained from these boreholes indicate widths of 50 m and 5 m, respectively /5-7/.

A summary of interpreted fracture zones within and adjacent to the Finnsjön area is presented in Table 5-1 and Figure 5-3. Of a total of 14 interpreted fracture zones, 8 have been investigated with boreholes. For fracture zones that haven't been investigated with boreholes, assumed geometric and hydraulic data have been based on lineament interpretations, surface observations and comparisons with other similar fracture zones where boreholes results are available.

Table 5-1. **Geometric data for interpreted fracture zones /5-7/. By "Boreholes" is meant how many boreholes penetrate the zone.**

| Zone | Strike | Dip | Length (km) | Width (m) | Boreholes |
|---|---|---|---|---|---|
| 1 | N30E | 75SE | 5 | 20 | 2 |
| 2 | N28W | 16SW | 1.5 | 100 | 9 |
| 3 | N15W | 80W | 5 | 50 | 1 |
| 4 | N50W | 65SW | 1 | 10 | - |
| 5 | N50W | 60SW | 5 | 5 | 3 |
| 6 | N55-65W | 60SW | 2 | 5 | 1 |
| 7 | N55W | 60SW | 2 | 5 | - |
| 8 | N50W | 90 | 3 | 5 | - |
| 9 | N10W | 15W | 2 | 50 | 1 |
| 10 | NW | 85SW | 2.5 | 5 | 1 |
| 11 | N5W | 35W | 2 | 100 | 4 |
| 12 | N-S | 90 | 6 | 25 | - |
| 13 | N30E | 75SE | 7 | 20 | - |
| 14 | NW | 90 | 50 | 100 | - |

Most fracture zones have a northwesterly orientation with a dip of 60 degrees towards the southwest. These fracture zones are relatively narrow and are judged to have little influence on geohydrological conditions in the area. However, this does not apply to the 5 km long and 20 m wide Zone 1 (Brändan zone). This northeasterly and steeply dipping fracture zone divides the Finnsjön area into two smaller blocks: the northern and the southern block, see Figure 5-2. Several indications suggest that these two blocks have been displaced several hundred metres in relation to each other along Zone 1 /5-7/. For one thing, the flat Zone 2 is completely missing in the southern block. In drill cores, Zone 1 is characterized by a high fracture frequency with large amounts of hematite and asphalt.

Besides the fracture zones mentioned above there are three interpreted flat fracture zones – zones 2, 9 and 11 – with a subhorizontal to flat dip. Of these fracture zones, Zone 2 is well substantiated, whereas there are uncertainties as to the existence, size and importance of the other flat-lying zones. As is evident from section 5.3, Zone 2 is of great importance for the geohydrological and geohydrochemical conditions. This zone is therefore described in greater detail below.

Zone 2 was originally formed more than 1,700 million years ago at a depth of about 10 km /5-20/. Fracture-mineralogical studies show that Zone 2 has been reactivated on a number of occasions since its formation. Among other things there are numerous fractures that are sealed with many different kinds of fracture-filling minerals deposited under different pressure and temperature conditions /5-21/.

The upper boundary of Zone 2 has been located in nine boreholes from 105 m to 295 m below the ground surface. All of these boreholes are situated in the northern block. No outcrop of the fracture zone at the ground surface has been identified. Owing to a generally higher degree of tectonization in the rock block under the zone, it is more difficult to determine a distinct lower boundary, but in general the width of the zone appears to be around 100 m. The strike of Zone 2 is north-northwesterly with a dip of 16 degrees towards the southwest.

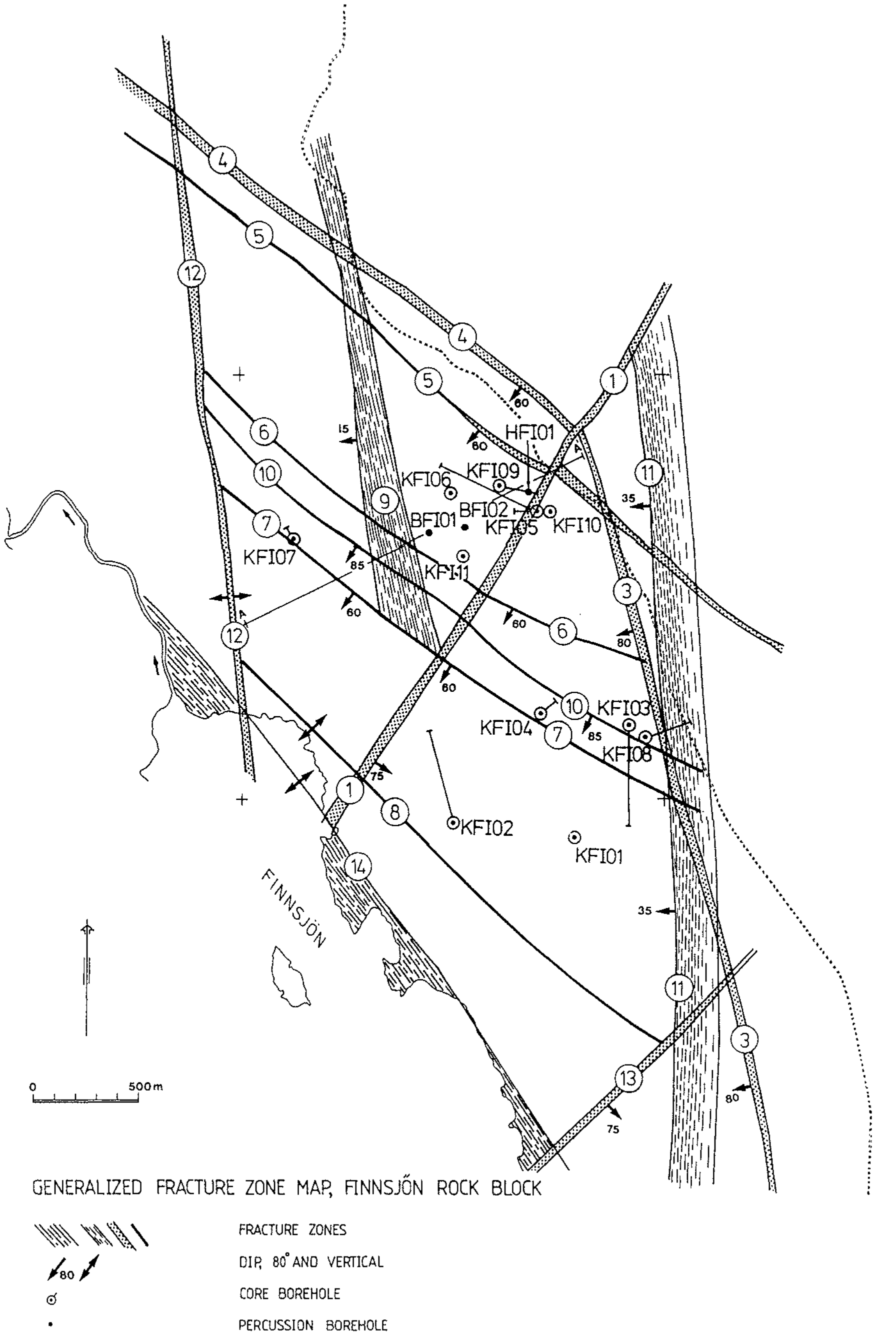



***Figure 5-3.*** *Interpreted fracture zones within the Finnsjön area /5-7/. A-A' indicates the location of the profile in Figure 5-4.*

Within an area of 500 x 500 m, Zone 2 has been investigated with 8 boreholes. The zone appears here as a continuous planar sheet, see Figure 5-4. The planar lateral extension of Zone 2 within this area indicates that no major vertical fault movements have taken place since Zone 2 was formed. Outside this area, Zone 2 occurs in borehole KFi 07. At this distance, however, the zone cannot be followed as a continuous plane. It is possible that minor faults have displaced Zone 2, but other explanations are also possible /5-7/. Zone 2 is bounded on the south by Zone 1 (the Brändan zone).

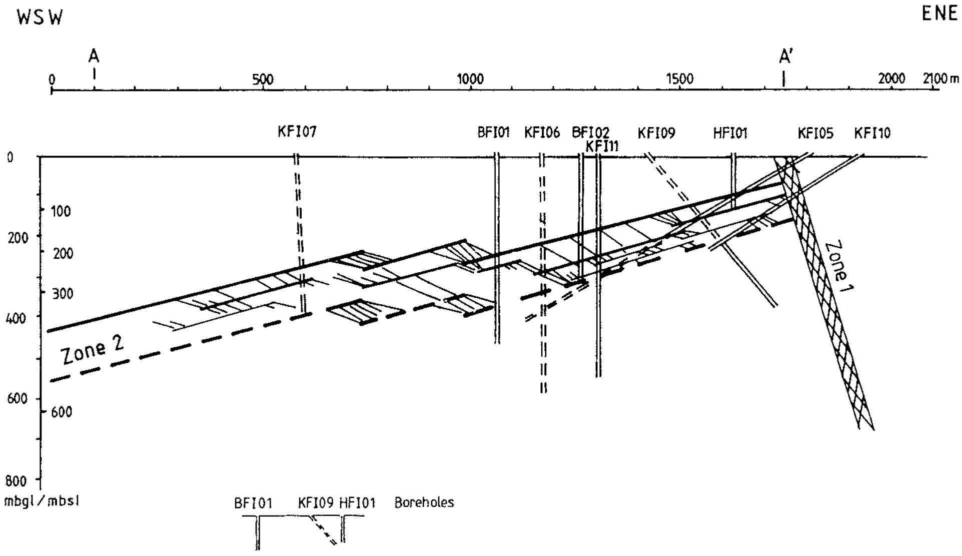



*Figure 5-4. Schematic illustration of Zone 2 /5-7/. The location of the profile is shown in Figure 5-3. Boreholes drawn with solid lines are located in front of the profile, while boreholes drawn with dashed lines are located behind the profile.*

### 5.2.4 Fracture systems

Fracture measurements in the northern block show that there are two steeply dipping fracture groups: northeast fractures and northwest fractures /5-19/. A third fracture group consists of subhorizontal fractures, normally with a gentle dip to the southwest. Fracture-mineralogical studies show that by far most of these fractures have been formed early in the area's geological history and have later been reactivated on a number of occasions /5-20/. For example, the fracture-filling mineral prehnite is common in northeast fractures, whose age has been determined in other places in Uppland to be 1,250-1,100 million years /5-21/. The other steeply dipping fracture group, northwest fractures, is presumably older /5-19/.

The fracture frequency measured on outcrops spread out all over the Finnsjön block is 2.9 fractures/m /5-22/. The fracture frequency calculated from drill cores above Zone 2 is 3.5 fractures/m, while the corresponding value below Zone 2 is 2.7 fractures/m /5-23/.

### 5.2.5 General validity of the properties

The presence of fracture zones in the Finnsjön block has been interpreted from topographical maps and aerial photos, surface observations of outcrops and from drill cores. These observations have been interpreted and reported in a conceptual model /5-7/. To get some idea of how much general validity these data and interpretations have for the region, it is interesting to compare with the conditions in SFR and, to some extent, with the Dannemora iron mine, see Figure 5-1. These two underground facilities lie within the same tectonic region as the Finnsjön area and can therefore, at least in part, be assumed to have been affected by similar tectonic forces.

What is particularly striking is the presence of major flat-lying fracture zones in all three areas /5-5/, /5-24/, /5-25/. The frequency of these fracture zones at greater depth is unknown, but for the time being there is no reason to assume that they should occur at an appreciably different frequency that steeply dipping zones. Under the SFR facility, at a depth of 100-160 m below sea level, there is a highly permeable subhorizontal fracture zone. The width of this zone varies between 5 and 20 m /5-24/. In the Dannemora Mine, rock blocks above subhorizontal faults are normally displaced towards the south in relation to the lower rock block /5-25/. Similar conditions are also found when comparisons of fracture frequency, fracture orientations /5-7/ and rock stress conditions /5-26/ are made between the Finnsjön area and SFR. The maximum horizontal stress has a NW-SE orientation in both areas.

Comparisons can also be made with other areas studied by SKB, the so-called "study sites". The Finnsjön area is then found to have a higher fracture frequency compared with other areas. Even though flat-lying zones have been encountered in some of the other study sites, thickness and hydraulic conductivity are much greater for Zone 2. On the other hand there is no appreciable difference in average distance between steeply dipping regional and local fracture zones.

## 5.3 HYDROLOGICAL CONDITIONS

### 5.3.1 Groundwater table and hydrometeorology

The Finnsjön area comprises a rock block running in a north-south direction lying 5-10 m above the surrounding low-lying areas. The location of the groundwater table inside and outside the Finnsjön area is shown in Figure 5-5.

The watershed divide is located in the area's western and southern portion. This means that most of the superficial groundwater within the Finnsjön area runs off towards the clay areas in the east. Surface water from Finnsjön and the clay area east of the Finnsjön area is first drained towards the north and then towards the east via the Forsmark river.

The groundwater table's gradient within the Finnsjön area is on the order of 0.3%. Because the surface of Finnsjön Lake is located about 5 metres above the clay plain in the east, however, there is also an easterly-directed regional hydraulic gradient of roughly 0.2% that can act on deeper-lying groundwater within the Finnsjön area. Viewed over a longer distances (tens of kilometres), 0.3% is a maximum value for the regional hydraulic gradient.

Average annual precipitation for northern Uppland is 670 mm/y /5-4/. Potential and actual annual evaporation is calculated to be 540 and 430 mm/y, respectively.

### 5.3.2 Hydraulic properties of the bedrock

Hydraulic conductivity (permeability) has been determined by means of water injection tests in all cored holes. The section length used has been 3 m for most boreholes, but 2 and 20 m measurement sections have also been used. An example of results from water injection tests is shown in Figure 5-6. In the northern block, in and above Zone 2, extensive cross-hole tests have also been performed with pumping in one

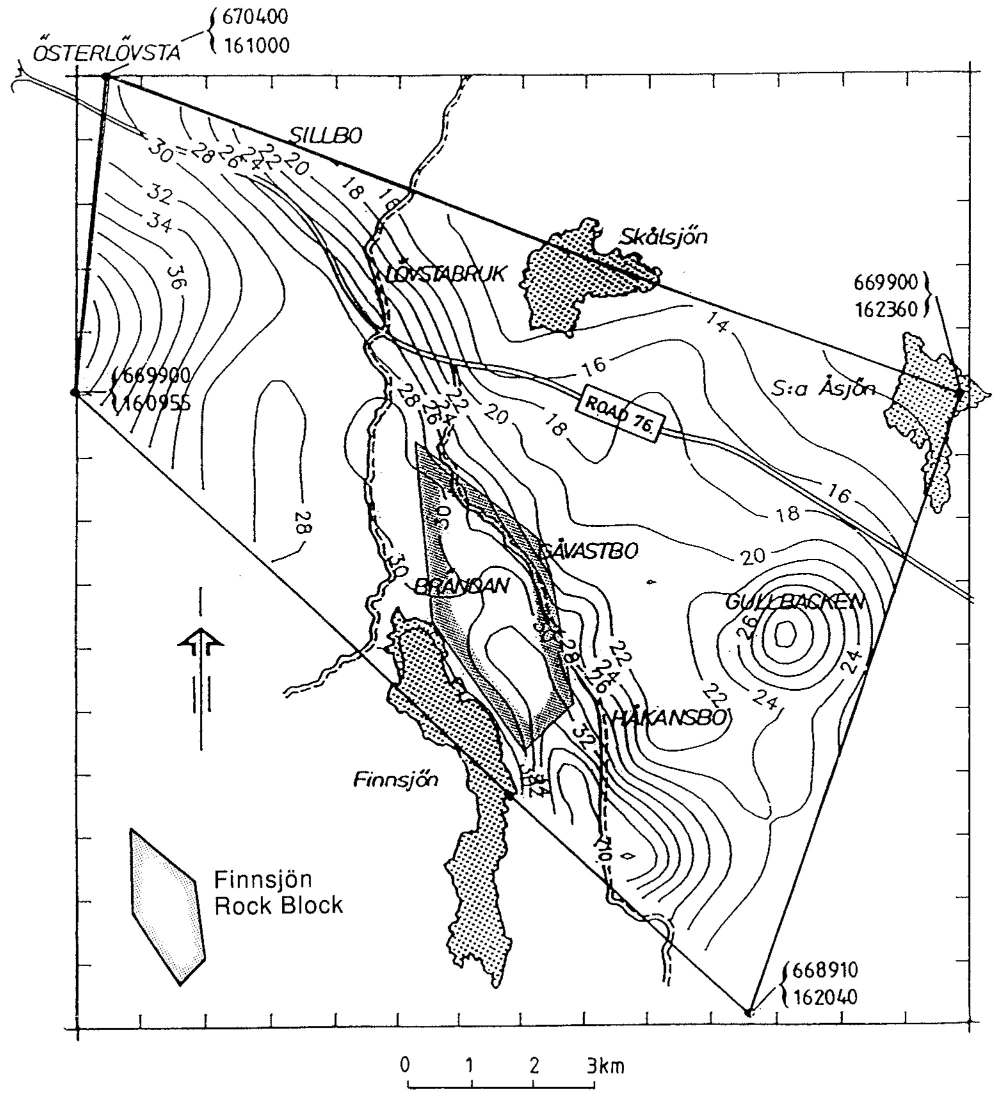



*__Figure 5-5.__ Location of groundwater table on semi-regional scale /5-28/. Contour lines are 1 metre above sea level.*

borehole and measurements of hydraulic disturbances in other boreholes. These tests have yielded data on hydraulic conductivity on a larger scale, as well as data on hydraulic connections, hydraulic anisotropy and storage coefficient.

A large number of tracer tests have been performed to study groundwater transport in Zone 2, where the hydraulic gradient has been increased by pumping in a borehole. In addition, data are available from two boreholes on the natural groundwater flow in and around Zone 2 /5-29/. Taken together, there is therefore a large body of data in the northern block which together provide a good understanding of the geohydrological conditions in this block. Corresponding data are lacking for the southern block.

The results from the water injection tests in 2-3 m sections provide a general idea of how hydraulic conductivity varies with depth inside the rock mass, i.e. excluding fracture zones. Calculations have been carried out for both the northern and the southern Finnsjön blocks /5-28/. The results show that the mean conductivity of the

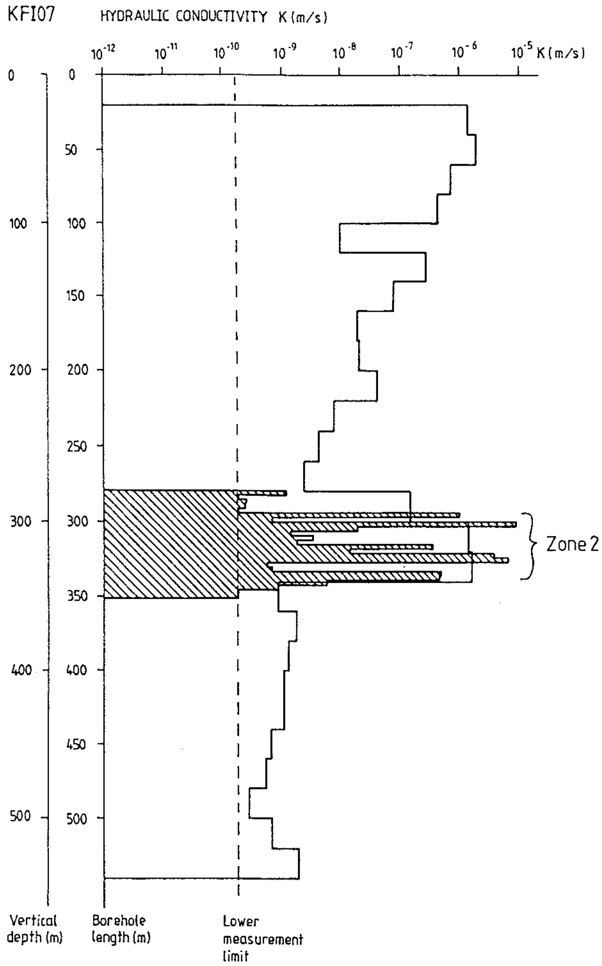



***Figure 5-6.*** *Example of results from water injection tests, borehole KFi 07 in the northern block /5-32/. The measurements show a distinct decline of hydraulic conductivity with depth, which is however interrupted by Zone 2.*

rock mass declines in a similar manner for the two blocks, see section 5.3.4. At 100-200 m depth, the geometric mean value is $10^{-8}$ m/s, while the corresponding value at 500-600 m depth is $10^{-9}$ m/s. These means may be affected by a relatively high measuring limit, between 2 and $8 \cdot 10^{-10}$ m/s.

As mentioned previously, there are boreholes through 8 of the 14 interpreted fracture zones. Results from water injection tests of these fracture zones are presented in Table 5-2. The table shows that the hydraulic conductivity of most fracture zones lies within the range $10^{-5}$ – $10^{-7}$ m/s. The exception is Zone 2, which has volumes with higher conductivities, and Zones 6, 9 and 10, which are relatively impermeable.

Table 5-2. **Transmissivity and conductivity for fracture zones and variation of conductivity calculated from single-hole tests. Corresponding values from test pumpings (P) are also given for Zone 2. From /5-28/.**

| Fracture zone | Number of bore-holes | Width (m) | T-value ($m^2/s$) | K-value (m/s) | K range (m/s) | Section length (m) |
|---|---|---|---|---|---|---|
| 1 | 1 | 20 | $2 \cdot 10^{-4}$ | $1 \cdot 10^{-5}$ | $1 \cdot 10^{-10} - 5 \cdot 10^{-5}$ | 2 |
| 2 | 8* | 100 | $2 \cdot 10^{-3}$ | $2 \cdot 10^{-5}$ | $1 \cdot 10^{-10} - 1 \cdot 10^{-3}$ | 2 |
| 2 | 8* | 100 | $3 \cdot 10^{-3}$ | $3 \cdot 10^{-5}$ | $2 \cdot 10^{-5} - 4 \cdot 10^{-5}$ | (P) |
| 3 | 1 | 50 | $1 \cdot 10^{-4}$ | $2 \cdot 10^{-6}$ | $2 \cdot 10^{-10} - 9 \cdot 10^{-6}$ | 3 |
| 5 | 3 | 5 | $4 \cdot 10^{-5}$ | $8 \cdot 10^{-6}$ | $8 \cdot 10^{-9} - 1 \cdot 10^{-5}$ | 2 |
| 6 | 1 | 5 | $3 \cdot 10^{-8}$ | $6 \cdot 10^{-9}$ | $3 \cdot 10^{-9} - 7 \cdot 10^{-9}$ | 3 |
| 9 | 1 | 50 | $3 \cdot 10^{-6}$ | $5 \cdot 10^{-8}$ | $2 \cdot 10^{-10} - 2 \cdot 10^{-6}$ | 3 |
| 10 | 1 | 5 | $3 \cdot 10^{-8}$ | $6 \cdot 10^{-9}$ | $3 \cdot 10^{-9} - 6 \cdot 10^{-9}$ | 3 |
| 11 | 4 | 100 | $2 \cdot 10^{-4}$ | $2 \cdot 10^{-6}$ | $2 \cdot 10^{-10} - 9 \cdot 10^{-5}$ | 3 |

*not counting borehole HFi 01.

### 5.3.3 Hydraulic conditions in and around Zone 2

In the uppermost part of Zone 2, all boreholes exhibit a volume with very high conductivity. Why this volume is so permeable and so persistent is unclear. One explanation may be reactivation during the most recent ice age due to high water pressures /5-30/, /5-31/. Further down in Zone 2, the borehole measurements show that there are one or several more high-conductivity volumes. The hydraulic conductivity of the permeable volumes in Zone 2 lies between $10^{-4}$ and $10^{-5}$ m/s, based on water injection tests with 2 m measurement sections. Between these volumes the conductivity is low, between $10^{-8}$ and $10^{-10}$ m/s.

Water injection tests with extremely short measurement sections, 0.11 m, show that the "hydraulic width" of the transmissive volumes in Zone 2 is only 0.4 m each /5-27/. Since the total width of Zone 2 is much greater, hydraulic transmissivity is a better measure than conductivity of Zone 2's permeability. The transmissivity of the permeable volumes varies between $1 \cdot 10^{-3}$ and $5 \cdot 10^{-4}$ $m^2/s$, while the value for all of Zone 2 varies between 2 and $3 \cdot 10^{-3}$ $m^2/s$ for different boreholes /5-27/.

Direct measurements of the natural groundwater flow have also been performed with a dilution probe /5-32/. The results of these measurements in borehole BFi 01 are presented in Figure 5-7, together with the results of measurements of hydraulic conductivity. As is shown by the figure, high conductivity values correspond to high flows down to the upper boundary of Zone 2. Down to this depth there is therefore a hydraulic gradient that can "drive" the groundwater. The high natural groundwater flow in the upper part of Zone 2 also shows that this volume must have contact with other fracture zones that can charge and discharge the zone of groundwater. Further down in Zone 2 there is another high-conductivity volume. However, this volume is not matched by any measurable groundwater flow. This is presumably due to the fact that a driving hydraulic gradient is lacking. A likely explanation is that the overlying high-conductivity volume of Zone 2 acts as a "hydraulic barrier", i.e. it short-circuits the topographically-induced hydraulic gradient. The presence of relict saline groundwater below Zone 2 also indicates stagnant conditions, see further section 5.4.

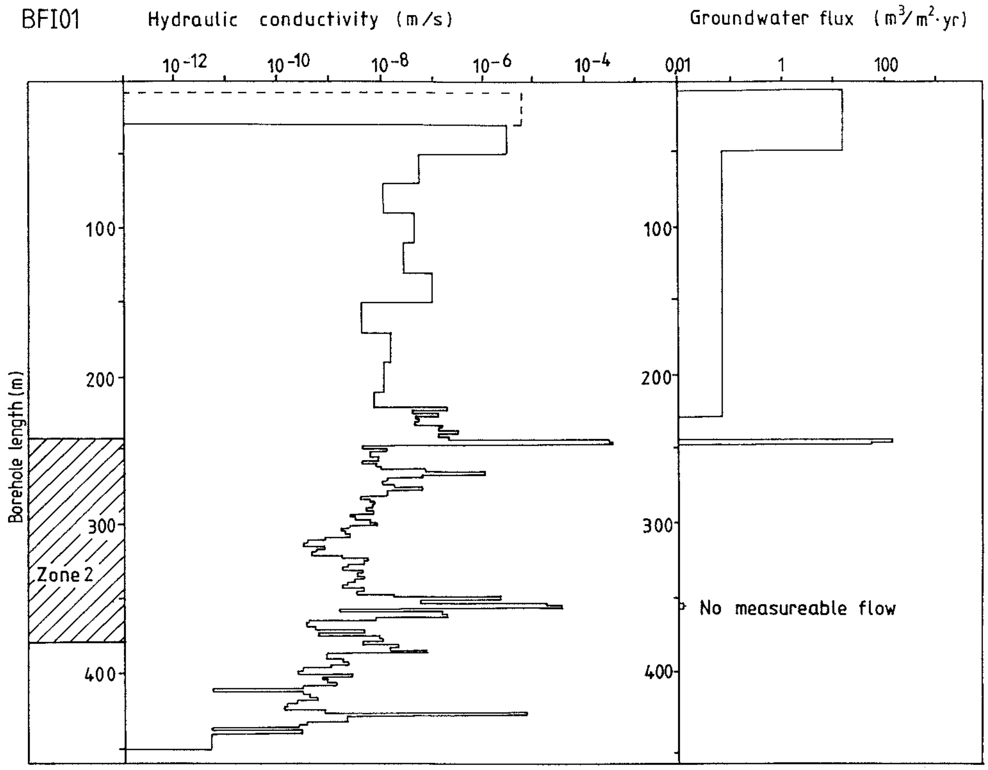



***Figure 5-7.*** *Measurements in borehole BFi 01 of the hydraulic conductivity in 2 and 20 m sections (left) and measurements of the natural groundwater flow (right) /5-33/.*

The natural flow in the upper part of Zone 2, over a cross-section of 1,000 m calculated from the aforementioned dilution probe measurements, amounts to something on the order of 150,000 – 370,000 $m^3$ per year /5-33/. Similar flows are also obtained from calculations based on results from hydraulic cross-hole tests and piezometric measurements. These high natural flows cannot be explained solely by local infiltration through the overlying bedrock; rather, most of the groundwater must be infiltrated and drained through fracture zones outside the Finnsjön block. Infiltration presumably takes place below Finnsjön, via regional fracture zone 14, see Figure 5-3, while drainage takes place via a number of regional fracture zones (1, 5, 11) just outside the northeastern margin of the Finnsjön block.

A schematic summary of the hydraulic conditions in and around Zone 2 is presented in Figure 5-8.

### 5.3.4 General validity of the properties

In comparison with other study sites investigated by SKB, the Finnsjön area has a low hydraulic gradient and a relatively high hydraulic conductivity. The latter applies both to fracture zones and the rock mass as a whole. The low hydraulic gradient is due to the flat topography around the Finnsjön area. The gradient in this area is 0.3% or lower, while the corresponding value for Kamlunge is 10% and for Klipperås 0.4%.

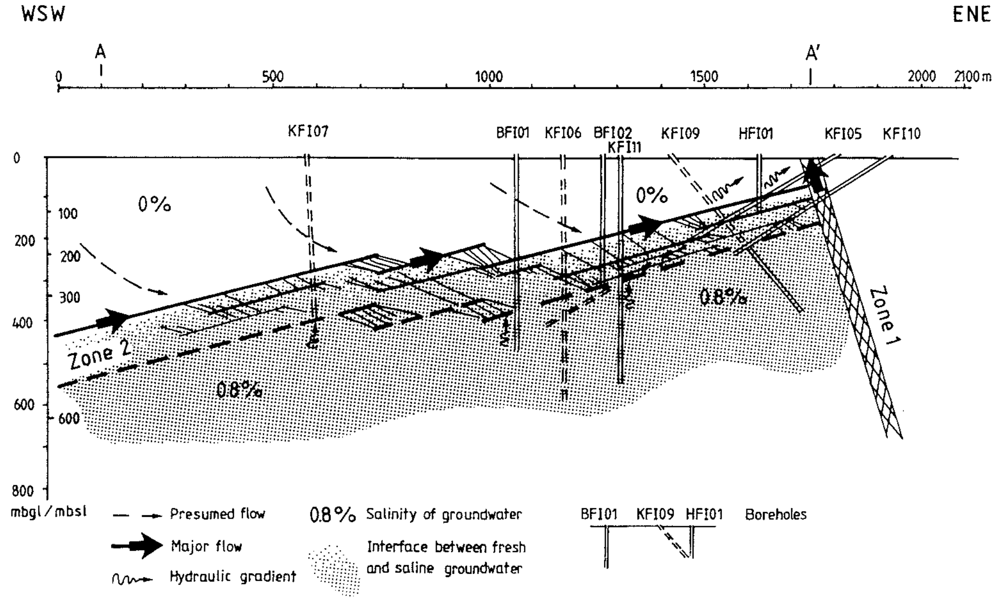



***Figure 5-8.*** *Schematic illustration of groundwater movements in and around Zone 2 /4-7/.*

A comparison between the hydraulic conductivities of fracture zones in the Finnsjön area and on the study sites investigated in conjunction with the KBS-3 report is shown in Figure 5-9. Even though these regression relationships are to be viewed as rough generalizations, the fracture zones in the Finnsjön area stand out as being more conductive than those in other areas. A similar comparison for the hydraulic conductivity of the remaining rock mass is presented in Figure 5-10. In this case as well, the Finnsjön area is found to be more conductive.

The really big difference between the Finnsjön area and the other areas is, however, the presence of Zone 2. Through its low dip and unusually high hydraulic conductivity, it strongly affects the geohydrological conditions in the underlying bedrock. Direct measurements indicate no or very low groundwater flows. Even though similar hydraulic effects of flat-lying fracture zones have been calculated for other areas /5-34/, no flat zone has so far been identified in SKB's site investigations that can match Zone 2's thickness and permeability.

All factor considered, the Finnsjön area comprises an area with a low hydraulic gradient but with relatively high values of hydraulic conductivity, for both fracture zones and the rock mass. Even though these conditions and features should be weighed in when comparing/transferring the results of SKB 91 to other areas, it is the influence of the flat-lying fracture zone in particular that makes the geohydrological conditions in the Finnsjön area special.

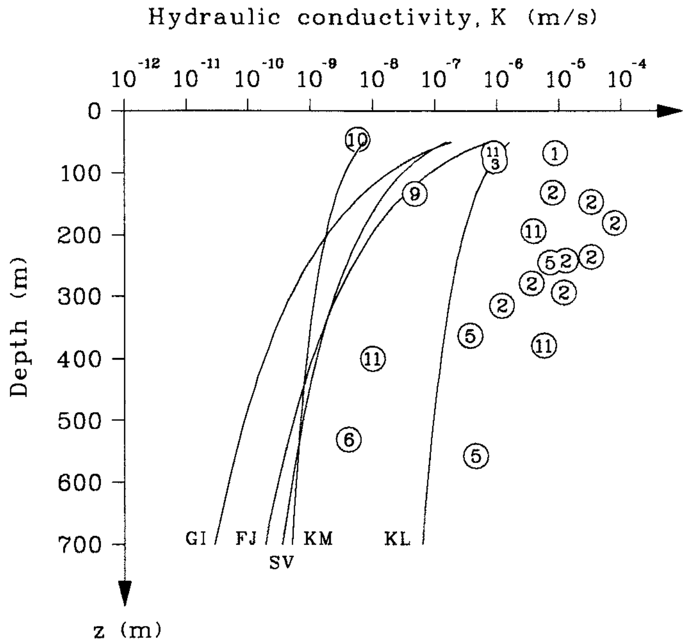



*__Figure 5-9.__ Hydraulic conductivity for the fracture zones in the Finnsjön area (numbered rings). Regression curves for fracture zones in other study areas are also shown for comparison. FJ = Fjällveden, GI = Gideå, KL = Klipperås, KM = Kamlunge, SV = Svartboberget /5-28/, /5-29/.*

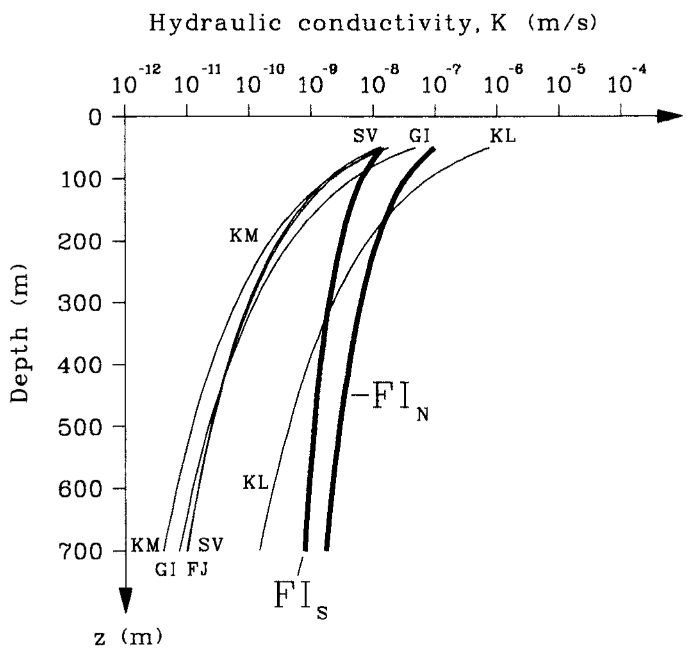



*__Figure 5-10.__ Regression curve based on geometric means of hydraulic conductivity in the rock mass (excluding interpreted fracture zones) $FI_N$ for the northern and $FI_S$ for the southern block in the Finnsjön area, and equivalent curves for other areas /5-28/, /5-29/. Based on results of water injection tests with 20 and 25 m measurement sections.*

## 5.4 CHEMICAL CONDITIONS

### 5.4.1 Groundwater sampling and geochemical investigations

The geohydrochemical conditions in the Finnsjön area have been investigated on a number of occasions since 1977 in 12 boreholes altogether. Sampling levels have varied between 100 and 700 m. The results have been compiled in /5-28/, /5-35/, /5-36/ and /5-37/. The geochemical investigations also include mapping and analyses of the occurrence of fracture-filling minerals and their importance for the composition of the groundwater /5-39/.

The methodology for sampling and analysis of borehole water has been developed considerably since the investigations were initiated in Finnsjön. Among other things, a mobile laboratory was put into use in 1984. This made it possible to analyze the most sensitive components immediately and to carry out sampling under well-controlled conditions. At the same time equipment was put into use for measurement of Ph and Eh directly in boreholes. These improvements mean that the most reliable analyses of deep groundwater are from the most recently sampled boreholes, mainly KFi 09 and BFi 01.

### 5.4.2 Minerals in the rock

The granodiorite that dominates the Finnsjön area consists of the principal minerals quartz (25-31%), plagioclase (30-34%), potassium feldspar (microcline) (14-21%), hornblende (9-12%) and biotite (7-11%).

Calcite is the most commonly occurring fracture-filling mineral. Some fractures are filled with pure calcite, while most calcite-sealed fractures also contain other minerals such as prehnite, laumontite and chlorite. Some of the calcite sealings are very old and probably of hydrothermal origin, while others may be recent precipitations, e.g. since the most recent ice age. Prehnite is also a common fracture-filling mineral. Like calcite it is present in at least two different generations. Other commonly occurring fracture-filling minerals are laumontite, pyrite and quartz. All of these were formed under hydrothermal conditions.

### 5.4.3 Groundwater chemistry

The groundwater in the Finnsjön area can roughly be divided into fresh and saline. Fresh groundwater has been encountered in the superficial parts of all boreholes as well as at great depths in boreholes KFi 01 and KFi 02, south of Zone 1, see Figure 5-2. These water also exhibit – based on tritium data – a shorter retention time and a larger fraction of recently formed groundwater than others. In the rock block north of Zone 1, saline groundwater has been encountered in all boreholes at the upper boundary of Zone 2. Depending on where the boreholes are situated, Zone 2 – and thereby the saline groundwater – has been encountered at depths varying between 100 and 300 m. Saline groundwater has also been encountered in the borehole (KFi 08) drilled through the eastern boundary of the Finnsjön block.

A selection of typical water compositions at different sampling depths is reported in Table 5-3. The data in the table are taken from certain samplings in boreholes KFi 02 and BFi 01 performed with the mobile field laboratory /5-37/.

**Tabell 5-3. Composition of groundwater from two boreholes in the Finnsjön area. The shaded field marks the groundwater composition chosen for the reference case in SKB 91.**

| BOREHOLE | | KFi 09 | KFi 09 | KFi 09 | KFi 09 | BFi 01 | BFi 01 | BFi 01 | BFi 01 | BFi 01 |
|---|---|---|---|---|---|---|---|---|---|---|
| Level | (m) | 94-99 | 114-119 | 182-187 | 360-365 | 71-85 | 169-191 | 234-247 | 284-294 | 439-459 |
| pH | | 7.3 | 7.5 | 7.4 | 7.6 | 6.9 | 7.7 | 7.7 | *** | *** |
| Eh | (mV) | -245 | -300 | -212 | – | +40 | -320 | -270 | *** | *** |
| Alkalinity (mg/l hydrogen carbonate) | | 285 | 116 | 160 | 32 | 220 | 200 | 260 | *** | *** |
| Calcium | (mg/l) | 115 | – | 700 | 1700 | 76 | 270 | 320 | 1500 | 1600 |
| Magnesium | (mg/l) | 16 | – | 91 | 84 | 6.3 | 36 | 40 | 126 | 140 |
| Sodium | (mg/l) | 415 | – | 960 | 1500 | 23 | 610 | 650 | 1600 | 1700 |
| Potassium | (mg/l) | 5.8 | – | 15 | 7.4 | 3.2 | 6.5 | 8.7 | 15 | 13 |
| Iron(II) | (mg/l) | 0.56 | 0.36 | 1.07 | 0.34 | 8.86 | 0.50 | 0.87 | *** | *** |
| Iron(Tot) | (mg/l) | 0.56 | 0.35 | 1.08 | 0.35 | 9.01 | 0.51 | 0.90 | *** | *** |
| Manganese | (mg/l) | 0.19 | 0.45 | 0.82 | 0.36 | 0.50 | 0.37 | 0.42 | *** | *** |
| Sulphide | (mg/l) | 0.22 | – | 0.44 | 0.03 | <0.01 | 0.01 | <0.01 | *** | *** |
| Sulphate | (mg/l) | 175 | – | 210 | 340 | 8.3 | 150 | 140 | 380 | 380 |
| Chloride | (mg/l) | 680 | 2100 | 2800 | 5200 | 61 | 1300 | 1500 | 5200 | 5500 |
| Bromide | (mg/l) | 2.0 | – | 14 | 27 | 0.3 | 4.5 | 7.0 | 26 | 29 |
| Iodide | (mg/l) | 0.01 | – | 0.03 | 0.07 | <0.002 | 0.02 | 0.04 | 0.07 | 0.12 |
| Silicon | (mg/l) | 7.6 | 1.8 | 4.6 | 7.6 | 6.2 | 8.3 | 7.5 | 5.5 | 5.4 |
| TOC | (mg/l) | 18 | – | 7.5 | 1.0 | 16 | 12 | 6.9 | *** | *** |
| Ammonium | (mg/l) | – | – | 1.1 | – | 0.15 | 0.34 | 0.63 | 0.46 | 0.35 |
| Nitrate | (µg/l) | 20 | – | 19 | 10 | 6 | <5 | 5 | <5 | <5 |
| Phosphate | (µg/l) | 1 | 2 | 3 | 4 | 1 | 1 | <2 | <5 | <5 |
| Uranium | (µg/l) | 2.1 | – | 1.6 | 8.2 | 4.6 | 13 | 3.9 | *** | *** |

*** The values of these parameters are affected by the drilling method used (pneumatic) and are not reported.

– Has not been analyzed.

The table shows that the chloride concentrations increase with depth in the two boreholes. The deepest sampling sections exhibit chloride concentrations of 5,200 and 5,500 mg/l. This is in agreement with older samplings of boreholes KFi 05, KFi 06 and KFi 08 with chloride concentrations of between 2,500 and 5,900 milligrams per litre. Based on carbon-14 and tritium data, all of these saline groundwaters exhibit a very long retention time and a low fraction of recently formed groundwater.

It can also be seen that the sodium and calcium concentrations follow the chloride concentration. At higher chloride concentrations the fraction of calcium increases over sodium. The magnesium and sulphate concentrations also increase with increasing chloride concentration, but much more slowly. The relative concentrations of magnesium and sulphate are much lower than in seawater. The potassium and silicon concentrations are constant and the hydrogen carbonate concentration declines with increasing chloride concentration. The sulphide concentration varies between <0.01 mg/l and 0.44 mg/l and is independent of the other parameters. This is presumably due to local conditions.

The concentrations of bivalent and total iron are the same, i.e. trivalent iron is not present. The concentrations vary between 0.3 and 9 mg/l. The manganese concentrations follow the iron concentrations to some degree and vary between 0.2 and 0.8 mg/l. The uranium concentration varies between 1.6 and 13 µg/l.

The pH varies within a very narrow range, from 6.9 to 7.7.

The measured Eh values vary within a range from +40 mV to -320 mV. The low Eh values, the presence of sulphide, the low uranium concentrations and the fact that all dissolved iron is present in bivalent form show that the groundwater below about 100 m is oxygen-free as well as reducing.

The concentration of organic matter, TOC, lies between 1 and 18 mg/l. The high concentration is encountered in the near-surface levels, while the low concentrations are encountered at depth.

The concentration of particle-bound material has been analyzed in BFi 01 at the 234-metre level and KFi 09 at 182 and 360 m. The median value is 80 µg/l.

### 5.4.4 Chemical impact on radionuclide transport

The transport of dissolved radionuclides is affected to a high degree by their chemical properties. Sorption of dissolved radionuclides on mineral surfaces in the rock stops or at least retards their outward transport, providing more time for them to decay in the rock.

Dissolved radionuclides are sorbed not only on the surfaces of the fractures in which the groundwater flows. By diffusing into the rock matrix's interconnected system of microfissures with virtually stagnant water, the radionuclides are removed from the water flow and the surface area available for sorption increases considerably. This diffusion into microfissures and sorption makes the dominant contribution to radionuclide retention.

Sorption involves numerous different mechanisms. Some are partially irreversible. The strength of the sorption is highly dependent on the charge of the radionuclide ions, hydrolysis and the presence of complexes with strong complexing agents. It is therefore essential to know the groundwater's pH, redox conditions and content of complexing agents. Humic and fulvic acids in the groundwater form relatively strong complexes with some radioactive elements, such as $Am^{+}$.

Ion exchange is an important sorption mechanism for e.g. $Cs^{+}$ and $Sr^{2+}$. The salinity of the water is therefore also of great importance.

The minerals that constitute the actual substrate for the sorption have different capacities to sorb radionuclides and there are different mechanisms for sorption. Some minerals, for example, are good ion exchangers, while others aren't. There are also some shared sorption mechanisms, however. Most minerals expose an oxide/hydroxide surface to the solution, which gives them surface complexing properties. Coefficients of distribution, $K_d$, are used as simple means of quantifying the sorption so that it can be used for transport modelling. These coefficients are determined experimentally in the laboratory by using minerals and water compositions that are typical of the repository site and then varying the parameters that are of importance, such as pH, ionic strength, concentration of radionuclides etc. The $K_d$ values that will later be used in the safety assessment are chosen so that the retardation in the radionuclide transport is not overestimated /5-49/. Complexation with humic and fulvic acids can reduce sorption for some of the radionuclides. The amount of the reduction depends on how the radionuclide behaves as a dissolved ion and the concentration of humic substances in the groundwater (which is less than 500 $mg/m^3$). The chosen $K_d$ values are compensated for this /5-49/.

Development of more detailed models for sorption, which better take into account the physical and chemical processes that are involved, is being pursued both in Sweden and in several other countries. It has not been practically possible to make use of these results in SKB 91, but developments in the field have permitted a better understanding of the sorption mechanisms and how they are affected /5-43/.

In-situ tests are being conducted to test the models for radionuclide transport. Tests with sorbing radionuclides show that the chosen parameters do not lead to an overestimate of retardation due to sorption. Even when rapid flows and high-conductivity zones or very short migration distances are utilized in the tests, it is difficult to get nuclides through that are more sorbing than, for instance, $Sr^{2+}$. Even if the tests continue for months or years, it happens that $Cs^{+}$ and similar elements never come through /5-38, 5-39, 5-40/.

In-situ tests with technetium carried out in Finnsjön show that technetium is sorbed strongly /5-40, 5-41/. This confirms the fact that technetium is reduced from low-sorbing pertechnetate to high-sorbing technetium(IV). This has also been demonstrated in laboratory experiments /5-41, 5-42/. The in-situ test plays an important role here, since it is difficult for practical reasons to completely simulate natural reducing conditions in the laboratory.

The existence of an interconnected system of microfissures in granitic rock has also been confirmed by in-situ tests /5-43/.

In summary it can be concluded that laboratory tests and in-situ tests show that the sorption of radionuclides on mineral surfaces and diffusion into the microfissures in the rock are robust retardation mechanisms that are not affected appreciably by changes in external conditions.

Sorbing radionuclides could in principle be transported with the water if they adhered to colloidal particles in the groundwater. The concentration of colloids in the groundwater is less than 0.4 mg/l. They consist of inorganic particles such as calcite, iron hydroxide, clay etc. and can of course sorb radionuclides. It makes no difference to the nuclide transport if the uptake of radionuclides on colloidal particles is reversible. Somewhere in the pathline the nuclide is transferred to the rock. If, on the other hand, the nuclide should adhere irreversibly, this is an entirely different situation. In this case the nuclide will be transported with the particle and, in the worst case, not be retarded at all by sorption in the rock. Laboratory tests confirm that radionuclides actually can form colloids. To a large extent the sorption on the mineral colloids is reversible. The strength of the sorption is roughly equivalent to measured $K_d$ values for corresponding minerals and nuclides /5-45/.

Colloid transport has been observed in in-situ tests. In tracer tests with relatively rapid flows, it happens that a small fraction of a sorbing radionuclide sometimes appears as a colloid and is transported with little or no retardation /5-39/. The same phenomenon has been observed in laboratory tests that simulate transport in a fracture /5-51/. Studies of natural analogues also show quite clearly that strongly sorbing elements such as thorium and rare-earth metals are bound to particles in groundwater /5-50/. But it can also be observed in the same studies that these aggregates are of no importance for transport in slow flows. Further down the pathline the concentration of particles is insignificant and the small quantity of particle-bound nuclide that is left has changed in composition and is close to being in equilibrium with the groundwater.

In summary it can be concluded that radionuclides in the groundwater can occur as colloids and that the possibility cannot be ruled out that a small fraction are bound irreversibly to mobile natural colloidal particles. However, calculations show that even for such an extreme case the consequences are without importance for safety. The evaluation is summarized in /5-50/. In KBS-3, colloid transport was treated as a special case. This has not been considered necessary in SKB 91.

Careful analyses of the groundwater show that bacteria also exist at great depth. All species have not been identified, but methane bacteria and sulphate-reducing bacteria have been encountered /5-46/. The environment is poor in nutrients. The substances that could conceivably be utilized in the microorganisms' metabolism are methane, hydrogen, organic matter, carbonate, sulphate etc. Laboratory tests show that bacteria can ingest radionuclides. In theory, radionuclides could accompany bacteria in the same way as they accompany other colloidal particles in the groundwater. However, the concentrations of microbes are very low (less than 50 $mg/m^3$). The importance of bacterial transport for safety has been analyzed in the same way as for inorganic colloids /5-50/. The conclusions are the same – it is of no importance for safety.

It has been suggested that trace amounts of metals can be transported with gas bubbles in the rock. This conclusion is based on analyses of earth gas above relatively deep-lying orebodies. The gas has contained traces of metal from the ore. But the concentration of metal in the gas compared with the amount of metal in the ore shows that only extremely small quantities could be released and transported to the biosphere in this manner. Moreover, the necessary conditions for gas-induced transport do not exist in the deep repository. In order for gas bubbles to form, the water must be saturated with gas at the pressures prevailing at repository depth. The groundwater at these depths is greatly undersaturated with respect to dissolved gases, see Table 5-4.

**Table 5-4. Dissolved gas in groundwater from Äspö. The gas is composed of more than 90% nitrogen and is expressed in ml of gas at NTP per litre of water. The ratio represents the measured gas concentrated divided by the calculated soluble concentration at the prevailing hydrostatic pressure. The gas formation depth is the depth at which the measured dissolved quantity of gas enters a separate gas phase.**

| Sampling depth, m | Gas conc. ml/l | Pressure bar | Solubility ml/l | Ratio | Gas formation depth, m |
|---|---|---|---|---|---|
| 130 | 20 | 13 | 200 | 1/10 | 13 |
| 200 | 34 | 20 | 300 | 1/9 | 23 |
| 200 | 39 | 20 | 300 | 1/8 | 26 |
| 290 | 53 | 29 | 400 | 1/8 | 35 |
| 680 | 72 | 68 | 1000 | 1/14 | 50 |

### 5.4.5 General validity of the chemical properties

The Finnsjön area's granodiorite and its fracture-filling minerals represent chemical conditions that are common in Swedish bedrock. The groundwater composition and redox conditions in the Finnsjön area exhibit great similarities to fresh and saline groundwaters from other areas studied by SKB /5-48/, /5-49/. What distinguishes groundwater in the Finnsjön area from other areas is mainly higher carbonate concentrations in the upper fresh groundwater and the lack of low iron contents in the deep saline groundwater. The former is presumably due to the fact that the clay sediments in the area have absorbed calcium in exchange for sodium, which in turn has allowed more calcite to be dissolved. This has enabled the carbonate concentration to reach a higher level that if carbon-dioxide-rich water had dissolved calcite to saturation and nothing else had happened.

Data are lacking showing low iron concentrations, below 0.1 mg/l, from sampling of deep groundwaters in the Finnsjön area. In other areas, iron concentrations below 0.1 mg/l are common at great depths, say below 500 m. Whether this is the case or not in Finnsjön cannot be confirmed, since all reliable data come from the depth range 100-400 m. The iron concentrations in SFR lie at the same level as those in Finnsjön. All data in SFR also come from a relatively shallow depth, 150 m maximum.

The concentration of organic and particulate matter is of the same order of magnitude as at other investigated sites.

### 5.4.6 Chemical stability

For many substances, no essential changes are foreseen in the future owing to the fact that the concentrations are determined by solubility limitations. Examples of substances whose concentrations are limited due to low solubility and reactions with the rock are calcium, potassium, magnesium and carbonate. The pH of the water is above all determined and buffered by the calcium/hydrogen carbonate/carbon dioxide system. The sulphate concentration is also kept down by the formation of solid sulphates or biological processes.

The present-day distribution of fresh and saline groundwater in the Finnsjön area is dependent to a large degree on the existence of Zone 2. Above the zone the water is fresh, while below the zone it is saline. The saline water below the zone will, however, be replaced by fresh water as washing-out proceeds via precipitation. The character of the water will then become the same as that of the fresh water above the zone. The rate of this washing-out process is difficult to judge. It can be very low and linked to the washing-out of other, contiguous groundwater flow systems. But there may also be a parallel with the situation on Äspö, where fresh water has penetrated down to about 50 metres depth during the 3,000 years that have passed since Äspö rose from the sea /5-48/. As is mentioned in section 5.1.2, the Finnsjön area became dry land between 3,000 and 5,000 years ago. After the next ice age, sea water will probably once again infiltrate the bedrock and the process will be repeated.

As was previously mentioned, during the retreat of an inland ice sheet, the groundwater flow in the rock can increase. Biological activity in the surface of the ground is low during a glaciation. Oxygen-rich meltwater with a low concentration of carbon dioxide and dissolved salts can therefore penetrate deeply into the rock in hydraulically conductive zones. The oxygen can cause oxidative decomposition of redox-sensitive minerals in the rock, but in the first place this process is inhibited by the fact that the carbon dioxide concentration is low, and in the second place the deglaciation phase at a given location is of relatively short duration. The total increase in decomposition is therefore small or insignificant.

During a glaciation cycle it is also possible that permafrost will freeze salt out of the groundwater so that the salt content of the underlying groundwater gradually increases.

# 6 REPOSITORY DESIGN

*The layout of the repository and how it has been adapted to the conditions at Finnsjön are described in this chapter. The methods for construction and closure of the repository are commented on. Conditions that can influence safety are discussed.*

## 6.1 GENERAL

The deep repository for spent nuclear fuel that is assumed to have been sited in the bedrock at Finnsjön shall be able to receive 7,800 tonnes of spent nuclear fuel from the Swedish reactors. The fuel will then have been stored for 40 years in CLAB and subsequently have been encapsulated in corrosion-resistant cylindrical canisters.

The repository can be positioned in several different ways on the Finnsjön site: In the southern block, in the northern block or divided between the two blocks. It can also be built in one or several levels. A siting in the northern block has been chosen, since more data are available from there. Furthermore, the repository has been placed underneath the flat-lying fracture zone, which is favourable. Since sufficient space exists between the major vertical fracture zones, it has been assumed that the repository will be built in one level /6-1/. The communication pathways to the surface consist of vertical shafts.

The repository has been designed according to the same principles as in the KBS-3 study, i.e. in the form of a number of parallel drifts with separate deposition holes for each canister.

Only that part of the repository where the spent fuel is deposited is dealt with in SKB 91.

## 6.2 ADAPTATION OF THE REPOSITORY TO THE FINNSJÖN AREA

### 6.2.1 Underground sections

It has been assumed that the repository will be adapted to the expected fuel quantity and existing geological conditions as follows:

- The number of canisters to be deposited is 5,300. To permit an adaptation of the positions of the deposition holes so that minor fracture zones can also be avoided, a 10% increase of the length of the deposition drifts is judged to be suitable. The repository thus contains 5,830 canister positions;
- The minimum distances between deposition drifts and between canister positions are determined by the maximum permissible temperature and by practical building-related considerations. Temperature calculations show that even a very close spacing can be accepted /6-2/. With regard to practical buildability, a centre-to-centre distance of 6.0 m between canister positions and of 25 m between deposition drifts has been chosen.

- An exclusion zone of 100 m to major steeply-dipping fracture zones – such as zones 1, 4 and 12 /6-3/ – has been chosen for the assessment's reference case;
- The repository has been placed at a depth of 600 m to permit an exclusion zone of at least 100 m to the flat-lying Zone 2. For drainage reasons the deposition drifts are being built with a gentle (1:100) rise out from the central drift;
- Communication shafts etc. are being located outside the rock block being utilized for deposition;
- It has been deemed suitable to orient the deposition drifts so that they deviate by at least $75^{o}$ from the dip and strike directions of the dominant fractures, in order to limit the hydraulic disturbances caused by the drift and the risk of rock fall during construction /6-11/;
- In order to be able to evaluate the importance of the orientation of the drifts in relation to the hydraulic gradient, two drift geometries have been placed into the site, see Figure 6-1. Figure 6-1a, where the drifts run perpendicular to the gradient, is the reference case.

### 6.2.2 Shafts and surface facilities

The placement of the surface facilities in relation to the underground sections is governed mainly by practical considerations. All shafts except one ventilation shaft have been placed within the same fenced-in area, which can be placed relatively independently of the underground facility.

The placement of the surface facilities for the two alternative drift directions is shown in Figure 6-1. To reduce the likelihood that direct flow paths will be located or created between the deposition area and the ground surface, the placement has been done so that the shafts are separated from the deposition area by fracture zones 1 and 4. However, this means that the central shaft must be made longer and that the drift's disturbed zone has to be separated hydraulically from the fracture zones by means of plugging.

The balance between advantages and disadvantages as described above is site-specific and must be individually determined for each separate site.

## 6.3 CONSTRUCTION OF THE REPOSITORY

### 6.3.1 Access via shaft or ramp

All communication and transport between the ground surface and the repository take place in vertical shafts. Three service shafts – the central shaft, the canister shaft and the rock shaft – plus an evacuation shaft are included in the facility.

Alternative designs for communication are shafts at an inclination of $50\text{-}60^{o}$ from the horizontal, or ramps at an inclination of 1:4 or flatter. The advantage of inclined shafts or ramps is that the transports in the central, canister and rock shafts can be combined. However, a vertical duct is required for ventilation, which can also be used for personnel transports. The evacuation shaft is required regardless of the design of the central communication passage (two different escape routes).

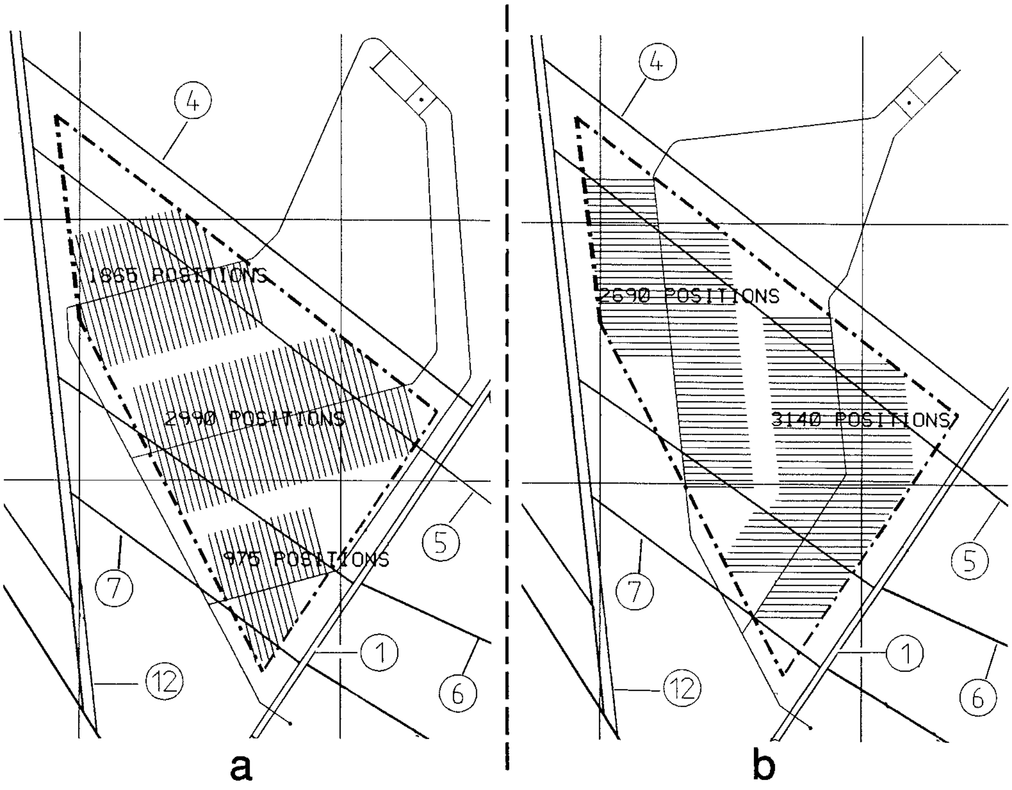



***Figure 6-1 a.*** *The orientation of the drifts in the reference case is shown in Figure a above. The drift directions are here perpendicular to the hydraulic gradient.*
***Figure 6-1 b.*** *In a calculation variation as shown in Figure b, the drift directions run parallel to the hydraulic gradient.*

### 6.3.2 Blasting/drilling

It has been assumed that the repository will be excavated by means of conventional drilling/blasting. By the use of high-density drilling in the outer contour of shafts and drifts and the use of special explosives, disturbances in surrounding rock are limited.

It has been assumed that the vertical deposition holes will be drilled to their full cross-sectional area with special drilling rigs.

### 6.3.3 Selection of deposition positions

It is assumed that the configuration of the repository will be based on extensive investigations in both boreholes and observation shafts. Nevertheless it is deemed important that some flexibility be retained even during the execution phase so that the layout can be adapted to the rock conditions that are successively encountered during construction.

The deposition positions are selected on the basis of the following principles. The centre-to-centre distance between the deposition holes shall be at least 6 m. The choice should be based on the hydraulic regime around the deposition hole and the fracture structure of the rock, which can affect water flow and mobility. Positions for deposition holes where conditions seem to be inappropriate will be rejected.

Relatively large water flows in the near rock can be tolerated without compromising long-term safety, but in practice it may be difficult to apply the buffer material with undiminished quality at large water seepage rates.

### 6.3.4 Sealing/grouting

During the blasting of the repository drifts, it is foreseen that pilot holes will be drilled from the face to provide information on the nature of the rock ahead. If these holes indicate large water flows, the rock will be pre-grouted. Sealing methods have been developed within the Stripa Project which lead to reductions of the rock's hydraulic conductivity /6-4/. In this way water seepage can be reduced to an acceptable level during construction and deposition.

In the event a fracture zone is intersected by the drift, some space can be left on both sides where no canisters are deposited. The risk of displacements along the fracture plane will probably determine – more than the hydraulic conductivity of the fracture zones – whether deposition positions are to be rejected. Methods exist for sealing even strongly water-bearing zones so that deposition can be carried out in a normal manner.

### 6.3.5 Plugging

Normally, deposition drifts and shafts are backfilled with a mixture of bentonite and sand. On passage of zones with high hydraulic conductivity, plugs of the type shown in Figure 6-2 are constructed. Access drifts and excavations in the central area are also backfilled in the same way. In the shafts, slots are made in the surrounding rock at appropriate levels and filled up with compacted bentonite so that vertical transport in the disturbed zone is interrupted, see Figure 6-2.

### 6.3.6 Backfilling

During the excavation of drifts, holes and shafts, changes occur in the fracture system in the surrounding rock as a consequence of blasting and redistributions of stress. A long open period can lead to increased loosening-up and temperature impact can reinforce these effects /6-11/. Certain spaces or parts of them can be rendered less pervious by means of sealing plugs. Thus, plugging with highly compacted bentonite was used during the investigation for SFR to plug parts of holes drilled from an overlying lake; shallower and deeper parts were filled with cement. The swelling material shall be kept confined in order for its properties to be preserved.

The function of the backfill material is to seal drifts and shafts and to serve as a buttress against the buffer material in deposition holes and as a support for the rock.

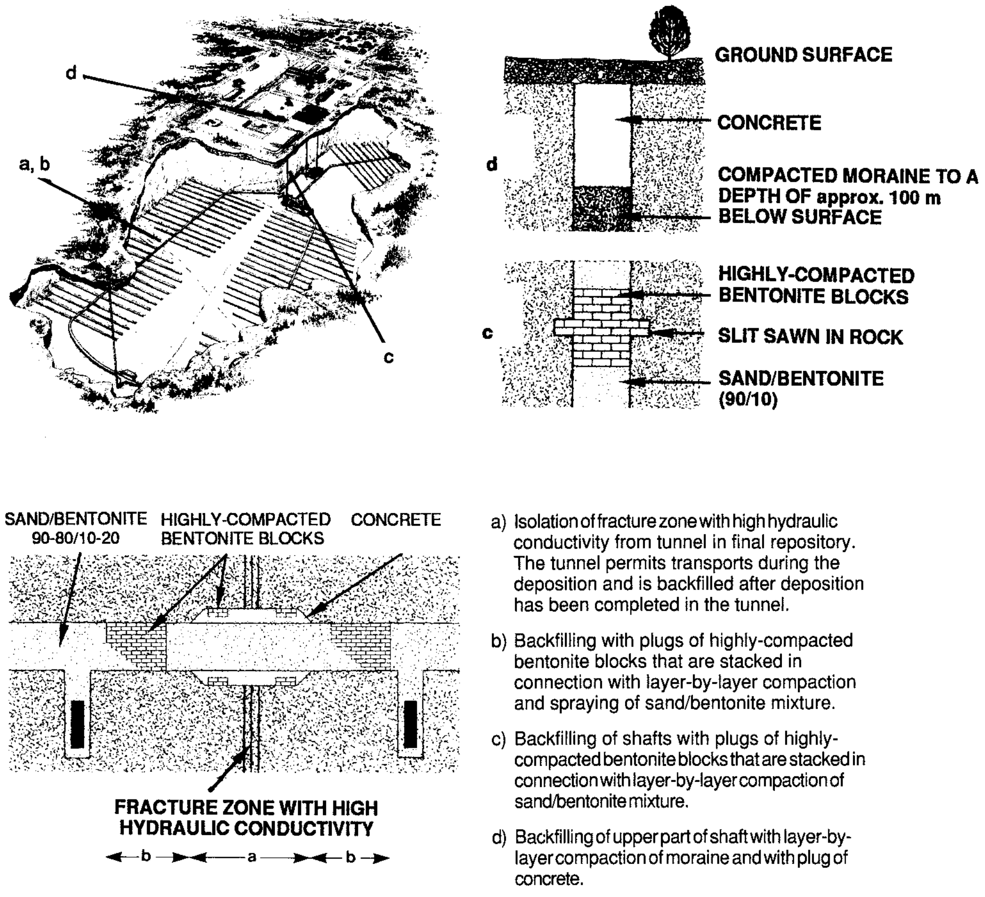



***Figure 6-2.*** *Construction of plugs with highly compacted bentonite in drifts and shafts.*

Essential properties for the backfill material are:

- low hydraulic conductivity;
- low compressibility;
- long-term stability so that the material retains its properties without having a detrimental effect on the environment in the deposition holes.

Natural water-bearing zones that impinge upon the system of deposition drifts can communicate with the disturbed zone that is formed around drifts and shafts and cause flow in a persistent such zone. Measures to prevent such communication are local pluggings and sealings, whereby an attempt is made to moderate this "short-circuited" flow in the vicinity of the waste canisters by redirecting it to waterways at greater distances. This requires good information on the system of waterways in the rock.

## 6.4 SAFETY-RELATED FACTORS

### 6.4.1 Temperatures

The fuel in the canisters gives off heat, which leads to a temperature rise in the repository. An elevated temperature in relation to the surrounding rock masses gives rise to changes in the stress field in the rock and can affect the groundwater movements in the rock and the properties of the bentonite. To limit such effects, and to prevent the bentonite from drying out rapidly after deposition, the temperature has been limited to well under 100°C.

The selected distances between drifts and between canister holes mean that the temperature doesn't reach higher than about 70°C. This temperature maximum for the contact surface between canister and buffer is reached about 10 years after deposition and has a duration of 10 years or so /6-2/, i.e. a slightly lower temperature load than the one calculated for KBS-3.

Thermally induced rock movements in deposition holes or drift walls are so small at this temperature as to be negligible in comparison with the room for movements left by the bentonite's plasticity /6-5, 6/. Nor are the water movements around the repository appreciably affected by such a limited temperature increase /6-7/.

As far as the temperature's effect on the bentonite's plasticity and swelling capacity are concerned, the process of illitization has proved to be strongly temperature-dependent. In order for appreciable portions of the bentonite to be converted to illite with the potassium concentration measured in groundwater in Swedish bedrock (Finnsjön has a relatively high concentration), temperatures higher than 100°C for thousands of years are required /6-4/.

### 6.4.2 Rock stresses

The rock stresses are moderate in the normal case (vertical stress about 16 MPa and a horizontal stress between 17 and 27 MPa /6-3/) at 600 m depth in Finnsjön and do not entail any risk for overloading of intact rock. Fracture zones and their properties can vary, however, which means that the directions of the largest and smallest rock stresses, rather than their magnitudes, are of importance. Drifts parallel to the principal stress direction cause less redistribution of the stress situation around the drift (the vertical and horizontal stresses are roughly of equal size). A circular drift would come close to an ideal shape. In the event the drift is oriented perpendicular to the maximum stress direction, a standing ellipsoidal compressive stress situation is created and thereby an ellipsoidal shape of the disturbed zone around the drift (major disturbed zone).

The deposition drifts do not affect the stress field for adjacent drifts when the centre-to-centre distance is 25 m.

### 6.4.3 Fracture directions

The impact of drifting on the near field is strongly dependent on existing fracture geometries and fracture directions. Certain types of fracture systems have been studied in the Stripa Project /6-8, 9/.

Perpendicularly intersecting fractures are affected least. It would therefore be most strategic to intersect the strongly water-bearing fractures at right angles and follow the strike for less water-bearing fractures. In practice, compromises must be made based on an assessment of advantages and disadvantages for long-term function. Knowledge of the rock at a depth of 600 m in Finnsjön is not so detailed that the actual outcome can be discussed. Such knowledge requires investigations at repository level. The safety assessment assumes that strongly water-bearing fracture zones that are intersected, are intersected at right angles.

Strongly water-bearing zones should preferably be avoided entirely. The exclusion zone to such zones is 100 m.

### 6.4.4 Disturbed zone

After filling of the deep repository with water, a disturbed zone with higher hydraulic conductivity can be expected to have formed around all blasted-out openings during development. Available information on the disturbed zone and its effect from the safety viewpoint has been gathered /6-10/.

The properties of the zone are dependent partly on the rock's elastic properties and existing fracture geometries, and partly on the development method that is used. Full-face driving only opens marginal fractures in the rock very close to the opening, while the blasting opens fractures farther into the rock.

If the drift lies parallel to the horizontal principal stress direction in Finnsjön, the cross-section of the zone will be circular, whereas if the drift is oriented perpendicular to the principal stress direction it will have the shape of a standing ellipse. A conceptualization of the disturbed zone around a drift with a diameter of 4.5 m, situated at a depth of 500-600 m, is sketched in /6-11/. Two models are presented, a standard case and a conservative case. Only the standard case is shown here, see Figure 6-3. It is assumed that the direction of the drift deviates more than $15^{o}$ from steeply dipping, major fracture systems. The vertical and horizontal stresses are of roughly equal magnitude in the plane that intersects the drift at a right angle. (In Finnsjön this corresponds to the case with drifts parallel to the horizontal principal stress direction.) The disturbed zone extends approximately one drift diameter out from the drift wall. The hydraulic conductivity is assumed to increase from $K_R$ in the virgin rock to a maximum of 100 $K_R$ m/s in a 1 m wide zone nearest the drift. A 3.5 m zone with a conductivity of up to 10 $K_R$ m/s is formed around this.

The deposition holes are drilled, with moderate diameter, whereby the extent of the zone is limited and the hydraulic conductivity increase is small.

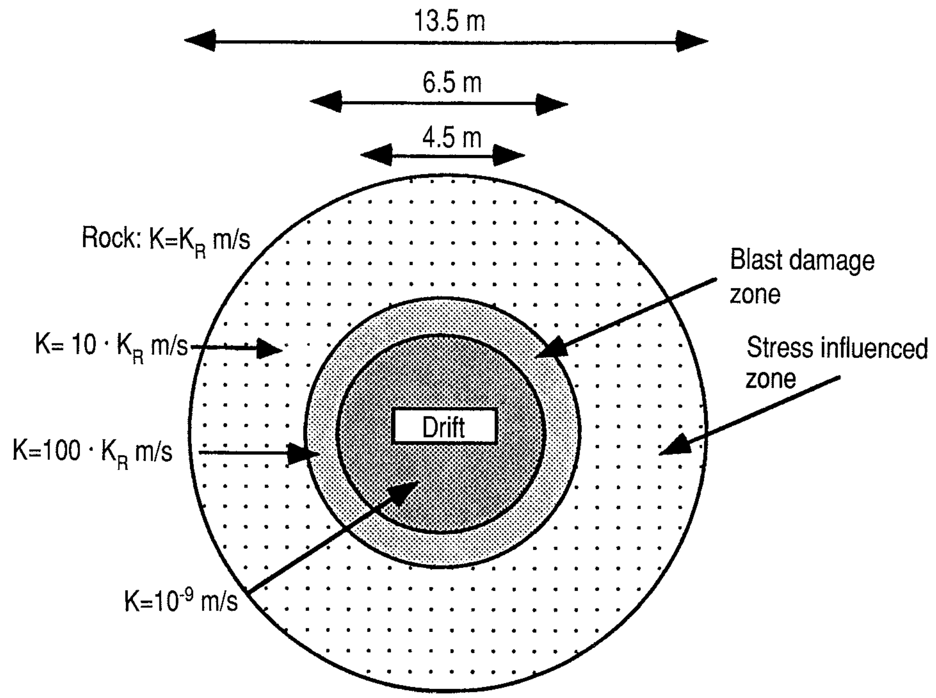



***Figure 6-3.*** *Conceptualization of the disturbed zone around a drift with a diameter of 4.5 m situated at a depth of 500-600 m. $K_R$ designates the hydraulic conductivity of the undisturbed rock.*

### 6.4.5 Sealing of fractures

Pre-injection-grouting during development of the repository seals off water-bearing fractures and reduces the inflow of water to the drift (seepage). In the full-face-bored tunnel *Ormen*, 3.5 m in diameter, under central Stockholm, the goal was to keep seepage to 2 l/min and 100 m tunnel length, which has been achieved.

A test was conducted in Stripa involving sealing of a fracture zone from an already blasted drift with special cement /6-12/. The results showed that it is possible to reduce the hydraulic conductivity from $10^{-8}$ m/s to $10^{-9}$ m/s in the grouted zone. Penetration was measured to several metres depth in 50-100 µm wide fractures and about 0.1 m in 20 µm wide fractures. Measurements also showed that the water took other paths around the sealed area, which has also often been found to be the case following post-injection-grouting in underground facilities.

Thus, methods do exist for reducing water seepage during the operating period (the deposition phase), if deposition so requires.

The long-term effect is dependent on a number of factors such as the long-term stability of the cement, the application method for pre- or post-injection-grouting and possible movements and displacements in the rock during the temperature pulse and in the long-range perspective.

The stability of the cement has been theoretically analyzed in /6-13/ with results that show that chemical degradation takes tens of thousands to millions of years.

The quantity of injection-grouting material can only be determined theoretically today. The upper limit is determined by the rock's porosity, which in granite is normally about 0.5%. In fracture zones, porosity can constitute up to 2% of the volume.

### 6.4.6 Reference description of the near field

**Repository design**

The spent fuel is encapsulated in lead-filled copper canisters. The canisters are deposited in holes drilled in the floor of the drift and surrounded by blocks of highly compacted bentonite. The centre-to-centre distance between the deposition holes is 6 metres. The deposition drifts are backfilled with a mixture of compacted quartz sand and bentonite.

**Temperature**

The temperature limit on the canister surface in a repository of the KBS-3 type has been set at 100°C. A higher temperature leads to several complications:

- There is a risk of thermally induced groundwater flow around the repository;
- The risk of rock movements around the deposition holes increases;
- The bentonite's long-term properties are jeopardized;
- Thermodynamic data on the nuclides in the fuel are insufficient.

Calculations have been carried out to show that the maximum temperature lies under 100°C for all times /6-2/. These show that the temperature on the canister surface for the selected reference fuel reaches about 70°C after 10 years and then falls. This temperature increase does not appreciably affect the water flow in the repository /6-7/.

**The rock**

A highly standardized and simplified model of the discontinuities in undisturbed granitic rock is described in /6-11/. The model is based on extensive mapping, compilation and statistical processing of rock structures on all scales in crystalline rock, particularly from the Finnsjön area, SFR and Stripa, as well as theoretical and experimental studies of fracture development. The fracture systems are classified into first- to seventh-order discontinuities, depending on size, see Table 6-1. The classification is to be regarded as relatively arbitrary. In actuality the borders between the orders are fluid.

**Table 6-1. Fracture zones and fractures in undisturbed granitic rock.**

| | Typical spacing m | Typical hydraulic conductivity 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 | Different | $10^{-13}$ |

5th-order fractures do not conduct any water in undisturbed rock, but the blasting of repository drifts and the drilling of deposition holes causes them to open and widen. The premises for the rock in the near field for SKB 91 have been chosen on the basis of the model in /6-11/ and the description of the disturbed zone in section 6.4.4.

The rock's hydraulic properties have been modelled on the basis of results obtained from the field measurements.

**Drifts**

- The repository is surrounded by an exclusion zone of 100 m to major fracture systems;
- The drifts run at a greater angle than $75^{0}$ from the dip and strike of 5th-order fractures;
- The blast-damaged zone around the drifts extends 1 metre out from the periphery of the drift and has a hydraulic conductivity about 100 times higher than that of the undisturbed rock in the axial direction.

**Deposition holes**

- All deposition holes are intersected by fractures of the 4th and 5th order. This gives a fracture spacing of 0.5 m for the reference case;
- The groundwater flux at the different canister positions in the repository is calculated on the basis of the gradients in the area and the properties of the rock.

# 7 THE BIOSPHERE

*This chapter describes present-day conditions in the biosphere around Finnsjön and discusses what changes can be expected with time. The biosphere conditions that have been chosen for the safety assessment are presented and justified. A future glaciation scenario is described and discussed.*

## 7.1 PRESENT-DAY CONDITIONS AT FINNSJÖN

The area at Finnsjön can be characterized as a flat forest ecosystem, rich in outcrops and with a lot of boggy land. The groundwater flows from the repository towards the northeast, see the fold-out map at the back of this report. There are discharge areas about 500–1,000 m northeast of the repository consisting of two marshy areas, about 1 $km^2$ and 0.3 $km^2$. These are drained by creeks that run north and empty into Skålsjön Lake about 4 in northeast of the Finnsjön block. Marshy areas also occur sporadically between the Finnsjön block and two large lakes, North and South Åsjön, about 7 km northeast of the repository area. A creek system drains these marshy areas towards South Åsjön /7-1/.

Groundwater from the repository area will be transported different distances into the rock mass, towards the discharge areas described above, depending on the permeability of the rock mass and fracture zones and the homogeneity of the fracture zones.

If the regional Imundbo zone (see fold-out map at back of report) has a high hydraulic persistence and permeability, it should constitute a barrier to the flow of groundwater from the repository area. This means that the groundwater discharges into the marshy areas a kilometre or so northeast of the Finnsjön block or in the Imundbo zone. If, on the other hand, the Imundbo zone is assumed to be non-homogeneous, certain pathlines from the repository could conceivably have discharge areas east of the Imundbo zone. The marshy areas constitute a place where certain radionuclides can accumulate /7-2/.

## 7.2 FUTURE CONDITIONS AT FINNSJÖN

The Finnsjön area will probably not undergo any essential changes during the next 1,000 years. The soil cover is thin and consists mainly of moraine, Finnsjön and Skålsjön lakes are deep and will not change radically. Agriculture will be pursued, but probably only on a limited scale.

How the situation will develop over the longer term is more difficult to predict, all kinds of scenarios are conceivable. Major climatic changes can be expected over the long term – several thousand years. A probable scenario for a future ice age is presented in section 7.5. Its importance for the safety of a final repository is discussed in section 9.2.

The biosphere could also be affected by acidification caused by the combustion of fossil fuels. The effects have been studied in /7-3/. Acid precipitation is neutralized to begin with in the soil layer, where the carbonate system buffers the pH to 6.2. If the carbonate system is used up, weathering reactions in the rock will buffer the pH to 5.0-6.2. Consequently, groundwater acidification will more or less follow the weathering front. The study has been concentrated on the increasing erosion of the bedrock.

The effects are dependent on how quickly the fossil fuels are consumed, as well as on what restrictions are imposed on emissions of combustion products. It has been assumed that the earth's reserves will be used up within the next 300 years. The effects of this have been extrapolated 60,000 years ahead. Three different alternatives have been considered: mild, moderate and severe restrictions on emissions of sulphur dioxide in particular.

In the two cases where moderate or severe emission restrictions are imposed, an increase in the weathering rate of 1-2% is obtained during the next 500 years. This will not be traceable, nor will it affect a final repository located several hundred metres down in the rock.

The third case with no or mild restrictions may result in such severe acidification and extensive forest death that it is doubtful whether Scandinavia could be regarded as livable. In this case, over a period of 60,000 years, weathering could reach down to a depth of about 150 m. But even this increased weathering would not substantially affect the performance of a deep repository.

## 7.3 BIOSPHERE MODEL IN SKB 91

To be able to compare releases of radionuclides from different variations in the near- and far-field modelling, the different radionuclides are added after being weighted with regard to their radiological toxicity. With the aid of a standard biosphere, dose factors for different nuclides can be calculated and used for the weighting /7-4/.

### 7.3.1 Receiving bodies of water

The receiving bodies for deep groundwater from the Finnsjön area are small watercourses, lakes and the sea. The reference case is more conservative and only considers wells and lakes /7-5, 6/. Variations have been carried out with only the sea /7-7/ and with only wells as the recipients.

#### Wells

Wells, and particularly a drilled rock well, constitute a short circuit between the geosphere and the biosphere. The groundwater travel time can be shortened in the upper part of the geosphere, and the dilution can be much less than in large water volumes such as lakes, watercourses or superficial groundwater storage reservoirs. Water from a well is normally used only to a small extent as drinking water – most is

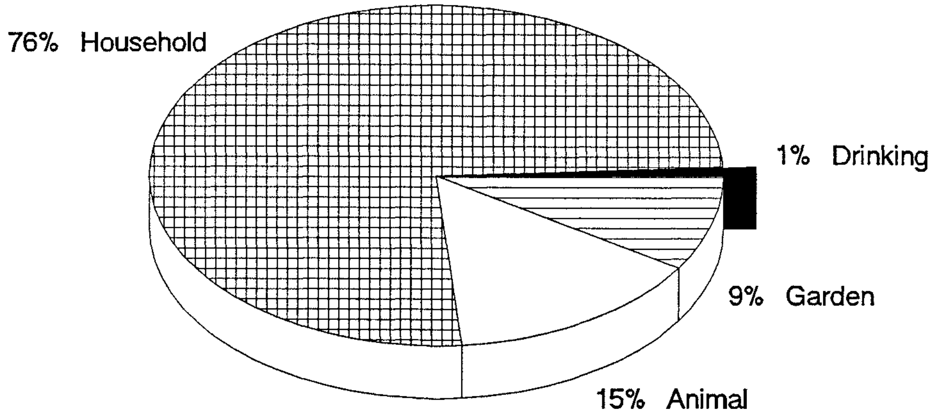



***Figure 7-1.*** *Pattern of use for well water, total 1,600 $m^3$/y.*

used as household water (laundry, dishwashing etc.) and in some cases for irrigation /7-8/, see Figure 7-1.

The dose to man from radionuclides in a well is dependent on how the well water is used and how much water is taken from the well. A well that gives a lot of water could draw more water from the repository area and thereby more radionuclides in the event a canister leaks. In normal cases, only a small portion of the water withdrawn from the well is used for drinking water, and this portion is probably smaller for wells with large withdrawal rates than for small wells. The withdrawal rate can vary from one or two $m^3$/y to several thousand $m^3$/y. A rock-drilled well can be estimated to have a useful life of 50-200 years. During the centuries to come, it can be assumed that wells will be situated at many different points in the vicinity of the repository at different points in time.

In the reference case it has been assumed that 1% of the radionuclides that reach the biosphere come up via well water. The rest are assumed to come to a lake. This is regarded as a pessimistic but not unreasonable assumption.

It is difficult to prove conclusively that no more than 1% of the radionuclides that reach the biosphere can come up via well water. A variation has therefore been carried out assuming that 100% of the nuclides reach the biosphere in this manner.

### Watercourses

In watercourses such as ditches, creeks, brooks and rivers, the groundwater that is returned to the biosphere will be mixed with a large quantity of surface water. This means that any radionuclides present in the groundwater will be greatly diluted. The important exposure pathways are largely the same as for a well, but irrigation is of relatively greater importance /7-8/. Dredging of watercourses constitutes an important link between groundwater and farmland. fish and shellfish as well as bathing are other possible exposure pathways.

**Lakes**

Dilution is even greater in lakes. Fish and shellfish, other types of aquaculture and bathing are of greater importance than in the case of watercourses. External exposure on beaches is another exposure pathway.

Crop cultivation on the exposed bottom sediments of dried-up lakes after land uplift, eutrophication or drying-out has been studied /7-9, 10/, whereby it has been found that this scenario can give rise to a 10 times higher dose than if the lake is not drained.

**Sea**

If the radionuclides reach the biosphere via the world oceans or the Baltic Sea, such a large dilution is obtained that the doses to the critical group are only a few tenths of a percent of the doses from inland releases. Doses are mainly obtained from fish. One variation assumes that all radionuclides that reach the biosphere come up with the groundwater to the Baltic Sea /7-7/.

### 7.3.2 Dispersal model

The following time-constant model is used for the reference case to calculate biosphere dispersal and doses to man, see Figure 7-2 /7-5/.

- The receiving bodies for the radionuclides that reach the biosphere with the groundwater are:
  - a rock-drilled well – 1% of the nuclides – and
  - a lake – the rest of the nuclides;
- A small farm represents the "critical group" with 25 persons, 8 animals, 0.1 ha garden and 13 ha cropland. A high proportion of local food production is assumed. The choice of data for consumption, irrigation, animal husbandry etc. is based on present-day conditions;
- Water from the well is used for drinking water, household water, animals and irrigating the garden (see Table 7-1). The annual withdrawal rate is 1,600 $m^3$;

**Table 7-1. Use of well water in the reference case.**

| | Best estimate | Range of variation min | max | |
|---|---|---|---|---|
| Drinking water | 0.6 | 0.4 | 0.75 | $m^3$/y and adult |
| Drinking water | 0.15 | 0.05 | 0.2 | $m^3$/y and child |
| Washing, hygiene | 50 | 30 | 70 | $m^3$/y and person |
| Drinking water | 30 | 25 | 34 | $m^3$/y and animal |
| Irrigation | 0.15 | 0.03 | 0.3 | $m^3/m^2$/year |

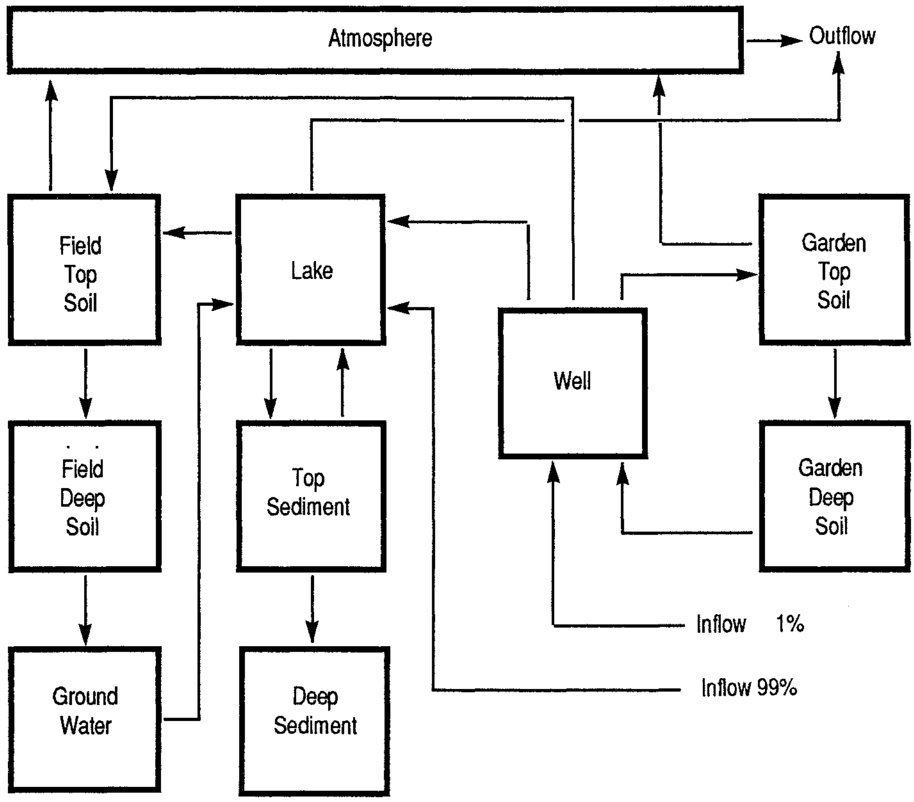



*Figure 7-2. Model structure for dispersal in biosphere.*

- Irrigation of cropland is done with lake water;
- Calculations are performed for a period of 500 years /7-8, 11/;
- The dose calculations take into account intake of water, milk, vegetables, grain and fish as well as exposure from soil (dust to lung) and land, see Figure 7-3 /7-5/. The present-day pattern of consumption is assumed;
- ICRP's weighted dose factors /7-12/, including supplement according to the latest ICRP publication /7-13/, are used.

### 7.3.3 Dose factors

Radiation dose is reported as dose commitment to individuals in a "critical group". This measure should only be used up to 10,000 years – principle 3 in /7-4/. After this the consequences of any releases are assessed by comparison with the natural turnover of naturally occurring radionuclides. This means that the outflow of radionuclides to the biosphere is compared with maximum permissible values – principle 4 in /7-4/.

Calculation of dose factors has been reported in /7-5, 6, 7/. Individual doses are expressed in units of Sieverts per year to adults and children for a continuous release of 1 Bq per year to the biosphere. Variation with respect to the fraction of radionu-

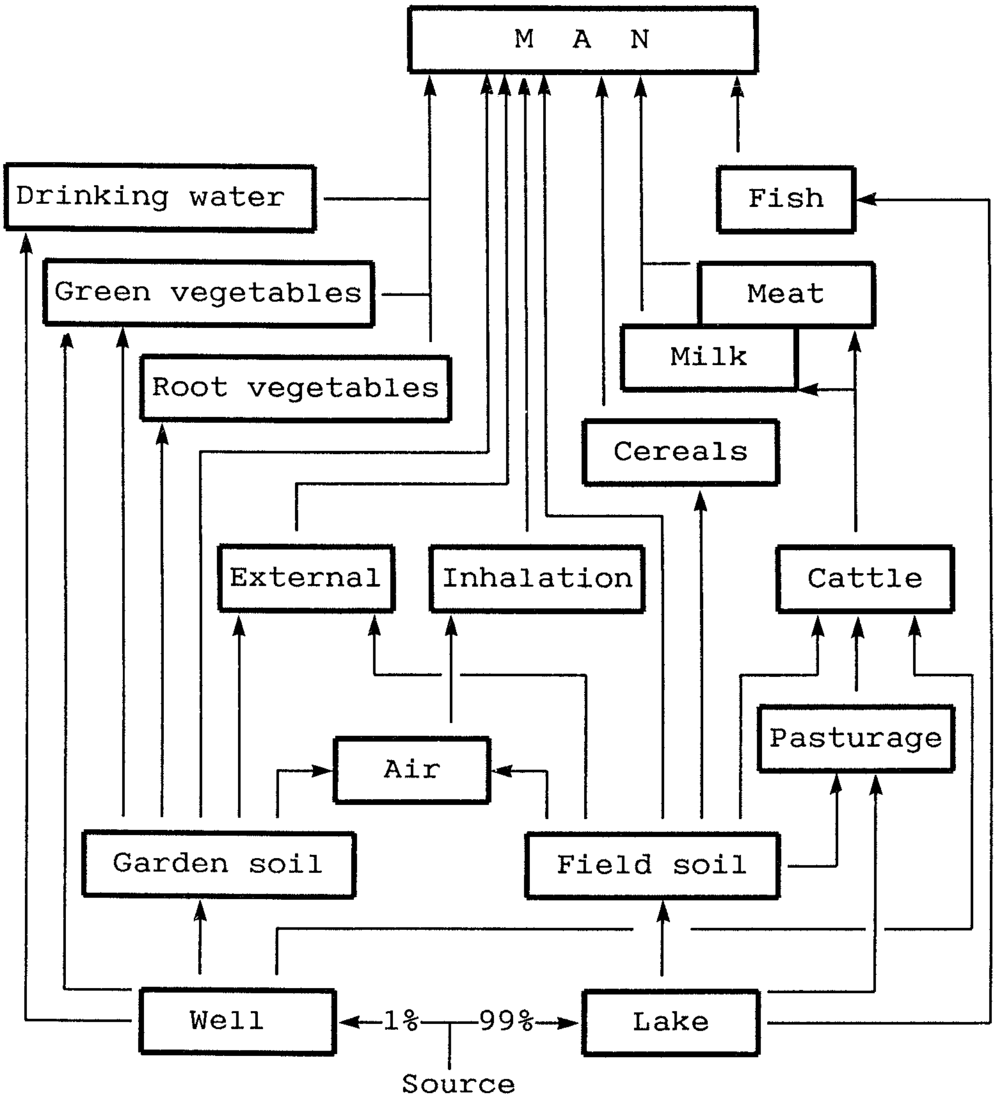



*Figure 7-3. Exposure pathways for critical group.*

clides (0.01-10%) that are carried up to the biosphere via well water has also been carried out /7-13/. The dose factors are presented in Table 7-2.

Dose contributions from different exposure pathways and uncertainties associated herewith are reported in /7-5, 6, 7/. Drinking water and vegetables are dominant exposure pathways for most nuclides. Exceptions are cesium and carbon-14, where fish dominates, and selenium, where the contribution from potatoes is greatest.

In SKB 91, the dose factors from the background reports /7-5, 6, 7/ have been corrected for ingrowth of daughter nuclides in the biosphere for Zr-93 and Th-229. The 100% values for all nuclides are calculated by multiplying the fraction of the dose that does not come via the fish exposure pathway by 100. Pooling of the nuclides has been done for Ra-226 (+ Pb-210 + Po-210), Pa-231 (+ Ac-227 + Ra-223) and Th-229 (+ Ra-225). The dose factor for Cl-36 has been calculated by comparing the ALI value according to ICRP-30 with I-129. In the same way, Ni-59 and Pd-107 have been compared with Pa-231 and Th-232 with Th-229.

**Table 7-2. Dose factor (Sv/Bq) for a hypothetical release of all radionuclides to a well, 1% to the well or all to the Baltic Sea. The boxed-in column in the middle (1% well) has been used in the reference scenario.**

| Nuclide | 100% well | 1% well | Baltic Sea |
|---|---|---|---|
| C-14 | $4.2 \cdot 10^{-13}$ | $1.3 \cdot 10^{-14}$ | $3.5 \cdot 10^{-17}$ |
| Cl-36 | $2.0 \cdot 10^{-13}$ | $2.0 \cdot 10^{-15}$ | $2.0 \cdot 10^{-18}$ |
| Ni-59 | $8.0 \cdot 10^{-14}$ | $8.0 \cdot 10^{-16}$ | $2.0 \cdot 10^{-19}$ |
| Se-79 | $5.4 \cdot 10^{-12}$ | $6.3 \cdot 10^{-14}$ | $2.9 \cdot 10^{-16}$ |
| Sr-90 | $2.2 \cdot 10^{-11}$ | $2.2 \cdot 10^{-13}$ | $8.2 \cdot 10^{-18}$ |
| Zr-93 | $2.7 \cdot 10^{-13}$ | $2.7 \cdot 10^{-15}$ | $5.9 \cdot 10^{-19}$ |
| Tc-99 | $1.7 \cdot 10^{-13}$ | $1.7 \cdot 10^{-15}$ | $1.8 \cdot 10^{-19}$ |
| Pd-107 | $7.0 \cdot 10^{-14}$ | $7.0 \cdot 10^{-16}$ | $2.0 \cdot 10^{-19}$ |
| Sn-126 | $3.1 \cdot 10^{-12}$ | $3.7 \cdot 10^{-14}$ | $3.8 \cdot 10^{-16}$ |
| I-129 | $4.9 \cdot 10^{-11}$ | $5.4 \cdot 10^{-13}$ | $4.1 \cdot 10^{-16}$ |
| Cs-135 | $1.6 \cdot 10^{-12}$ | $3.9 \cdot 10^{-14}$ | $1.1 \cdot 10^{-17}$ |
| Cs-137 | $8.6 \cdot 10^{-12}$ | $2.4 \cdot 10^{-13}$ | $6.1 \cdot 10^{-17}$ |
| Ra-226 | $1.8 \cdot 10^{-10}$ | $1.8 \cdot 10^{-12}$ | $7.2 \cdot 10^{-16}$ |
| Th-229 | $6.0 \cdot 10^{-10}$ | $6.0 \cdot 10^{-12}$ | $2.0 \cdot 10^{-15}$ |
| Th-230 | $7.5 \cdot 10^{-11}$ | $7.5 \cdot 10^{-13}$ | $1.9 \cdot 10^{-16}$ |
| Th-232 | $4.0 \cdot 10^{-10}$ | $4.0 \cdot 10^{-12}$ | $2.0 \cdot 10^{-15}$ |
| Pa-231 | $1.0 \cdot 10^{-08}$ | $1.0 \cdot 10^{-10}$ | $2.0 \cdot 10^{-14}$ |
| U-233 | $1.6 \cdot 10^{-10}$ | $1.6 \cdot 10^{-12}$ | $4.3 \cdot 10^{-16}$ |
| U-234 | $1.6 \cdot 10^{-10}$ | $1.6 \cdot 10^{-12}$ | $4.2 \cdot 10^{-16}$ |
| U-235 | $1.5 \cdot 10^{-10}$ | $1.5 \cdot 10^{-12}$ | $4.0 \cdot 10^{-16}$ |
| U-236 | $1.5 \cdot 10^{-10}$ | $1.5 \cdot 10^{-12}$ | $4.1 \cdot 10^{-16}$ |
| U-238 | $1.4 \cdot 10^{-10}$ | $1.4 \cdot 10^{-12}$ | $3.8 \cdot 10^{-16}$ |
| Np-237 | $2.2 \cdot 10^{-10}$ | $2.2 \cdot 10^{-12}$ | $5.9 \cdot 10^{-16}$ |
| Pu-239 | $4{,}3 \cdot 10^{-10}$ | $4.3 \cdot 10^{-12}$ | $4.2 \cdot 10^{-16}$ |
| Pu-240 | $4{,}3 \cdot 10^{-10}$ | $4.3 \cdot 10^{-12}$ | $4.2 \cdot 10^{-16}$ |
| Pu-241 | $7{,}9 \cdot 10^{-12}$ | $7.9 \cdot 10^{-14}$ | $7.9 \cdot 10^{-18}$ |
| Pu-242 | $3{,}9 \cdot 10^{-10}$ | $3.9 \cdot 10^{-12}$ | $3.7 \cdot 10^{-16}$ |
| Am-241 | $4{,}1 \cdot 10^{-10}$ | $4.2 \cdot 10^{-12}$ | $7.8 \cdot 10^{-16}$ |

## 7.4 DISCUSSION

The radionuclides' dispersal in the biosphere and doses are calculated in the reference case with a pessimistic and time-constant model. The purpose is that variations in the biosphere should not dominate the results of an evaluation of the geological parameters.

The transport pathways for radionuclides in the biosphere, from superficial groundwater via different exposure pathways to intake in man, are dependent on a variety of factors. Examples are land use, irrigation, distribution of water and food, etc. In addition, climate and weather have both long- and short-term impacts /7-14/. Reasonable predictions can possibly be made several hundred years ahead in time. It is therefore necessary to abandon the ambition of making a probable estimate of the consequences and instead concentrate on setting a ceiling by describing an unfavourable but not improbable case /7-11/.

Previous studies of uncertainties and variations /7-9, 10, 15/ suggest that the biosphere contributes between 2 and 5 orders of magnitude of variation in final dose to man, depending on the radionuclide. These uncertainties are so great that there is a risk they might conceal smaller differences in other site-related factors. Therefore, no allowance is made in this safety assessment for uncertainties and variation in the biosphere; rather, the dispersal conditions in the biosphere are used to link the results of the rest of the chain of calculations to the consequence. By keeping the biosphere constant, i.e. by using time-constant conversion factors between release and dose, a clear measure is obtained of the importance of the geological factors for safety.

During the first period after closure of the repository (several hundred years), the site-specific conditions in the biosphere today could be of importance in the choice of site, but since no releases will occur so early this situation is of no interest. If any attention is to be paid to conditions in the biosphere in a site evaluation, interest should be focused on how land and water could conceivably be used in the future and what kind of settlement is likely. If an area with small gradients is postulated, the area could come to be used as farmland, at least during some period. The geographic location can provide an indication of how intensive settlement could be with regard to the need for water and food production. Hypotheses regarding the future climate can also provide frames for conceivable agricultural production.

The different dispersal pathways in the biosphere will change constantly due to changes in living and eating habits, new crops, new methods of cultivation etc. Even though certain exposure pathways will always exist (one example is that man has to drink water), the drinking water could come from a large waterworks or from a small well, which strongly influences dilution and individual dose.

Thus, any differences existing today in the biosphere at different potential repository sites will be of virtually no importance after 1,000 years and are therefore of very little importance in site selection.

## 7.5 GLACIATION

### 7.5.1 Climate changes

According to the Milankovitch theory, the variations in the Earth's orbit around the sun and in the tilt of the Earth's axis cause changes in the distribution of insolation, which in turn cause ice ages. These astronomical fluctuations are cyclical with periods of 23,000, 41,000 and 100,000 years. By adding the influence on insolation from all of these variations, Milankovitch was able to distinguish extended periods of time with lower insolation, which he suggested could represent ice ages. In lieu of detailed data regarding the climatic variations of past ages, it was long impossible to either prove or dismiss this theory.

During the past 20 years, however, a large quantity of detailed data have been collected which support Milankovitch's theory. These data come, for example, from ice cores taken from the ice caps on Antarctica and Greenland, but it is above all from studies of drill cores taken from deep seabeds that a detailed and continuous description of climatic conditions over hundreds of thousands of years has been obtained. By, for example, analyzing the oxygen isotope ratios in the shells of foraminifers in these drill cores, it has been shown that there have been regularly recurring ice ages during the past 750,000 years that conform perfectly to the Milankovitch cycles.

Oxygen isotope ratios can also be used to approximate how large the inland ice sheets have been during the different ice ages. This is because when water evaporates, the light isotope oxygen-16 is enriched in the water vapour compared with the heavier isotope oxygen-18, which remains in a higher concentration in the seawater. Normally, this fractionation does not lead to any change in the isotope composition of the seawater, since the evaporated water returns to the oceans after a short time. During a glaciation, however, the evaporated water will not be returned to the oceans, but instead be bound in the inland ice sheets, leading to a change in the oxygen isotope ratio in the seawater. Analyses of oxygen isotope ratios in sedimented material on the bottoms of the oceans, for example shells for foraminifers, can therefore be used to estimate the sizes of the inland ice sheets when this material is deposited. An extensive body of data from such analyses shows a very good correlation between periods of low insolation to the northern hemisphere according to Milankovitch and periods with large ice sheets.

In summary, there is a very good correlation between the climate variations predicted by the Milankovitch cycles and the climate changes that have occurred during the past 750,000 years. Milankovitch cycles can therefore also be used to predict when future glaciations will occur and how big they will be. This assumes, however, that man does not change the composition or circulation of the atmosphere in any significant way. The greenhouse effect may be such a change. However, many researchers believe that over the ten-thousand-year perspective, this effect – if it exists – will merely cause the present-day warm period to be prolonged by a few hundred or thousand years. In a longer time perspective, the climate variations will presumably follow the Milankovitch cycles once again.

### 7.5.2 Extent of glaciation

There are several climate models based on Milankovitch cycles, usually calibrated with known climate data from previous periods of glaciation. These models also permit forecasts to be made of the future climate. For SKB/TVO's ice age scenario /7-16, 17, 18/, we have chosen to use ACLIN /7-19/ and Imbrie & Imbrie's /7-20/ models.

Both of these models show that the warm period we have experienced since the most recent ice age has been unusually warm. The next time a similar warm period will occur will be in 120,000 years. A period with a temperate climate can, however, be expected in 75,000 years. Since this is the first time when man, after a long period of ice ages, will once again be able to settle in Scandinavia, this is also the time to which SKB/TVO's ice age scenario extends. The scenario describes climatic conditions for Scandinavia as a whole, as well as specifically for the Stockholm-Helsinki region. When future ice ages can be expected and the extents and thicknesses of the inland ice sheets during these periods are shown in Figure 7-4.

Briefly, the future climate in the Nordic region looks like this, according to SKB/TVO's ice age scenario:

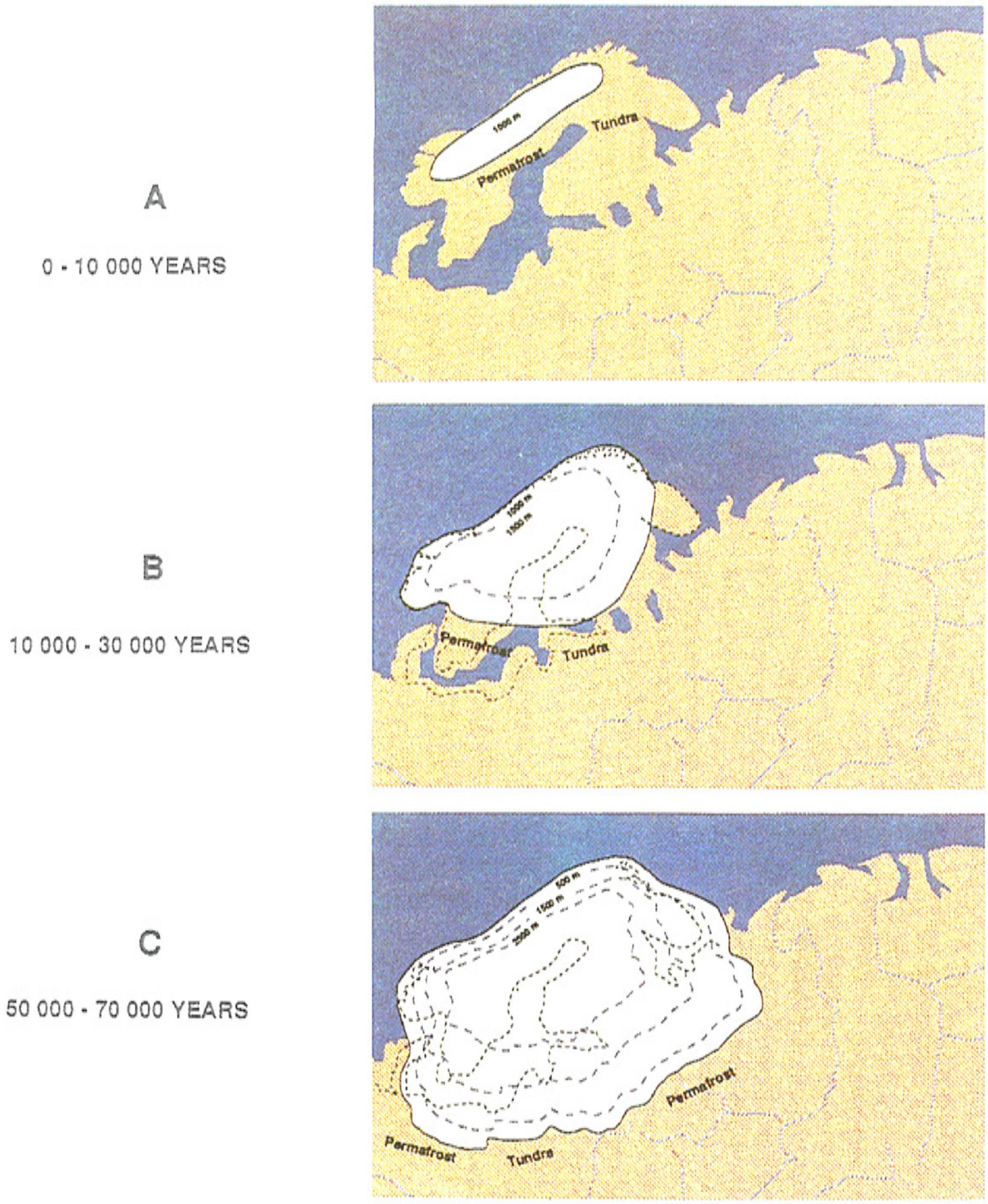



*Figure 7-4. Extent and thickness of future inland ice sheets according to SKB/TVO ice age scenario.*

### 0 – 10,000 years

The climate in Scandinavia will gradually become colder and an inland ice sheet will develop in the mountains in 5,000 years. The thickness of the ice will be 1,000 m, which will cause a subsidence of the rock surface (crustal downwarping) of about 300 m. The global sea level is expected to drop between 5 and 50 m during this period, owing to the growth of the Scandinavian and North American inland ice sheets. Permafrost will form in Sweden and Finland.

**10,000 – 30,000 years**

After a brief and slightly warmer period, the climate will once again become colder and the inland ice sheets will grow. The glaciation will reach its peak around 20,000 years from today. The inland ice sheet will then cover all of northern Sweden down to a level south of the Lake Mälaren valley. The thickness of the ice in the central portion of the inland ice sheet will be 1,500 m, and in the Stockholm region 800 m. The land subsidence will be 500 m in the central portion of the ice sheet and 60 m at Stockholm. The combination of a lowering of the global sea level by 85 m with a crustal downwarping of 60 m in the Stockholm region means that the relative sea level in this region will lie 25 m below today's coastline. Permafrost is expected in all of southern Sweden.

**30,000 – 50,000 years**

The climate will once again become slightly warmer. However, cold conditions such as in present-day Greenland will still prevail in Scandinavia. Large glaciers will form in the mountain range, along with extensive permafrost in northern Sweden. A land uplift of 50 m in the Stockholm region and a rise in the global sea level of 25 m from -85 m to -60 m can be expected. Taken together, these changes will mean that the coastline at Stockholm will lie 50 m below the present-day coastline at this time in the future.

**50,000 – 70,000 years**

Full glaciation will prevail during this period. The cold conditions of the preceding period will cause rapid growth of the ice sheet. The peak will be reached in 60,000 years. The ice sheet will then cover all of Sweden and Finland and down to northern Germany. At this point in time the thickness of the ice in the central portion of the ice sheet will be 3,000 m, while the thickness at Stockholm will be 2,500 m. The land subsidence will be 700 m in the central portion of the ice sheet and 600 m at Stockholm. Since the retreat of the ice sheet will proceed faster than the land uplift, the ice front will, when it reaches Stockholm, lie in a sea whose surface lies 100 m above today's coastline.

**70,000 – 80,000 years**

A rapid deglaciation will culminate in a relatively warm climate in 75,000 years. The climate in southern Sweden is expected to be like today's climate in northern Sweden. Small glaciers will remain in the mountains and permafrost in the far north. Parts of Scandinavia will presumably be populated and conditions may permit crops to be grown in southern Sweden. The land uplift is estimated to be 700 m in northern Sweden and 600 m in Stockholm. SKB/TVO's ice age scenario extends up to and includes this period. Based on Milankovitch, however, the climate during the following time periods can be roughly expected to be as follows:

### 80,000 – 120,000 years

The climate will once again grow colder with full glaciation in 100,000 years. The extent of the ice sheet will be great.

### 120,000 – 130,000 years

Warm period. It is not until this period that a warm climate similar to that of today can be expected.

# 8 MODELLING OF RADIONUCLIDE TRANSPORT

*The chapter describes the modelling strategy that has been used in SKB 91. Models and parameters used in the assessment are presented.*

## 8.1 MODELLING STRATEGY

### 8.1.1 General

The complexity of the studied processes and the time spans being analyzed make it necessary to use mathematical models and computer programs in the safety assessment, just as was done in KBS-3 and previous safety assessments. A chain of calculation models, linked together with the computer program PROPER, has been used for most of the calculations. The model strategy chosen is described and justified below, with an emphasis on this chain. Models used are described in detail in sections 8.2 – 8.5.

### 8.1.2 Problem formulation

In order to be able to evaluate the influence of the geology of the repository site and different layouts and placements of the repository, the actual spatial/geometric extent of the repository must be taken into account. Different parts of the repository are situated in different hydrological conditions. The local flow is of potential importance for e.g. canister corrosion and the outward diffusion of radionuclides from the near field.

The forces that drive the transport of radionuclides are gradients in hydraulic potential, which drive the water, which in turn drives the advective transport, and chemical potential, which drives the diffusive transport.

In addition, we know that:

- there are inhomogeneities and spatial variability in the properties of the rock, which moreover are only measured in a limited number of points;
- different phenomena require description on different scales. The diffusive part of the transport in the far field requires a model resolution where fracture patterns and fracture apertures are of importance. The latter determines the surface area that is available for diffusion of radionuclides into the rock matrix.

The inhomogeneities and the matrix diffusion are reflected in what is usually described as dispersion, which is the result more of a combination of different processes than one well-defined process.

### 8.1.3 Main requirements on the modelling

Finnsjön is modelled with site-specific data. The site-specific geology is taken into account as far as possible. Consideration is given to the repository's actual spatial-geometric extent and the fact that it shall be possible to distinguish between different conceivable emplacements of the repository in the rock.

The modelling mainly covers the degradation of the canister, the subsequent release from the fuel, the migration of the radioactive materials from the repository to the biosphere, and their turnover in the biosphere.

The large quantity of data from Finnsjön consists of hydraulic conductivities obtained by means of single-hole injection tests. The models used must be able to utilize this quantity of data.

A previous study of spatial variability and uncertainties in the hydraulic properties of the rock /8-1/ demonstrated its great potential importance. Thus, the assessment should take this variability/uncertainty into consideration. The previous study also showed that modelling in three dimensions is necessary for a realistic assessment.

Moreover, in order to shed light on the importance of the characteristics of the repository site, it must be possible to vary them so that they deviate from those of the Finnsjön area.

In view of the great uncertainties that are associated with the evolution of the biosphere, a standardized and fixed model for the biosphere and the future radiological consequences of releases from the repository can be used.

### 8.1.4 Main lines in the model chain

To satisfy the above requirements, it was decided for practical reasons in SKB 91 to model the groundwater flow and the nuclide transport separately. The requirement on the hydrology model is that it must take into account the spatial variability in the hydraulic properties of the rock. The intention is that it should provide an accurate picture of the net flows over cross-sections on a macro scale and that the dispersion on this scale should be incorporated implicitly.

The portion of the dispersion that is not obtained directly from the hydrology model is incorporated in the transport model. For practical reasons, the transport model is divided into a near-field portion and a far-field portion.

The modelling of the rock with its spatial variability is done with the aid of a stochastic continuum model that can be based on different statistical descriptions of the properties of the rock. Using Monte Carlo technique, realizations of conductivity and potential fields are generated based on measured values. These fields are then used to calculate corresponding realizations of the Darcy flux field.

The description of the structure and geometry of the rock that is provided by the hydrology model also serves as a basis for the near-field and far-field models, which have been designed as separate programs or separate sub-models in PROPER. The reason for this is that the water flow and its variations are of potential importance for the nuclide transport in the near and far field..

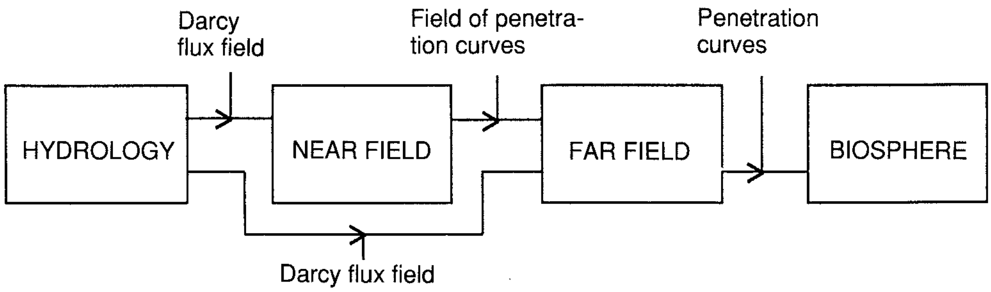



***Figure 8-1.*** *Coupling of models in model chain for safety assessment.*

The near-field model provides the source term for the entire repository and is designed to utilize the Darcy flux field generated by the hydrology model. Given a realization of this field, plus an emplacement pattern and a configuration of the repository, a realization of this source term and its spatial distribution is calculated. The model is based on descriptions of canister corrosion, fuel dissolution and outward diffusion of nuclides on the individual canister level, taking into account solubility limitations and chain decay. A geometric description of the fracture pattern in the near field is required.

The far-field model also includes the entire repository and is designed to utilize the Darcy flux field generated by the hydrology model. The source term from the near-field model constitutes the boundary condition, taking into account the distribution over the repository. Matrix diffusion/sorption and chain decay are taken into account. Some type of geometric description of the fractures in the rock is required in order to model diffusion into the rock matrix.

The biosphere model calculates the individual dose commitment to an individual in the critical group under unchanged future conditions in the biosphere.

The chain of calculation models is coupled together with the aid of the computer program PROPER, see Figure 8-1.

### 8.1.5 Execution

A brief description of the way models have been used in SKB 91 follows below. Detailed descriptions of most of the models are found in sections 8.2 – 8.5.

#### Hydrology model

Initial deterministic calculations on different scales have been carried out using the FEM program NAMMU to determine the general groundwater balance of the area. The rock is modelled here as a homogeneous continuum with water-bearing fracture zones having elevated hydraulic conductivity.

For the detailed modelling of the local area, SKB has developed a stochastic continuum model for conditional simulation and equation solving called HYDRASTAR, based on Darcy's equation.

Different detailed designs of the statistical model have been tried. Alternative ways to estimate the required statistical parameters and to validate the models by means of “jackknifing” have been carried out with the program INFERENS. The different statistical models can be ranked with the aid of this method.

Special NAMMU calculations on a regional scale have been carried out to provide boundary conditions in the form of hydraulic heads at the boundaries of the rock block for which conditional simulation with HYDRASTAR is performed.

NAMMU has also been used to study the influence of permafrost and glaciation.

Calculations of the influence of salinity and heat on groundwater conditions at Finnsjön have been performed in 2-D and 3-D. The program PHOENICS has been utilized for this purpose.

Well hydrology has been dealt with and modelled separately.

**Stochastic continuum modelling**

Stochastic continuum modelling of groundwater flow in rock is based on methods originally developed within the mining industry for determining the extent and spatial variability of ore deposits. The basis of the methodology is a statistical interpolation method called “kriging”. This is made possible by the fact that the specific characteristic of the rock being studied is described as a spatial stochastic property whose spatial covariance can be estimated with the aid of the existing measurements. In our case, this property of the rock is its hydraulic conductivity.

With the aid of kriging a mean value of the conductivity is obtained in each point in the rock, along with a variance that is equal to zero in each measurement point but is greater the further away from a measurement point a point in the rock is located.

Carrying out a calculation of groundwater flows and travel times on the basis of mean values of the conductivities is not correct, since it would not take into account the spatial variability in the correct manner. It is therefore necessary to use a technique with random sampling from the entire spatial distribution of conductivities in all points. This is done with Monte Carlo simulation technique, see separate section below. In practice, the method uses logarithms of the conductivities, which are assumed to be normally distributed. Input data are either the absolute (logarithmed) values of the measured conductivities – intrinsic model – or else a so-called trend function is used, which is a kind of estimated spatial average function, whereby all values are instead expressed as the difference between the trend and the value in question. The covariance is expressed with what is known as a semivariogram. With the aid of the information obtained on the total distribution, simulation of the conductivity field is performed with the measured values locked in the points where they were measured.

Stochastic continuum modelling and continuum modelling in general has been called into question in terms of its applicability to fractured media. One of the main reasons usually cited is that the very local and persistent anisotropies represented by fractures and fracture zones are not modelled in the right way. The stochastic continuum model is very “honest” and unbiased and does not simply assume that two points with high conductivity are connected with a persistent structure. This is not merely to its disadvantage, however. In order for a good model of an area to be obtained, a certain quantity of data is required – the more data the better. As far as the Finnsjön area is concerned, Zone 2 is well represented in the measurements. In order to compensate for the lack of data in zones identified primarily on the basis of the judgements of geologists, different trend functions have been applied to these structures. These must be regarded as uncertain, however, since hard data in the form of conductivity measurements are in short supply. The aim is to represent even the small-scale fracture pattern in a correct manner by means of the averaging procedure.

When SKB 91 was begun, an assessment was made of the feasibility of using a "discrete fracture" model for the hydrology. The conclusion reached was that this type of model was not fully developed conceptually. A judgement was also made that it was not possible to carry out simulations of the groundwater flow in a block of an order of magnitude of 20 $km^3$ conditioned on the local fracture patterns around each measurement section. Discrete modelling also requires numerous different assumptions and parameters that describe the character and connectivity of the fracture pattern, variations in fracture apertures etc. All of these parameters are uncertain at the present time. The strength of the stochastic continuum model is that it is based on only a few assumptions and parameters. It also permits simulation of groundwater flows conditioned on measured conductivities, which are directly related to the permeability of the rock in the points where they are measured.

There is also a potential for further development aimed at eliminating the weaknesses of the continuum model with the aid of nested covariances (different covariances on different scales) and so-called indicator simulation. These should be able to provide a better picture of the rock's fracture pattern. Stochastic continuum modelling can also be extended to include inverse modelling, whereby conditioning can also be done on measured heads and flows, reducing the uncertainty in the results. All of the aforementioned methodologies have a solid theoretical foundation and have also been tested practically to some extent.

Nevertheless, initial studies of discrete fracture modelling have been carried out for SKB 91 with two purposes in mind: to provide an alternative model for calculating conductivities from transient injection tests and to provide data for the specific surface area for diffusion of nuclides into the rock matrix. The results have not been used in SKB 91, however, other than as reference material.

**Near-field model**

In preparation for SKB 91, the process model for the individual canister developed for PROPER has been updated, based on the model from the KBS-3 study. The new ideas concerning the failure modes of the canister, the disturbed zone, the availability of corrodants, the dissolution of the fuel and diffusion out into the rock have been incorporated. The model, called "Tullgarn", has been used directly for the assessment of the entire repository's near field, whereby the assessment modelling has been divided into two main parts: 1) description of and conceptualization for the individual canister, and 2) compilation of the individual canisters into a total near field for the entire repository.

For modelling of the near field, the repository is divided into segments, each containing a number of canisters that can be assumed to be exposed to the same flow.

An initial review of an extended list of radionuclides in order to determine which ones decay during the transient phase has been carried with the computer program TRUMP.

### Far-field transport model

For modelling of the far field, a number of possible alternatives were evaluated at the beginning of SKB 91: double porosity in three dimensions, stream tubes based on particle tracking, stochastic model directly based on the statistical features of the conductivity field, discrete fracture networks etc. Modelling with stream tubes was chosen for SKB 91. It takes into account all essential processes, but requires the averaging of several parameters into effective ones, since they must be given as constants for practical reasons. The flow is allowed to vary along the flow path, however.

Models based on double porosity in three dimensions or discrete fracture models provide a more detailed picture of the transport but were deemed neither to be practical to use nor technically and scientifically mature enough. Stream tubes were considered sufficient for SKB 91, in view of the fact that the main purpose of the assessment was to compare the importance of different hydrogeological premises. A previously developed stream tube model, FARF31, based on individual stream tubes and designed to be used with PROPER, has been used. It takes into account advective and dispersive (Fickian) transport, one-dimensional matrix diffusion and sorption, and chain decay. The model can handle arbitrary boundary conditions.

### Biosphere model

The model chain ends with a model of the biosphere. In this model, the outflow of each radionuclide in Becquerels per year from the far field is multiplied by a conversion factor from Bq/y to Sieverts per year in weighted whole-body dose commitment to an individual in the critical group. These conversion factors have been obtained using a detailed dynamic compartment model of the biosphere. Calculations have been carried out using the computer program BIOPATH for three different primary receiving bodies of water: lake (1% of the activity has been assumed to find its way directly into a well), well (100% of the activity) and a large brackish-water body of water (the Baltic Sea).

The use of conversion factors in the model chain, rather than taking into account the transient process in the biosphere, is warranted by the fact that the time constants for turnover in the biosphere are much shorter/faster than for the transport through the far field.

### Reporting of results obtained with probabilistic analysis methodology

The hydrology model chosen for the model chain is stochastic and the results of the calculations with the chain therefore bear a probabilistic stamp. With the aid of Monte Carlo technique, random samples are taken from the highly complex spatial distribution for the conductivity that is represented by a log-normal distribution in each point in space. The distribution of conductivities for the individual point is conditioned on the values in all other points. Each random sample represents, within the frame of the model's accuracy, a possible realization of the actual conductivity field. Each realization also represents a random sample from the resulting, similarly complex, spatial distribution of head/potential. The flow is calculated using the model for the random sample of fixed conductivity values that has been drawn. Based on the results of realizations, conclusions can then be drawn regarding the distributions of these parameters (statistical inference).

## 8.2 GEOHYDROLOGICAL MODELLING

A number of calculation models and computer programs are used to calculate the movements of the groundwater in the Finnsjön area. For large-scale groundwater modelling, with the assumption that the rock mass can be regarded as a continuum, NAMMU is used. For conditional stochastic simulation of the flow conditions in the Finnsjön block, HYDRASTAR is used. These models are included in the actual analysis chain.

Furthermore, PHOENICS is used for modelling of the coupled problem with salt transport and groundwater flow, and FRACMAN/MAFIC is used to provide an alternative description of the flow pattern in the rock with the aid of, among other things, the discrete properties of the rock and fracture statistics.

The following sections describe generally used models for geohydrological analysis in SKB 91 with the emphasis on HYDRASTAR. Furthermore, the application of the models to the Finnsjön data is described, and particularly the statistical analysis that has been carried out for hydraulic conductivity measured in the area. Several model-specific variation cases within SKB 91 are described with regard to premises and results. In one section, comparisons are made between the deterministic and the stochastic modelling. Finally, simulation of groundwater flows in different borehole sections is described. This calculation has been carried out with HYDRASTAR. The flows have been compared with natural flows measured with a point dilution probe.

### 8.2.1 General about models used

**NAMMU**

NAMMU is a general finite element program for modelling of groundwater flow and nuclide transport. The program calculates:

- Groundwater flow and heat transport in 1-, 2- or 3-D. The groundwater flow is modelled as Darcy flux. Flow and transport are assumed to take place in a continuum;
- Saturated and unsaturated flow;
- Nuclide transport through groundwater flow. Sorption and dispersion are taken into account. The program can be used for transient and steady-state calculations.

There are, however, certain limitations on the possible combinations of the above types of calculations; for example, heat and nuclide transport cannot be calculated in the same simulation.

The head and flow field can be calculated, and with a given flow porosity pathlines can be generated and presented.

The scientific background of NAMMU is described in /8-2/. NAMMU can be regarded as being well-verified, for example within the HYDROCOIN project /8-3/. Comprehensive manuals are available /8-4/.

## PHOENICS

PHOENICS is a general equation solver for fluid-dynamics problems /8-8/. The hydrology equations are solved using the finite volume method. The program is one of the few today that can practically handle the coupled problem of salt transport and groundwater flow in 3-D. The code has been used for this purpose in SKB 91.

## FRACMAN/MAFIC

MAFIC is a code for simulation of groundwater flow and nuclide transport in discrete fractures. The program has been developed within the framework of the Stripa Project. The program calculates:

- Groundwater flow in two- or three-dimensional networks of discrete fractures. A approximation with finite elements is used to determine the flow in the fractures. The flow in the fractures is assumed to follow Darcy's law;
- Three-dimensional groundwater flow in the rock mass. The flow in the rock mass is assumed to follow Darcy's law;
- Nuclide transport through groundwater flow in the discrete fractures. Account is taken of dispersion, which is modelled stochastically. The transport is modelled through particle tracking;
- Transient and steady-state calculations.

FRACMAN is an interactive program package for analysis and modelling of discrete fracture geometries. The program has the following functions:

- Analysis of fracture data from field measurements. Analysis with respect to fracture orientation, size, intensity and transmissivity;
- Stochastic simulation of fracture geometries;
- Post-processing and analysis of MAFIC results.

MAFIC has also been included as one of the discrete fracture models in the Stripa Project /8-5/. Comprehensive manuals are available for both FRACMAN /8-6/ and MAFIC /8-7/.

## HYDRASTAR

HYDRASTAR carries out Monte Carlo simulation of the steady-state form of the hydrology equation for a model area in the form of a rectilinear block. The coupling to reality is obtained through the statistical model, which describes the hydraulic conductivity field, and through data from water injection tests in individual boreholes. The program generates realizations of the conductivity field conditioned on measured data. Corresponding head and velocity fields are then calculated.

The flow diagram in Figure 8-2 provides a more detailed description. HYDRASTAR is provided with an interface to other computer programs: INFERENS for statistical inference and model optimization, and FEMVIEW for graphic presentation of head fields, velocity fields, conductivity fields and pathlines.

Simulation of groundwater flow with HYDRASTAR is preceded by a geostatistical analysis where available conductivity data from water injection tests with different packer straddle intervals are processed. The analysis is done for the desired averaging

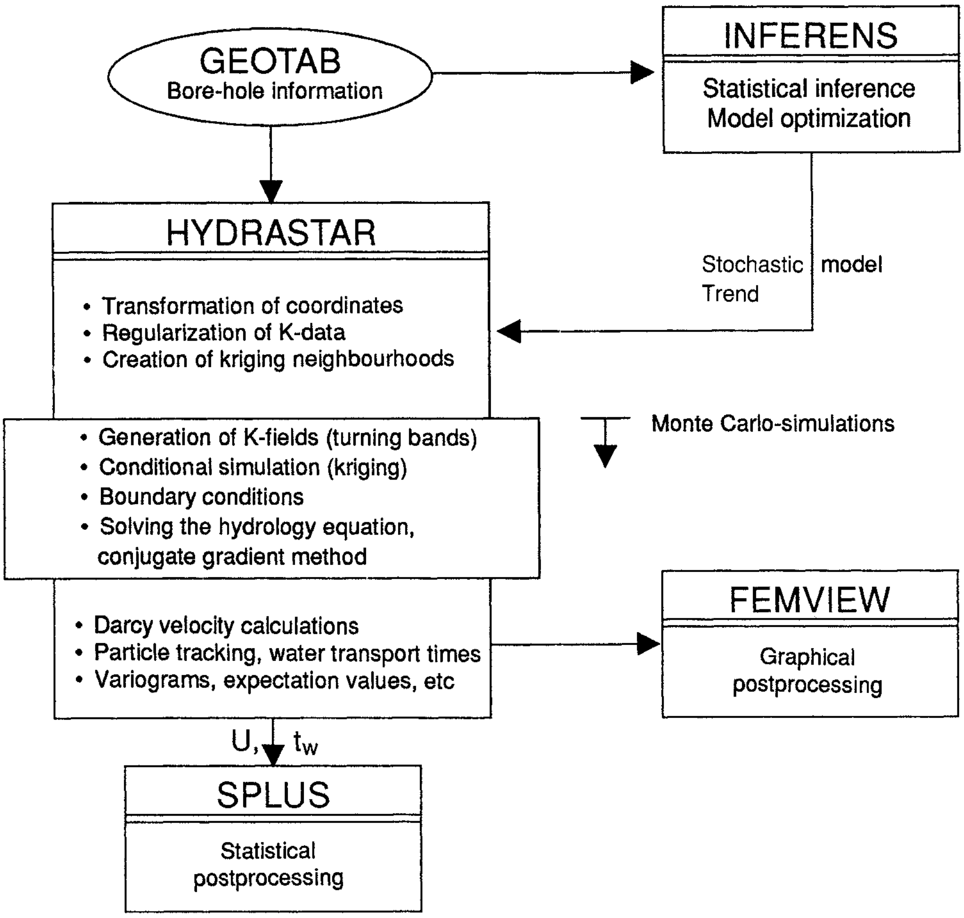



***Figure 8-2.*** *Flow chart for stochastic continuum modelling of the geohydrology with HYDRASTAR.*

scale, which means that the measurements are first scaled up before the statistical processing is carried out. The program INFERENS can be used for this. Furthermore, different models can be compared by means of a method called "cross validation" or "jackknifing", see also section 8.2.3. The analysis results in a statistical description with a given variance, correlation length and, where applicable, trend. These values are used as input data in HYDRASTAR to recreate the spatial variability in stochastic modelling of the groundwater flow.

Figure 8-2 also shows that borehole data are taken from SKB's database GEOTAB for both INFERENS and HYDRASTAR. In HYDRASTAR, coordinates are first transformed to the desired system, after which regularization, i.e. scaling-up of the measurement results to the desired averaging scale, starts according to what is described in section 8.2.3.

Under the assumption of a given statistical model, different realizations of the conductivity field are generated with a method called "turning bands" /8-9/. The method ensures that the desired correlation structure is obtained.

"Kriging" is a method that is used to obtain an optimal estimate of a quantity that has a spatial variation, in our case conductivity. The estimate is optimal when the least squares error reaches a minimum. With the aid of kriging it is possible to create a set of Monte Carlo simulations of the conductivity field, all of which are in agreement with measured data. Several different types of kriging methods are described in /8-10/. This reference also describes the special form of kriging where the estimate only takes into consideration a given environment around the area to be estimated, the "kriging neighbourhood" method.

HYDRASTAR also provides an opportunity to specify repository drifts and the associated disturbed rock zone, see section 6.4.4. It is possible to allow the particle tracking to start from canister positions along the drifts. The disturbed zone and the backfilling material in the drifts can be given an absolute conductivity or a relative conductivity in relation to the surrounding rock. For more details around the implementation of the disturbed zone in HYDRASTAR, see /8-11/.

Boundary conditions are imposed on the boundaries of the rectilinear block. This is done by transferring a potential field from a regional NAMMU calculation. Alternatively, simpler boundary conditions can be imposed.

The actual hydrology equation is then solved. It is done here by means of a finite difference method, which, together with an iterative solver based on the conjugate gradient method, enables the calculations to be performed with sufficient speed. Problems with up to a million grid points have been solved. A head field and a Darcy field are obtained as results.

A coupling has been devised to the post-processing program FEMVIEW /8-12/, which enables desired cross-sections of the model to be presented for each realization in the form of head fields, velocity fields or conductivity fields. With an algorithm for particle tracking in HYDRASTAR, the appearance of flow pathlines can be calculated and presented in FEMVIEW. Groundwater travel time can also be calculated under the assumption of a given flow porosity. Travel times and flows etc. can also be processed statistically with different computer programs.

In conclusion, it can be mentioned that the algorithm for pathline simulation that is used in HYDRASTAR includes extrapolation beyond the actual model domain. In other words, the simulation is not interrupted at the vertical model boundary but continues, based on information on the velocity field near the boundary /8-13/. Through the choice of a suitable area for modelling, however, most pathlines will reach the top boundary within the domain, and extrapolation does not have to be utilized.

### 8.2.2 Use in SKB 91

Basic data for geohydrological analysis are described in Chapter 5 and in background report /8-14/.

**NAMMU**

NAMMU has been utilized for calculations of the steady-state groundwater flow in 3-D. The rock is modelled as a homogeneous porous medium with fracture zones superimposed as high-conductivity elements. The selection of data that has been used in the initial modelling with NAMMU is presented in /8-15/. These calculations are not included in the analysis chain, but shall be regarded rather as separate initial

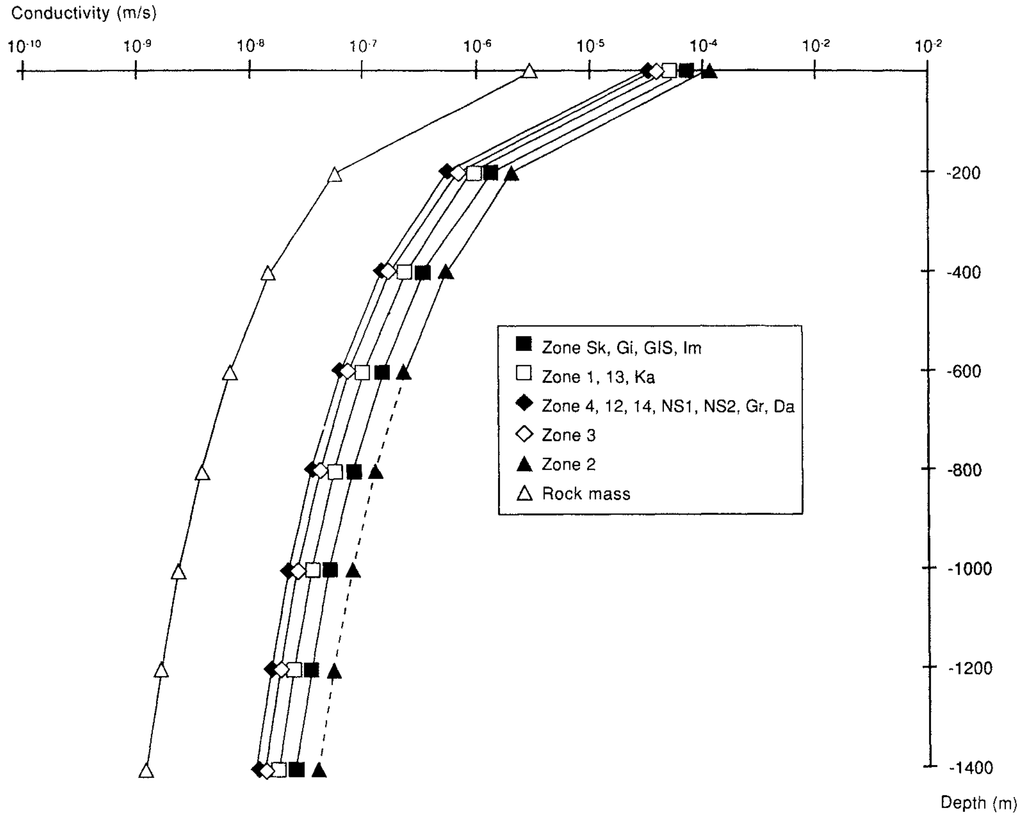



***Figure 8-3.*** *Regression curves for hydraulic conductivity as a function of depth for the rock mass and for major fracture zones in the Finnsjön area (used as trends in the stochastic hydrology model).*

calculations of the groundwater movements in the area. Conclusions have been drawn regarding the discharge areas, which have been of importance for subsequent calculations.

Renewed NAMMU calculations have been carried out /8-16/ to give boundary conditions to the area where conditional simulation with HYDRASTAR has been carried out. Compared with the initial model exercise, a larger regional area has been analyzed, around 100 km and down to depth of 1,500 metres, which has been found necessary in order to be able to deal correctly with the repository's discharge area. Furthermore, an implicit method for introducing fracture zones in the finite element model has been used, which has greatly simplified the modelling work at the same time as equivalent results have been obtained /8-17/.

Finally, new conductivity-versus-depth relationships have been used for rock mass and for fracture zones that take into account the averaging scale used (the 36 metre scale). Regression analysis has been used to adapt a depth-declining conductivity relationship for Zone 2 and for the rock mass with the aid of conductivity data from the Finnsjön area /8-10/. Measured data are not available to a sufficient extent for other defined structures. Input data are given as relationships between conductivity and depth and have been scaled in between Zone 2 and the rock mass, taking into account the geohydrological interpretation of the other structures, see Figure 8-3.

A brief commentary on the results of the NAMMU calculations is provided in section 8.2.5.

## PHOENICS

Reference is made to /8-18/ for a description of the modelling that has been carried out with PHOENICS. The coupled problem with salt transport and groundwater flow has been analyzed separately with the program and the results are discussed in section 9.2.

## FRACMAN/MAFIC

Discrete fracture modelling with the computer program FRACMAN/MAFIC has been used to obtain statistical distributions for fracture orientations and fracture lengths.

Data from fracture mapping of outcrops and drill cores have been utilized. Furthermore, data from injection tests are used to determine the transmissivity of the fractures.

The application of the method to the Finnsjön area is described in /8-19, 20/. These reports present the body of data, fracture data analysis, rock block simulations on different scales, interpretation and validation against transient single-hole measurements, etc. The material comprises a complementary body of data for stochastic continuum simulation with HYDRASTAR. With the aid of fracture statistics and injection tests, block conductivities on different scales can be obtained. It is thus possible to carry out conditional simulation with HYDRASTAR even against these alternatively generated data /8-20/, although this has not been done within SKB 91.

## HYDRASTAR

The application of HYDRASTAR in SKB 91 follows by and large the description given in section 8.2.1, since the program has to a large extent been developed specifically to achieve the objectives set up by the project. However, the potential of the method would have been more fully utilized if borehole information from the area had been more widely spread over the model block and if more data had been available at greater depth than around the flat-lying zone.

In order to obtain consistency in the model coupling NAMMU-HYDRASTAR, the scale being regarded, i.e. 36 metres in the reference case, has been taken into consideration, as mentioned above. With the aid of the regional NAMMU calculations, head boundary conditions are transferred to the rectilinear block within which conditioned simulation with HYDRASTAR is being carried out. This means that the influence of the groundwater levels is also included via NAMMU. The model areas are illustrated in the fold-out figure at the back of the report, where the repository area and the groundwater levels are also marked. The HYDRASTAR block is around 5 x 3 x 1.5 km in size. A borehole map is shown in Figure 5-3.

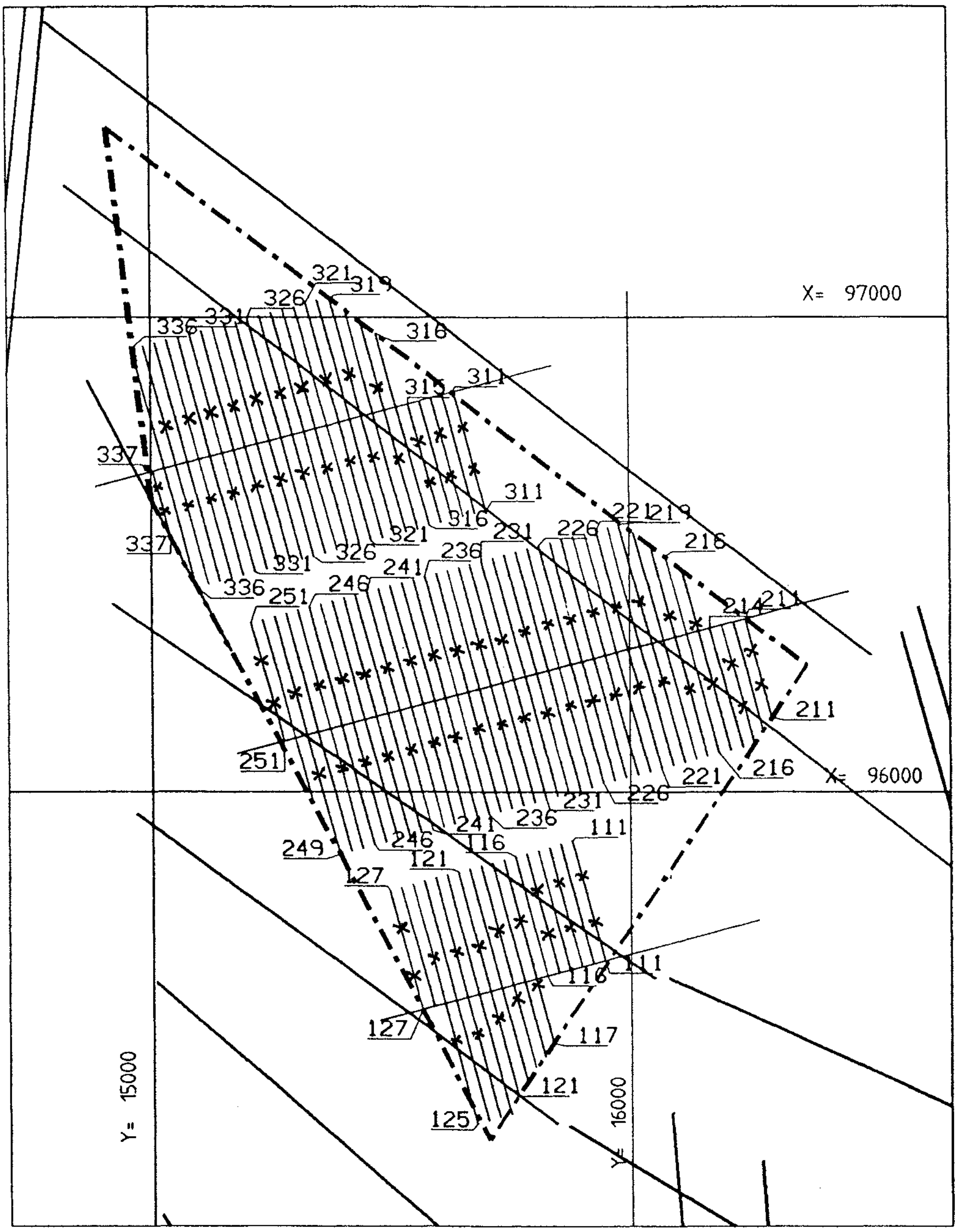



***Figure 8-4.*** *Starting points for particle tracking in the stochastic hydrology model. The coordinates are RAK coordinates.*

Statistical processing of borehole information is carried out for the selected averaging scale as described in section 8.2.3, after which the result is imposed on HYDRA-STAR. Repository drifts are inserted according to the repository description in /8-21/. 88 different canister positions are distributed along the repository drifts according to Figure 8-4. These drifts are assumed to represent different parts of the repository. The points act as starting positions for the algorithm for particle tracking that calculates the water travel times from the repository.

The disturbed zone is introduced with properties that are described for the reference case in section 9.3.

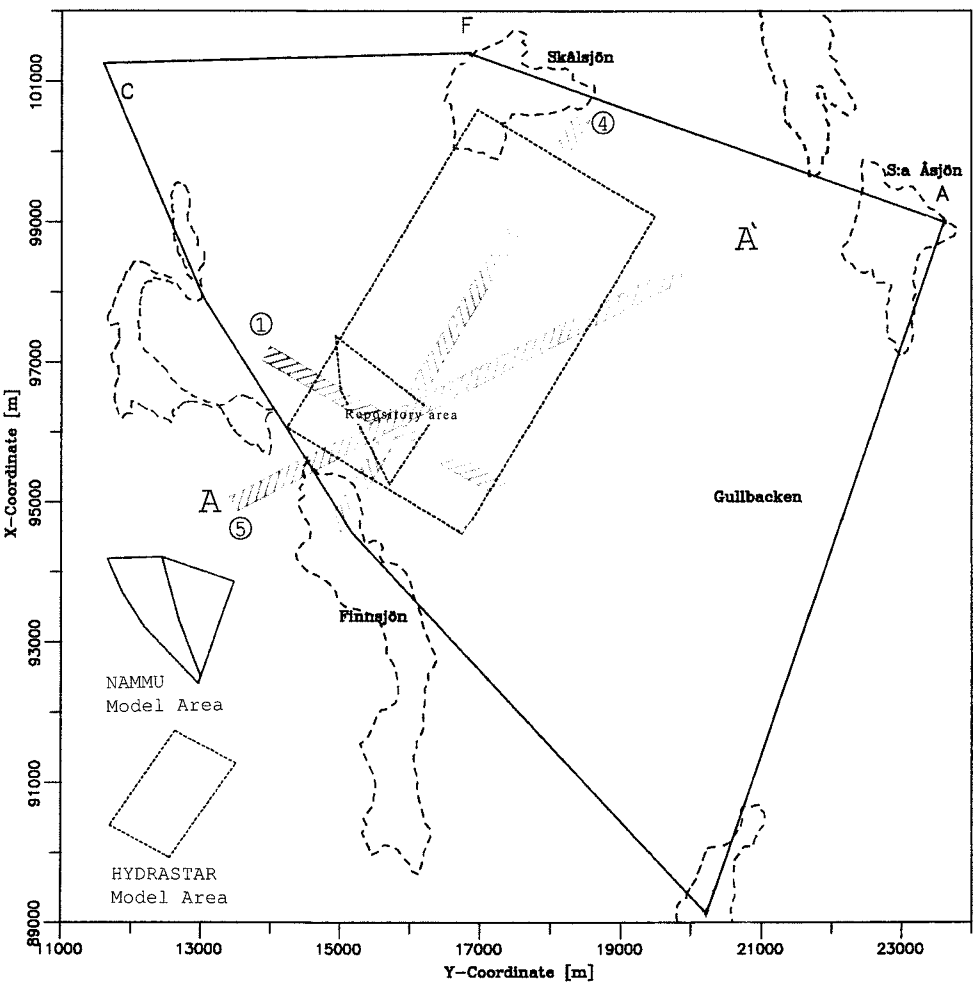



***Figure 8-5.*** *The placement of the HYDRASTAR block in the Finnsjön area, the extent of the repository area and three vertical sections that have been chosen for presentation of results from calculations with HYDRASTAR. Section 1 runs along the short side of the block straight through the repository area, section 4 is a vertical longitudinal section in the middle of the model block, and section 5 coincides with section A-A' presented in Figure 5-3. All sections are around 200 m wide and 1,500 deep.*

## Results from HYDRASTAR

A selection of results from the HYDRASTAR simulations is presented in Chapter 9. As far as head, flow and conductivity fields are concerned, a number of different cross-sections through the calculation area are used throughout. These are defined in Figure 8-5. The three vertical sections are around 200 metres wide, which means that what is reported is an arithmetic mean of the values from a number of calculation points through the section. Note that one of the sections has been chosen around the A-A' section defined in Figure 5-3. For certain calculation cases, results along a thin horizontal section at a depth of 600 metres have been deemed suitable to report.

A realization of the potential field typical for the reference case is presented in Figure 8-6. It is a level plot along the vertical section 4, which runs alongside the calculation area. Each colour represents a given interval according to the scale. Compare the potential field with the groundwater level map in the figure at the back of the report.

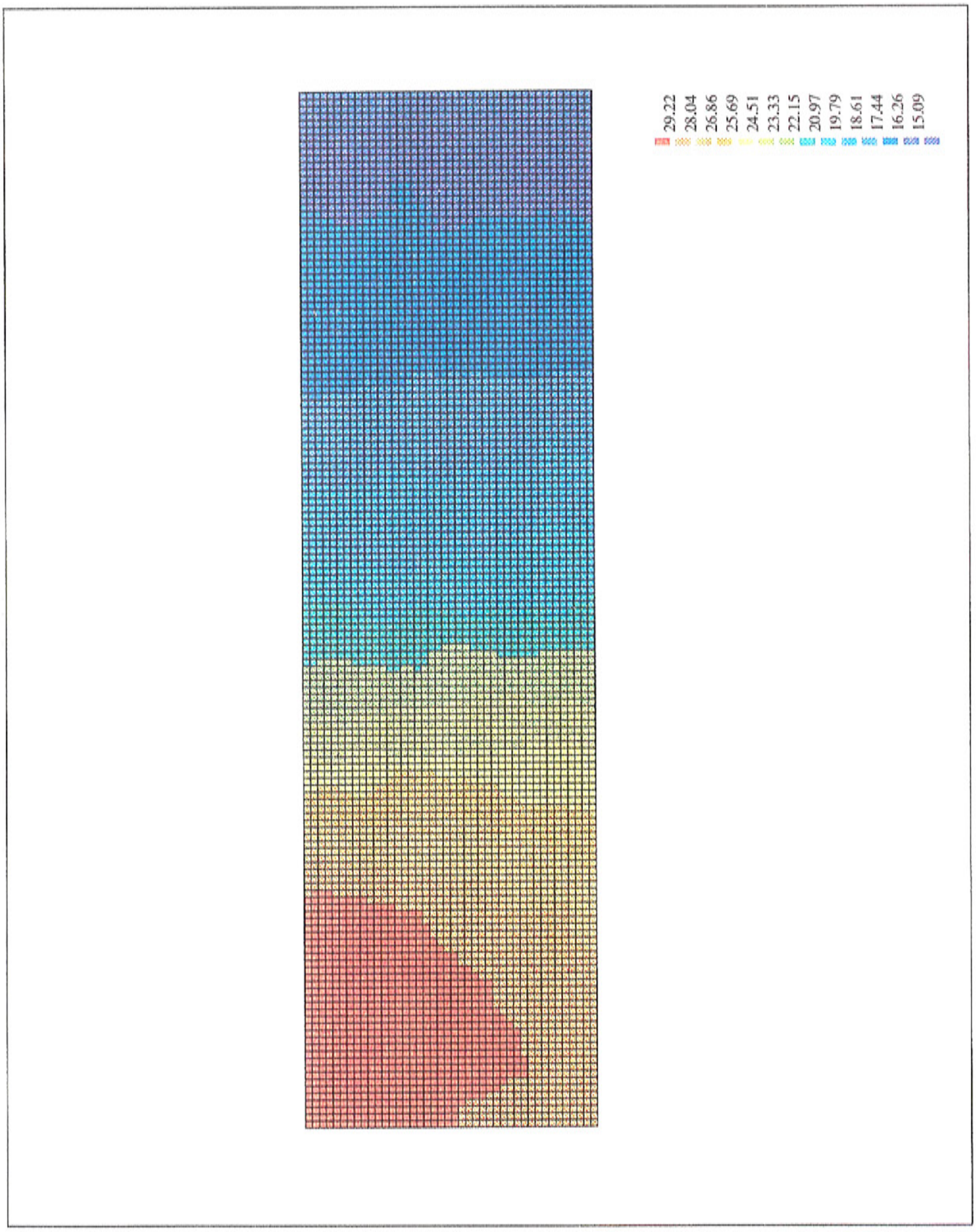



***Figure 8-6.*** *Potential field in section 4 according to Figure 8-5 for a typical realization in the reference case, given as hydraulic heads. The different colours correspond to a given interval according to the colour scale. The background grid shows the computational grid for the head nodes.*


***Figure 8-7.*** *The conductivity field in m/s for section 4 according to Figure 8-5 for a typical realization in the reference case. The different colours correspond to a given interval according to the colour scale. The background grid shows the calculational grid for the conductivity nodes.*

The hydraulic conductivity in the same section is presented in Figure 8-7. Dark colour corresponds to low conductivity.

Another type of result is pathlines from the repository level. An example of this is given in section 8.2.5.

Groundwater travel times and Darcy fluxes have been analyzed statistically.

A detailed description of the different calculation cases is provided in a series of work reports, see Table 9-3 in section 9.6.1.

### 8.2.3 Statistical analysis of conductivity data

The modelling of groundwater movements in the rock is thus performed with the aid of HYDRASTAR, which regards the rock as a stochastic continuum. A stochastic continuum is described via a statistical model. The choice of statistical description has been made after comprehensive analysis of measurement data from the Finnsjön area. The measurement data consists of hydraulic conductivity from steady-state water injection tests conducted in different boreholes with packer straddle intervals of 2 and 3 metres. The averaging scale which the model is supposed to represent is also taken into account in the analysis. After adaptation to the measurement data, the different statistical models have been tested in an optimization study /8-10/. The program INFERENS has been used for the analysis.

#### Regularization

One of the cornerstones of the analysis is the assumption that conductivity data measured in 2- and 3-metre sections can be scaled up to the desired averaging scale. The big advantage of this is that the correlation scale for the conductivity field increases, which makes it possible to study larger areas with the model. The disadvantage is that poorer resolution is obtained in the system.

The method used is described in /8-10/, according to which steady-state conductivity measurements with different section lengths can be brought together to a new set of measurements on another scale. What is obtained in practice is an arithmetic mean of the individual conductivity measurements, except for a correction factor. This factor is dependent on the packer straddle intervals in the original measurements, the averaging scale and the borehole radius, but is on the order of one. The statistical analysis has been carried out for scaled-up conductivity values on different averaging scales. This procedure differs markedly from the one used in previous studies, in which effective conductivities used have been based on geometric averaging.

#### Statistical inference and optimization of statistical model

The purpose is to find a sufficiently good statistical model for the spatially varying hydraulic conductivity. Statistical inference is used to devise parametric models on the basis of scaled-up, regularized data.

Statistical inference has been carried out for models both with and without trend. The latter has been done in view of the fact that very few of the structures that have been identified by geologists in the area can be distinguished in measurement data. Most measurements are, after all, limited to the area around the flat-lying Zone 2. Introducing an explicit trend in HYDRASTAR means that the different fracture zones in the area are introduced as increases in an expectation value function.

Different parametric models have been adapted to semivariograms and compared with an optimization method called "cross validation" or "jackknifing" /8-10/. The optimization study aims at testing different assumed models by gradually taking away measured conductivity data in boreholes, one measurement at a time, and then using the model and remaining data for prediction in the borehole. Kriging is used for this and an error vector is obtained that can be processed statistically. In this way, different models can be tested and compared for different averaging scales. In the case with a trend in the model, regression analysis must also be performed, after which the above-described procedure is used on the residuals.

#### Statistical models and chosen reference case

Two fundamentally different types of statistical models or variogram functions have been used: a spherical and an exponential model type. Isotropic as well as anisotropic models have been adapted. Parameters for the different models are adapted in connection with statistical inference, and variance and correlation lengths for the logarithm of the conductivity field can be estimated on the basis of the parameters.

In the case with trends, the spherically isotropic model has been found to possess features that make it sufficiently good for our reference case. The averaging scale chosen is 36 metres. The reference case model has a variance of 1.25 and a correlation length of 106 metres for the logarithm of the conductivity.

A variance of 1.74 and a correlation length of 270 m is obtained for the same model without trend. This alternative description comprises a variation case in SKB 91.

### 8.2.4 Model variations with HYDRASTAR

In the following section, the sensitivity of the calculation results for a number of more or less model-related parameters in HYDRASTAR has been investigated in comparison with the reference case. These parameters are: the statistical description presented in the preceding section, the calculation scale chosen, the trend imposed, the extent of the calculation area, etc. Comparisons are made regarding groundwater fluxes at repository level, groundwater travel times from the repository to the upper boundary of the calculation area, conductivity fields and the groundwater flow pattern.

#### Calculation scale chosen

One of the most important choices in stochastic simulation of groundwater flow is the calculation scale to be analyzed. By "calculation scale" or "averaging scale" is meant here the scale to which available measurement values for hydraulic conductivity are scaled up before statistical analysis and simulation are carried out. There is reason to go down in scale as far as the available computer power allows, since most of the measurements of hydraulic conductivity have been carried out with 2- and 3-metre measurement sections. A scale of 36 metres has been chosen in the reference case, while 24 and 48 metres have been specially analyzed.

The distance between the calculation points, the head nodes, should not be confused with the averaging scale. The node distance in most calculation cases is also 36 metres, but in the case with 24 metres averaging scale the node distance has also been reduced to 24 m to obtain a stable numerical solution.

Both variation cases give results that agree with the reference case. This applies both to the distribution of groundwater travel times from the repository level and discharge areas /8-22, 23/. The pattern for the flow through the model block shows, however, that the pathlines have an increased tendency to merge at an increased calculation scale. At a decreased scale, increased tortuosity is obtained in the transport pathlines without this having any appreciable impact on the statistics for water travel times.

Nor is the result affected to any appreciable extent by a reduction of the node distance to 24 m for the reference case's averaging scale (36 m) /8-24/.

**Statistical description of the rock, anisotropy**

When it comes to the statistical description, a so-called spherically isotropic model has been used for HYDRASTAR in the reference case, see section 8.2.3. It has been found in the model optimization study /8-10/ to provide the best fit for the Finnsjön data. An alternative model is the spherically anisotropic model, which also exhibits acceptable features for model optimization. The influence of anisotropy in the statistical description chosen can be illuminated here. Hydraulic conductivity is still of equal magnitude in all directions, while a statistical anisotropy has been introduced, with three times longer a correlation length horizontally than vertically.

The statistical model has a variance of 1.20 and a correlation length of 240 metres in the horizontal direction and 79 metres in the vertical direction.

Regarding the pattern for water flow, good agreement is obtained with the reference case. However, the increased correlation length in the horizontal direction leads to less curved pathlines and a reduced tendency for the pathlines to reach the upper boundary within the calculation area /8-25/.

**Statistical model without trend**

A trend function has been used for the reference case to define the vertical fracture zones that are not defined to an acceptable extent via borehole data in conditional simulation. As discussed in section 8.2.3, it is necessary to introduce trends and residuals to be able to make it possible to shed light on the importance of different vertical structures in the area. A description free from trends and based directly on measured conductivities has also been used as an alternative. The variance is thereby 1.74 and the correlation length 270 metres.

The higher values of the statistical parameters make themselves felt in the form of a smaller fraction of pathlines that reach the ground surface within the calculation area.

However, the fast stream tubes have 2-3 times shorter times due to the increase in spread. The pattern of the groundwater flow has a slightly increased clustering of stream tubes without having been altered in any crucial way /8-26/.

Figure 8-8 summarizes the model variations carried out with HYDRASTAR in the form of four so-called "floating histograms". What is presented are collected statistics on the flow at the repository level, 600 metres, and on the groundwater travel times from the repository to the limit of the calculation area. Each point on the curves in the graphs represents on the y axis the fraction of the total number of values that falls within a factor of 4 around the value on the x axis, from a factor of 1/2 below to a factor of 2 above.

The model variations have been carried out with two different-sized model areas, the "reference case" and "smaller block".

In the case of the water travel times, statistics are only presented for those stream tubes that have groundwater travel times to the surface that are less than the posited maximum time, 10,000 years. For more details, reference is made to the work report for the calculation case in question, see Table 8-1. Potential and conductivity fields are reported there, along with complete statistics, including ordinary histograms for each calculation case.

**Table 8-1. Overview of model variations performed with HYDRASTAR.**

| Calculation case | Description | Reference |
|---|---|---|
| Reference case | Reference premises | SKB AR 92-33 |
| Scale 48 | Averaging scale 48 m | SKB AR 92-30 |
| No trend | Statistical model without trend | SKB AR 92-29 |
| Anisotropic | Statistical anisotropy | SKB AR 92-32 |
| Smaller block | Smaller calculation domain | SKB AR 92-31 |
| Smaller block 24 | Denser calculation grid | SKB AR 92-27 |
| Scale 24 | Averaging scale 24 m | SKB AR 92-28 |

The case "Smaller block" has been carried out with reference premises on a smaller model area.

What can be concluded from the histograms, see Figure 8-8 a and b, is that none of the variations has any crucial impact on the results in comparison with the reference case. The case that diverges the most is the statistical description of the rock without trend.

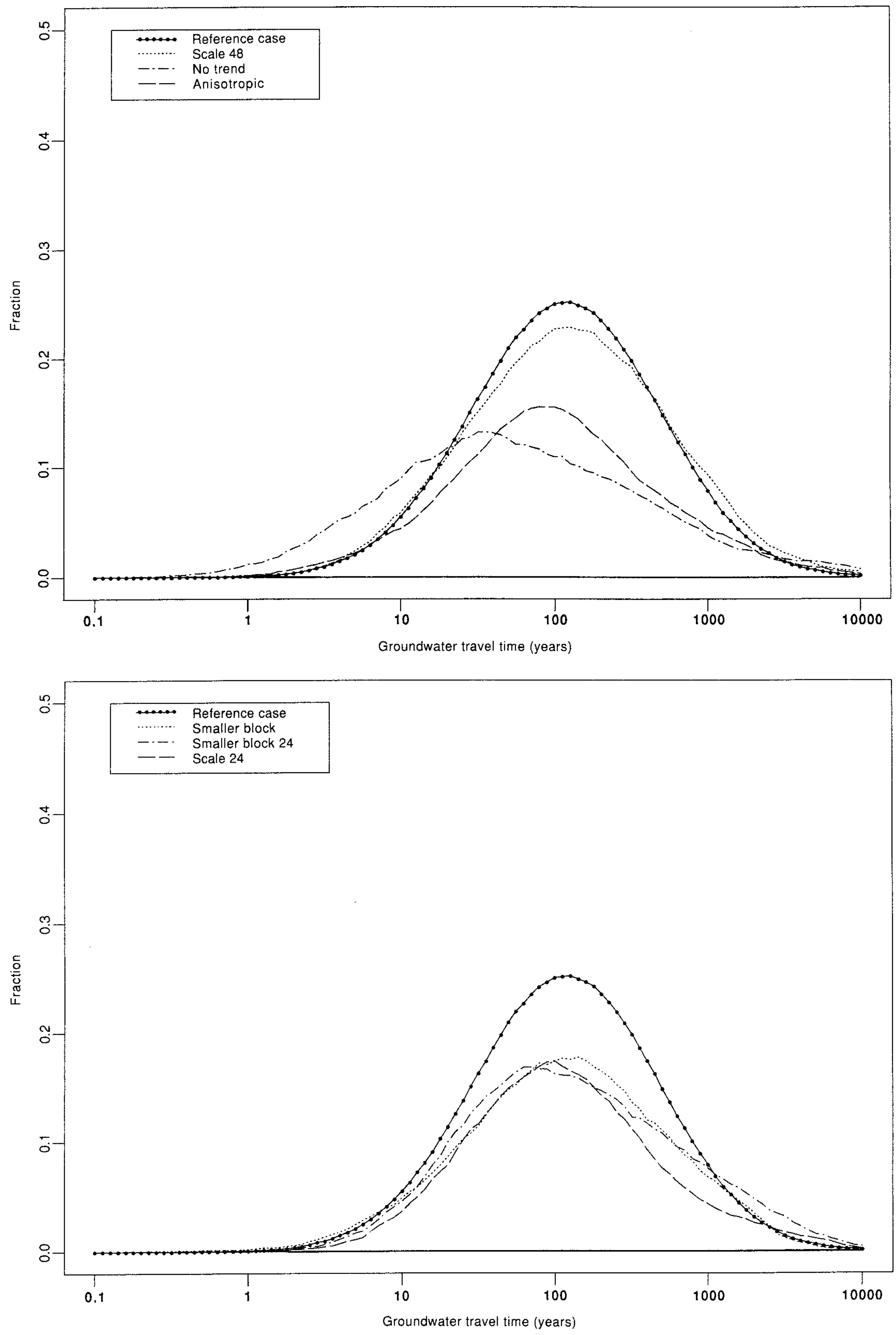
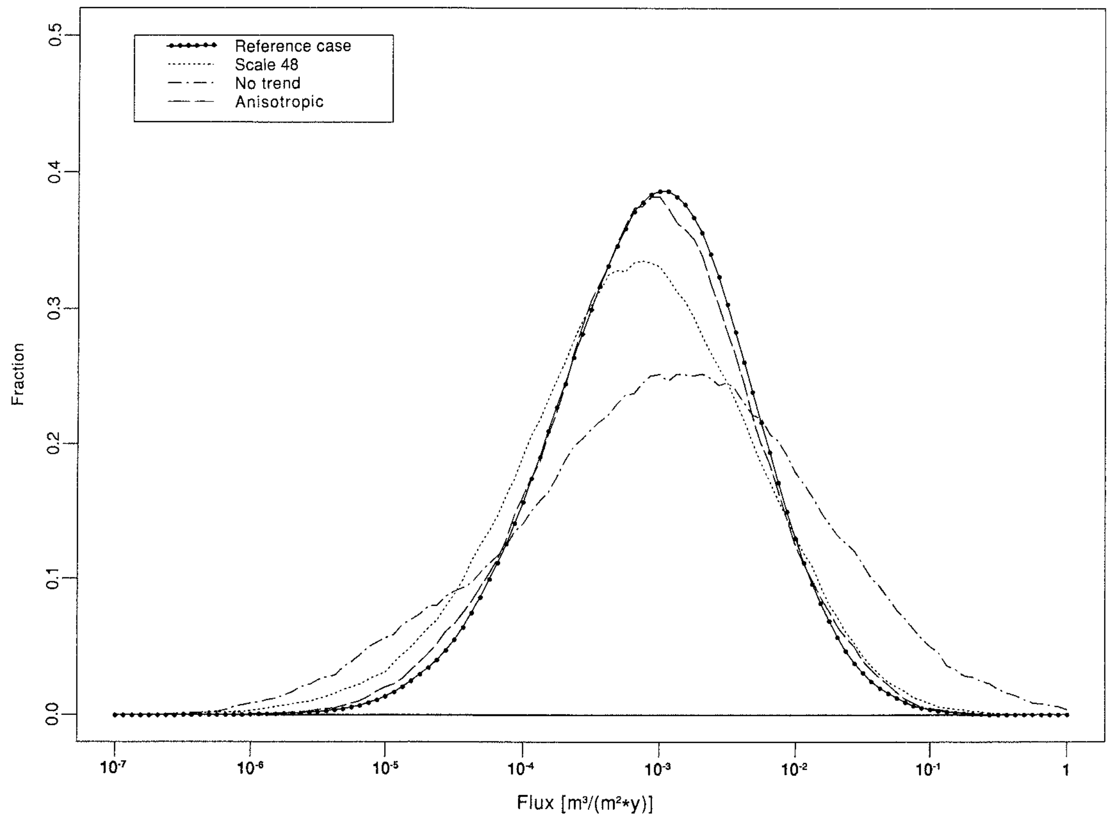



***Figure 8-8 a.*** *Floating histogram of all groundwater travel times to the surface shorter than 10,000 years from all realizations of a number of model variations. Each point on the curve represents on the y axis the fraction of the total number of values that falls within a factor of 4 around the value on the x axis (from a factor of 1/2 below to a factor of 2 above). The data have been divided into two histograms, since two different model blocks have been analyzed. The flow porosity is* $10^{-4}$.



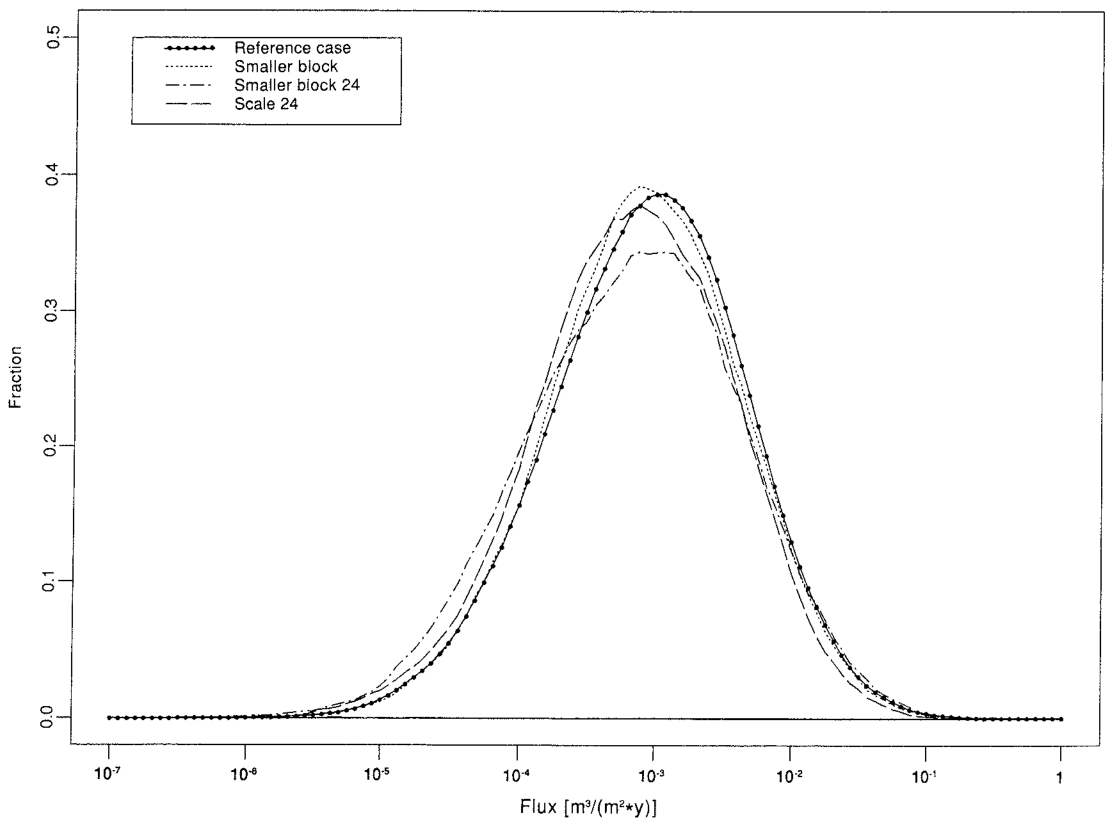




***Figure 8-8 b.*** *Floating histogram of all Darcy fluxes at the repository level from all realizations of a number of model variations. The data have been divided into two histograms, since two different model blocks have been analyzed.*

### 8.2.5 Deterministic versus stochastic modelling

An essential difference in the geohydrological analysis in SKB 91, compared with previous safety assessments, is the stochastic modelling. Deterministic modelling has also been done with HYDRASTAR, which means that direct comparisons can be made regarding fluxes and pathlines.

Figure 8-9 shows the pathlines from deterministic modelling with HYDRASTAR in comparison with a realization from stochastic modelling. The figure clearly shows how spatial variability influences the pathlines. The actual flow pattern is similar, however. As expected, a smaller spread in the distribution of water travel times is obtained in the deterministic case, see Figure 8-10. The extremely short times are obtained only in stochastic analysis, although the median is roughly the same. These conclusions are not altered by a comparison with the NAMMU calculations.

The variation cases described in section 9.6 have, for many of the cases, been carried out both with NAMMU /8-16/ and with HYDRASTAR. Similar conclusions can be drawn regardless of the model concept when it comes to the importance of the variations. The difference that can be noted has to do with the representation of the flat-lying zone in the area, which for HYDRASTAR only enters the picture in the conditional simulation against borehole data. In NAMMU modelling, the zone is posited as a persistent high-conductivity structure.

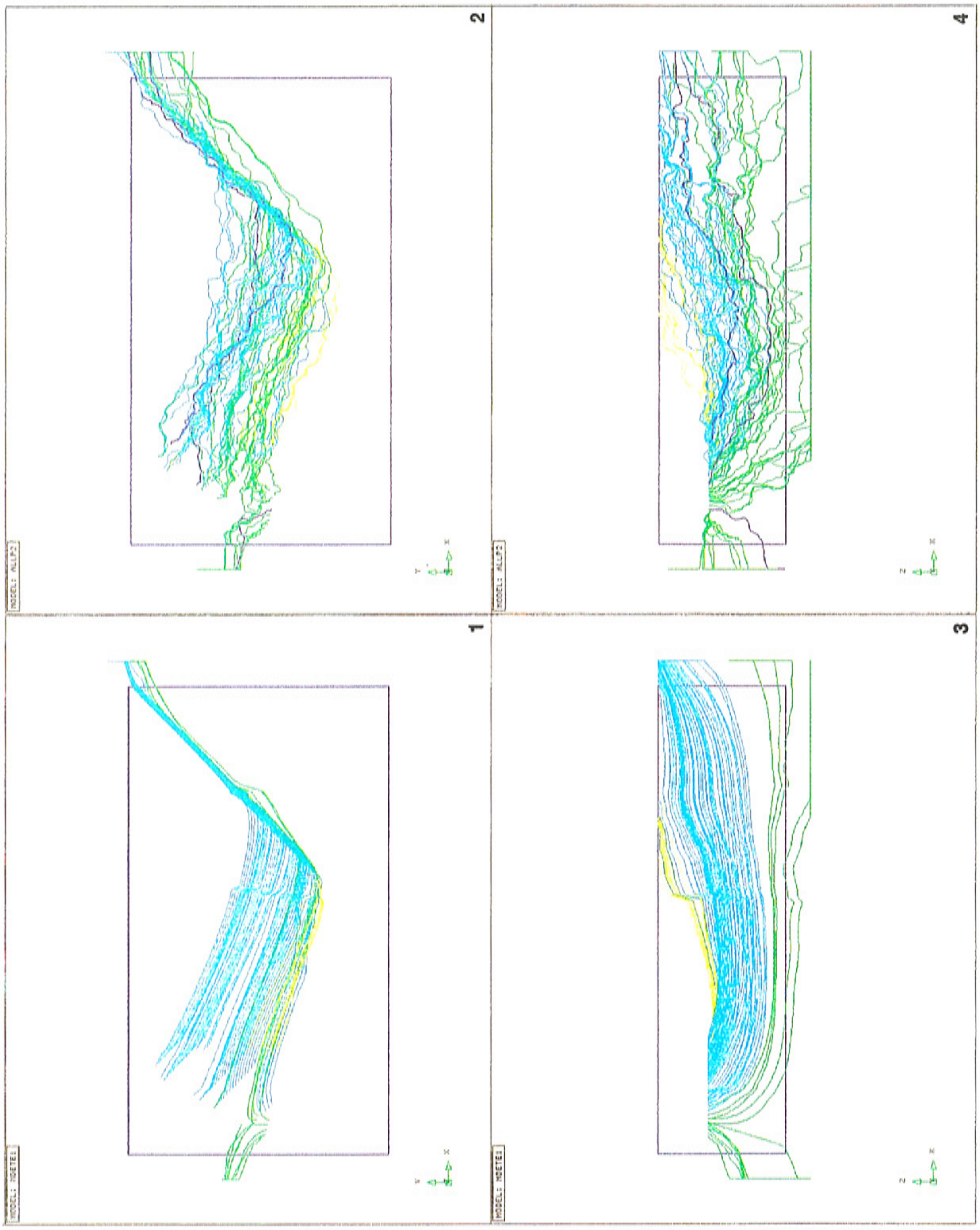
### 8.2.6 Verification and validation of HYDRASTAR

Verification of HYDRASTAR /8-9/ is done via

- verification of the equation solver for the hydrology equation and the algorithm for particle tracking by comparison with HYDROCOIN, case 2 /8-3/;
- verification of the unconditional simulation by comparison with results obtained with an analytical method, based on a perturbation solution of the stochastic hydrology equation.

An attempt at validation of HYDRASTAR has been carried out in /8-27/, where the groundwater flow has been simulated in different boreholes in the Finnsjön area. The modelled flows have been compared with results from field measurements of the natural flow obtained with a point dilution probe /8-28/.

Figure 8-11 shows the results along borehole BFi 01. The median value for the flow after 50 realizations with HYDRASTAR has been determined for the borehole. As a comparison, the measured flows are shown in the same figure. As expected, the conditional simulation with conductivity data from BFi 01 pushes up the flows at the upper and lower boundaries of Zone 2. The extremely high Darcy fluxes measured on the metre scale cannot be recreated on the modelled 36-metre scale. The order of magnitude of the total flow at the upper boundary of Zone 2 does appear to be realistic, however (about 50 $m^3$ per year and metre in the horizontal direction of the zone), considering how narrow (about 0.5 m) the high-conductivity part at the upper boundary of Zone 2 is. In the lower, permeable part of Zone 2, the groundwater flow is below the measurement limit, see Figure 5-7. This situation has not been recreated with HYDRASTAR. This is because HYDRASTAR does not take into account the presence of a more saline and heavier groundwater at this level.



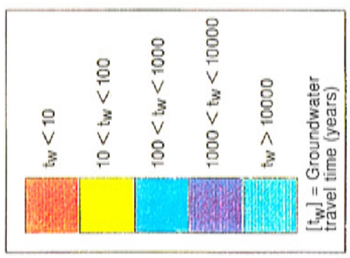
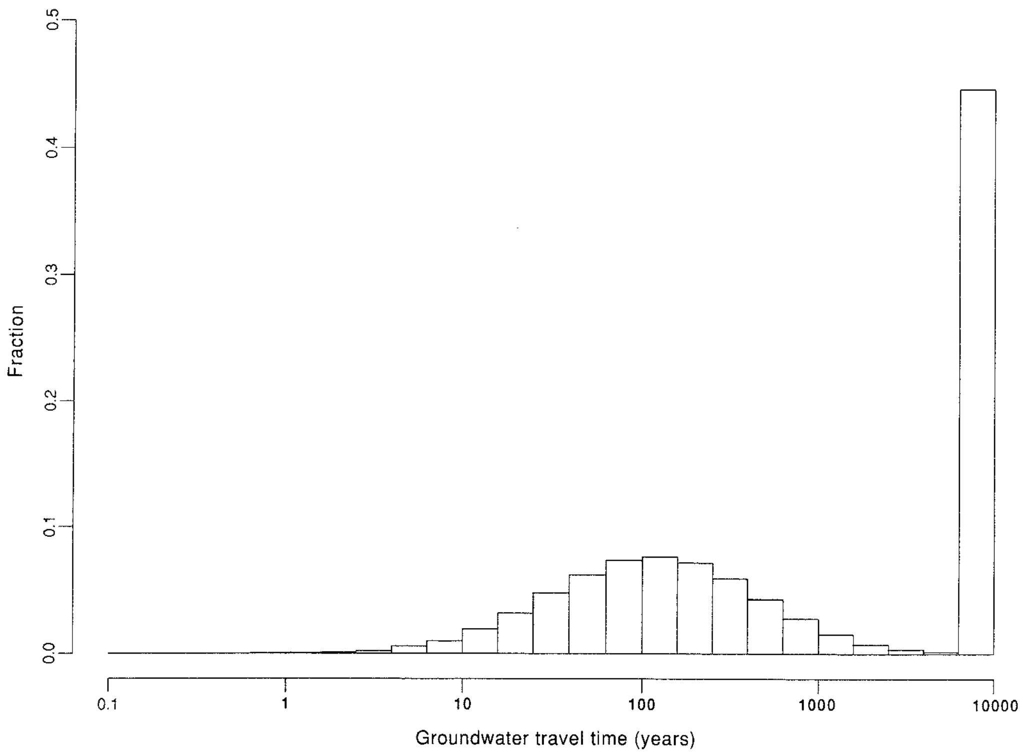




***Figure 8-9.*** *Pathlines for a typical stochastic realization for the reference case (view nos. 2 and 4) and for deterministic realization with HYDRASTAR (view nos. 1 and 3). Nos. 1 and 2 are views from above, 3 and 4 are from the southeastern long side of the block, see the fold-out figure at the end of the report.*



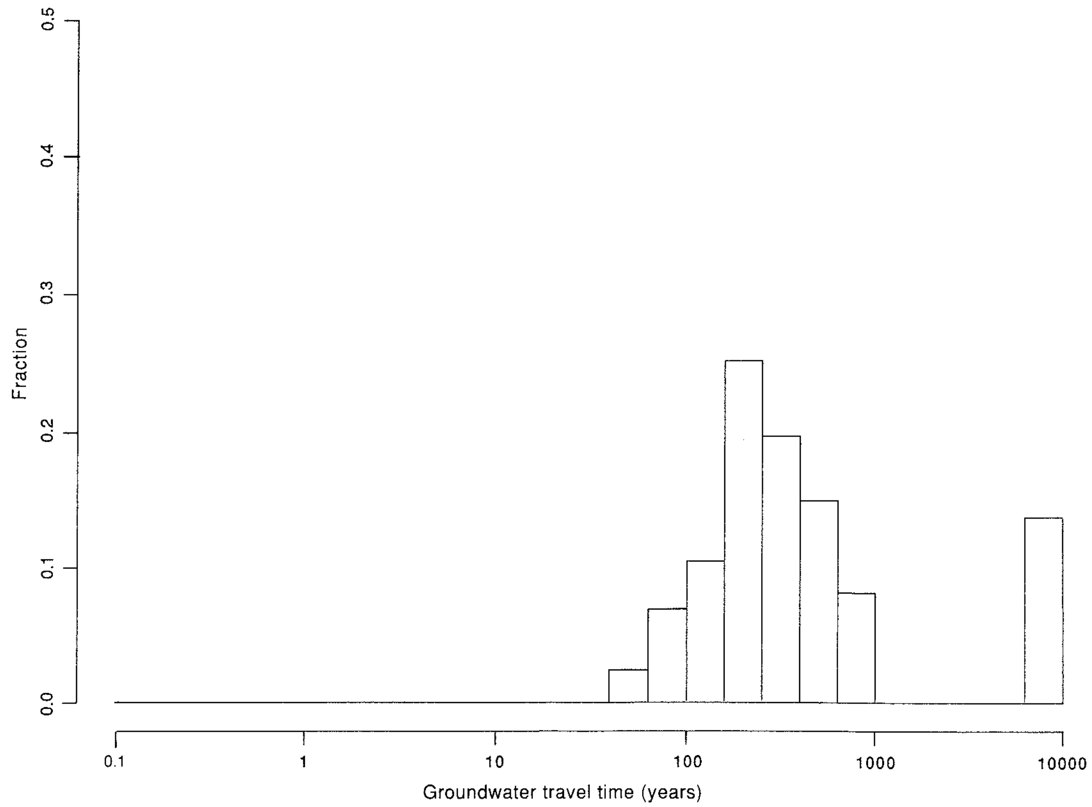




***Figure 8-10.*** *Travel time distribution for groundwater in a stochastic simulation of the reference case (upper histogram) and for deterministic realization with HYDRASTAR (lower histogram). The graph is analogous to the one in Figure 8-8 a. Flow porosity* $10^{-4}$.

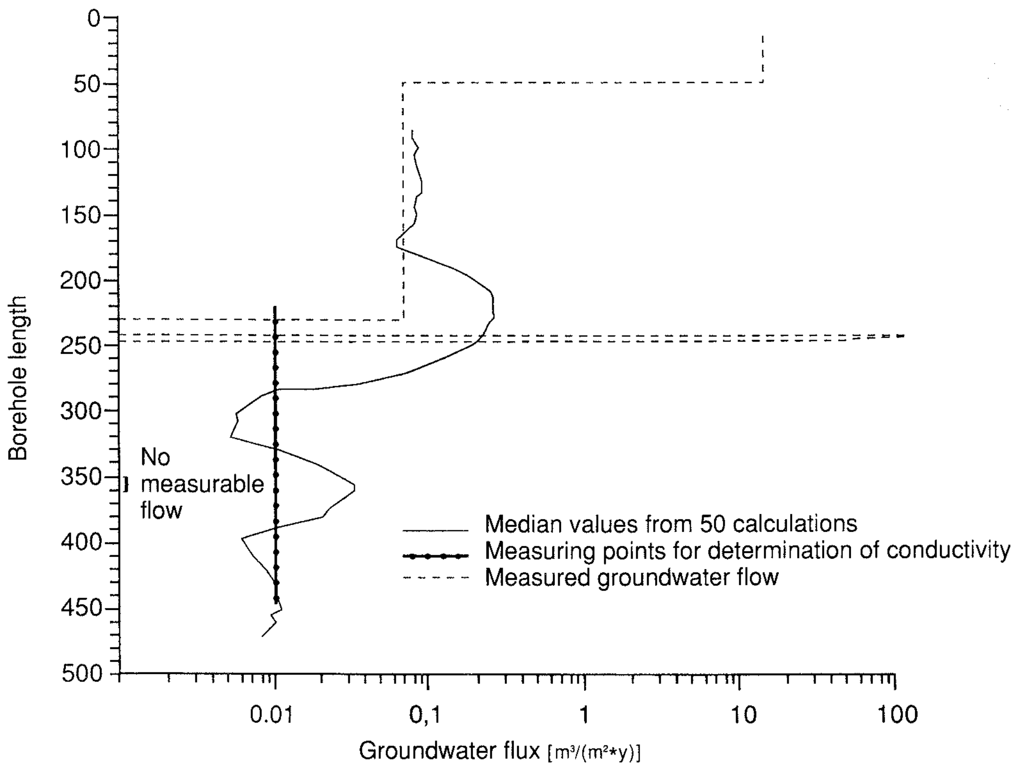



*Figure 8-11. Calculated and measured flow in borehole BFi 01. The flow is only measured in the sections marked with a dashed line.*

Calculations with PHOENICS show that the presence of salt water reduces the groundwater flow in the saline domain ten to a hundred times compared to a case without salt water, see section 9.2.

# 8.3 THE NEAR FIELD

## 8.3.1 General

The near field is defined here as the spent fuel, the canister, the buffer, the backfill in the drifts and the portion of the rock that has been affected by the repository. The rock will be affected both mechanically and chemically. The mechanical impacts are caused by the blasting of drifts and the drilling of deposition holes. Chemical impact includes mineral alterations caused by the elevated temperature and possible oxidation of the rock due to leakage of oxidants from defective canisters.

## 8.3.2 Reference description of the near field

The premises for the near-field model in terms of temperature, assumed distribution of fractures in the rock and location of drifts and deposition holes are presented in section 6.4.6.

### 8.3.3 Transport modelling for the near field

In all likelihood many millions of years will pass before any canister in the repository leaks radioactive materials, but since the possibility that this will happen sooner cannot be ruled out entirely, the consequences of leaking canisters must be examined. Three processes are of importance for nuclide dispersal in the near field:

- The mechanism for canister penetration;
- Dissolution of the uranium dioxide matrix;
- Outward transport to the flowing water in the rock.

**Important radionuclides**

The radionuclides that are responsible for most of the radioactivity at deposition and at all times in the future are taken into account in SKB 91. They are tabulated in Tables 3-1 – 3-3. The selection has been made primarily with respect to half-life and inventory. Nuclides that decay during the interim storage period have been omitted.

**Canister failure modes**

A prerequisite for nuclides to leak out from the repository is that the copper canister has somehow lost its integrity. There are three processes that could lead to this:

- An initial defect;
- Mechanical overload;
- Corrosive penetration.

The modelling in SKB 91 takes all canister failure modes into account.

*Initial defect*

The possibility cannot be entirely ruled out that a canister has an initial defect that is not discovered by the quality control. The defect may have arisen due to an unsuccessful weld and is assumed to be 5 $mm^2$, cf. section 4.1.4. It is very difficult to assess the probability that a canister with a through defect is missed by the quality control. One initial defect per 1,000 canisters is used in the calculations, which must be regarded as a conservative value.

*Mechanical defect*

Two types of mechanical stress could damage a canister: internal overpressure from helium produced by $\alpha$-decay and external stress due to rock movements. Since the void volume in a lead-filled canister is relatively limited, the internal pressure caused by gas production will eventually exceed the canister's ultimate tensile strength, if the diffusivity and solubility of helium in copper and lead are disregarded. The fact that the canister creeps and the void increases with increasing pressure is also disregarded in the modelling, which makes the model conservative. Nevertheless, canister penetration takes place after a very long span of time. Since there is no evidence to suggest that rock movements could take place that could damage the canisters at a depth of 600 m, it is assumed in SKB 91 that no canisters are damaged by external overloading.

*Corrosion*

Copper is thermodynamically stable in reducing water. Sulphide ions in the bentonite's pore water can, on the other hand, reduce the concentration of free copper ions and thereby cause a corrosion process. Sulphide in pore water has two sources: sulphide present in dissolved form in the groundwater and sulphide mineral present as an impurity in the bentonite. In SKB 91, it is assumed that the bentonite will not be heat-treated to minimize the sulphide content. Impurities are therefore the dominant source of sulphide during a very long span of time. Pitting in the ordinary sense is not observed on copper under reducing conditions, see section 4.1.3, but the possibility cannot be ruled out that the corrosion attacks will be unevenly distributed over the canister surface. A "pitting factor" of 2 is used in the calculations, which means that the time to penetration of the canister is shortened to half of what is given by the average corrosion rate.

*Lead*

Only when the copper canister has a through defect can groundwater come into contact with the lead surrounding the spent fuel. The distance from the periphery of the lead to the fuel for a reference canister with 8 BWR assemblies is at least a couple of centimetres (in the canister top at the weld at least 6 cm). In the event of an early defect (welding defect), it is conceivable that dissolved oxygen remains in drifts and deposition holes. A very pessimistic estimate of oxygen-controlled corrosion on lead in a single point is presented in /8-29/. It is shown there that 2.7 cm of lead is penetrated in a thousand years, which gives a very pessimistic value for the earliest point in time when water can come into contact with the fuel rods in an initially defective canister.

Lead is highly resistant to corrosion under reducing conditions /8-29/. This means that if the copper shell is penetrated, the lead will provide total containment of the fuel for hundreds of thousands of years. This is the most realistic estimate. However, 1,000 years has been used in the reference case, see section 9.3.

**Fuel dissolution**

If groundwater comes into contact with the spent fuel, radionuclides will be released from the fuel matrix. The quantity of dissolved radionuclides in the aqueous phase inside the canister is defined by:

- The readily accessible fraction of the nuclide inventory;
- The matrix dissolution rate;
- The solubility of the nuclides in groundwater.

The mechanisms for release of the readily accessible fraction are described in detail in section 3.1.2 and the fuel dissolution model for SKB 91 is described in section 3.1.3. The readily accessible fraction is assumed to be 100% for carbon, 10% for chlorine and iodine and 5% for cesium.

*Solubilities*

Owing to the very low water flux inside the canister, many of the radioelements will be precipitated as secondary minerals. This will probably take place as some form of coprecipitation. Since our knowledge of the dissolution and precipitation mechanisms is limited, it is assumed in SKB 91 that only pure secondary minerals precipitate. Pure phases give higher solubilities than the solid solutions formed by coprecipitation.

The solubility of the secondary phases is of decisive importance for the leakage of radionuclides, and variations in the solubilities have a great impact on the result of the leakage calculations. The solubility values presented in Table 8-2 are regarded as "best estimates". They have been calculated using the computer program EQ3/6 for fresh groundwater according to section 5.4 /8-30/. The solubilities are used in the calculations without variations in order to prevent uncertainties in thermodynamic data from having a greater impact on the final result of the analysis than variations in the geology.

*Nuclides in the fuel's metal parts*

There is some radioactive nickel in the steel and Inconel/Incoloy parts of the fuel assemblies. This is modelled as if it were solubility-limited by a secondary nickel phase. The fuel's Zircaloy contains 50% of all the C-14 in the repository and all the Nb-94. This is released congruently with the dissolution of Zircaloy, which takes place very slowly.

*Redox conditions*

When the spent fuel comes into contact with the groundwater, the $\alpha$-radiation from the fuel will produce oxidants through decomposition of water. This oxidant production is balanced by an equally large production of reductants, mainly $H_2$, but owing to the fact that $H_2$ has very low reactivity, the redox potential inside the canister may increase when the hydrogen diffuses out. The oxidants, on the other hand – mainly $H_2O_2$ – react with the uranium dioxide matrix and oxidize it from U(IV) to U(VI). The large quantity of quadrivalent uranium acts as an oxidant sink, so that the naturally low redox potential is preserved everywhere except on the fuel surface. SKB 91 also analyzes the consequence of a so-called "redox front", i.e. a case in which oxidants are transported out from the canister and oxidize the rock in the near field.

**Tabell 8-2. Radionuclide solubilities, which are used in all calculations in SKB 91.**

| SOLUBILITIES IN FRESH FINNSJÖN WATER | | | | |
|---|---|---|---|---|
| | **Reducing conditions** | | **Oxidizing conditions** | |
| | **solubility (mol/l)** | **limiting phase** | **solubility (mol/l)** | **limiting phase** |
| Se | very low | $M_xSe_y$ | high | – |
| Sr | $1 \cdot 10^{-3}$ | Strontianite | $1 \cdot 10^{-3}$ | Strontianite |
| Zr | $2 \cdot 10^{-11}$ | $ZrO_2$ | $2 \cdot 10^{-11}$ | $ZrO_2$ |
| Tc | $2 \cdot 10^{-8}$ | $TcO_2$ | high | – |
| Pd | $2 \cdot 10^{-6}$ | $Pd(OH)_2$ | $2 \cdot 10^{-6}$ | $Pd(OH)_2$ |
| Sn | $3 \cdot 10^{-8}$ | $SnO_2$ | $3 \cdot 10^{-8}$ | $SnO_2$ |
| I | high | – | high | – |
| Cs | high | – | high | – |
| Sm | $2 \cdot 10^{-4}$ | $Sm_2(CO_3)_3$ | $2 \cdot 10^{-4}$ | $Sm_2(CO_3)_3$ |
| Am | $2 \cdot 10^{-8}$ | $AmOHCO_3$ | $2 \cdot 10^{-8}$ | $AmOHCO_3$ |
| Pu | $2 \cdot 10^{-8}$ | $Pu(OH)_4$ | $3 \cdot 10^{-9}$ | $Pu(OH)_4$ |
| Pa | $4 \cdot 10^{-7}$ | $Pa_2O_5$ | $4 \cdot 10^{-7}$ | $Pa_2O_5$ |
| U | $2 \cdot 10^{-7}$ | $UO_2$ | $3 \cdot 10^{-3}$ | Schoepite |
| Th | $2 \cdot 10^{-10}$ | $ThO_2$ | $2 \cdot 10^{-10}$ | $ThO_2$ |
| Ra | $1 \cdot 10^{-6}$ | $RaSO_4$ | $1 \cdot 10^{-6}$ | $RaSO_4$ |
| Rn | high | – | high | – |
| Pb | $3 \cdot 10^{-15}$ | Galena | $2 \cdot 10^{-6}$ | Cerrusite |
| Np | $2 \cdot 10^{-9}$ | $Np(OH)_4$ | $1 \cdot 10^{-3}$ | $NpO_2OH$ |
| C | high | – | high | – |
| Cl | high | – | high | – |
| Ni | $1 \cdot 10^{-4}$ | $Ni_3S_4$ | $6 \cdot 10^{-4}$ | NiO |
| Nb | $1 \cdot 10^{-5}$ | $Nb_2O_5$ | $1 \cdot 10^{-5}$ | $Nb_2O_5$ |

**Nuclide transport**

The transport of radionuclides in the near field can be divided into several stages:

- From fuel pellet to defect in canister;
- Through defect in canister;
- Through buffer;
- Out to fracture.

*From fuel pellet to defect in canister*

To reach a hole in the canister, the radionuclides must be transported in the gap between the Zircaloy tubes and the fuel up to a defect in the tubes and from there through the lead fill to the hole in the canister. In order for this to be possible at all, there must be defects in the copper, lead and Zircaloy simultaneously. All three of these materials are very resistant to corrosion. Even if all three materials were defective simultaneously, the gaps that can be utilized for transport inside the canister will be very limited. The potential transport resistance is thus very great. However, it is difficult to quantify the transport resistance inside the canister, and it is therefore assumed in SKB 91 that all radionuclides are available for transport directly inside the hole in the canister. This is a very great simplification that leads to a substantial overestimate of the nuclide transport.

*Through hole in canister*

A defect in the canister may take different forms depending on the cause:

1 An initial defect due to a unsuccessful electron beam weld causes a through hole with a small diameter;
2 A canister that ruptures due to internal overpressure will probably only have a smaller hole, since the bentonite's swelling pressure keeps the canister in place;
3 If the canister is penetrated by corrosion, it is possible that a larger portion of the canister wall will be lost due to the fact that corrosion takes place relatively evenly over the canister surface.

In the event of an initial defect in the weld, it is assumed that the lead in the canister completely prevents contact between water and fuel for 1,000 years. After this, there is assumed to be no transport resistance whatsoever in the canister.

In SKB 91, the first case is modelled as a small hole with a 5 $mm^2$ area, while in cases 2 and 3 above it is assumed that the entire transport resistance in the canister has been lost.

$Q_{eq}$ is an inverted measure of the diffusion resistance in the barriers, including the water outside the buffer, and corresponds to a kind of imaginary water flow that leaves the near field with the saturation concentration of the poorly soluble radioelements.

A limited hole in a canister gives rise to a large transport resistance out to the rock owing to the small cross-sectional area available in the hole. This resistance has a very great impact on $Q_{eq}$. Figure 8-12 shows how $Q_{eq}$ is dependent on the local flow at repository level and the size of the hole in the canister. The flow in the rock is thus of very little importance for the near-field transport as long as the canister only has a limited defect, which is always the case for a copper canister and for times shorter than several million years.

*Through buffer*

A number of radionuclides are sorbed very strongly on the surface of the clay particles in the buffer material. As a result, even fairly long-lived nuclides decay to insignificant levels during the transient outward diffusion. A simplified and conservative modelling /8-31/ of the transient diffusion of radionuclides through bentonite has been done to see which nuclides need to be regarded in the steady-state modelling. Boundary conditions and input data for the modelling were:

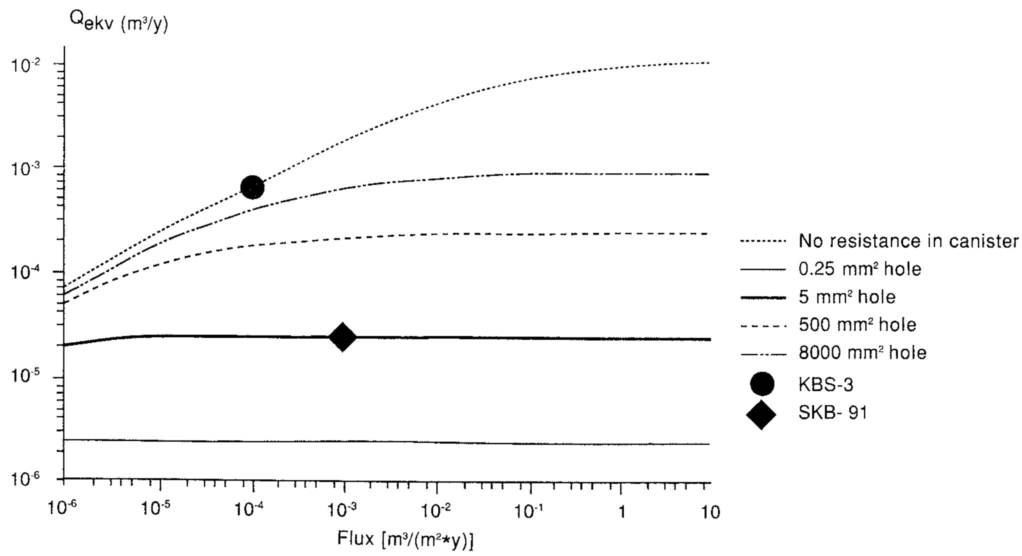



***Figure 8-12.*** *$Q_{eq}$ as a function of the Darcy flux at repository level. Comparison between different sizes of canister defect and a case where the canister's transport resistance is neglected. Typical fluxes for the KBS-3 study and SKB 91 are marked.*

- Radioelement solubility (matrix dissolution was not considered, release of elements with high solubility was modelled as pulse release);
- Diffusivity and $K_d$ values in bentonite as per Table 8-3;
- Nuclide concentration = 0 in the flowing water in the rock, i.e. very high flow.

The results, see Table 8-4, show that most nuclides are strongly retarded in the buffer and some, e.g. all isotopes of americium and plutonium except possibly Pu-242, in principle never get through.

*To fracture*

The nuclides that do not decay to any appreciable degree during the transient phase migrate further from the bentonite out into the water flowing in the fractures in the rock. The flow rate there is so low that the concentration profile that is built up in the water outside the buffer greatly contributes to the transport resistance, if the canister is degraded.

*Disturbed zone*

The disturbed zone in the rock below the drifts has a higher hydraulic conductivity than the undisturbed rock. It is therefore possible that nuclides will diffuse axially through the bentonite up to the disturbed zone instead of diffusing radially to fractures in the deposition hole. In that case, the diffusion distance will be longer and the nuclides will decay to an even higher degree.

Table 8-3. **Element-specific diffusion and distribution coefficients in bentonite /8-32/.**

| **Nuclide** | **$D_e$ $m^2/y$** | **$K_d$ $m^3/kg$** |
|---|---|---|
| C | $3.2 \cdot 10^{-3}$ | 0 |
| Cl | $7.9 \cdot 10^{-5}$ | 0 |
| Ni | $3.2 \cdot 10^{-3}$ | 0.5 |
| Se | $3.2 \cdot 10^{-3}$ | 0.003 |
| Sr | $7.9 \cdot 10^{-1}$ | 0.01 |
| Zr | $3.2 \cdot 10^{-3}$ | 2 |
| Nb | $3.2 \cdot 10^{-3}$ | 0.2 |
| Tc ox | $7.9 \cdot 10^{-5}$ | 0 |
| Tc red | $3.2 \cdot 10^{-3}$ | 0.1 |
| Pd | $3.2 \cdot 10^{-3}$ | 0.01 |
| Sn | $3.2 \cdot 10^{-3}$ | 3 |
| I | $7.9 \cdot 10^{-5}$ | 0 |
| Cs | $7.9 \cdot 10^{-1}$ | 0.05 |
| Sm | $3.2 \cdot 10^{-3}$ | 1 |
| Np | $3.2 \cdot 10^{-3}$ | 3 |
| Pu | $3.2 \cdot 10^{-3}$ | 50 |
| Am | $3.2 \cdot 10^{-3}$ | 3 |

Table 8-4. **Transient nuclide release through bentonite /8-31/.**

| **Nuclide** | **Maximum release rate** | **Time at max. rate** | **Released fraction at t = 500 000 years** |
|---|---|---|---|
| | **Mol/y** | **Years** | **Fraction** |
| C-14 | $1.46 \cdot 10^{-5}$ | 180 | 0.88 |
| Cl-36 | $7.18 \cdot 10^{-7}$ | 2 200 | 0.91 |
| Ni-59 | $2.41 \cdot 10^{-6}$ | 45 000 | 0.25 |
| Ni-63 | $2.01 \cdot 10^{-13}$ | 1 200 | $1.2 \cdot 10^{-9}$ |
| Se-79 | $1.72 \cdot 10^{-10}$ | >500 000 | $7.2 \cdot 10^{-4}$ |
| Sr-90 | $1.02 \cdot 10^{-1}$ | 6.5 | 0.60 |
| Zr-93 | $1.85 \cdot 10^{-10}$ | >500 000 | $3.9 \cdot 10^{-6}$ |
| Nb-94 | $3.92 \cdot 10^{-11}$ | 217 000 | $8.54 \cdot 10^{-4}$ |
| Tc-99, ox | $2.57 \cdot 10^{-4}$ | 2 300 | 0.87 |
| Tc-99, red | $9.65 \cdot 10^{-13}$ | >500 000 | $2.5 \cdot 10^{-8}$ |
| Pd-107 | $2.63 \cdot 10^{-8}$ | >500 000 | $3.8 \cdot 10^{-3}$ |
| Sn-126 | $2.99 \cdot 10^{-11}$ | >500 000 | $3.1 \cdot 10^{-5}$ |
| I-129 | $4.51 \cdot 10^{-5}$ | 2 200 | 1.0 |
| Cs-135 | $4.19 \cdot 10^{-2}$ | 10.5 | 1.0 |
| Cs-137 | $4.56 \cdot 10^{-2}$ | 8.0 | 0.28 |
| Sm-151 | $4.86 \cdot 10^{-21}$ | 2 300 | $8.8 \cdot 10^{-17}$ |
| Np-237 | $9.23 \cdot 10^{-12}$ | >500 000 | $2.48 \cdot 10^{-7}$ |
| Pu-238 | 0 | – | 0 |
| Pu-239 | $1.82 \cdot 10^{-15}$ | >500 000 | $2.1 \cdot 10^{-11}$ |
| Pu-240 | $2.96 \cdot 10^{-19}$ | 176 000 | $2.9 \cdot 10^{-15}$ |
| Pu-242 | $1.61 \cdot 10^{-12}$ | >500 000 | $6.8 \cdot 10^{-8}$ |
| Am-241 | $2.04 \cdot 10^{-18}$ | 11 200 | $2.9 \cdot 10^{-15}$ |
| Am-243 | $1.90 \cdot 10^{-12}$ | 106 000 | $2.8 \cdot 10^{-7}$ |

*Steady-state model*

The near-field code Tullgarn is used to model the transport processes that occur in the near field /8-33/. Tullgarn is a further development of the PROPER sub-model NEAR21 /8-34/. The processes which the model takes into account are:

- Radioactive chain decay;
- Three canister penetration mechanisms
  - initial defect,
  - canister bursting caused by internal helium overpressure. The ideal gas law does not apply at the very high pressures required to burst the canister, so the Benedict-Webb-Rubin model /8-35/ is used to calculate the internal pressure,
  - corrosion. The amount of copper that corrodes due to oxygen remaining in drifts and deposition holes is given as an input datum. Tullgarn then calculates the corrosion caused by sulphide minerals in the bentonite, and when these are consumed, corrosion caused by sulphide in the groundwater;
- Fuel dissolution. The matrix dissolution is calculated according to the model in section 3.1.3 with an effective G value, expressed as the number of transformed molecules of $UO_2$ per 100 eV, based on the total $\alpha$-activity;
- The transport calculations are done with a resistance network model /8-36/, where the transport resistances in the near field are described as coupled resistor, see Figure 8-13. Tullgarn calculates the steady-state outward transport of radionuclides from the fuel surface through the hole in the canister where R3 is the transport resistance offered by the hole's limited area and R2 is the diffusion resistance in the hole, via diffusion through the buffer (R4) to a fracture in the rock (R6) or axial diffusion (R7) to the disturbed zone (R8). The program can also calculate diffusion through the rock matrix to a fracture if the mouth of the fracture should be sealed with bentonite (R5). The leakage of the gap and grain boundary inventory is also modelled differently depending on the type of canister defect. If the canister has an initial defect, the gap and grain boundary inventory is dissolved in the canister's void volume and then released from there with $Q_{eq}$ according to the next-lowest curve in Figure 8-12. In the cases when the canister's transport resistance is neglected (corrosion or overpressure defect), the inventory is dissolved in the buffer's volume and then released with $Q_{eq}$ according to the uppermost curve in Figure 8-12, for which R2 and R3 are assumed to be equal to zero. Tullgarn does not take into account the transient phase of the outward diffusion of nuclides after canister penetration. This simplification can give pessimistic results for certain nuclides. The transport resistance inside the canister (R1) is neglected entirely.

Figure 8-14 shows results from Tullgarn runs for the reference case in SKB 91 with an initially defective canister. A PROPER sub-model of Tullgarn, TULL22, is used in the big model chain runs in SKB 91.

## 8.4 TRANSPORT OF RADIONUCLIDES IN THE FAR FIELD

As noted previously, the groundwater flow in crystalline bedrock is very unevenly distributed. Only some of the fractures conduct water, and the flow in these water-bearing fractures is also unevenly distributed. Moreover, the flow is limited to channels in the fracture plane. The geometry of the channels and the pattern in which they are connected are of great importance for the radionuclide transport. The former factor determines how large a surface area is available for diffusion of radioelements into the rock matrix, which is defined here as that part of the rock in which the water

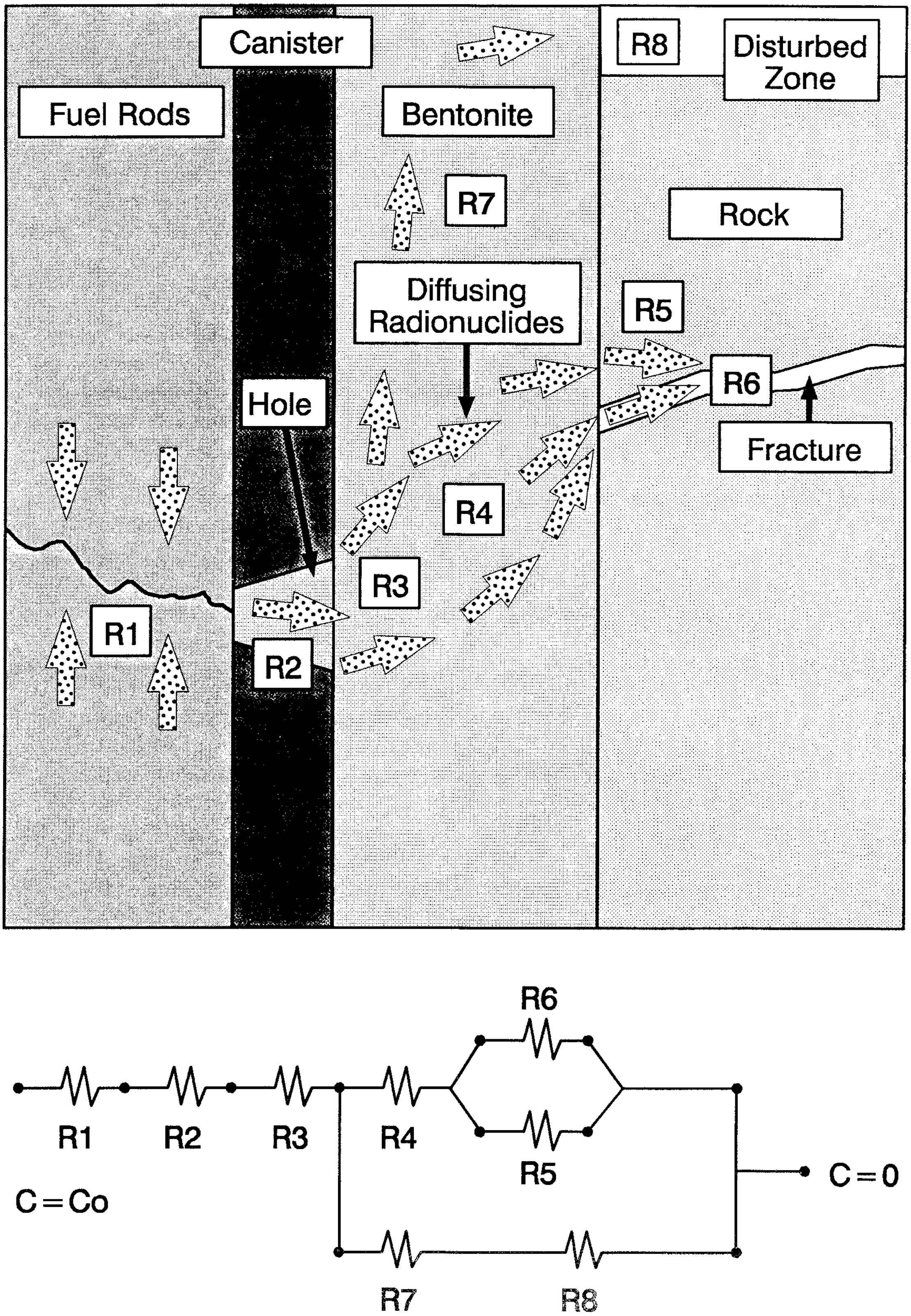



*Figure 8-13. Resistor network model for the transport resistance in the near field. R1, R2 and R5 have been neglected in the calculations for the initially defective canister In other cases, R3 has also been neglected.*

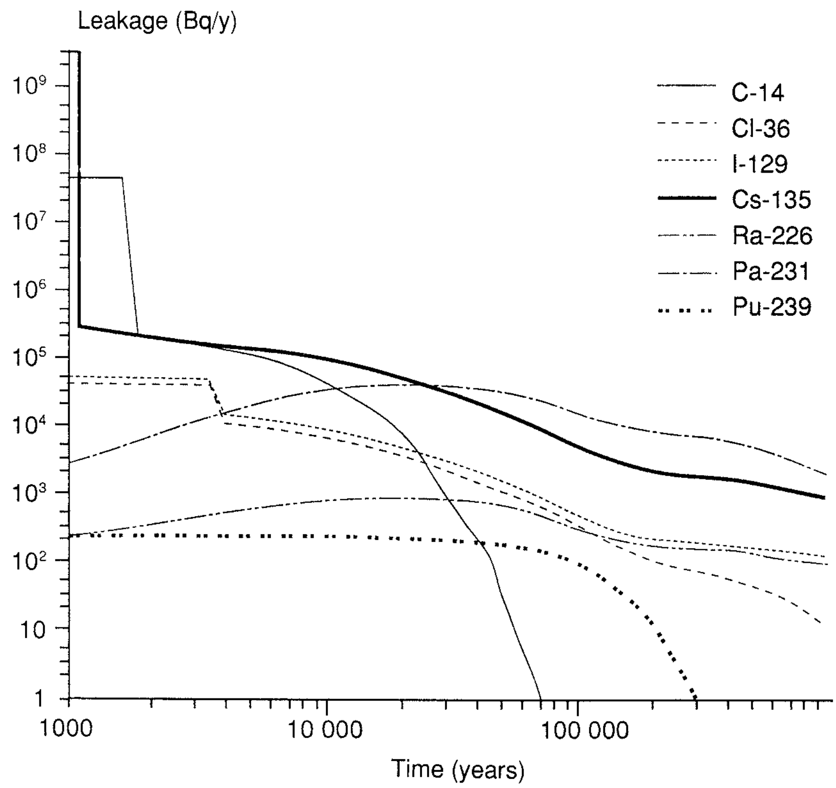



***Figure 8-14.*** *Leakage of radionuclides from the near field of an initially defective canister. All nuclides that leak out at a rate of more than 1 Bq/y are included in the figure.*

does not flow. The inward diffusion at depth is a slow process whose rate and retarding effect on the radionuclides is heavily dependent on the surface area over which the inward diffusion can take place. The channel pattern is also of great importance for the dispersion, which is determined in fractured rock by the structure of the solid medium. The purely hydrodynamic dispersion is negligible at the flows in question.

A review and discussion of non-chemistry-related transport properties of fractured rock has been performed specially for SKB 91 /8-37/. The review includes estimates of effective values of flow porosity, specific surface area for diffusion into the rock matrix and the Peclet number. The last-mentioned parameter represents the ratio between a characteristic time for dispersive transport and a characteristic time for advective transport – the smaller the ratio, the greater the dispersive contribution. The parameter is used in the advection-dispersion formulation for the transport in the rock that is used in SKB 91. The intention is that the truly large-scale dispersion shall be taken care of by the stochastic hydrology model, while the residual dispersion is handled in the transport model. Only longitudinal dispersion is taken into account. Transversal dispersion has been judged to be of little importance.

The model that has been used in SKB 91 to describe the transport of radionuclides in the rock, described in /8-37/, is based on the properties of the far-field model FARF31, originally developed for the simulation program PROPER /8-38/. FARF31 solves the equations for transport in a stream tube. The most recent version of the transport

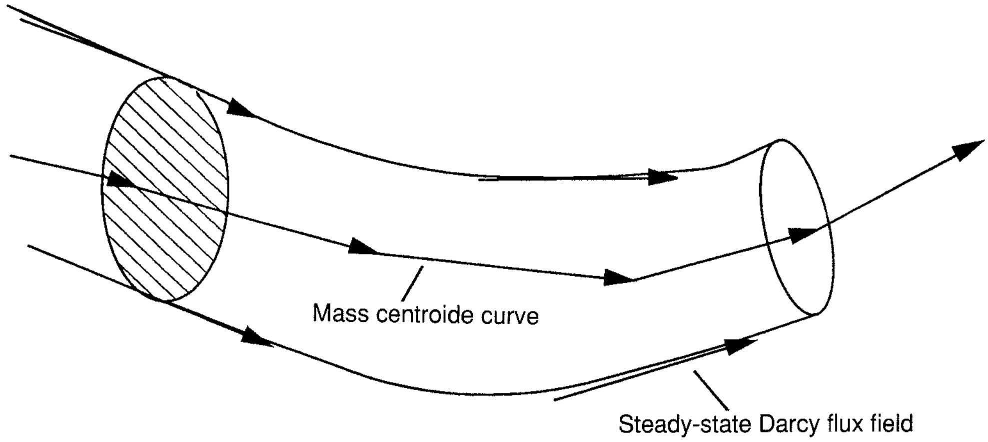



***Figure 8-15.*** *Schematic illustration of the flow in a stream tube.*

program is provided with a much faster numerical algorithm than the one described in /8-38/.

A stream tube consists of a bundle of uninterrupted streamlines, and its extent across the flow is also limited by streamlines, see Figure 8-15. This means that the total flow in a cross-section is constant, while the flux and the cross-sectional area can vary: the higher the Darcy flux, the narrower the stream tube.

Stream tubes have been used to build a transport model for the entire repository, which for this purpose has been divided into a number of segments (88). Each of these segments is assigned a stream tube, so that the entire repository is in principle covered by their upstream ends, see Figure 8-16. The total outflow of radionuclides from all canisters in a segment is then used as the inflow of radionuclides to the stream tube.

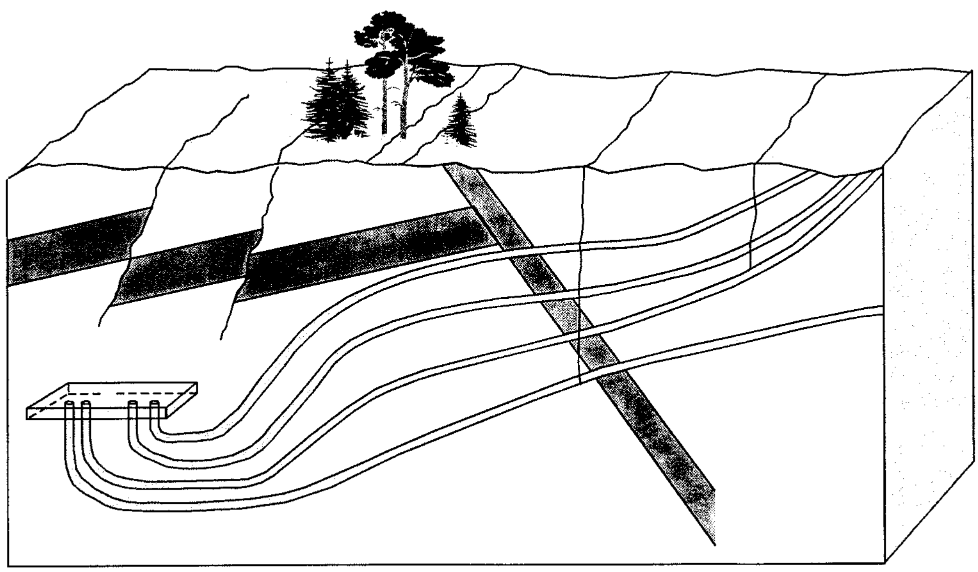


***Figure 8-16.*** *Stream tubes from the repository to the surface.*

The individual stream tube's transport equations are based on a double-porosity description of the fractured medium. The equations are in principle the same as those used in the far-field model for KBS-3. Under certain assumptions they can be shown to be valid for curved stream tubes with varying Darcy flux as well /8-38/. The processes included in the model are advective and dispersive (Fickian) transport, one-dimensional matrix diffusion and matrix sorption, as well as chain decay. The most important parameters are the travel time for the groundwater from the repository to the surface, the Peclet number – which determines the dispersive contribution – the matrix sorption coefficients ($K_d$) for the different radioelements, and the specific surface area per unit volume of rock that is available for diffusion into the rock matrix.

The groundwater travel times for the different stream tubes are obtained by means of particle tracking in HYDRASTAR. One particle per stream tube has been used. A flow porosity of 0.0001 has been assumed throughout, see /8-37/, even when estimating the specific surface area per unit volume of flowing water, which is the parameter used by the model.

The transport of radionuclides in the rock from the repository to the biosphere is affected by numerous interactions between the dissolved radioelements and solid material. Sorption takes place on fracture surfaces and fracture-filling minerals, as well as on particles in the water such as colloids and microorganisms. Sorption on fracture surfaces and fracture-filling minerals reduces the rate of transport of the nuclides in relation to that of the water and gives them more time to decay in the rock. Sorption on particulate matter, on the other hand, can result in radioactive materials being transported to the ground surface with the flow rate of the groundwater. A more exhaustive discussion of the chemical processes that influence the transport is presented in section 5.4.4.

The most important hydrochemical parameters are redox potential and pH, the presence of complexing agents, especially humic substances, and to some extent the total ion content of the water.

$K_d$ values are used throughout for the sorption modelling in SKB 91. It has not been considered warranted for the type of study represented by SKB 91 to use more sophisticated models of sorption phenomena. The estimated $K_d$ values are chosen to give, if anything, a pessimistic picture of the rock's retarding capacity. The $K_d$ values for a number of radioelements in different groundwaters are presented in /8-39/, including for the reference groundwater.

Tests have been carried out that clearly show that technetium is reduced in a deep bedrock-water environment /8-40, 41/. In-situ tests showing this have also been carried out in Finnsjön. On the basis of the results, only sorption coefficients, $K_d$, for natural reducing conditions are used in SKB 91.

An evaluation has also been carried out to shed light on the importance of the fact that radionuclides can be transported either as colloids or as complexes with humic substances. The possibility that radionuclides might migrate with microbes in the groundwater has also been considered. The evaluation is based on the compiled results of groundwater analyses and laboratory measurements of radionuclide uptake on colloids, humic and fulvic acids, and microbes.

One of the conclusions is that the organic complexes cause a slight reduction of the sorption coefficients $K_d$. The magnitude of the reduction of the $K_d$ value for a nuclide depends on how the nuclide behaves as a dissolved ion and on the concentration of the complexing agent.

Another conclusion is that mobile particles in the form of inorganic colloids and microbes can both take up and transport radionuclides. If the nuclide sorbs irreversibly on the particles, it will be transported with the water and, at worst, not be retarded by sorption in the rock. However, the calculations show that even for such an extreme case, the consequences are without importance. The evaluation is summarized in /8-39/.

Parameter values for the reference case are presented in Table 8-5. The same values are assumed to apply for all stream tubes.

**Table 8-5. Parameter values for the far-field model, the reference case.**

- Peclet number = 2;
- Specific surface area = 0.1 $m^2/m^3$ of rock = 1,000 $m^2/m^3$ of water;
- Matrix diffusion coefficient = $3.2 \cdot 10^{-6}$ $m^2/y$;
- Diffusion porosity in the rock matrix = 0.005;
- $K_d$ values ($m^3/kg$):

| | |
|---|---|
| • uranium | 2 |
| • neptunium | 2 |
| • plutonium | 0.2 |
| • thorium | 2 |
| • radium | 0.15 |
| • protactinium | 1 |
| • carbon | 0.001 |
| • chlorine | 0 |
| • nickel | 0.03 |
| • palladium | 0.001 |
| • selenium | 0.001 |
| • tin | 0.001 |
| • strontium | 0.015 |
| • cesium | 0.15 |
| • iodine | 0 |
| • technetium | 1 |
| • zirconium | 1 |

The choice of a constant Peclet number regardless of the length of the stream tube means that the effective dispersion coefficient has been assumed to be proportional to both the flow rate and the travel distance. No attempt has been made to relate the scale in the hydrology model to residual dispersion in the transport model.

The value of the specific surface area is based on, among other things, observations concerning the intersection of fractures with drifts and tunnels.

An estimate of the specific surface area and the flow porosity has also be done using a discrete fracture model /8-20/. Approximate flux-averaged values were 0.01 for the specific surface area and 0.000 01 for the flow porosity, which gives 1,000 $m^2/m^3$ of water. No correlation between these values could be found. However, in view of the general status of discrete fracture modelling, these estimates must be regarded as uncertain.

## 8.5 RADIOLOGICAL CONSEQUENCES

Conversion factors from Bq/y to Sv/y are used as a biosphere model in the model chain under the assumption that 99% of the release from the far field reaches a lake directly, while 1% passes a well, see Table 7-2.

# 9 CALCULATION RESULTS

*This chapter gives an account of how the calculations have been carried out. The reference case that constitutes the basis for the variations is presented. The results are reported and discussed.*

## 9.1 PLAN FOR CALCULATIONS

### 9.1.1 The reference case

The reference conditions have been defined based on a planned final repository, with a barrier system as described in Chapter 4, placed in the Finnsjön area as described in Chapter 6, and on best possible estimates of the hydraulic properties of the rock. Different geological structures have hereby been established, along with groundwater composition, redox conditions, solubilities, diffusion properties of the barriers, the specific surface area available for matrix diffusion, dispersion conditions, etc.

A complete assessment of the safety of the repository has been carried out for this reference case, based on nuclide release via transport of nuclides through the technical barriers and the geosphere up to an outflow of radionuclides from the geobarrier and further to individual doses.

The hydrology model for these calculations is stochastic, as is the distribution of a number of initially defective canisters. This affects the manner in which the results are reported. The hydrology and the distribution of the initially defective canisters represent the only factors that are treated probabilistically. Everything else has been kept constant in the calculations so as not to cause interpretation problems as regards the importance of variations in the hydrological characteristics of the site.

### 9.1.2 Variations

In order to shed light on the influence of site-related/site-specific factors, calculations have been carried out for some fifteen variations of the premises, with the reference situation as the point of departure. The results show the importance of:

- the hydraulic properties of the rock mass in the repository area in relation to:
  - the hydraulic properties of steeply dipping structures and their locations in relation to the repository;
  - the properties of flat-lying structures and their locations in relation to the repository, as well as their interaction with saline groundwater from great depth;
- the size of the regional hydraulic gradient in relation to the local gradients in the repository area and the relationship of the principal fracture directions to the direction of the principal hydraulic gradient;
- the placement of the repository in the rock block and its adaptation to the geological structures.

The potential importance of the repository site for the safety of the repository depends on two factors: the movements of the groundwater and the interaction of the radionuclides and the engineered barriers with their surroundings. Interaction with the surroundings is manifested as solubility limitations and various types of sorption phenomena. All features and processes that have to do with the influence of the site on safety can be related to these two factors.

As far as chemical interaction with the surroundings is concerned, it can be said that the large-scale picture of groundwater composition and mineralogy varies rather little between different investigated sites in granitic bedrock in Sweden. Variations associated with uncertainties in equilibrium constants and local variations in groundwater composition mean more than differences between different sites. Moreover, there are scarcely enough data available today to assess the properties of different sites against the background of properties related to matrix diffusion and matrix sorption. There are, on the other hand, quantifiable differences between different sites in their large-scale geohydrology. There is also a large quantity of data available from the site analyzed in the project as well as from SKB's other study sites.

The influence of site hydrology on fuel dissolution and the subsequent transport of radioactive materials has therefore been related in SKB 91 to:

- the groundwater fluxes around the canisters,
- the groundwater travel times from canister to biosphere,
- the extent and character of the discharge area related to the repository.

Figure 9-1 shows the importance of the flux for the diffusion resistance outside the canister for the solubility-limited substances. The easily soluble materials are not at

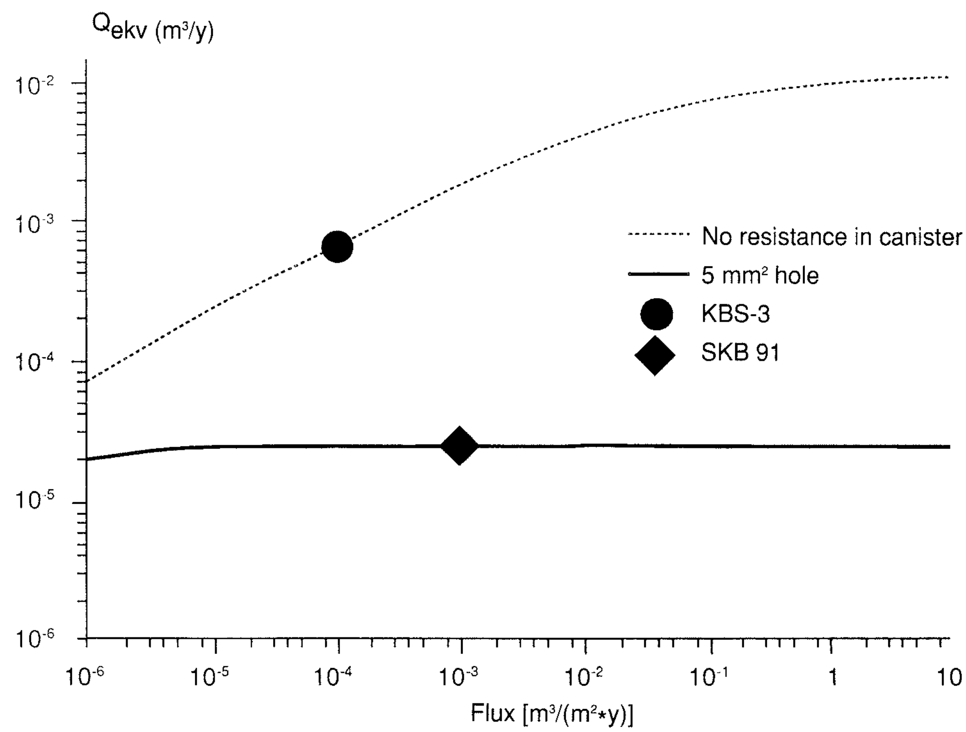



***Figure 9-1.*** *$Q_{eq}$ as a function of the Darcy flux at repository level. Comparison between initially defective canister and a case where the canister's transport resistance is neglected. Typical fluxes for the KBS-3 study and SKB 91 are marked.*

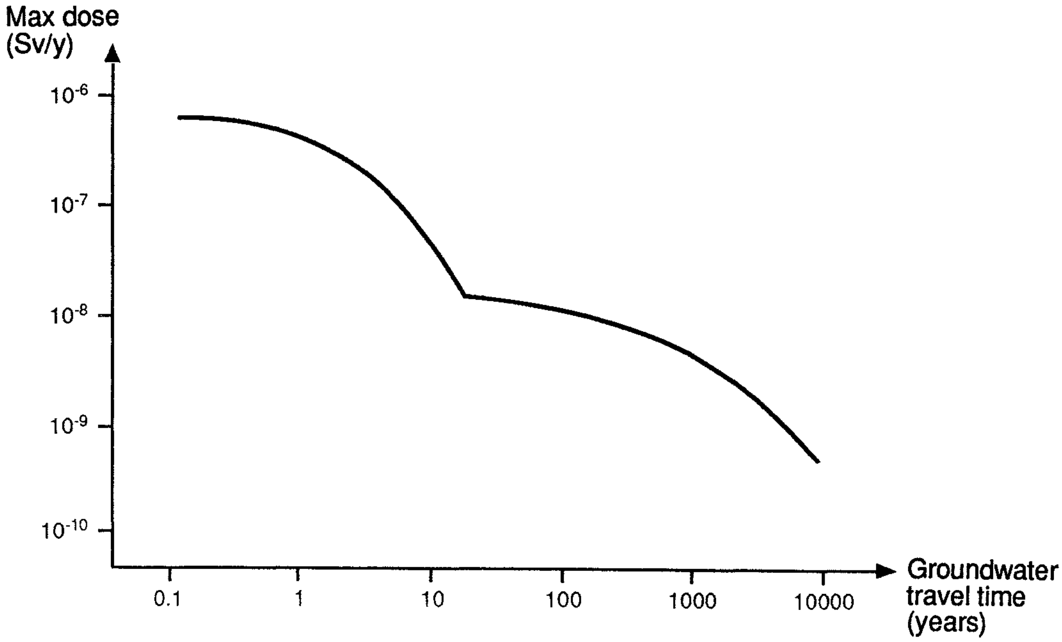



***Figure 9-2.*** *Maximum dose from an initially defective canister as a function of the groundwater's travel time to the surface.*

all affected by the flow, since fuel dissolution is not assumed to be dependent on transport mechanisms. $Q_{eq}$ is an inverted measure of the transport resistance for steady-state diffusion and can be most accurately described as the equivalent flow that leaves the near field with the saturation concentration of the poorly soluble substances. As is evident from the figure, the groundwater flux is of very little importance for the initially defective canisters.

The life of the initially intact canisters exceeds ten million years. In view of this fact, in combination with the above relationship, the assessment of the importance of the variations has been based mainly on groundwater travel times, not on fluxes.

Figure 9-2 shows how the maximum dose from a single initially defective canister varies with groundwater travel time to the surface under the reference premises, see section 9.3.

The groundwater travel time is dependent on the fluxes along the transport pathway, the length of the pathway and the flow porosity. The last parameter is generally uncertain and difficult to estimate – it has been set at 0.0001 in all calculations – and all reported groundwater travel times should therefore be regarded as relative. The importance of the flow porosity for the actual radionuclide transport and for the doses is, on the other hand, limited, since, for instance, a reduced flow porosity (unfavourable) tends to be offset by an increasing specific surface area, negatively correlated with the flow porosity (favourable). Thus, a change in groundwater travel time from a given point in the repository to the ground surface mainly reflects a change in hydraulic gradient or travel distance. The travel times can also be seen as a measure of the ratio of the Darcy flux to the length of the stream tube.

The extent and character of the discharge area has only been studied qualitatively.

Pathlines from different parts of the repository have been calculated for all the variations described above. The results have been processed statistically to give distributions of groundwater travel times to the surface and groundwater flows in the repository. Premises and results for each variation have been compiled in separate work reports, see section 9.6.1.

A number of variations have also been performed to shed light on the importance of uncertainties concerning the transport models, especially with regard to:

- redox conditions in the near field;
- dispersion conditions;
- matrix diffusion conditions.

These variations are reported under the transport and dose calculations for the reference case. The two last-named factors could conceivably vary between different potential repository sites, but at present there is no basis for quantification of the differences.

## 9.2 PRESENT-DAY AND FUTURE GEOLOGICAL CONDITIONS

### 9.2.1 Presence of saline water

In connection with the investigations of the Finnsjön area, saline water has been encountered in all boreholes that have penetrated the upper boundary of Zone 2, see Chapter 5. There is a sharp boundary layer between the fresh and the saline water at the upper boundary of Zone 2. The existence of this layer has been explained with the aid of model calculations with the computer program PHOENICS /9-1/, see Figure 9-3. Under certain assumptions concerning the existence of areas with superficial, saline groundwaters that surround the Finnsjön block, the present-day situation can be described as a state of equilibrium.

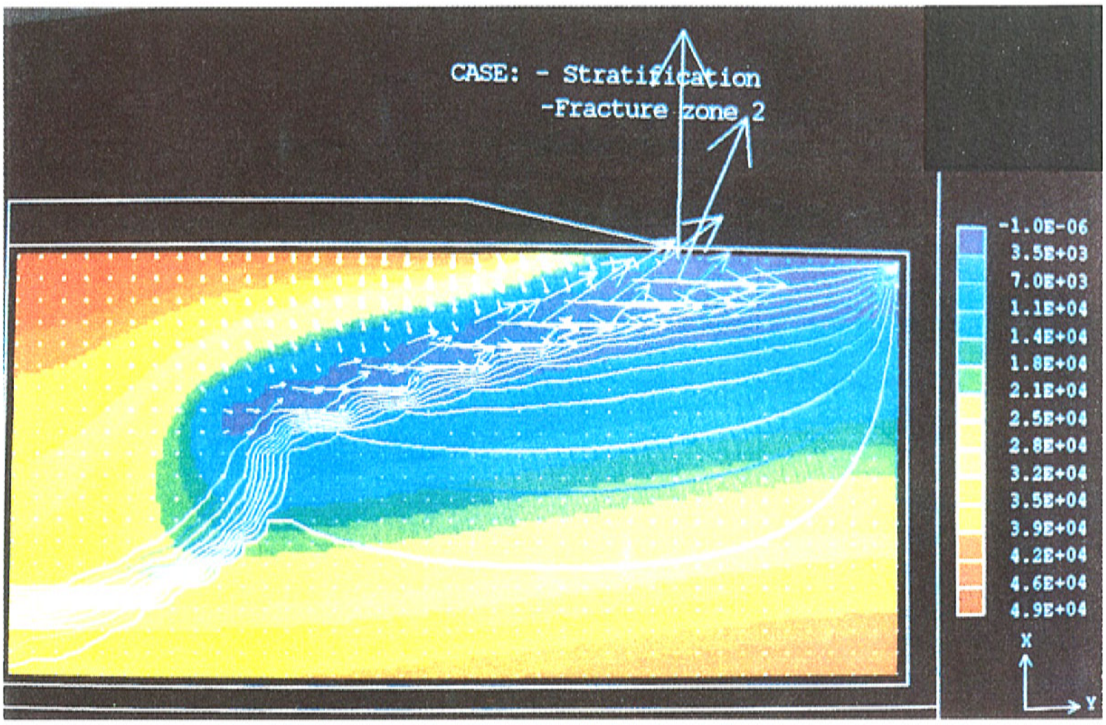
Equivalent calculations have also been carried out with PHOENICS under the assumption that no salt is present /9-1/. The flow pattern then changes entirely, see Figure 9-4. In this case the pathlines follow an entirely different route that does not lead up into Zone 2.

The calculated groundwater travel times to the surface are ten to a hundred times longer when salt is present, see Figure 9-5. This is due to the fact that conditions are completely stagnant under the boundary layer.

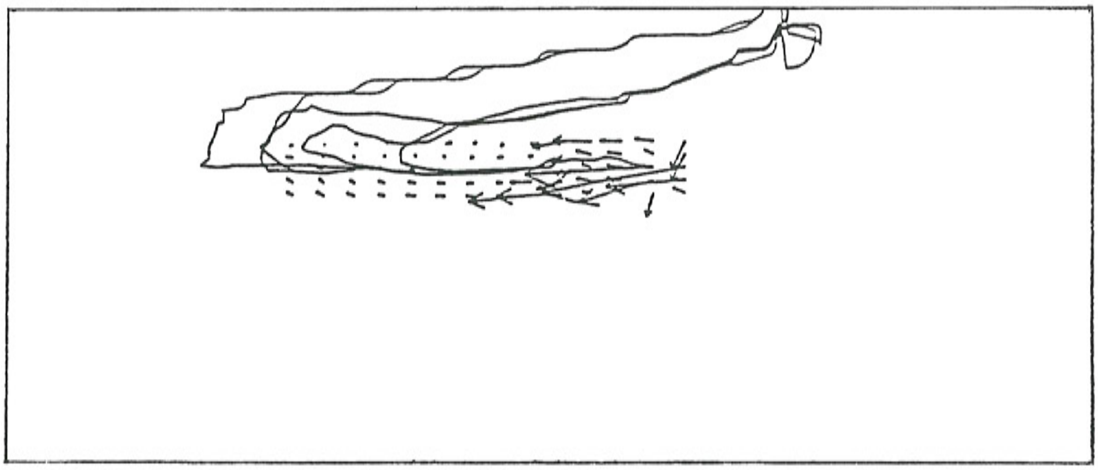
The assumptions and the boundary conditions must be regarded as uncertain, however, which means that the present-day situation could constitute an instantaneous "snapshot" in a slow washing-out process /9-2/. Moreover, the salt balance can change during the construction phase.

In conjunction with future glaciations and the formation of permafrost in the area, the geohydrological-hydraulic conditions will change drastically, see the following section and /9-3/, which could also lead to a washing-out of the salt.

It is in consideration of these circumstances that the stabilizing effect of existing salt contents has been neglected in the reference case, which is based on assumed fresh water conditions.

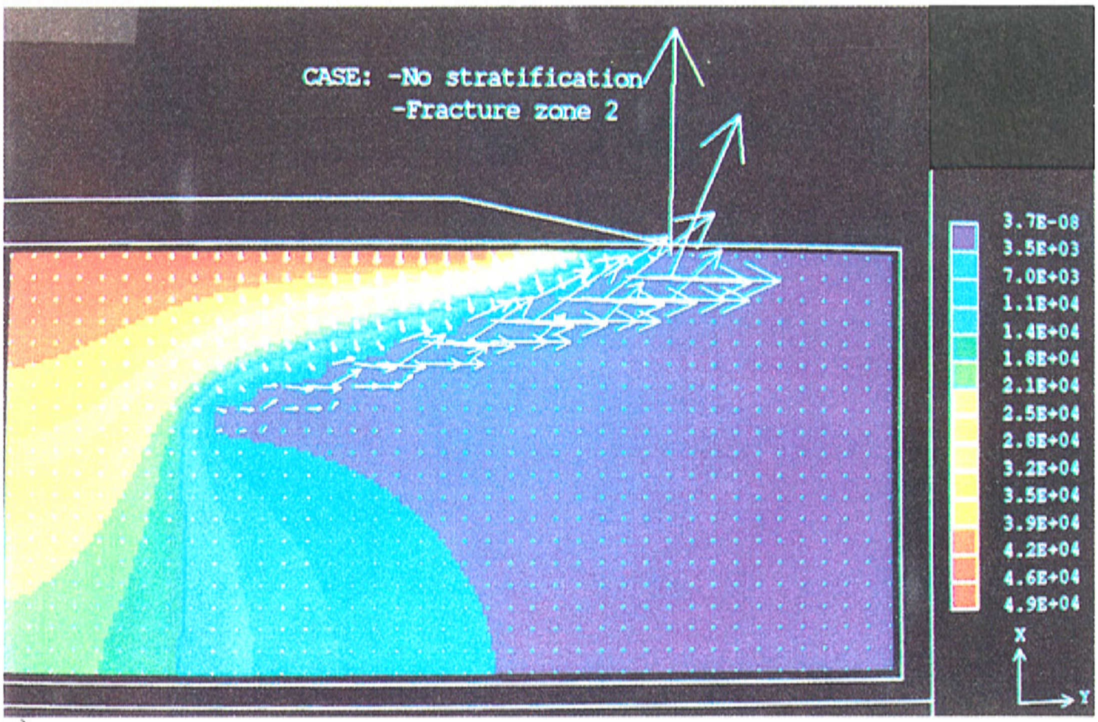



a)

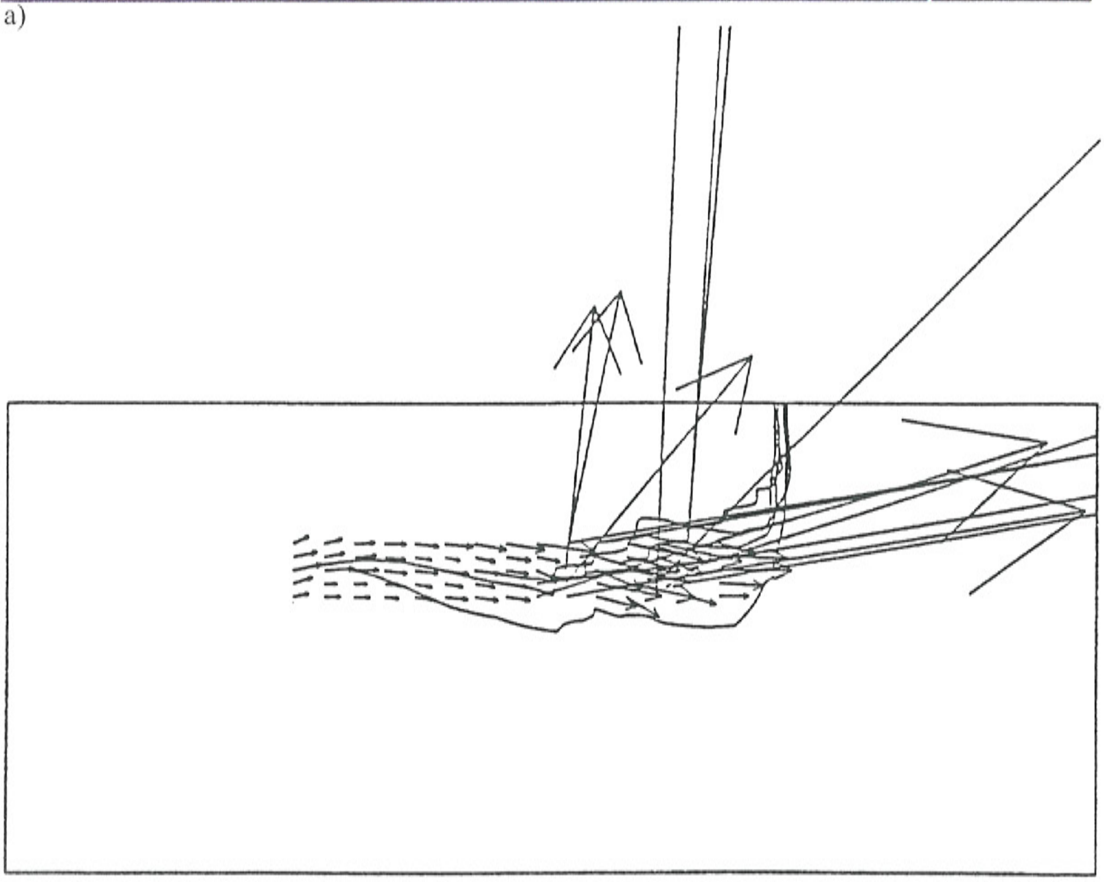


b)

***Figure 9-3.*** *Salt concentration isopleths (white lines), potential field and flows (arrows) (9-3a) as well as flow paths (9-3b) with salt present. The section roughly corresponds to A-A in Figure 5-3 or section 5 in Figure 8-5. The colours indicate the deviation from the hydrostatic fresh water head in Pa. The blue-coloured, slanting head reduction in Zone 2 is clearly visible, as is the accumulation of salt concentration isopleths immediately below the zone. The calculations were done deterministically with PHOENICS.*




a)



b)

***Figure 9-4.*** *Potential field and flows (9-4a) as well as flow paths (9-4b) under fresh water conditions analogous to Figure 9-3. The calculations were done deterministically with PHOENICS.*

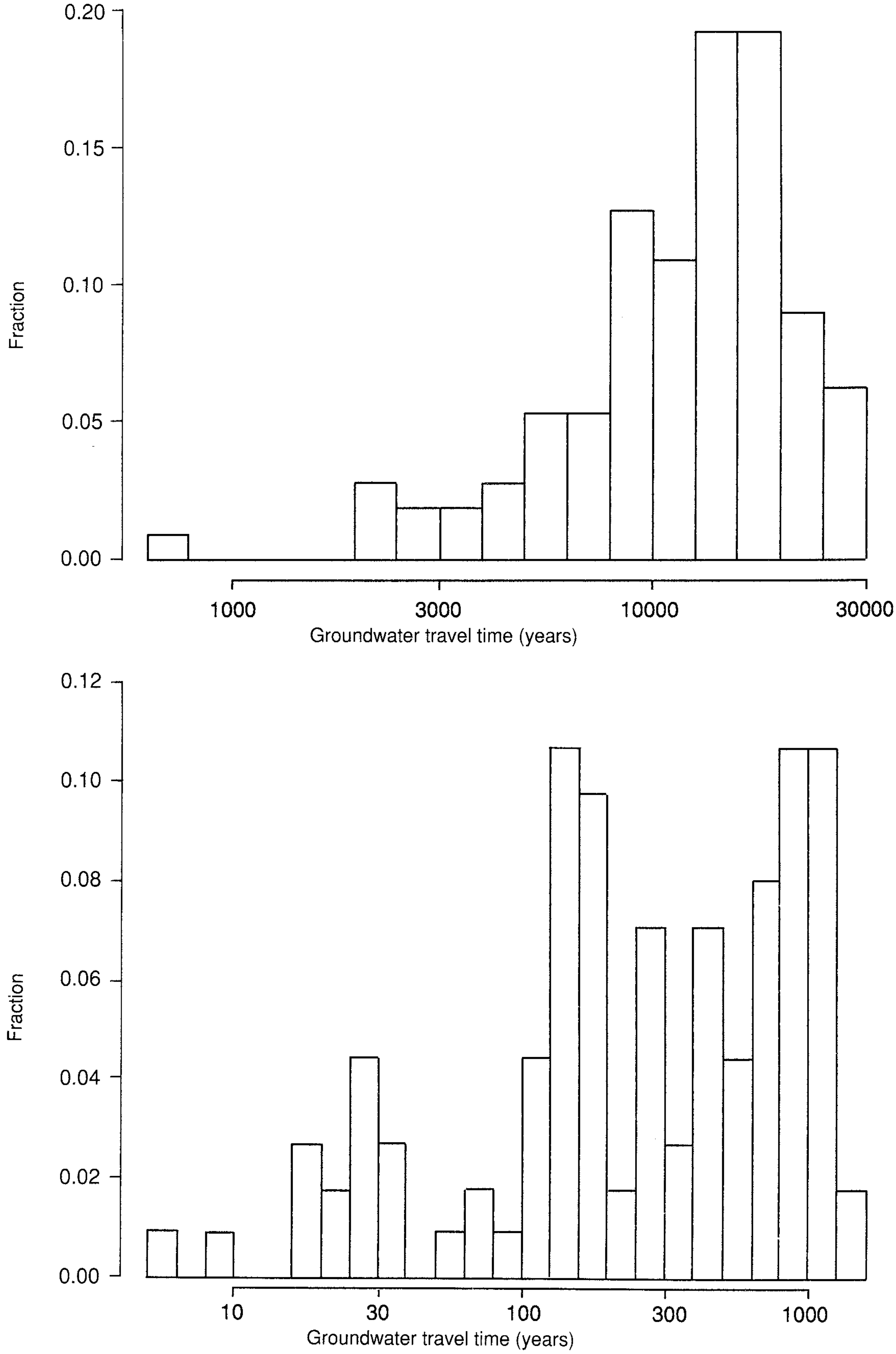



***Figure 9-5.*** *Histograms for groundwater travel time from repository level obtained from deterministic calculation with PHOENICS with salt present (upper histogram) and under fresh water conditions (lower histogram).*

### 9.2.2 Influence of glaciation

In about 60,000 years, an ice front will sweep southward over central Sweden and be built up to a thickness of about 3 km, leading to depression of the ground surface by a maximum of about 700 m and a general lowering of the sea level by about 120 m. During this period, the repository area will be covered with ice and any leaking radioactivity must be transported to deglaciation areas, where it will be diluted in very large quantities of meltwater.

The most unfavourable situation from the mechanical and hydraulic viewpoint arises when the ice front retreats after the big glaciation and passes the repository area, in about 100,000 years. Nearest the front the original ground level is probably still below sea level, but the change of pressure conditions can lead to rock movements. In order for a canister to be sheared off so that its contents come into direct contact with the bedrock, a displacement in the bedrock of around one metre is required. Seismically generated movements with such displacements require that the reactivated zones of weakness or fracture zones have a length of at least 10 km. Fracture zones of such an extent will be discovered and avoided when a final repository is built.

An ice age could affect a well-emplaced repository via the following mechanisms:

- The permafrost reduces the groundwater flow in the bedrock. The thermal balance between the repository's heat generation and the depth of the permafrost determines whether there are any unfrozen conductive bedrock sections;
- During a deglaciation phase, hydraulic gradients are obtained that alter the flow conditions in the rock mass;
- The ice's loading and unloading cause minor rock movements.

An ice age scenario has been described in section 7.5.

Possible alternations between salt water and fresh water conditions are discussed in the preceding section.

These phenomena have, within the framework of SKB 91, been examined in a general manner to obtain indications as to whether safety is significantly affected /9-3, 9-4, 9-5/.

The permafrost modelling shows that the bedrock above the repository does not remain unfrozen for significantly longer periods of time than the bedrock in the surrounding areas.

In conjunction with a deglaciation, increased hydraulic gradients are obtained near the ice front compared with conditions without an inland ice sheet. If permafrost is not present, locally elevated groundwater flows are obtained immediately outside the ice front. If permafrost is also present, the area with elevated flows extends all the way out to the edge of the permafrost. The calculations suggest that the flow can increase by a factor of ten. These flow peaks are, however, of short duration in this context, since the ice edge generally retreats at a rate of one to several hundred metres per year. The possibility cannot be ruled out that the composition of the groundwater is affected under the changed flow conditions.

These cases are deemed to be covered by the variations that have been analyzed. Large hydraulic gradients can thus – during brief spans of time, i.e. a few hundred years – increase the groundwater flow and change the groundwater composition. Some increase in nuclide release cannot be ruled out (if such release occurs), but this is more than compensated for by the high surface water dilution during the deglaciation phase.

As mentioned in section 5.1.3, there is no reason to expect a change in the plate-tectonic regime during the next 100,000 years. During this period of time we can, however, expect two or three glaciation cycles /9-6/. For this reason, a study has been carried out of the stability of the bedrock in the Finnsjön area during a glaciation cycle /9-5/. In the glaciation study, the response of the rock mass to a 3 km thick ice load with subsequent isostatic rebound was simulated. The influence of an ice lake was also simulated. The results can be summarized as follows:

The hydraulic pressure from an ice lake evens out the stress field in the bedrock. This causes the normal stresses, and thereby also the stress discontinuities near fracture zones, to decrease. During the retreat of the inland ice sheet, displacements will take place in the major fracture zones, especially the flat-lying zone, Zone 2. The relative displacement between the outer edges of a repository area (500 m) is estimated to be on the order of 0.15 m. The stress increase around existing zones and the reactivation of certain zones warrants placing the repository to avoid dominant zones. The above-mentioned study indicates that a suitable distance in the Finnsjön area is about 100 m from major zones of weakness, mainly Zone 2. The calculation results are naturally sensitive to the choice of input data. The glaciation modelling will therefore be augmented with a sensitivity study, but not within the framework of SKB 91.

## 9.3 THE REFERENCE CASE

The premises of the reference situation have been described in previous chapters. However, a brief summary follows below:

- The number of canisters to be deposited is 5,300;
- All canisters are represented by a "reference canister" with 8 BWR assemblies with a burnup of 38 GWd/tU excluding fuel channels. The radionuclide content is reported in section 3.2. The activity content in the fuel-clad gap is reported in section 8.3.3;
- The repository is situated at a depth of 600 m with an exclusion zone of 100 m to the steeply dipping zones 1, 4 and 12 and to the flat-lying Zone 2, see Figure 6-1a;
- The drifts are oriented perpendicular to the prevailing hydraulic gradient and perpendicular to the principal dip and strike directions for fractures of orders 4-5 according to section 6.4.6 in order to minimize the influence of the disturbed zone. The centre-to-centre distance between the drifts is 25 m. The repository has 5,830 canister positions at a canister spacing of 6 m, which corresponds to a 10% overcapacity. With 5,300 canisters, the average centre-to-centre distance is 6.6 m, but 6 m has been used throughout in the assessment;
- The extent of the disturbed zone is 1 m around the deposition drifts and its hydraulic conductivity is $10^{-6}$ m/s. The conductivity of the backfill is $10^{-9}$ m/s;
- The canisters are of the KBS-3 type with lead filling, see section 4.1.2. The deposition hole has a diameter of 1,500 mm and is so deep that the top of the canister is situated 2.5 m below the floor of the deposition drift;
- Each canister has a probability of 1/1,000 of having a 5 $mm^2$ defect through the copper shell in the welded joint at deposition, see section 4.1.4;
- Present-day conditions are assumed to prevail indefinitely as far as the properties of the site are concerned, with the exception of the salinity, which is assumed to be low, see discussion in section 9.2;

- Geohydrology data are presented in section 8.2;
- The composition of the groundwater is assumed to be as per Table 5-3 with the exception of: Eh = -200 mV, sulphide content = 0.44 ppm, pH = 7. These circumstances are also assumed to prevail in the near field, except where the actual fuel dissolution takes place. The solubilities in the near field are given in Table 8-2, the $K_d$ values in the buffer are given in Table 8-3 and the $K_d$ values in the rock are given in Table 8-5;
- Other data for the near- and far-field transport are given in Tables 8-3 and 8-5;
- The calculation of the annual dose commitment for an individual in the critical group uses a "standardized biosphere" with a lake as the receiving body for 99% of the leaking activity and a 1600 $m^3$/y well as the receiving body for the remaining 1%, see Chapter 7. Conversion factors from Bq/y to Sv/y are given in Table 7-2. For the longer time perspective, the outward transport rate of activity from the far field is used as the sole measure of repository performance, cf. section 2.4.2.

## 9.4 GEOHYDROLOGICAL CALCULATIONS FOR THE REFERENCE CASE

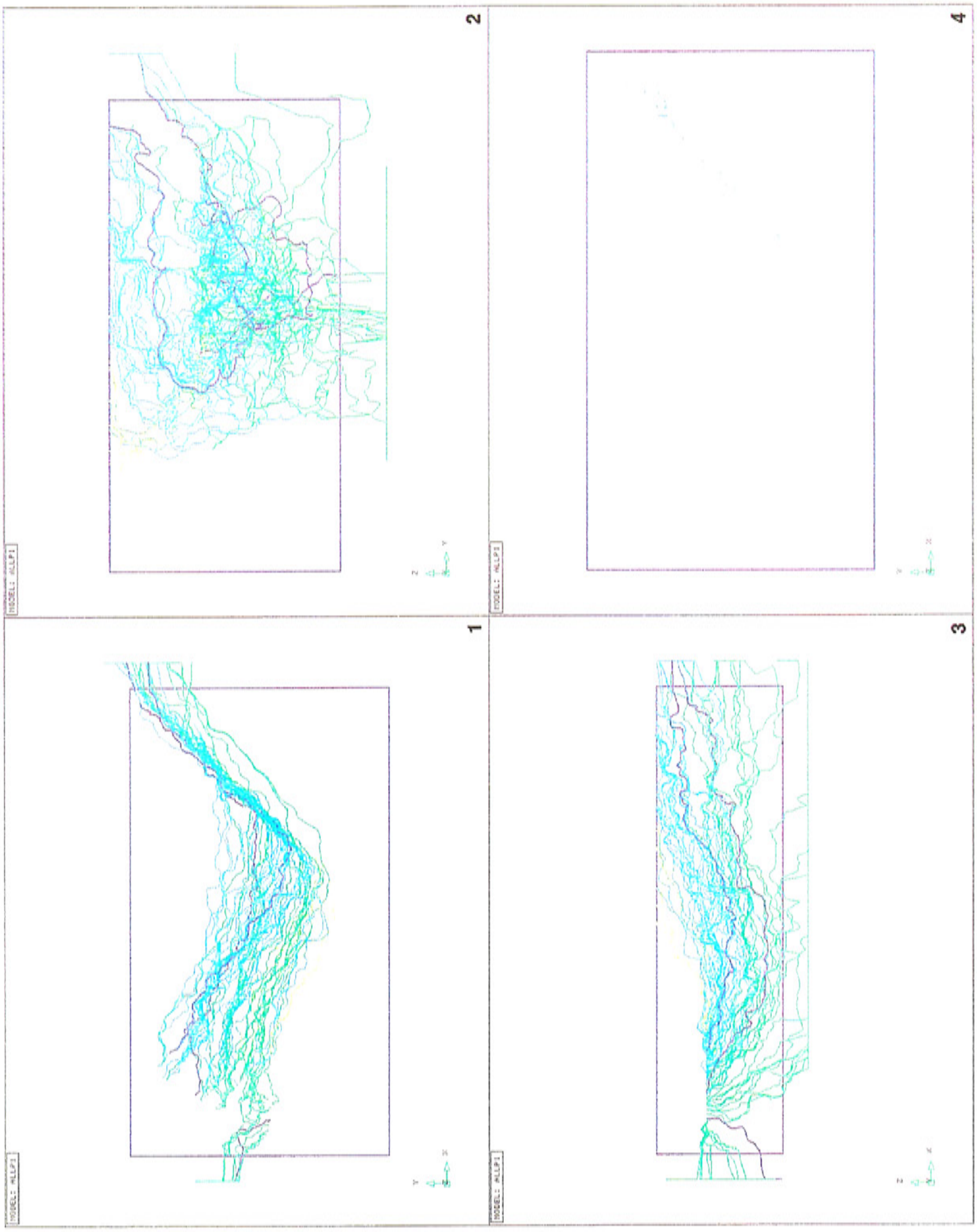
For the reference case, a Monte Carlo simulation with 500 realizations has been carried out of the flow field and of the groundwater travel times from 88 different positions in the repository, each position corresponding to a segment of the repository with its own stream tube in the manner described in Chapter 8. The starting positions for the particle tracks are uniformly distributed over the repository with two positions located in each deposition drift, see Figure 8-4.

The placement of the repository in the area is shown in the fold-out figure at the back of the report. The outer polygon constitutes the boundary of the block for the NAMMU model used to generate boundary conditions for the area for the inner HYDRASTAR model. The model blocks are 1,500 m deep.

Projections of pathlines from a typical realization are presented in Figure 9-6. Pathlines from a realization with unusually short times are presented in Figure 9-7. Both realizations show the same pattern with clearly converging flow in toward the Imundbo zone, where the majority of the pathlines reach the surface. The realization with unusually short times shows a tendency to more upward-directed flow than the typical realization. Otherwise they show the same large-scale pattern.

Figures 9-8 and 9-9 show histograms for the compiled statistical material for groundwater travel times and for fluxes at the canisters over all realizations.

Groundwater travel times over 10,000 years have been assumed to be 10,000 years, which does not affect the conclusions, see Figure 9-2. Figure 9-8 shows that a substantial portion of the travel times are 10,000 years or more. But there is also a clearly discernible peak at shorter times, centred around 100 years. This suggests the existence of several delimited discharge areas: one in the flat-lying area intersected by the Imundbo zone and one or more downstream at greater distances. The pathlines also indicate this, as well as a discharge area to the west for a very small portion of the repository.



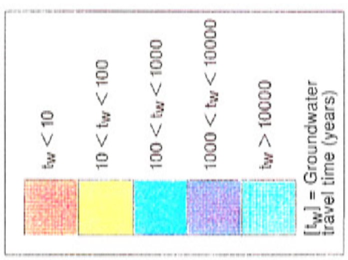




***Figure 9-6.*** *Pathlines from the repository for a typical realization of the reference case's flow field. The views are 1) from above, 2) from the northeastern short side of the HYDRASTAR block, and 3) from the southeastern long side of the block, see the fold-out figure at the end of the report. 4) is a view from above that shows where the pathlines reach the surface.*

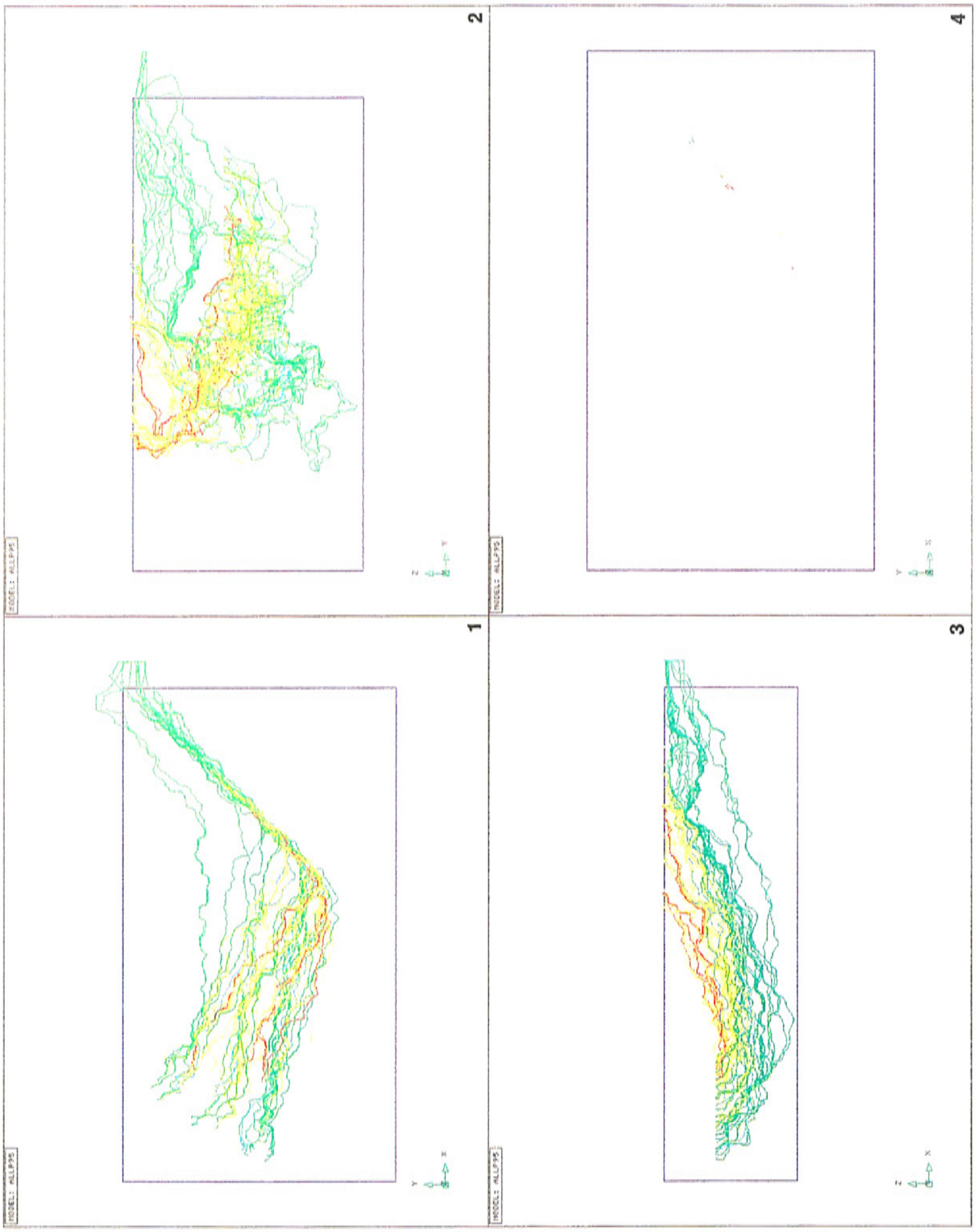
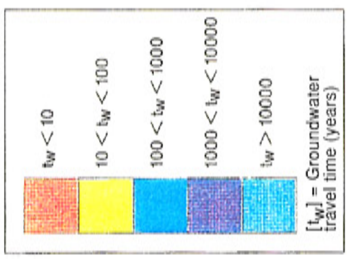



*Figure 9-7. Pathlines from the repository for a realization of the reference caseś flow field with unusually short groundwater travel times. The views and the colours are the same as in Figure 9-6.*



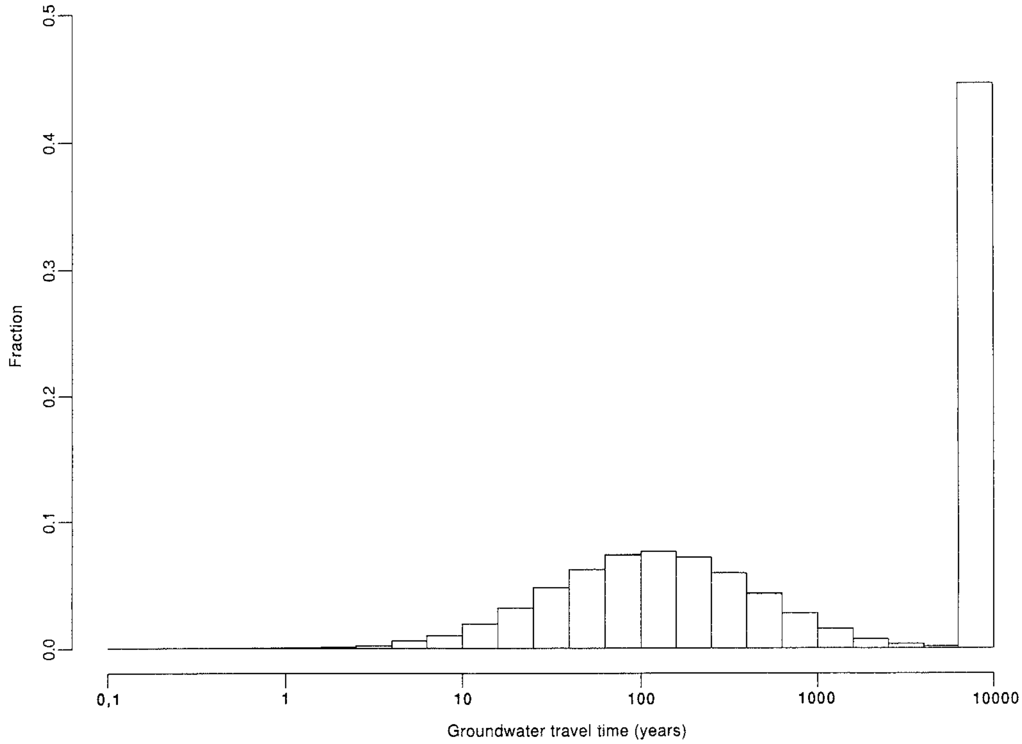



***Figure 9-8.*** *Histogram of all groundwater travel times for water from the repository to the surface from all realizations of the reference case.*

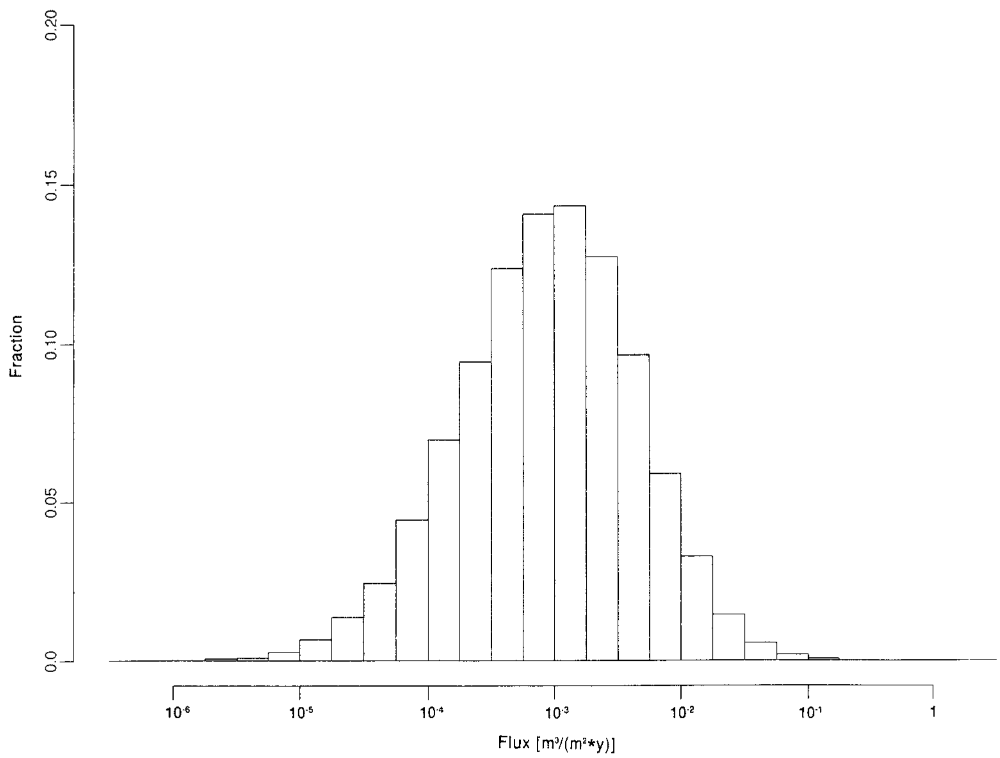



***Figure 9-9.*** *Histogram of the Darcy flux at repository level from all realizations of the reference case.*

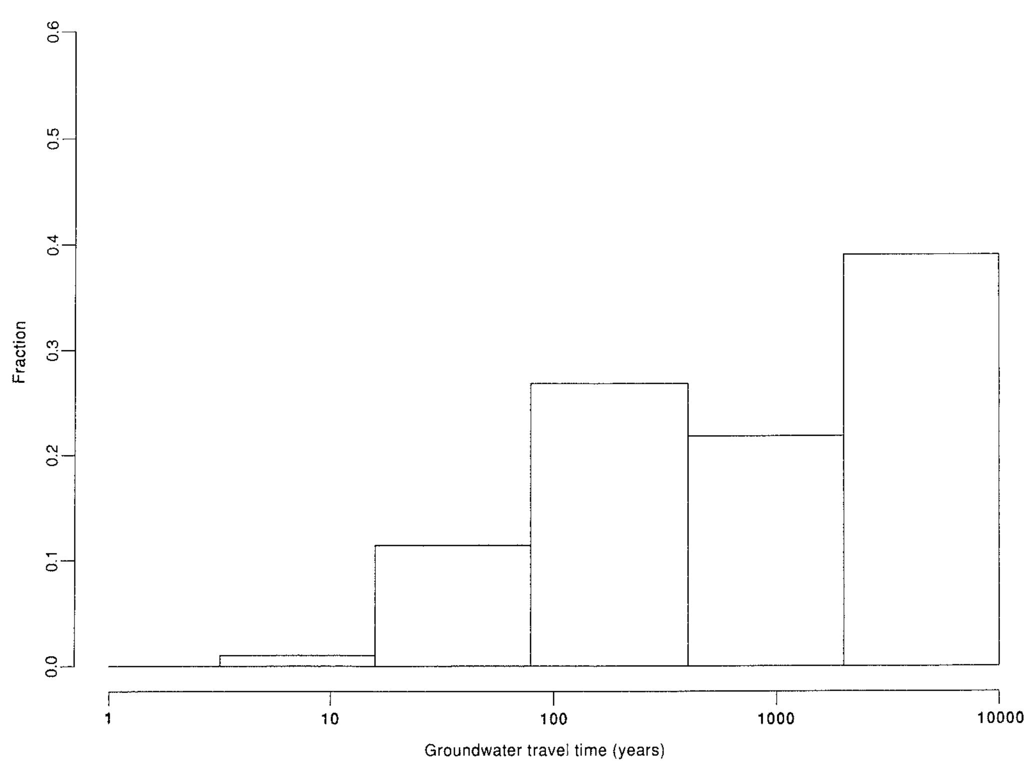



***Figure 9-10.*** *Histogram of the median of the travel time for water from the repository in each realization.*

The histograms contain all groundwater travel times and all flows from all 500 realizations. They do not show how much of the total variability derives from the spread between different realizations, and how much can be attributed to the spread within a realization. A statistically more stringent representation is presented in Figures 9-10 and 9-11. These graphs show the spread between the realizations for different quantiles with respect to travel times (median and 5 percentile) for each individual realization.

Figure 9-12 shows the statistics for the groundwater travel time for each of the 88 pathlines separately. It also shows that the travel time is very heavily dependent on the position in the repository. Only certain corners of the repository give short groundwater travel times. The three separate main parts of the repository can clearly be seen in the graph, see Figure 9-13.

For the continued analysis, the compiled statistics, represented in Figures 9-8 and 9-9, are used for comparisons between the reference case and the variations performed to shed light on the importance of the site characteristics. To further facilitate these comparisons, the histograms have also been converted to a "floating" form, see Figures 9-14 and 9-15.

Each point on the curve in the graph represents on the y axis the fraction of the total number of values that falls within a factor of 4 around the value on the x axis (from a factor of 1/2 below to a factor of 2 above). The focus will, as mentioned, be on comparisons between the travel time distributions.

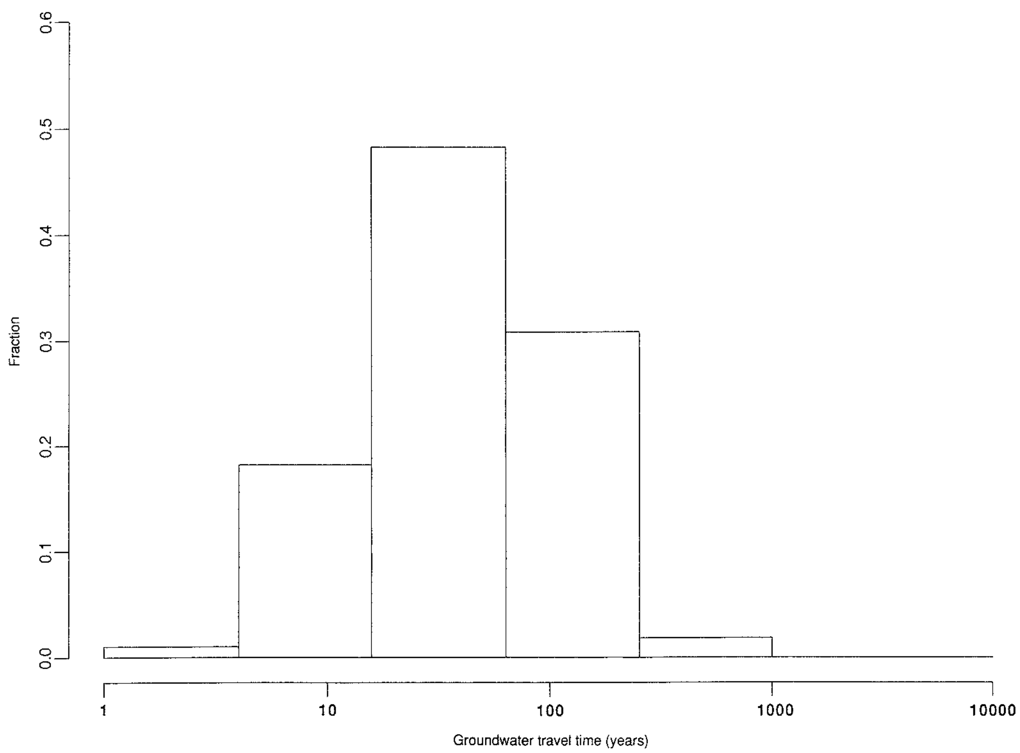



*Figure 9-11. Histogram of the lower 5 percentile of the travel time for water from the repository in each realization.*

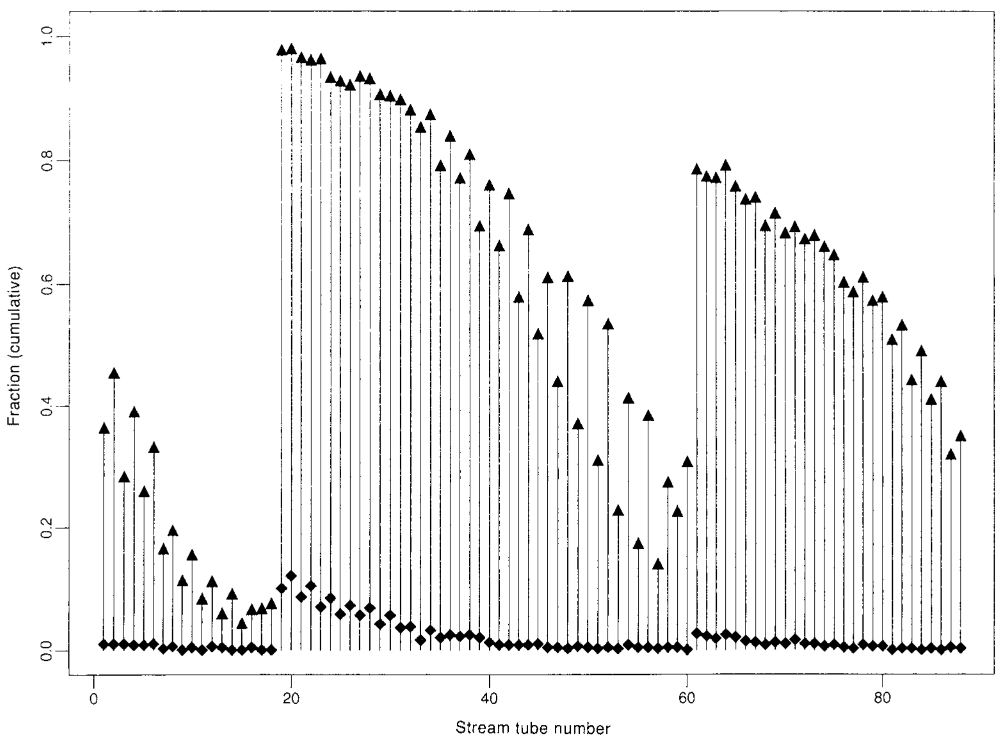



*Figure 9-12. Statistics on groundwater travel time from the different starting positions for pathlines in the repository. The triangles indicate the fraction of times shorter than 10,000 years. The diamonds indicate the fraction of times shorter than 10 years.*

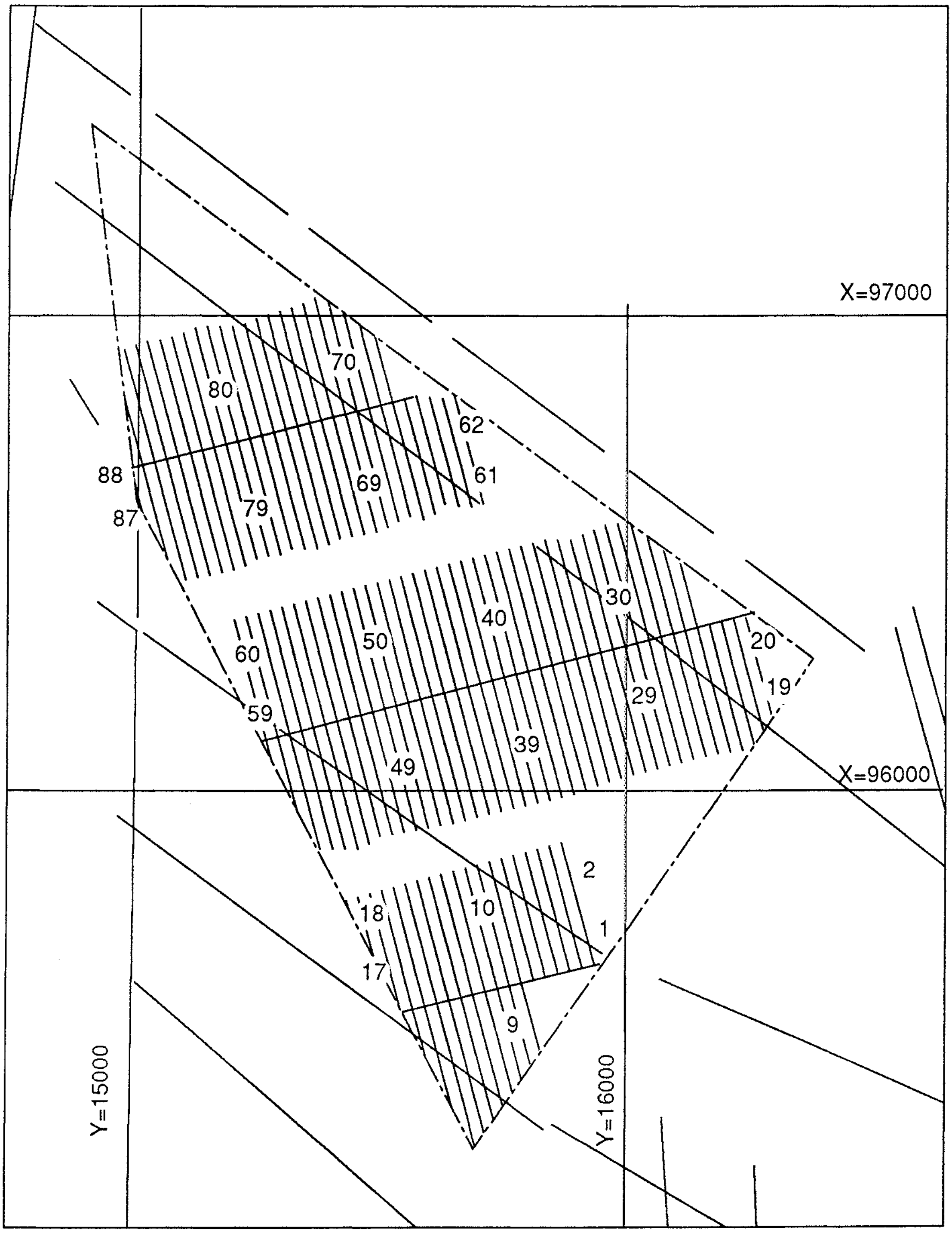



***Figure 9-13.*** *Repository layout for the reference case. The coordinates are RAK coordinates.*

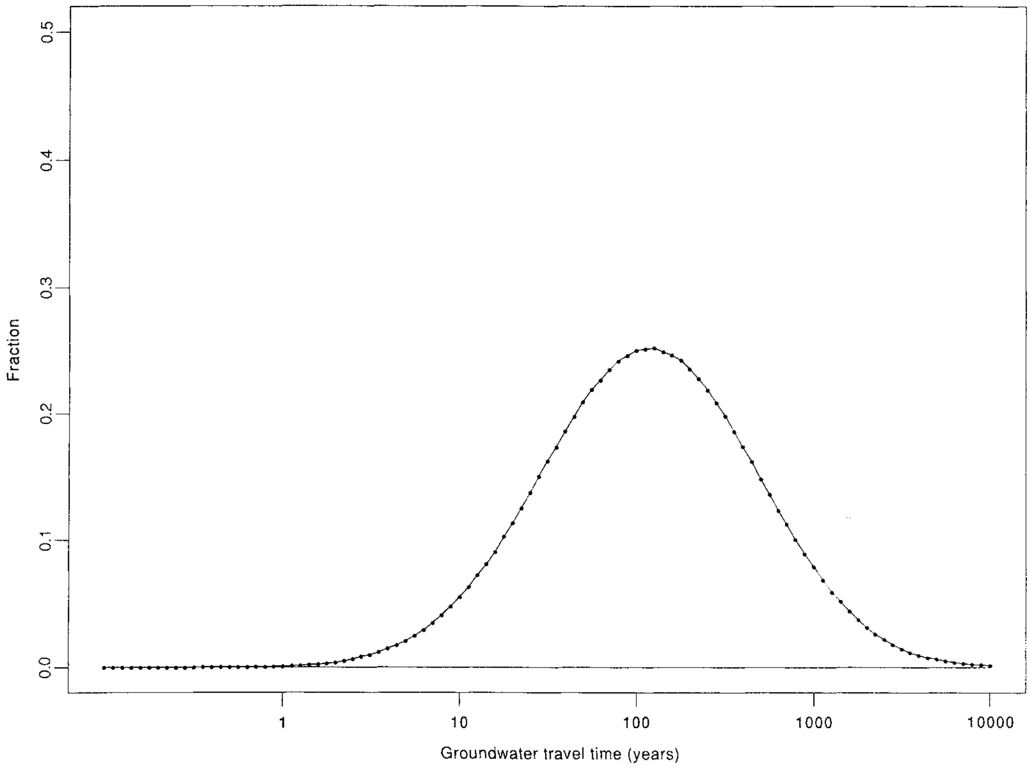



***Figure 9-14.*** *Floating histogram of all travel times for water to the surface shorter than 10,000 years from all realizations of the reference case. Each point on the curve represents on the y axis the fraction of the total number of times that fall within a factor of 4 around the value on the x axis (from a factor of 1/2 below to a factor of 2 above).*

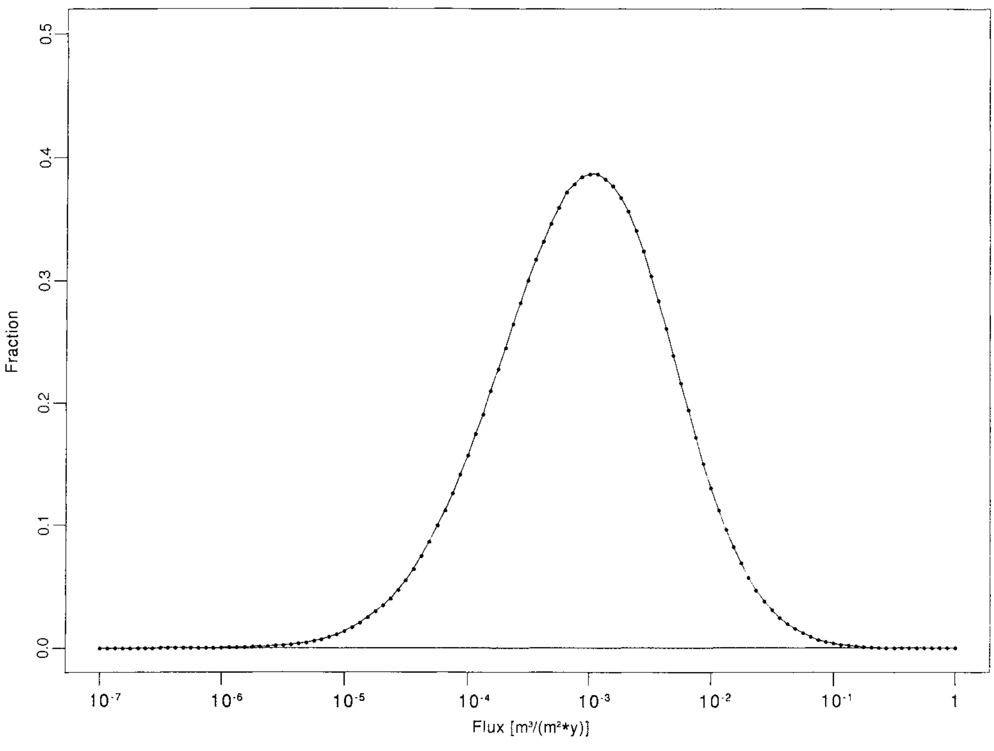



***Figure 9-15.*** *Floating histogram of all Darcy fluxes at repository level from all realizations of the reference case. Each point on the curve represents on the y axis the fraction of the total number of values that fall within a factor of 4 around the value on the x axis (from a factor of 1/2 below to a factor of 2 above).*

The linear correlation between the groundwater travel time and the flux at the starting position is weak: the correlation coefficient is around -0.3 for the logarithmed values.

The compiled statistics for the reference case's geohydrological calculations are presented in /9-14/. Conductivity fields, flow fields etc. are presented and discussed in /9-15/.

## 9.5 TRANSPORT AND DOSE CALCULATIONS FOR THE REFERENCE CASE

The five hundred realizations reported above have also included calculation of the radionuclide transport in the near field, the far field and the biosphere in the manner described in Chapter 8.

Figure 9-16 shows a histogram for maximum annual dose commitment for an individual in the critical group up to 10,000 years from closure of the repository.

Figures 9-17 and 9-18 present total dose and dose from dominant nuclides as a function of time for two realizations. One constitutes the median and the other the 95 percentile in the distribution for the maximum dose up to 10,000 years. The curves also show the dose for longer times.

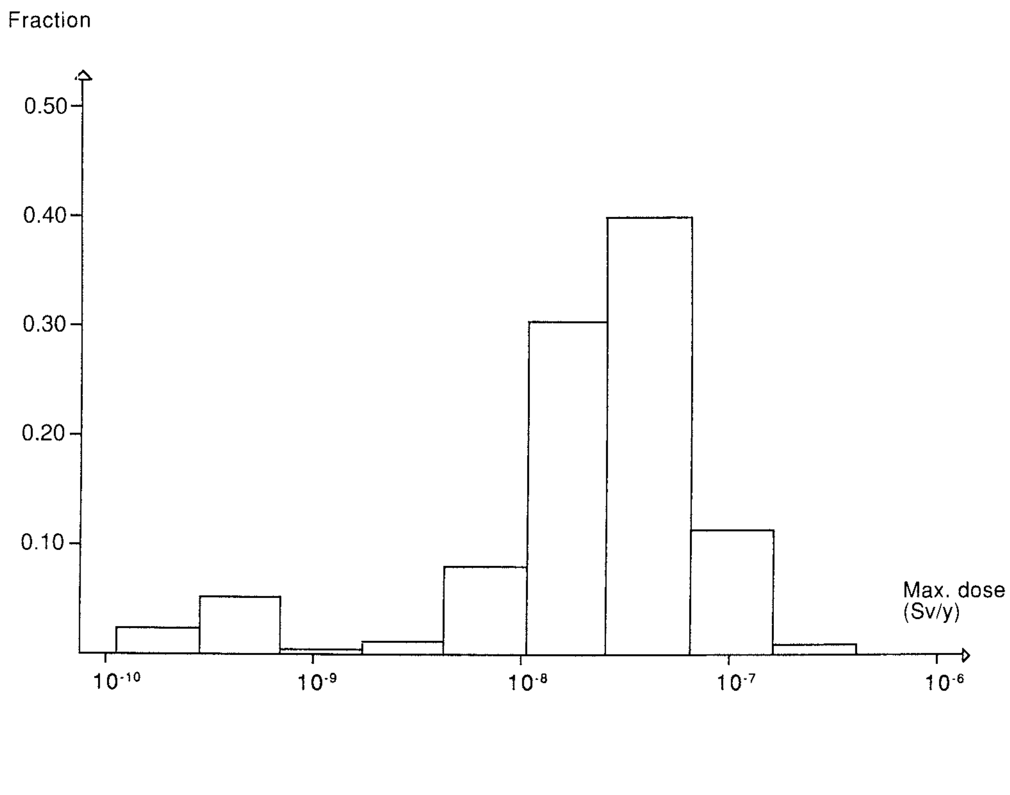



***Figure 9-16.*** *Histogram for maximum dose up to 10,000 years in the reference case.*

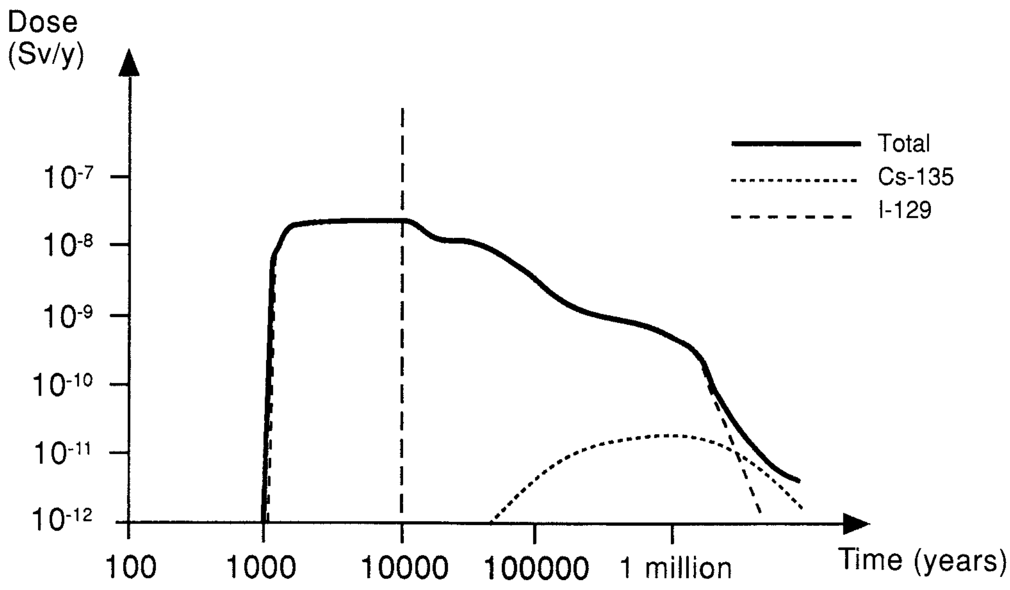



*Figure 9-17.* *Dose as a function of time for the realization that corresponds to the median on the distribution for the maximum dose up to 10,000 years in the reference case.*

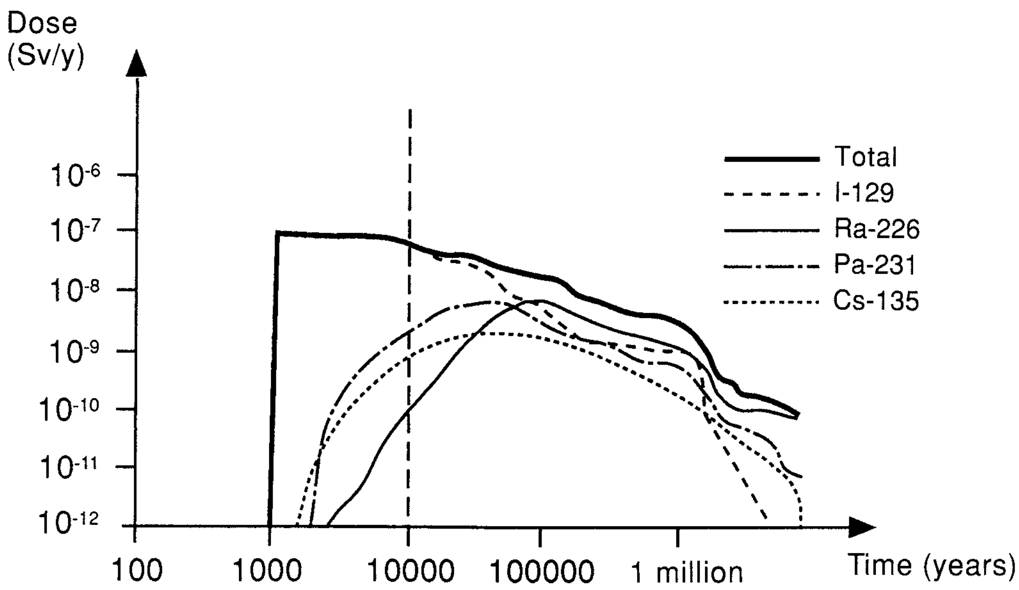



*Figure 9-18.* *Dose as a function of time for the realization that corresponds to the 95 percentile on the distribution for the maximum dose up to 10,000 years in the reference case.*

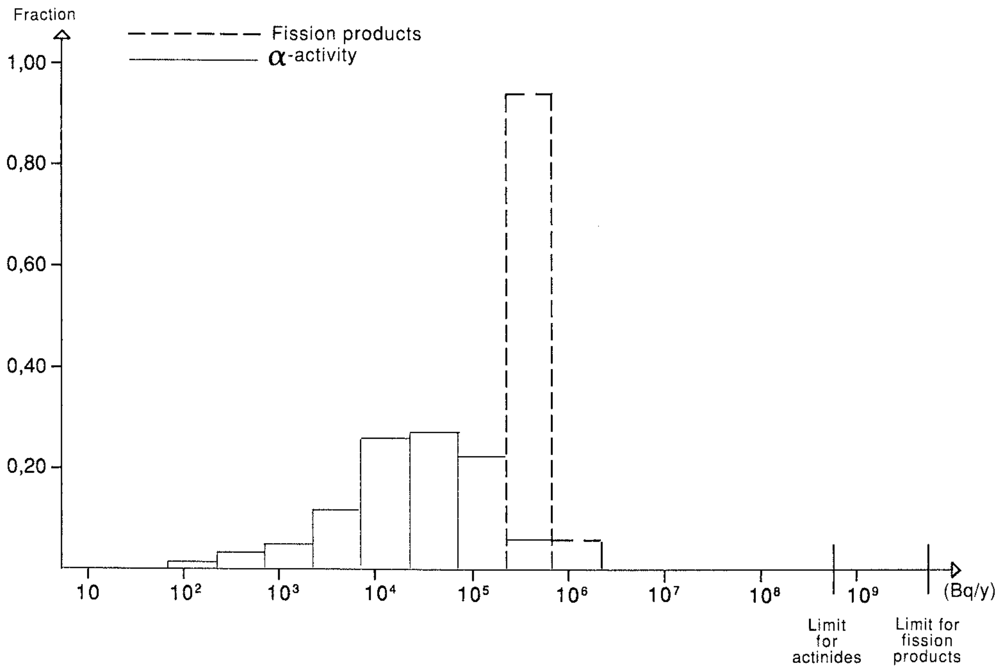



***Figure 9-19.*** *Histogram for maximum release over all times in the reference case. The indicated limits are those referred to in section 2.4.2.*

A histogram for maximum releases of long-lived fission products and α-emitters in Bq/y to the biosphere over all times is shown in Figure 9-19. The narrow histogram for the fission products is caused by the fact that the release is dominated by I-129, which is affected very little by the conditions in the rock. The quantity of natural uranium originally used to produce the fuel in the repository is approximately 50,000 tonnes. The greatest release values correspond to around 60 Bq/y and tonne of natural uranium, to be compared with the $10^5$ for fission products and $10^4$ for actinides that are given as limits in the proposal for guidelines /9-7/ and Principle 4 in section 2.4.2. Time curves for the releases corresponding to the median and the 95 percentile on the distributions are presented in Figures 9-20 and 9-21.

To shed light on the importance of uncertainties in the modelling of the radionuclide transport in the near field and the far field, calculations have also been performed for a number of cases in which certain input data have been changed compared with the reference case. These cases have entailed that the following factors have been changed and parameters have been given the following pessimistic extreme values:

- the redox front in the near field with Eh = +650 mV (air-saturated conditions) in the oxidizing layer close to the canisters (increased solubility for some nuclides, reduced solubility for others) /9-8/;
- the specific surface area available for matrix diffusion = 0.01 $m^2/m^3$ of rock (reduced matrix diffusion capacity) /9-9/;
- Peclet number = 0.2 (increased dispersion) /9-9/.

The factors have been changed one at a time separately. Figure 9-22 shows the variation of the maximum dose with the groundwater travel time for a single initially defective canister for the original data. The contribution from Cs-135 derives primarily from the content in the fuel-to-clad gap.

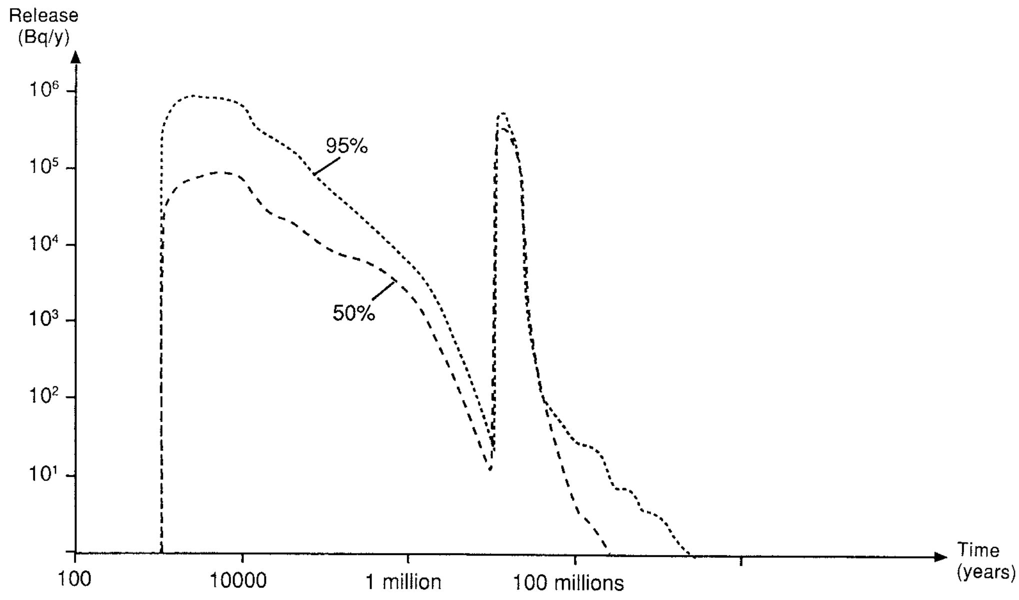



***Figure 9-20.*** *The release of fission products as a function of time for the realizations corresponding to the 50 and 95 percentiles on the distribution for maximum release over all times in the reference case.*

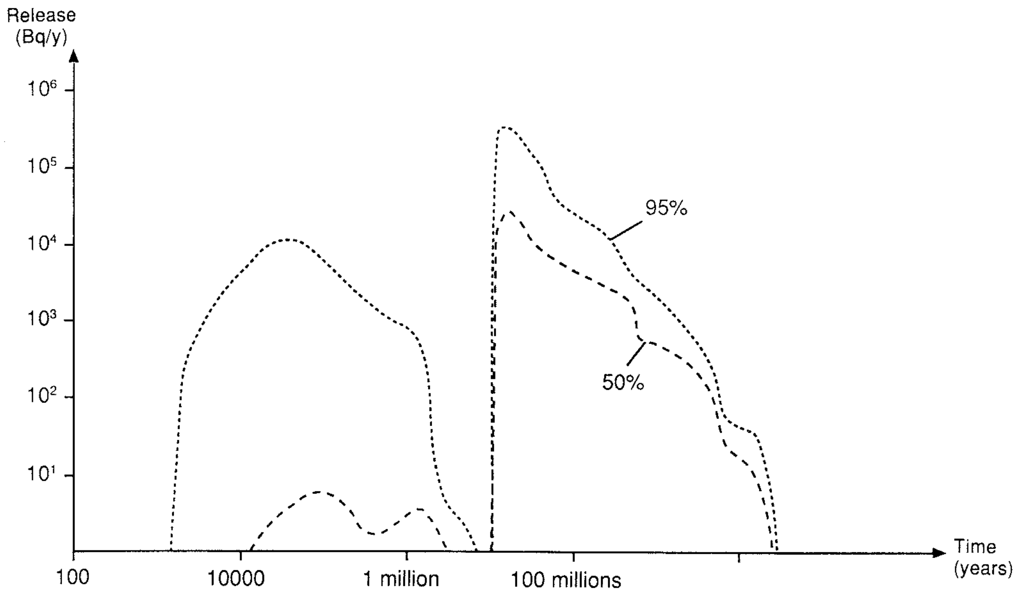



***Figure 9-21.*** *The release of α-emitters as a function of time for the realizations corresponding to the 50 and 95 percentiles on the distribution for maximum release over all times in the reference case.*

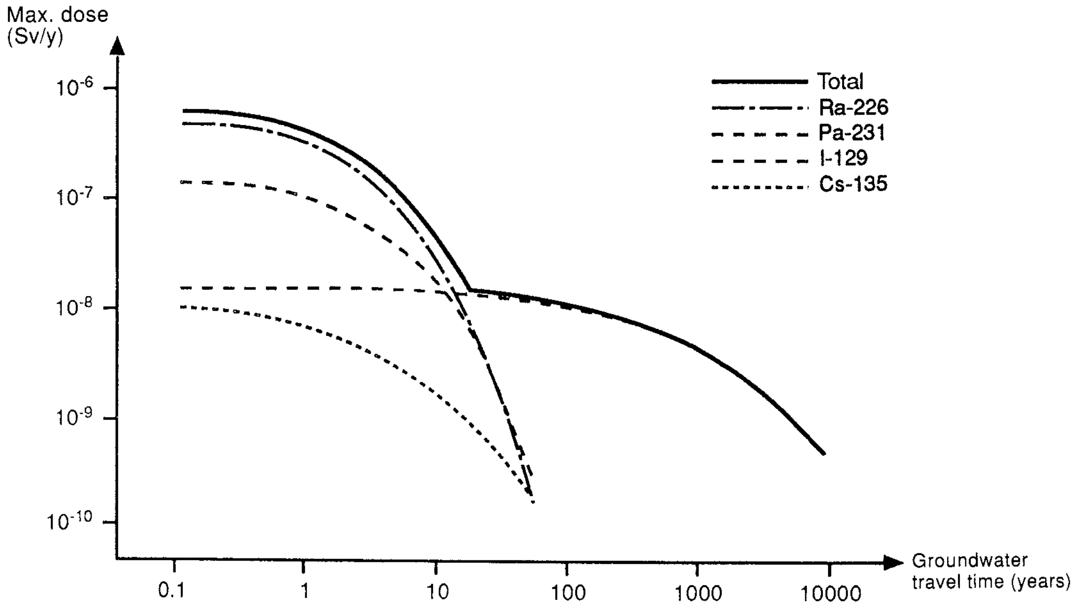



***Figure 9-22.*** *Maximum dose up to one million years from an initially defective canister as a function of the travel time for water to the surface, total and broken down for the dominant nuclides.*

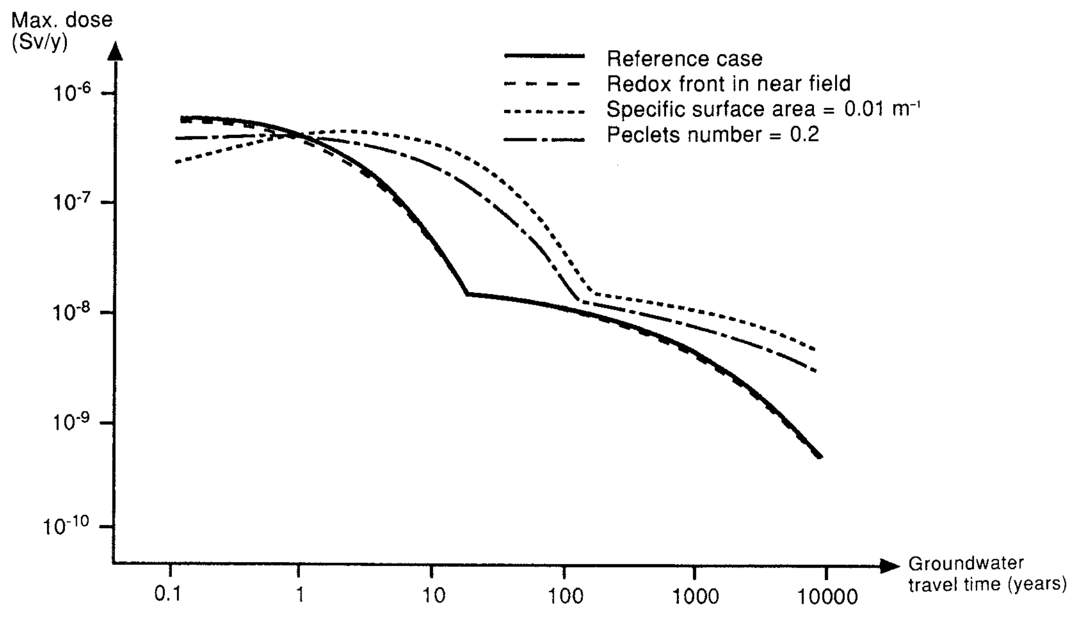



***Figure 9-23.*** *Maximum dose up to one million years from an initially defective canister as a function of the travel time for water to the surface for varied transport parameters.*

The total curves for the reference case and the variants are given in Figure 9-23. Changed redox conditions do not change the result much; none of the redox-sensitive radioelements break through. The reduced specific surface area and the increased dispersion both entail that some radionuclides do not have time to decay at groundwater travel times that were sufficient to allow virtually complete decay to take place with the original premises. This is particularly true of Ra-226 and Pa-231. The difference is small, however.

## 9.6 VARIATIONS

### 9.6.1 Description of the variations

For reasons of presentation, the variations have been compiled under a small number of headings, see section 9.6.2 – 9.6.6, to shed light on different main aspects of the properties of the repository site and the placement of the repository. A complete list of all variations is presented below with the designation (in bold face) that is then used throughout in the evaluation that follows. 50 realizations with HYDRASTAR have been done for each variation. This has yielded sufficient statistical convergence for reporting groundwater travel times and fluxes. In cases where the conductivity picture has been changed, new boundary conditions have been generated with NAMMU. The variations are reported in detail in a series of work reports where each case is defined and the results are presented and discussed. Results are reported in the form of comprehensive statistics on fluxes at repository level and groundwater travel times and in the form of pathlines, conductivity fields and head fields. Only NAMMU has been used in the evaluation of altered gradients /9-10/ in order to permit calculations on the 10 km scale. The variations are as follows:

**Depth 500 m**

Repository shifted 100 m upwards from its original position. No exclusion zone to Zone 2.

**Depth 700 m**

Repository shifted 100 m downwards from its original position. 200 m exclusion zone to Zone 2.

**No exclusion zone**

Repository shifted 100 m towards Zone 4 and 100 m towards Zone 1 so that it occupies a position immediately adjacent to these zones.

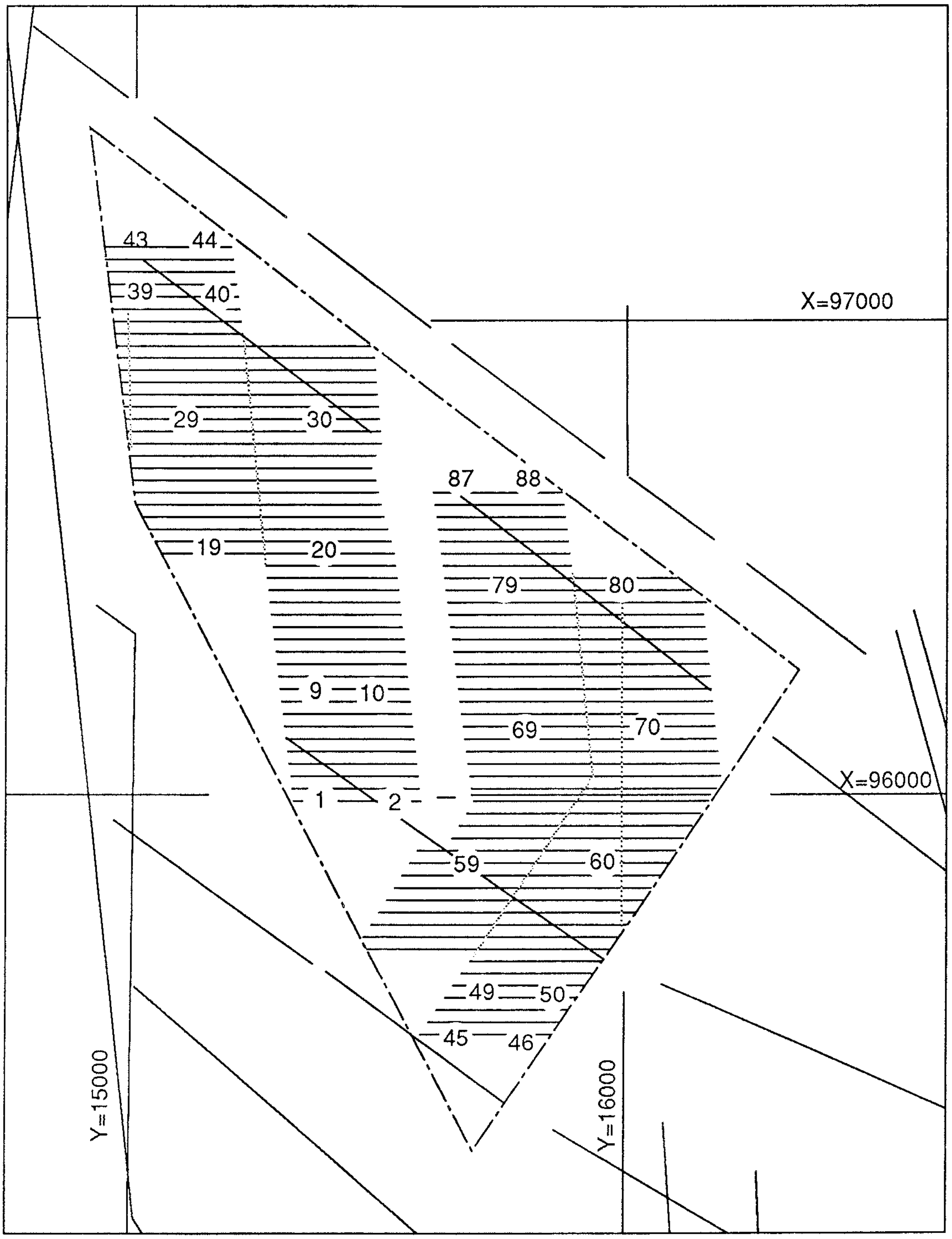



***Figure 9-24.*** *Repository layout with deposition drifts parallel to the hydraulic gradient. The coordinates are RAK coordinates.*

### Deposition drifts along the gradient

Changed repository layout as per Figure 9-24. The deposition drifts, and thereby the disturbed zones, are parallel to the large-scale gradient. 88 segments and particles are distributed over the repository according to the same principle as for the reference layout.

### Increased conductivity in steeply dipping zones

The hydraulic conductivity in the steeply dipping zones has been increased so that the conductivity contrasts in relation to the rock mass (the ratio between the conductivities) has been increased by a factor of two (2) compared with the contrasts in the reference case. The new contrasts correspond roughly to those given by the interpretations in /9-11/. This has been achieved by imposing changed trends on the stochastic model. Figure 9-25 shows the conductivity field in a horizontal section for a typical realization.

### Reduced conductivity in the rock mass

The conductivity in the rock mass outside the zones has been reduced so that a ten times lower expectation value than in the reference case is obtained at 600 m depth. Figure 9-26 shows the conductivity field in a vertical section for a typical realization.

### No Zone 2

Zone 2 has been removed from the model by manipulating all measured conductivities in Zone 2 so that a reduction of the conductivity to a level similar to that in the rock mass has been obtained via conditioning.

### Deep flat-lying zone

A new flat-lying zone has been added with the same strike and dip as Zone 2, located 600 m below Zone 2, imposed with a new trend with the same depth-dependent conductivity as Zone 2. The width of the exclusion zone from the repository to this new zone is about 100 m.

### No Imundbo zone

The Imundbo zone has been removed by removing the trend introduced in the reference case.

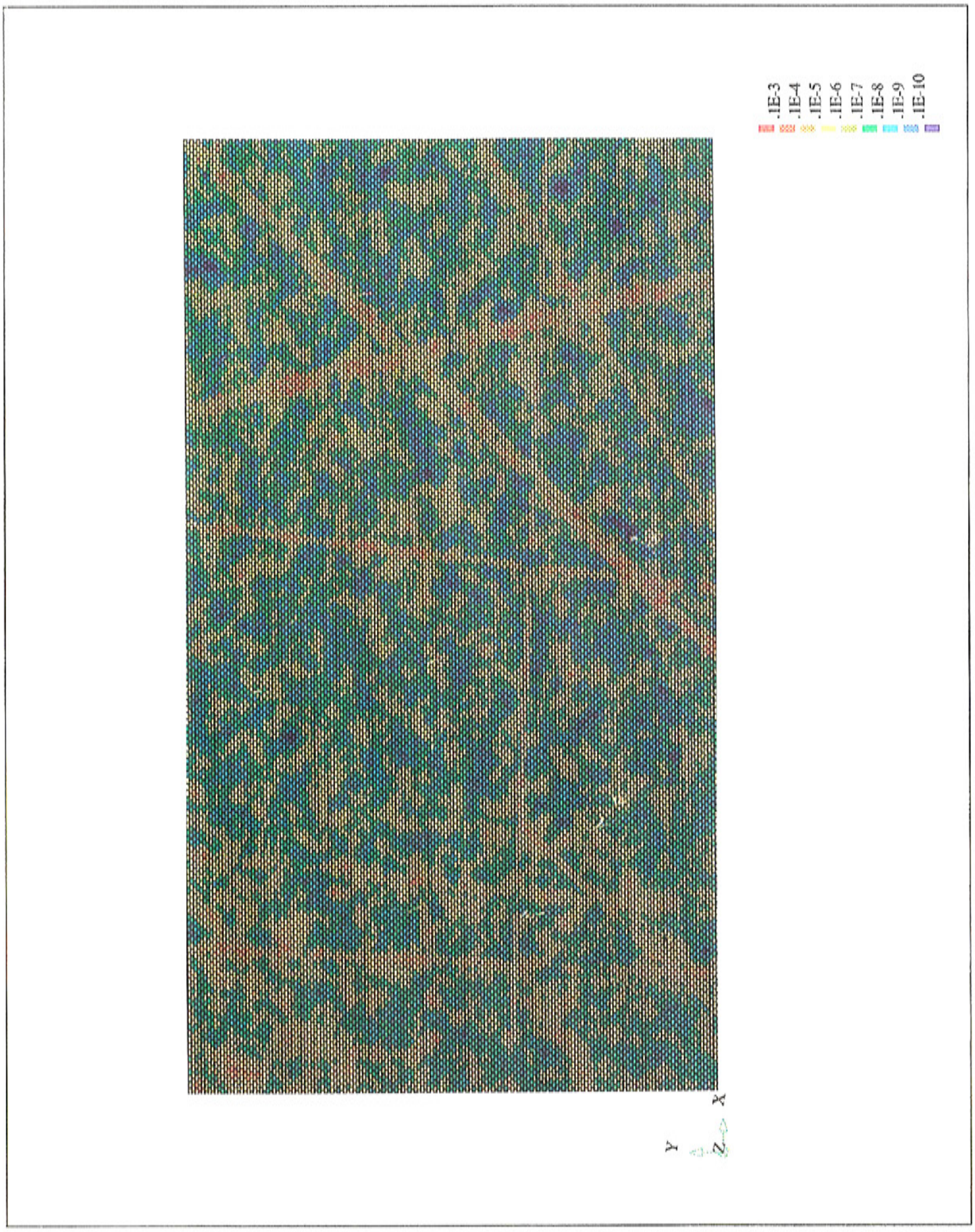



*Figure 9-25. The conductivity field in m/s in a horizontal slice at a depth of 600 m for a typical realization in the case* **Increased conductivity in steeply dipping zones.**

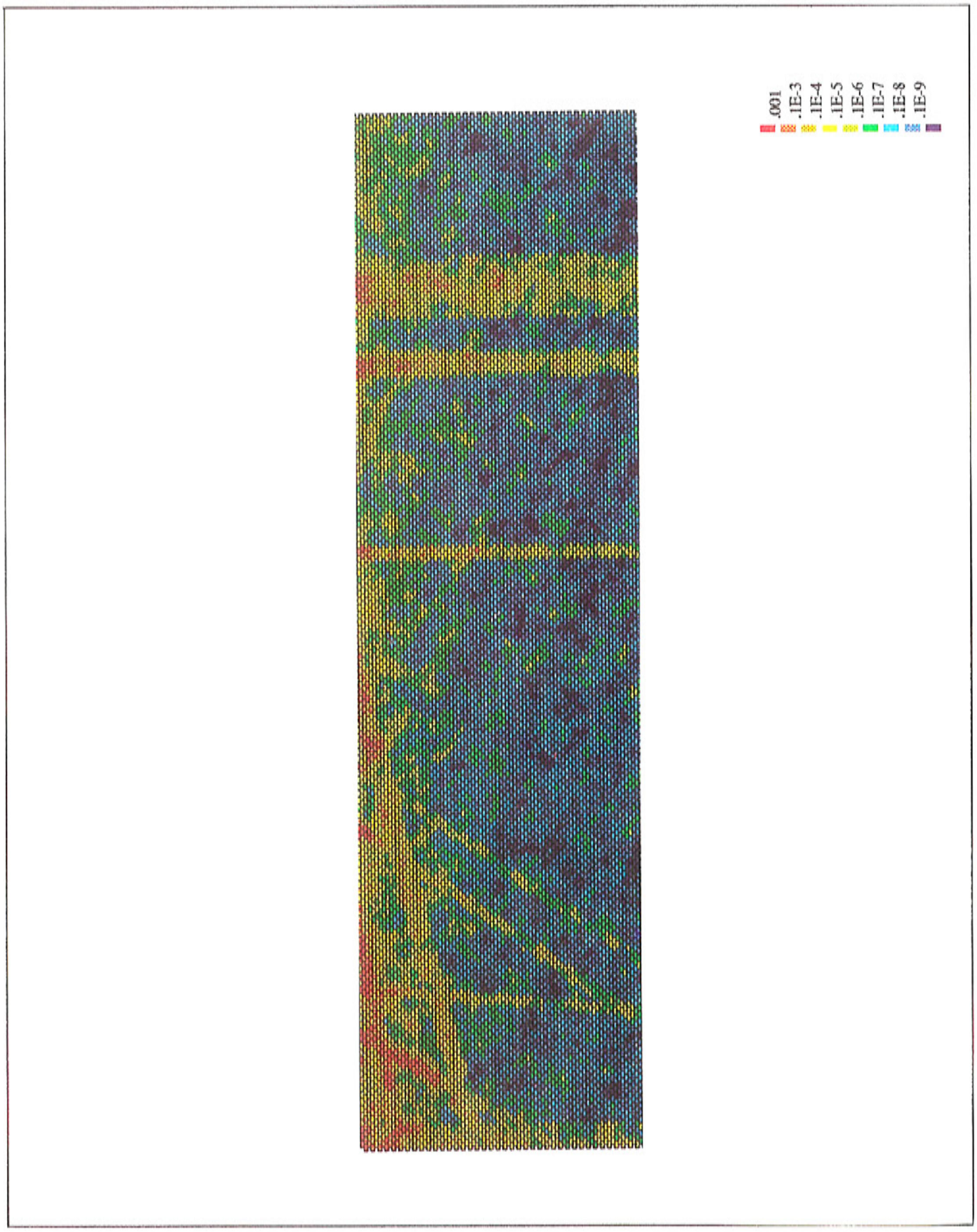



*Figure 9-26. The conductivity field in m/s in a vertical slice along section 4 in Figure 8-5 for a typical realization in the case* **Reduced conductivity in the rock mass.**

**Imundbo zone inclined 45°**

The vertical Imundbo zone in the reference case has been inclined 45° from the intersection with the ground surface and in towards the repository. The smallest distance between the repository and the inclined zone is 800 m compared with 1,750 in the reference case.

**Altered gradient**

has been brought about by manipulating the topography of the Finnsjön area by changing the inclination of the upper surface with imaginary "hinges" along two different lines. One line coincides with line A-B in the fold-out figure at the end of the report, the other with a line through the upper right-hand corner, point A, parallel to the southern part of the Imundbo zone. The inclinations towards A-B are presented in Table 9-1. The inclinations towards the other line are presented in Table 9-2. The regional gradients are the topographical ones in a section from a point in the southern block (D) to points A and F, respectively; the local one is the one along D-E.

**Table 9-1. Gradients (in %) as a result of different inclinations of the upper surface with imaginary "hinges" in the line A-B in the fold-out figure.**

| Case | A-D | A-C | E-F | D-E |
|---|---|---|---|---|
| Original | 0.20 | 0.17 | 0.16 | 0.57 |
| 1 | 0.40 | 0.42 | 0.02 | 0.89 |
| 2 | 0.60 | 0.65 | 0.09 | 1.14 |
| 3 | 0.30 | 0.30 | 0.09 | 0.70 |

**Table 9-2. Gradients (in %) as a result of different inclinations of the upper surface with imaginary "hinges" in a line through point A in the fold-out figure, parallel to the Imundbo zone.**

| Case | A-D | A-C | E-F | D-E |
|---|---|---|---|---|
| Original | 0.20 | 0.17 | 0.16 | 0.57 |
| 4 | 0.82 | 0.59 | 0.64 | 1.53 |
| 5 | -0.10 | -0.10 | -0.06 | -0.16 |
| 6 | 0.04 | 0.04 | 0.14 | 0.35 |

A number of variations have also been performed in which several changes have been combined, all except one by a combination of one or more of the above variations.

- No exclusion zone + Increased conductivity in steeply dipping zones;
- Deposition drifts along the gradient + Increased conductivity in steeply dipping zones;
- No exclusion zone + Deposition drifts along the gradient + Increased conductivity in steeply dipping zones;

– No Zone 2 + Deep flat-lying zone;

– Reduced conductivity in the rock mass + No Zone 4/5.

Table 9-3 summarizes the variations performed and gives the reference to the work report where the statistical results can be found.

**Table 9-3. Summary of variation cases performed.**

| Variation | Discussion in section | Reference |
|---|---|---|
| Depth 500 m | 9.6.6 | SKB AR 92-07 |
| Depth 700 m | 9.6.6 | SKB AR 92-08 |
| No exclusion zone | 9.6.3 + 9.6.6 | SKB AR 92-11 |
| Deposition drifts along the gradient | 9.6.5 + 9.6.6 | SKB AR 92-24 |
| Increased conductivity in steeply dipping zones | 9.6.3 | SKB AR 92-23 |
| Reduced conductivity in the rock mass | 9.6.2 | SKB AR 92-19 |
| No Zone 2 | 9.6.4 | SKB AR 92-20 |
| Deep flat-lying zone | 9.6.4 | SKB AR 92-16 |
| No Imundbo zone | 9.6.3 | SKB AR 92-17 |
| Imundbo zone inclined $45^{o}$ | 9.6.3 + 9.6.6 | SKB AR 92-18 |
| Altered gradient | 9.6.5 | SKB TR 92-11 |
| Reduced conductivity in the rock mass + No Zone 4/5 | 9.6.2 | SKB AR 92-14 |
| No exclusion zone + Increased conductivity in steeply dipping zones | 9.6.3 + 9.6.6 | SKB AR 92-12 |
| Deposition drifts along the gradient + Increased conductivity in steeply dipping zones | 9.6.3 + 9.6.5 | SKB AR 92-13 |
| No exclusion zone + Deposition drifts along the gradient + Increased conductivity in steeply dipping zones | 9.6.3 + 9.6.5 + 9.6.6 | SKB AR 92-22 |
| No Zone 2 + Deep flat-lying zone | 9.6.4 | SKB AR 92-21 |

### 9.6.2 Properties of the rock mass in the repository area

An increased contrast between the rock mass and all zones as a result of reduced conductivity in the rock mass results in the discharge area being moved to the steep zone Giboda South, see Figure 9-27. The flow lines are drawn there via Zone 4 and Zone 5 (Zone 5 intersects the repository). Despite the fact that the flow at repository level declines by a power of ten, the groundwater travel times are not increased. Moreover, the tails of the distributions are extended towards short times and higher flows (canisters in or near Zone 4 and Zone 5), see Figures 9-28 and 9-29. Figures 9-29 and 9-30 show that the presence of Zone 4 and Zone 5 is required for the radical change in the flow pattern to occur.

The parts of the repository that are located in zones with considerably higher conductivity than the rock mass will have short groundwater travel times, since the flow is strongly allocated to these zones. Low rock mass conductivity in an area is of limited benefit unless it is simultaneously possible to avoid water-conducting structures than could take the flow directly up to the surface.

### 9.6.3 Influence of steeply dipping fracture zones

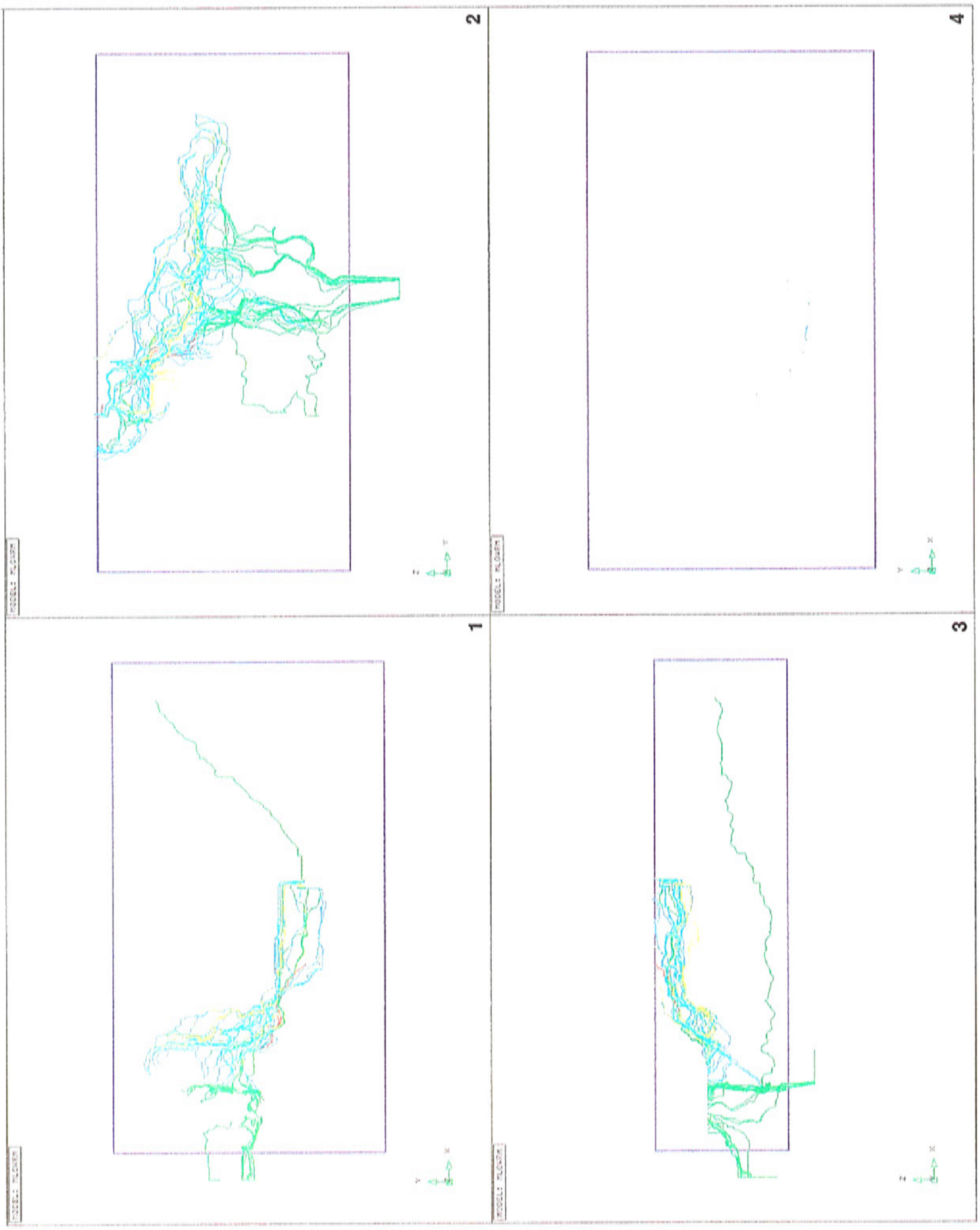
Figure 9-31 shows that the exclusion zone as such is meaningless as long as Zone 1 and Zone 4 are far from the discharge area corresponding to the repository. However, a larger portion of the repository's surface area ends up in the recharge area corresponding to the flat discharge area intersected by the Imundbo zone when the repository is moved eastward, thereof the larger fraction of pathlines that reach the ground surface before 1,000 years.

Nor does increased conductivity in the steeply dipping zones have any appreciable influence on the groundwater travel times. The increased conductivity in the Imundbo zone is not sufficient to shorten the groundwater travel times in general. A small increase in the fraction of short times can be discerned, however, caused by a tendency of the pathlines to find their way up in Giboda South and by an increased probability of some fast pathway up via Zone 4. Typical pathlines can be seen in Figure 9-32.

Nor does the combination of increased conductivity in the steeply dipping zones and reduced exclusion zone have any appreciable influence on the groundwater travel times. Not even combined with the alternative repository layout that places the disturbed zone along the gradient do they cause any fundamental change in the travel time picture, see Figure 9-31.

The flat-lying area that is intersected by the Imundbo zone serves as the first discharge area for the repository, regardless of whether the zone is there or not, see Figure 9-33. There is a tendency for the Imundbo zone to reduce the head at depth so that the flow is less upward-directed from the repository. When the Imundbo zone is included in the model, this leads to a slightly smaller fraction of pathlines reaching the discharge area during the first 10,000 years, see Figure 9-34. When the zone is inclined $45^{0}$ from the surface in toward the repository, the effect is further strengthened somewhat, see Figures 9-34 and 9-35.

In order for the steeply dipping zones in Finnsjön to have any appreciable influence on the flow and travel time picture, a higher contrast against the rock mass must be combined with the influence of a flat-lying structure, see section 9.6.2 and Figure 9-27, 9-28 and 9-30.



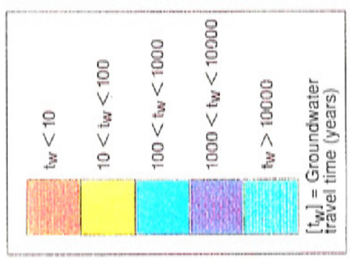




*Figure 9-27. Pathlines for a typical realization in the case* **Reduced conductivity in the rock mass.** *Views same as in Figure 9-6.*

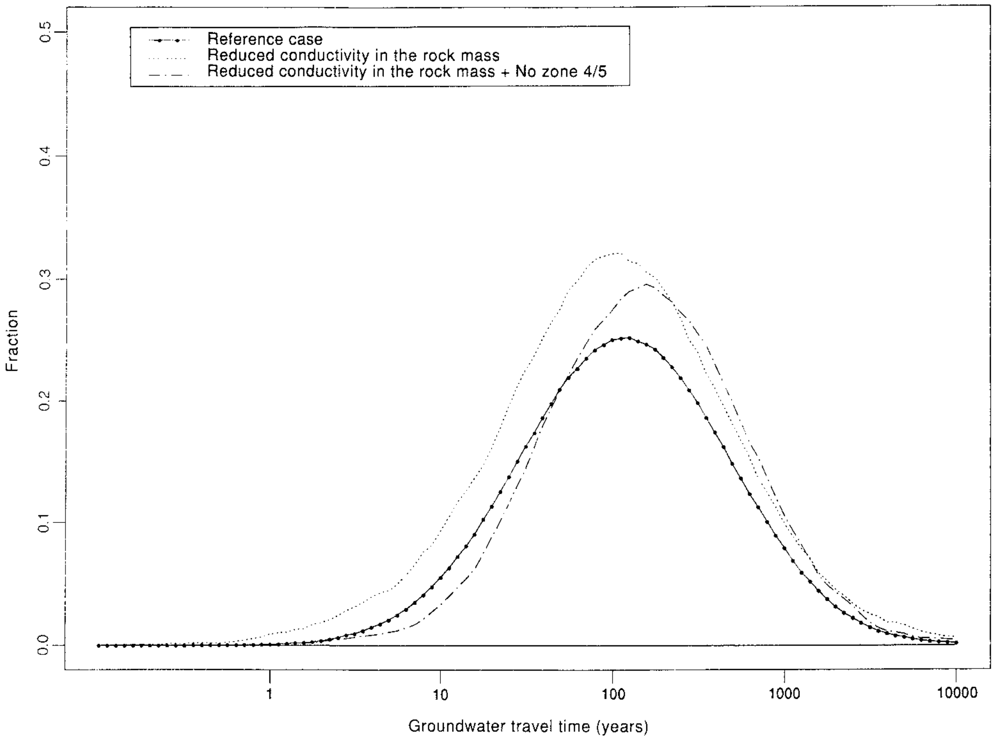



*Figure 9-28. Floating histogram of travel times for water from the repository to the surface for a number of variations.*

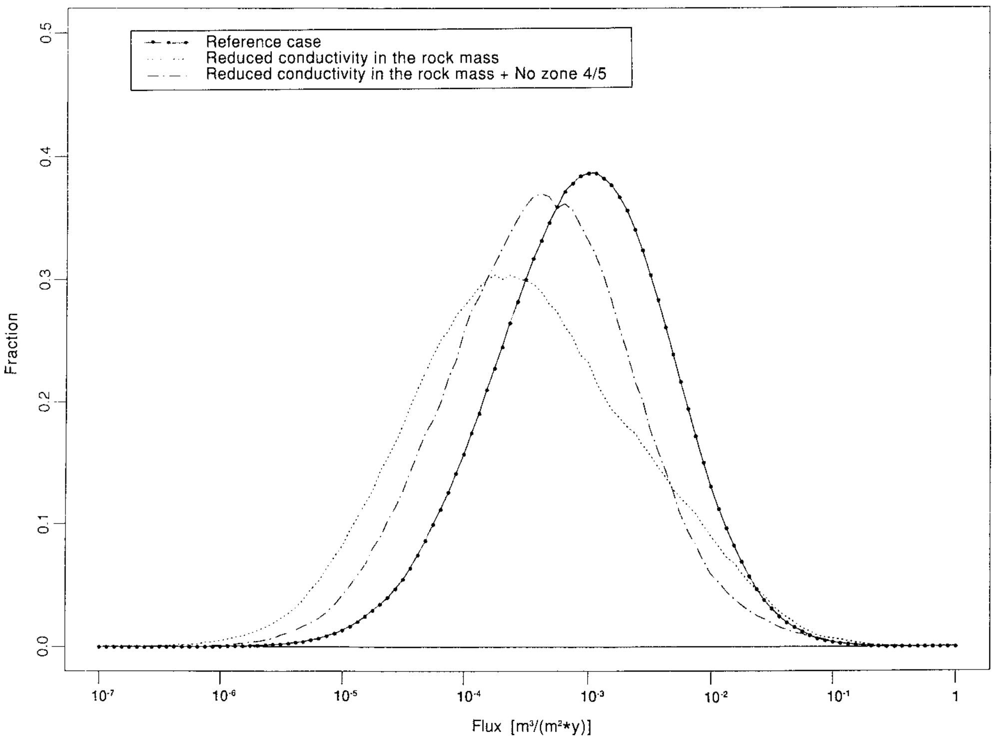
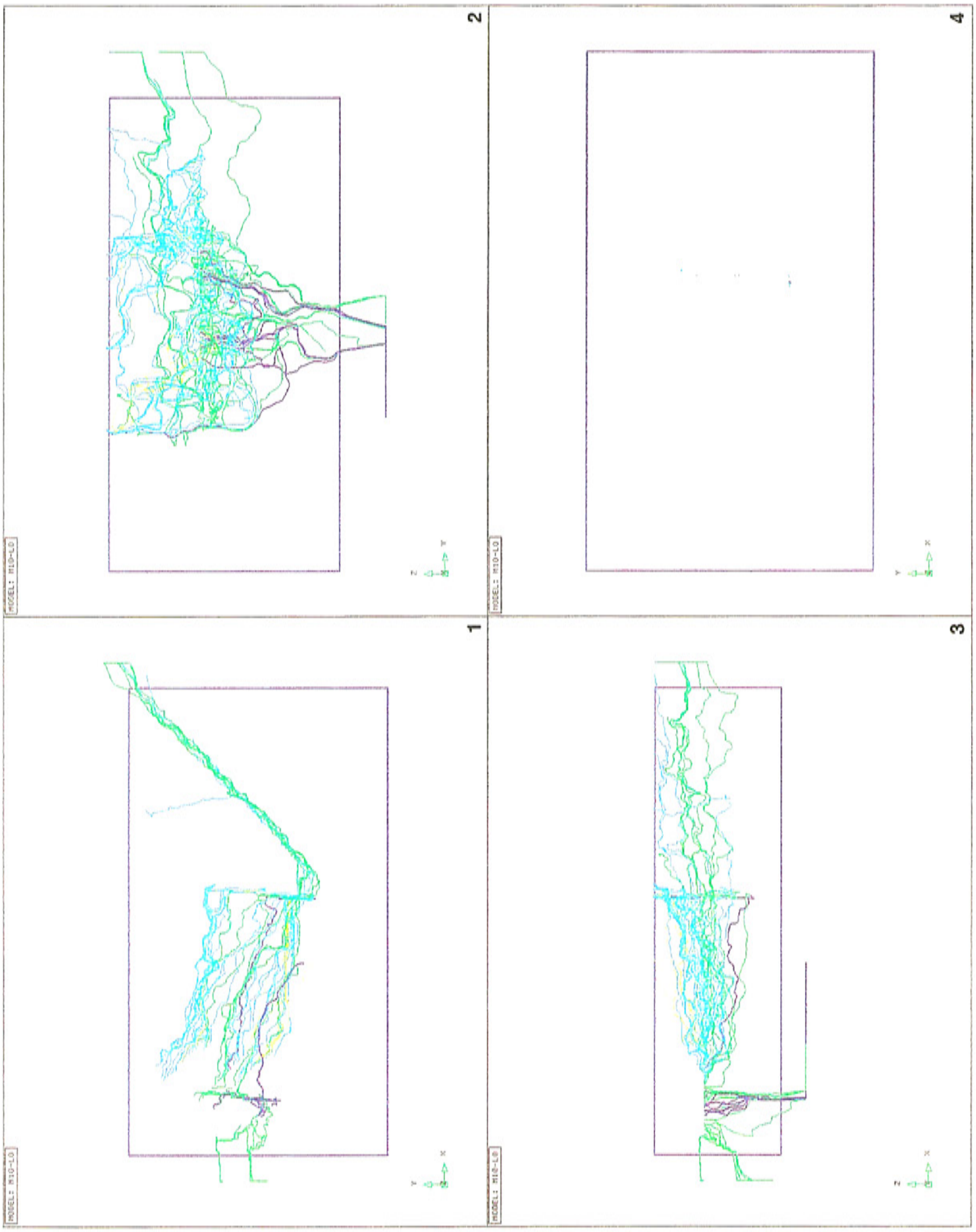



*Figure 9-29. Floating histogram of Darcy fluxes at repository level for a number of variations.*



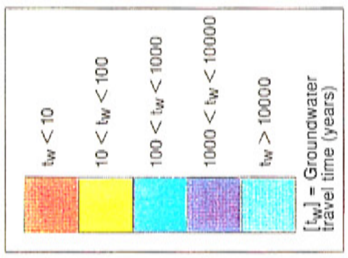




***Figure 9-30.*** *Pathlines for a typical realization in the case* **Reduced conductivity in the rock mass + No Zone 4/5**. *Views same as in Figure 9-6.*

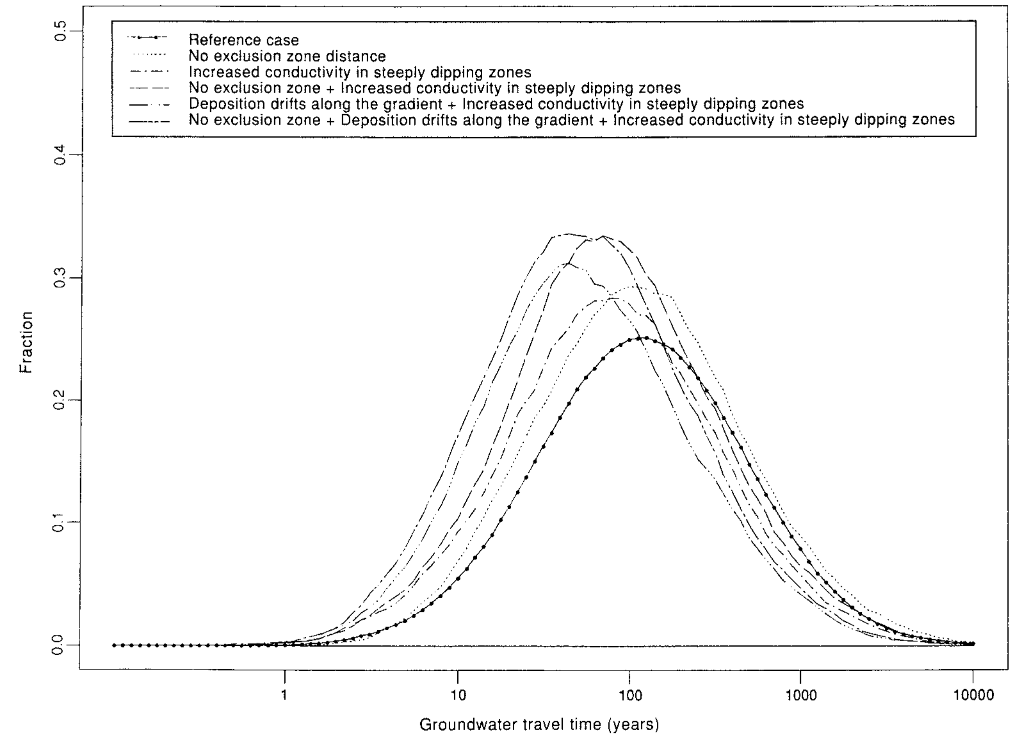


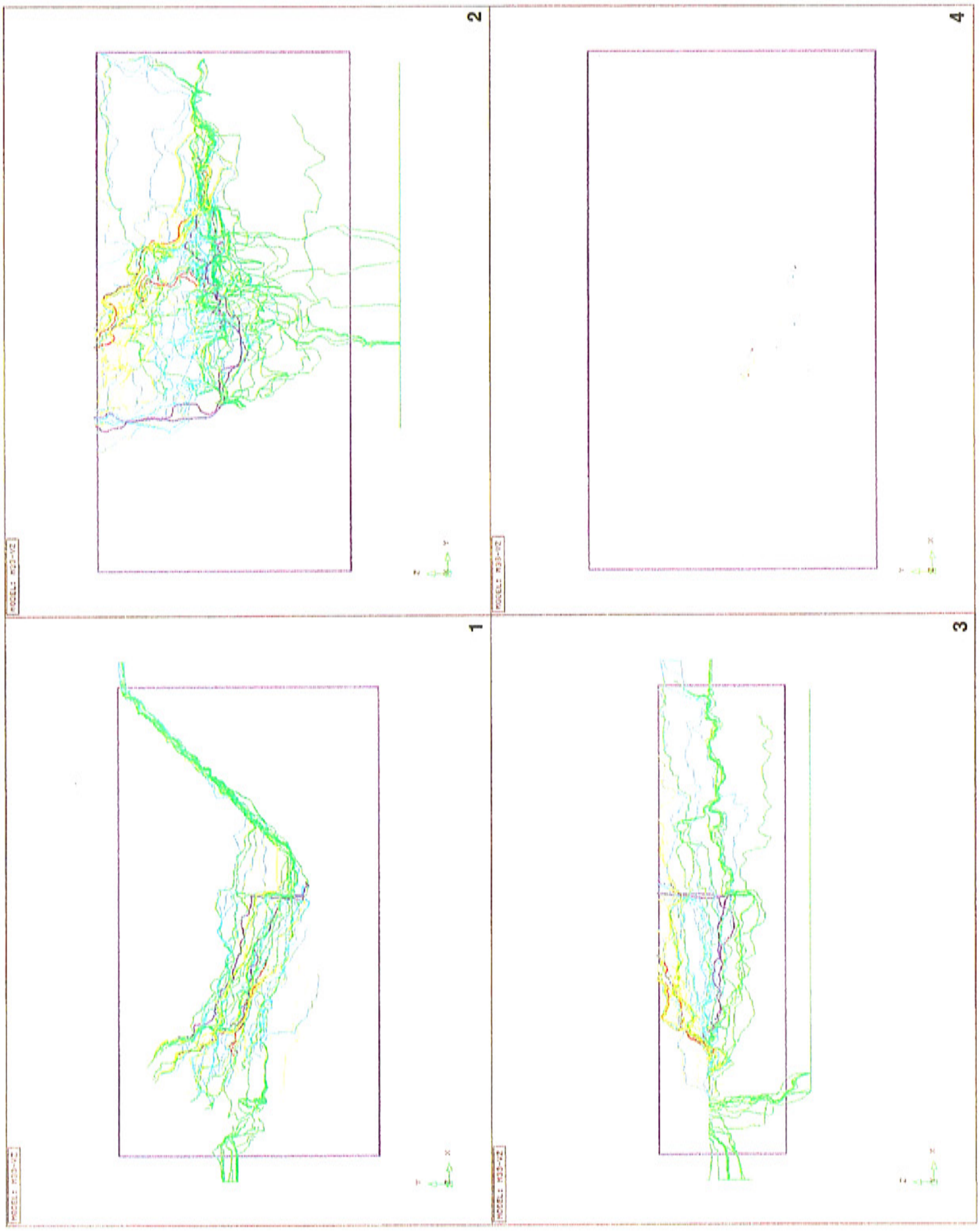

***Figure 9-31.*** *Floating histogram of travel times for water from the repository to the surface for a number of variations.*

## 9.6.4 Influence of flat-lying fracture zones

Figure 9-36 suggests that the exclusion zone to Zone 2 is unimportant, which presumably has to do with the fact that the flow is downward-directed from the zone. The same applies to the repository depth as such; the distance to the discharge area changes very little. The larger fraction of streamlines that reach the flat area intersected by the Imundbo zone at a repository depth of 500 m is connected with the fact that a larger portion of the surface area of the repository has ended up in the recharge area that has the flat area as its discharge area. The flow increase corresponds to the slightly higher conductivity at 500 m depth compared with 600 m. The smaller fraction of streamlines that reach the flat area in the 700 m case is in turn connected with the fact that a smaller portion of the surface area of the repository has ended up in the recharge area that has the flat area as its discharge area. The flow decrease corresponds to the slightly lower conductivity at 700 m depth compared with 600 m.

If the diverting and gradient-equalizing effect of Zone 2 is removed, the flows increase slightly at the same time as a larger fraction of the pathlines from the west corner of the repository reach the discharge area contained within the calculation block, see Figures 9-37 and 9-38.

If a deeper, flat-lying zone is placed in the area parallel to Zone 2, it ends up downstream of the repository. If it has sufficiently high transmissivity, its intersection with the ground surface and the Imundbo zone shifts the first discharge area nearer to the repository, see Figures 9-39 and 9-40. A substantial shift towards shorter times is caused in part by the fact that the streamlines end up in the new zone, in part by the high transmissivity of the zone, see Figure 9-38. An inclined Imundbo zone, however, is located too far from the repository to have any effect.



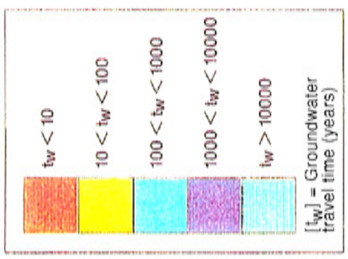
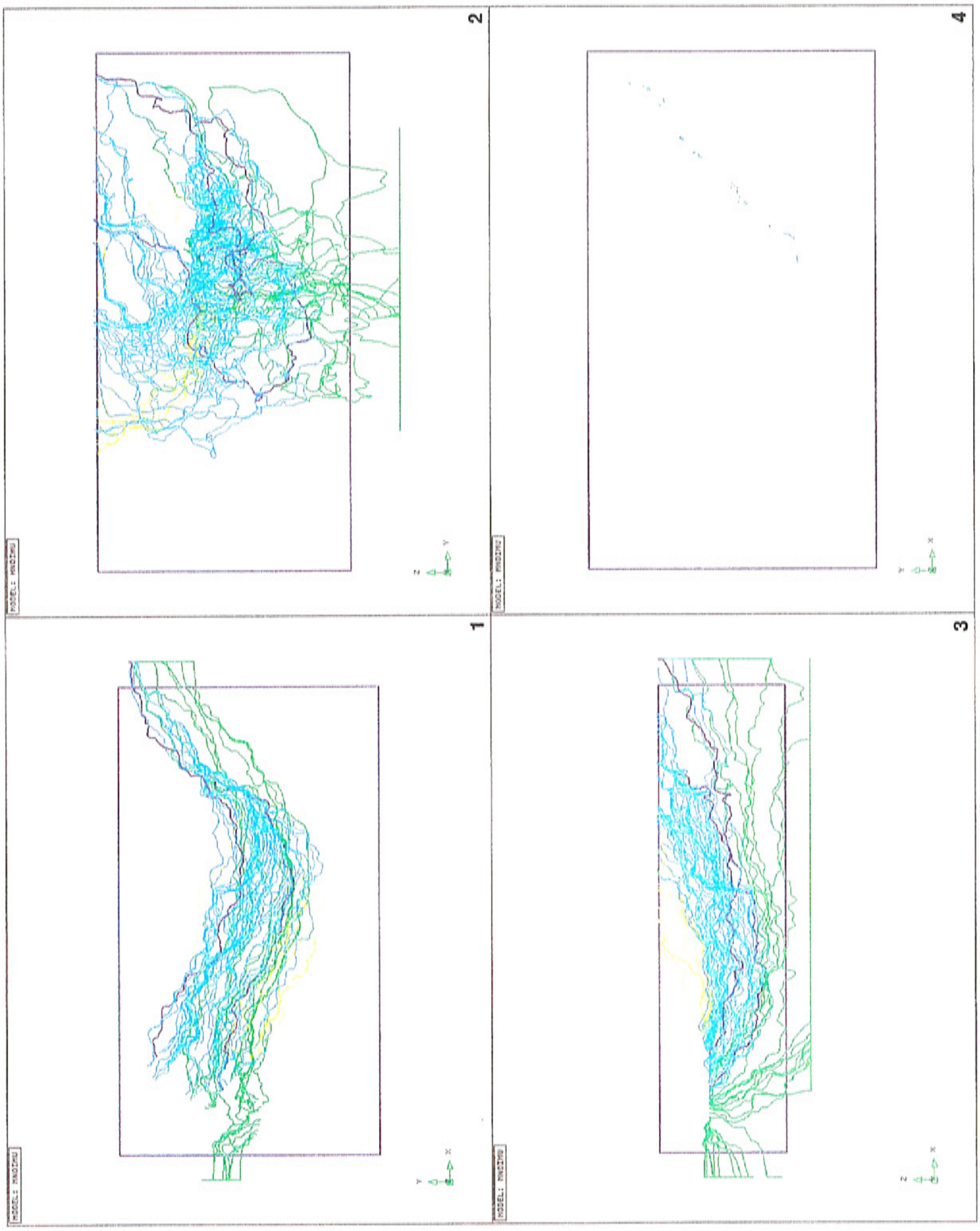




***Figure 9-32.*** *Pathlines for a typical realization in the case* **Increased conductivity in steeply dipping zones.** *Views same as in Figure 9-6.*



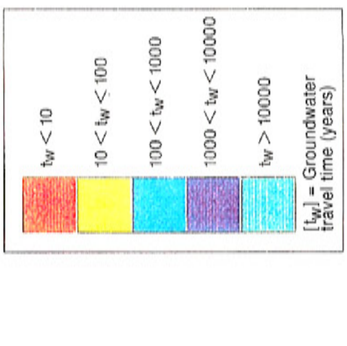




***Figure 9-33.*** *Pathlines for a typical realization in the case* **No Imundbo zone***. Views same as in Figure 9-6.*

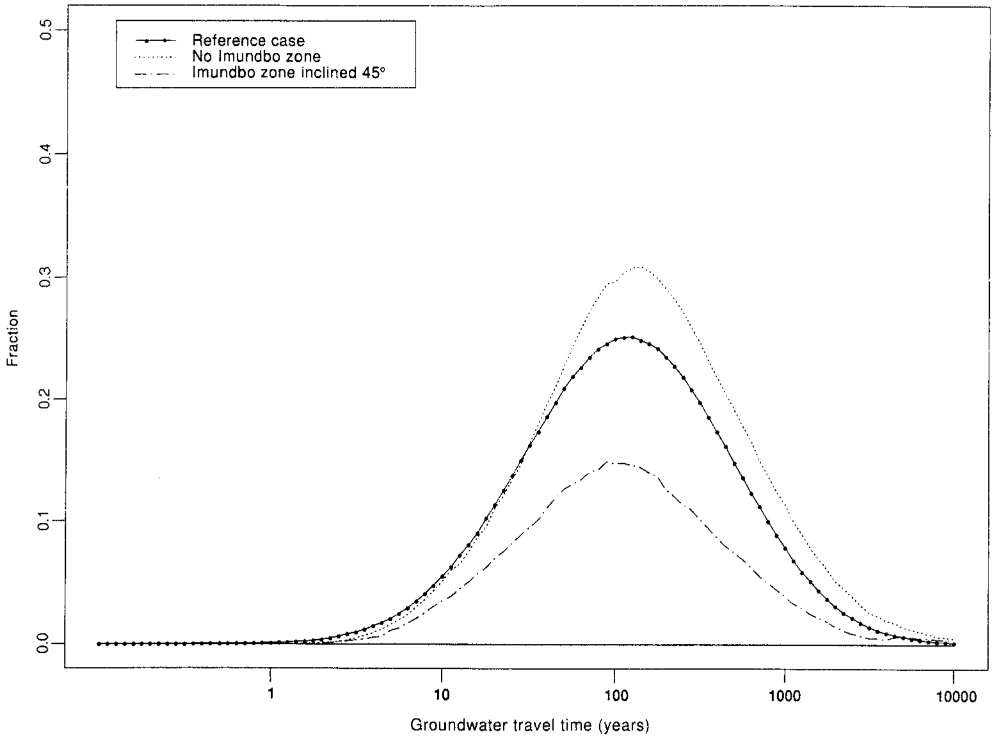



***Figure 9-34.** Floating histogram of travel times for water from the repository to the surface for a number of variations.*

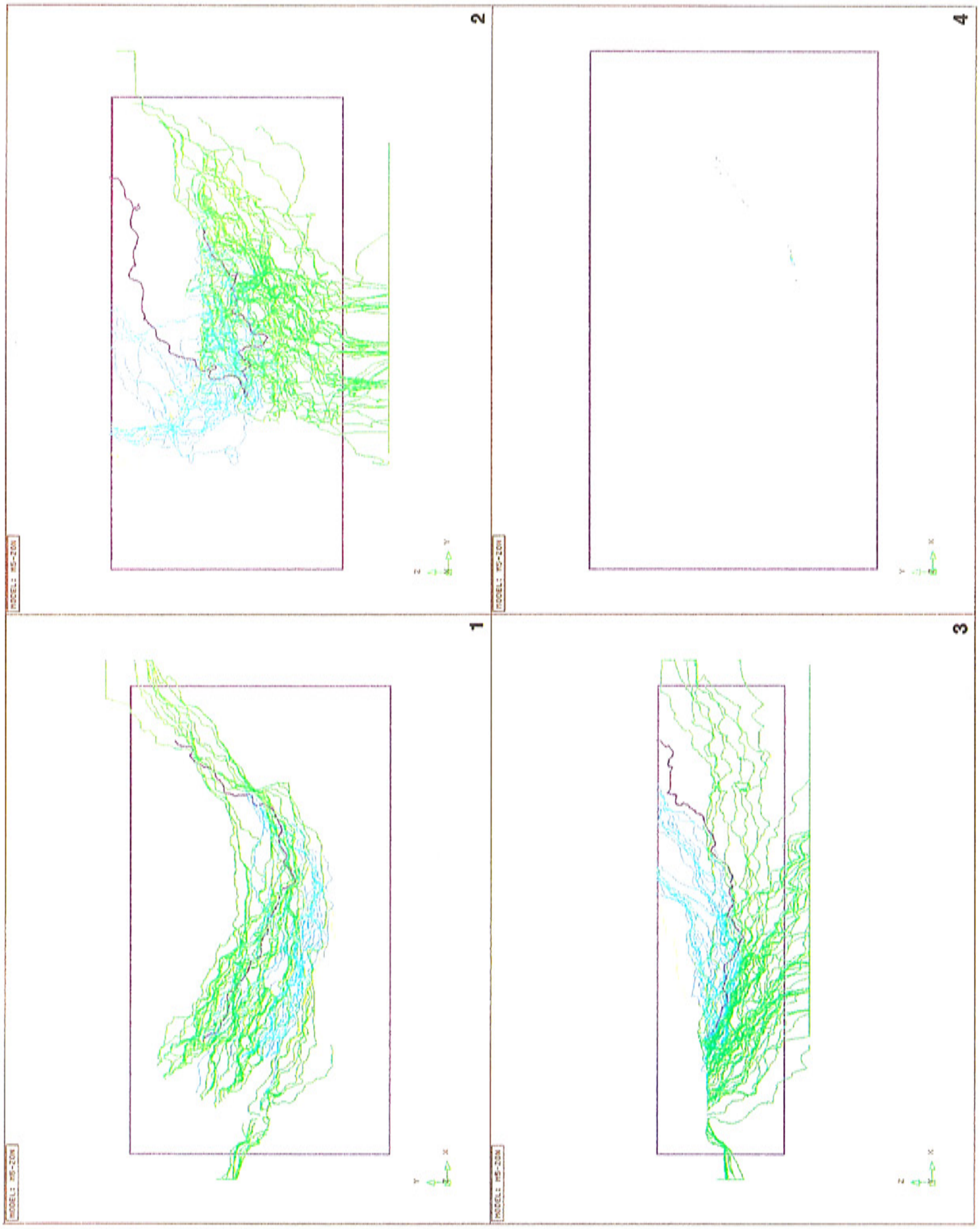
As described in section 9.6.3, certain interconnected structures of flat-lying and steeply dipping zones can create discharge areas that are controlled by the transmissivities of the zones rather than the topographical gradients, see also Figures 9-27, 9-28 and 9-30.

### 9.6.5 Regional and local hydraulic gradients

The influence on the flow pattern, represented by a single pathline with the same starting point in the different cases, of variations in the regional gradient through inclinations along the Dannemora zone (line A-B in the fold-out figure) is illustrated in Figure 9-41. The result of inclinations along a line parallel to the Imundbo zone is shown in somewhat greater detail in Figure 9-42. The variation in the influence of Gullbacken is worth noting. This influence is the cause of the northward flow along the Imundbo zone in the initial situation.

It is difficult to draw general conclusions from the calculation results. In summary, it can be said that the groundwater flow in the repository is normally controlled by both the local and the regional gradient, while the location of the discharge area and the groundwater travel times are normally controlled by the regional gradient. There is a tendency towards longer travel times at a lower regional gradient. At extremely small regional gradients, however, the local gradient takes over.

In the reference case it is assumed that the deposition drifts will lie perpendicular (with deviation <$15^{o}$) to both the principal dip and strike of fractures of the 4th-5th





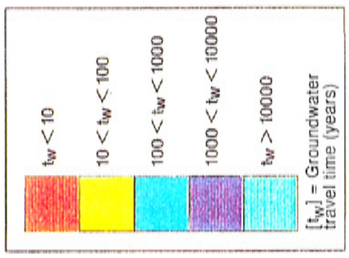




***Figure 9-35.*** *Pathlines for a typical realization in the case* **Imundbo zone inclined 45°.** *Views same as in Figure 9-6.*

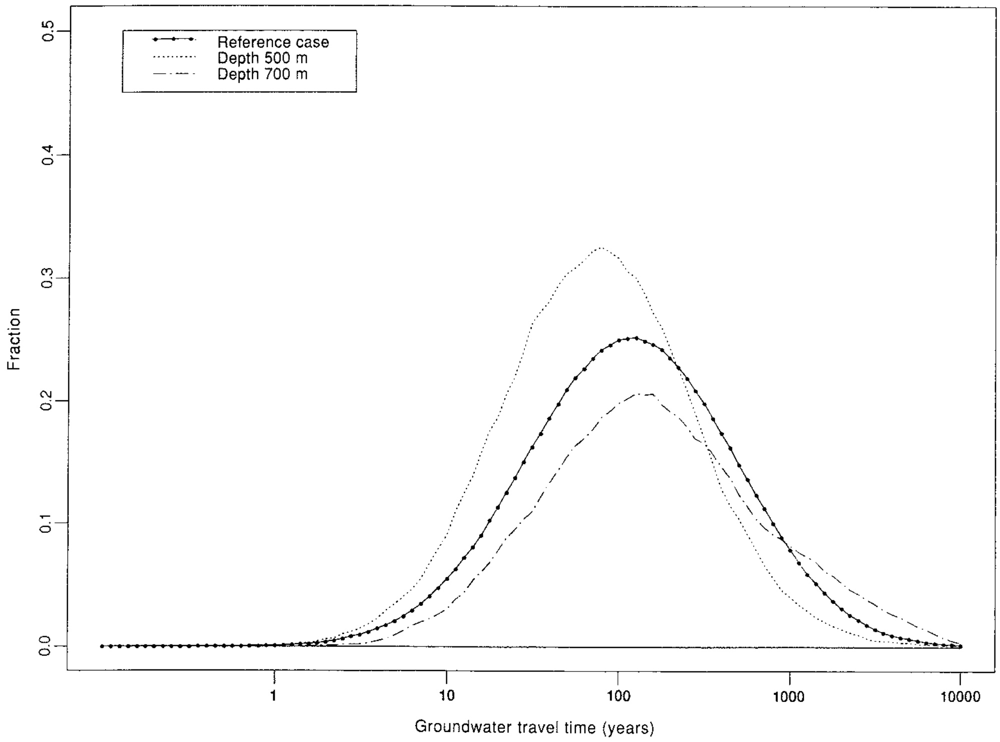


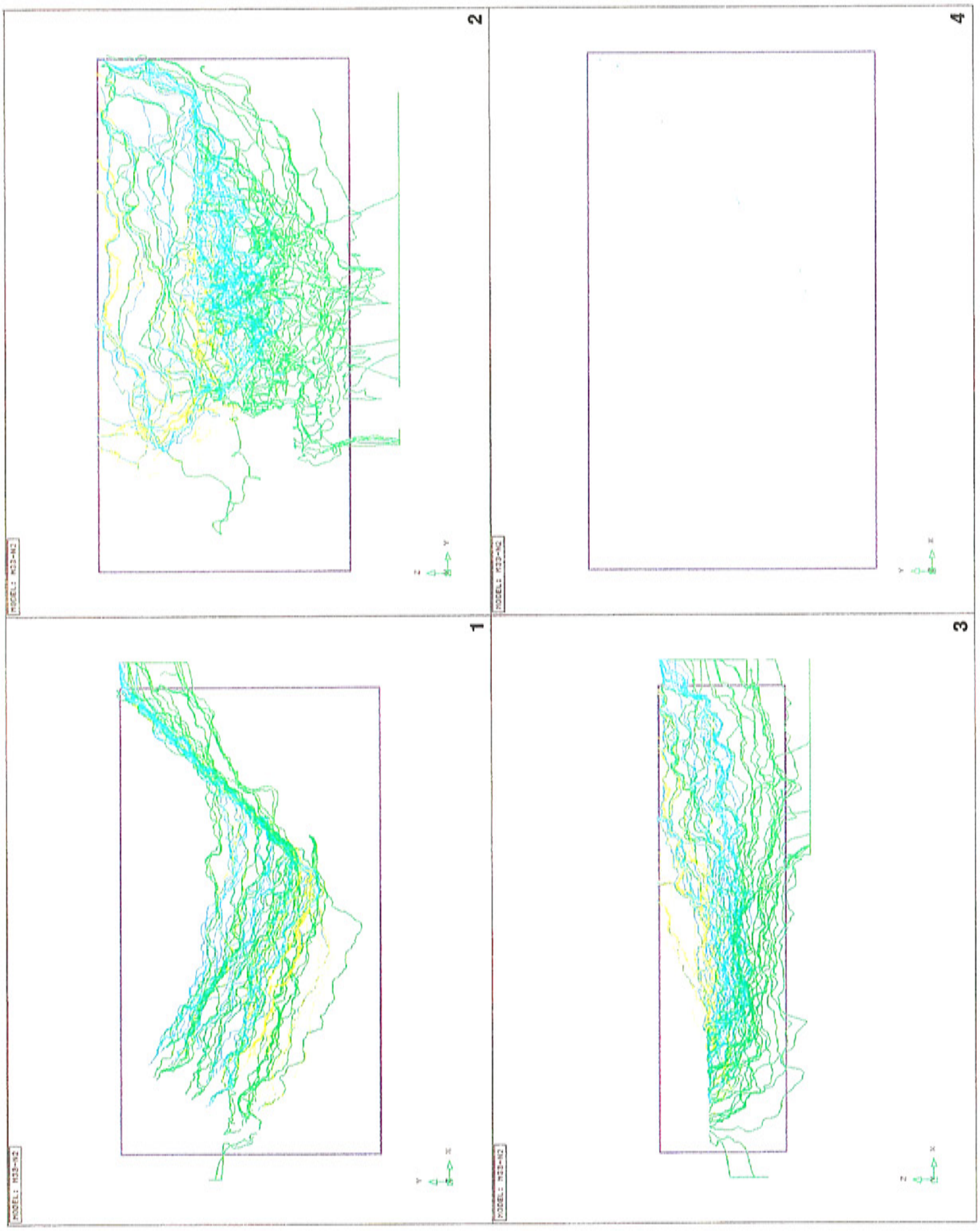

***Figure 9-36.*** *Floating histogram of travel times for water from the repository to the surface for a number of variations.*

order in order to minimize the influence of the disturbed zone. At the same time, the drifts will lie perpendicular to the gradient. This is possible in the Finnsjön area, but not necessarily at other sites.

An alternative layout with the hydraulic gradient along the deposition drifts causes the flow to have a tendency to gather in the disturbed zone. However, this has little effect on the groundwater travel times, even though the steeply dipping zones are given a higher conductivity and connectivity increases due to the fact that the width of the exclusion zone to the steep zones decreases, see Figure 9-43; the zones are too far from the discharge area. The distribution's low-flow area tends to be shifted to the right, resulting in a narrower distribution and a slightly higher median, see Figure 9-44.

Separate studies done of the disturbed zone also suggest that its importance is limited /9-12, 9-13/. It is expected to have relatively little transmissivity, since its radial extent is small. The surrounding rock and the transmissivity of any intersecting fracture zones also limit the inflow.

The disturbed zone has been represented in a simplified manner in HYDRASTAR in that its transmissivity has been distributed out to give equivalent conductivity increases in immediately surrounding nodes.



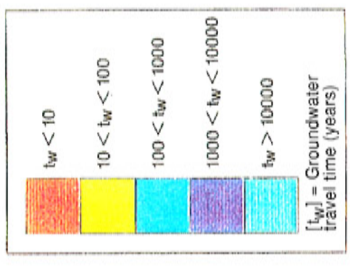



***Figure 9-37.** Pathlines for a typical realization in the case* **No Zone 2.** *Views same as in Figure 9-6.*

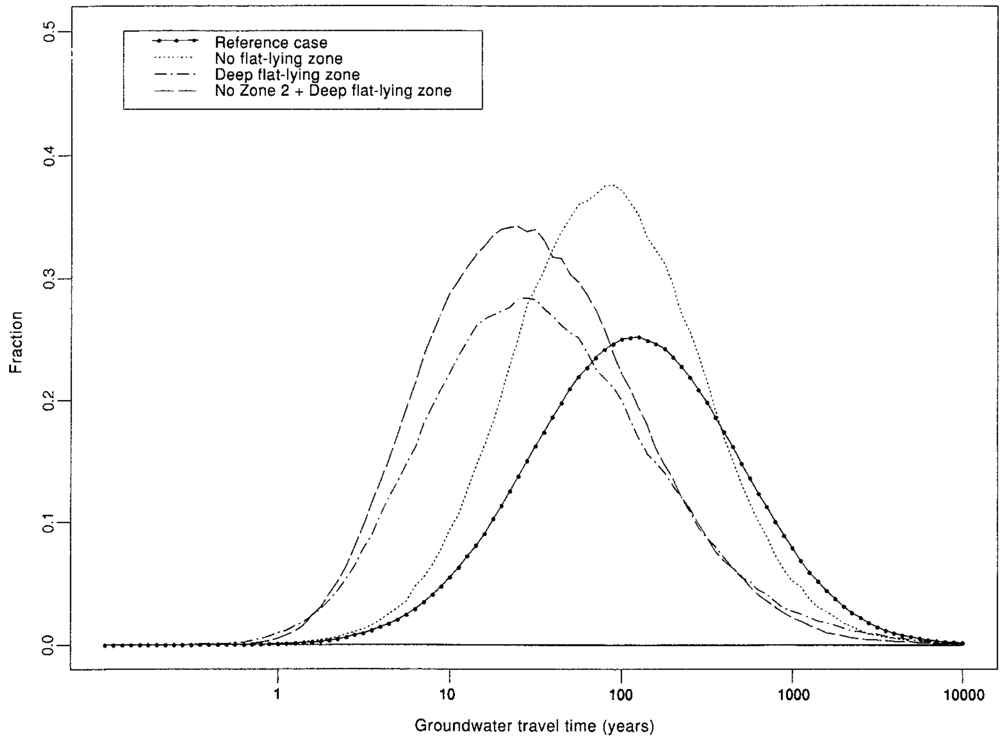
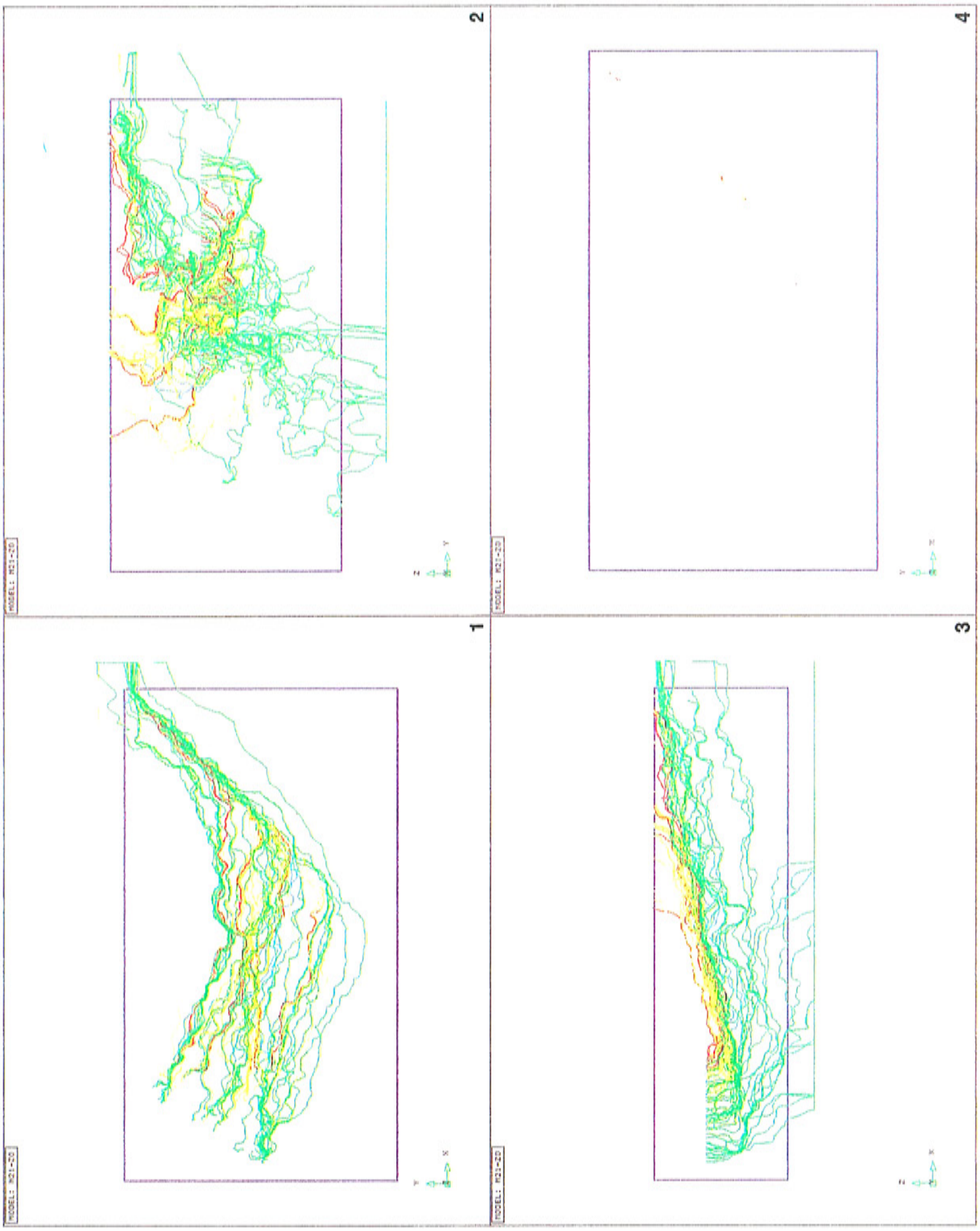



***Figure 9-38.*** *Floating histogram of travel times for water from the repository to the surface for a number of variations.*

### 9.6.6 Placement of the repository in the rock block and adaptation to the geological structures

Figure 9-45 summarizes the effect on the groundwater travel times of different ways of placing the repository in the rock block in relation to the gradient and to structures with different hydraulic properties.

None of the factors represented in the figure has any appreciable influence on the water travel times. What is more important is the existence of, and the placement of the repository in relation to, flat-lying structures. Figure 9-38 shows the importance of locating the repository underneath a flat-lying structure, if one exists, and avoiding placing the repository next to underlying flat zones.



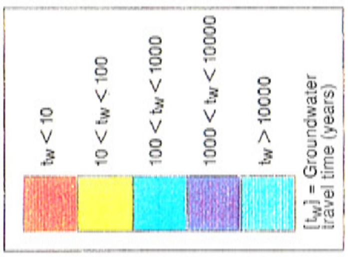
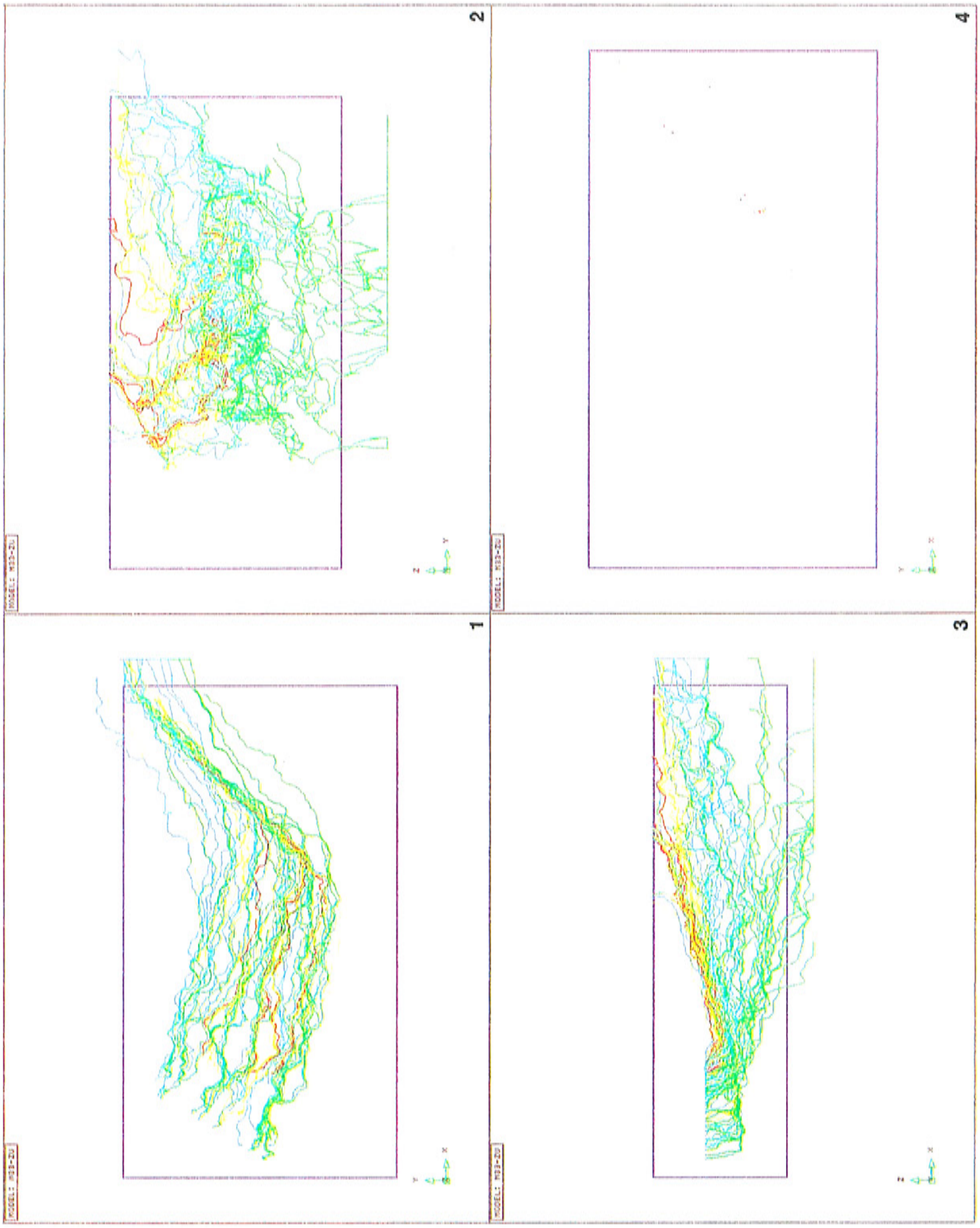




*Figure 9-39. Pathlines for* **Deep flat-lying zone.** *Views same as in Figure 9-6.*



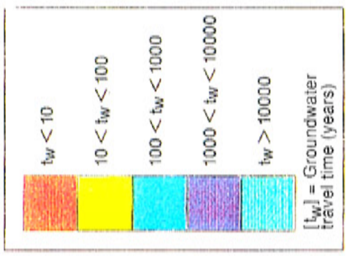




***Figure 9-40.*** *Pathlines for a typical realization in the case* **No Zone 2 + Deep flat-lying zone.** *Views same as in Figure 9-6.*

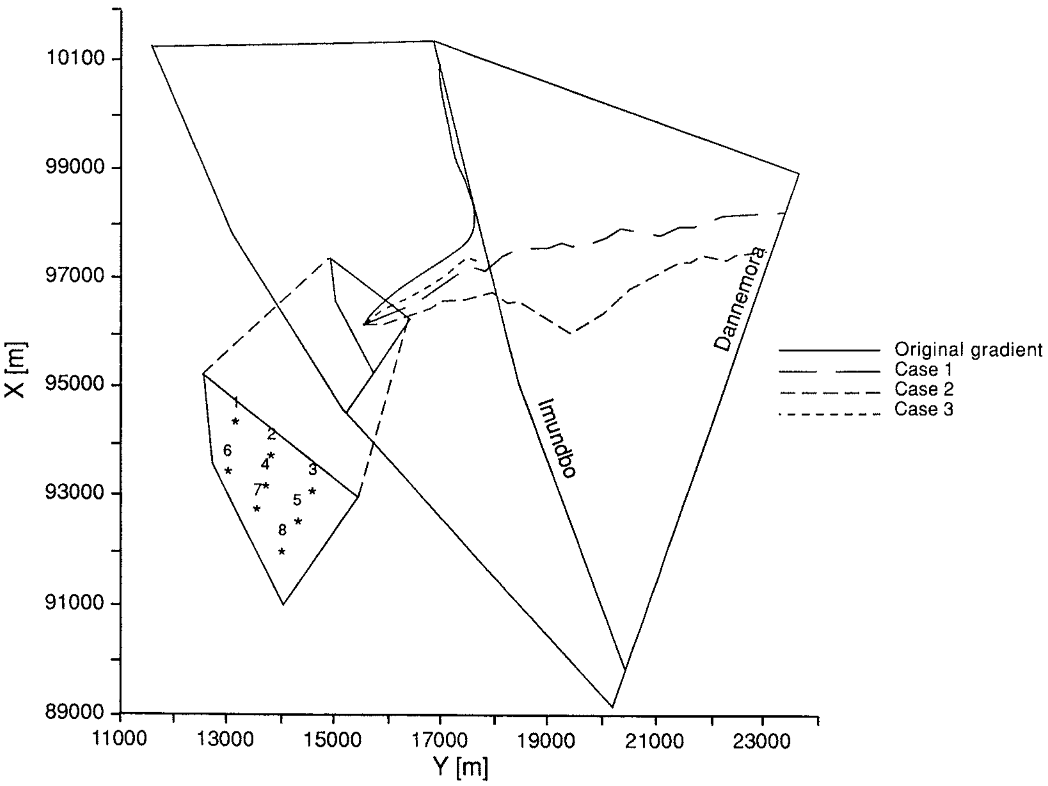



***Figure 9-41.*** *Horizontal projection of a pathline (no. 7 in the figure) for different gradient cases (calculations performed with NAMMU, see also fold-out figure at back of report). The coordinates are RAK coordinates.*

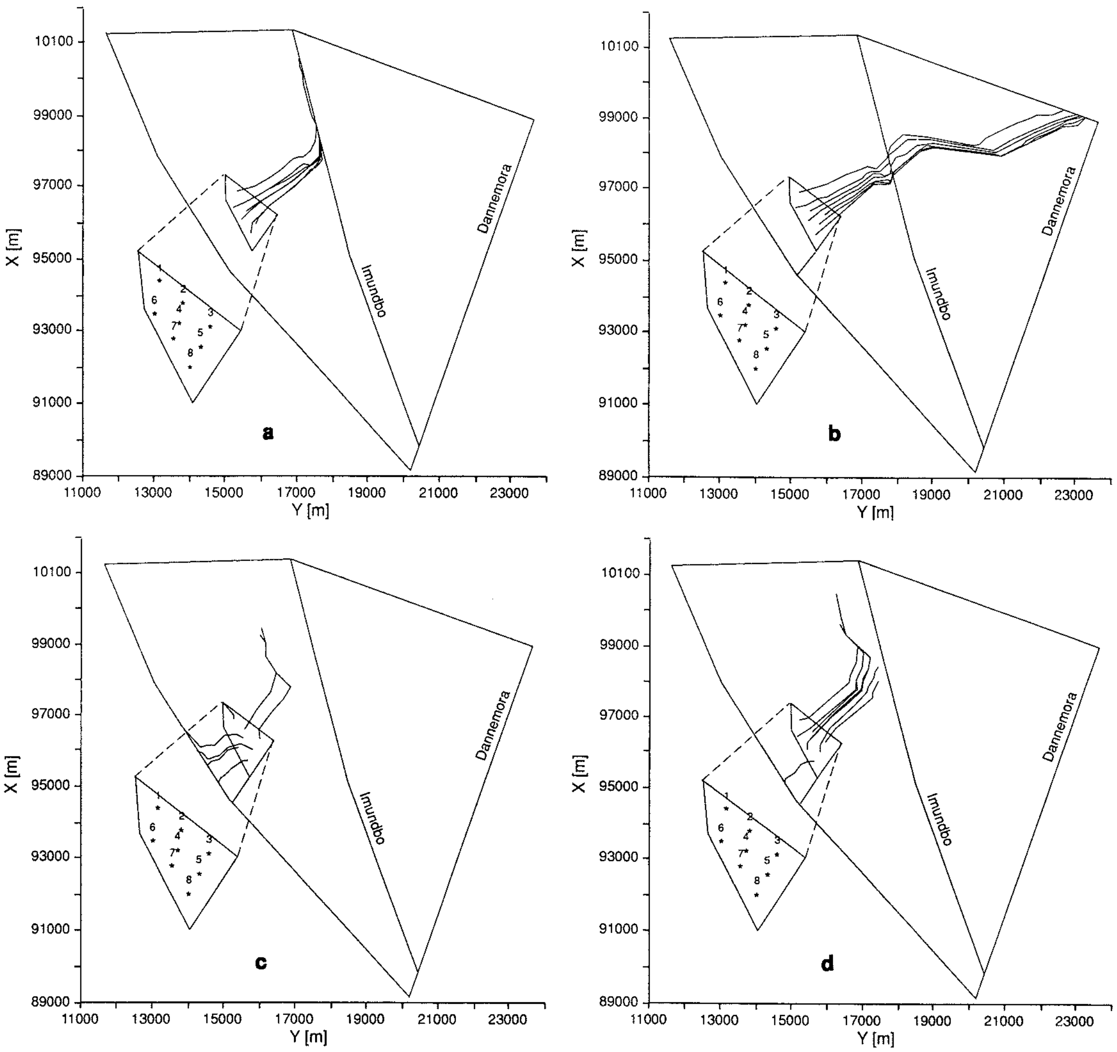



***Figure 9-42.*** *Horizontal projections of pathlines for different gradient cases: a) initial situation, b) case 4, c) case 5, d) case 6 (calculations performed with NAMMU, see also fold-out figure at back of report).*

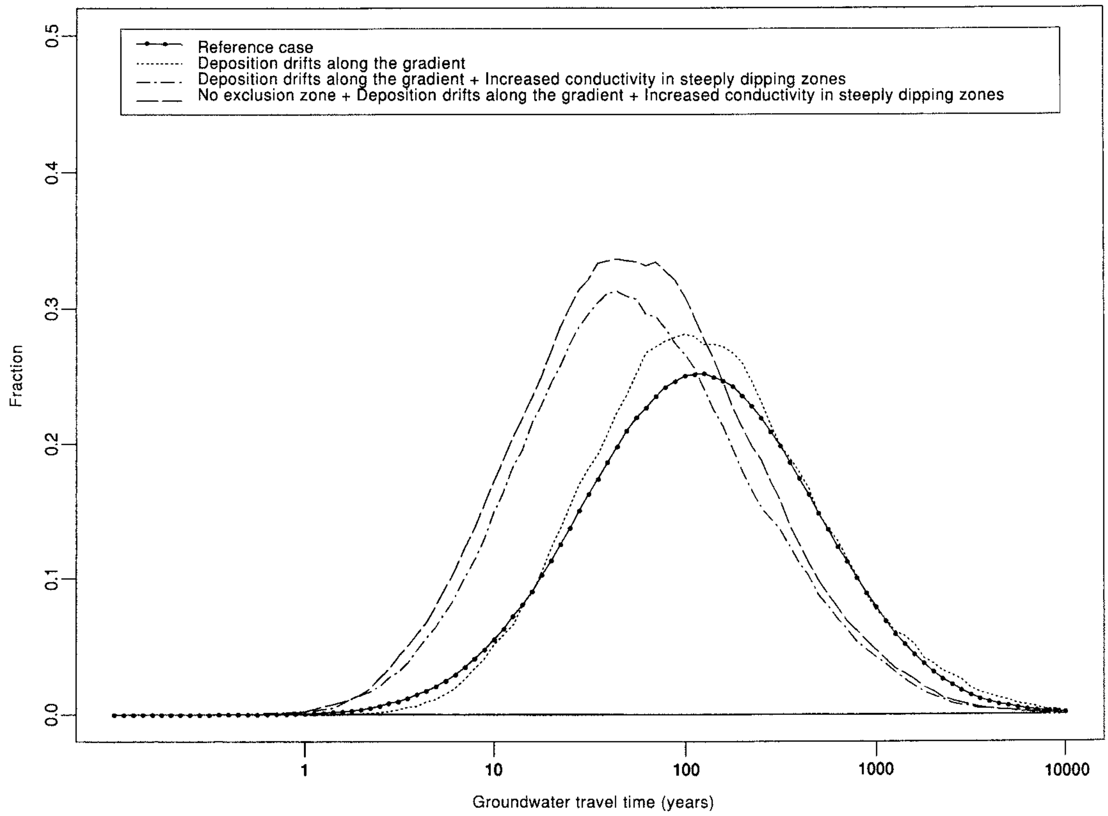



***Figure 9-43.*** *Floating histogram of travel times for water from the repository to the surface for a number of variations.*

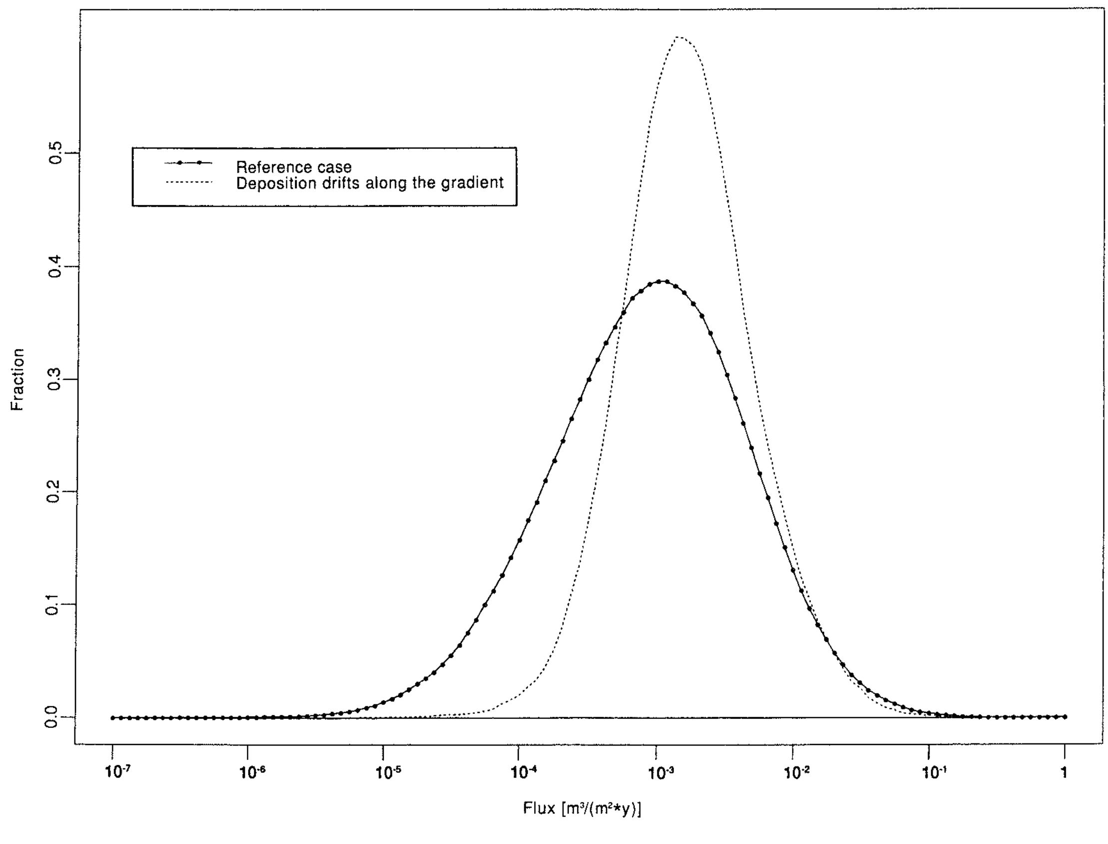



***Figure 9-44.*** *Floating histogram of Darcy fluxes at repository level for a number of variations.*

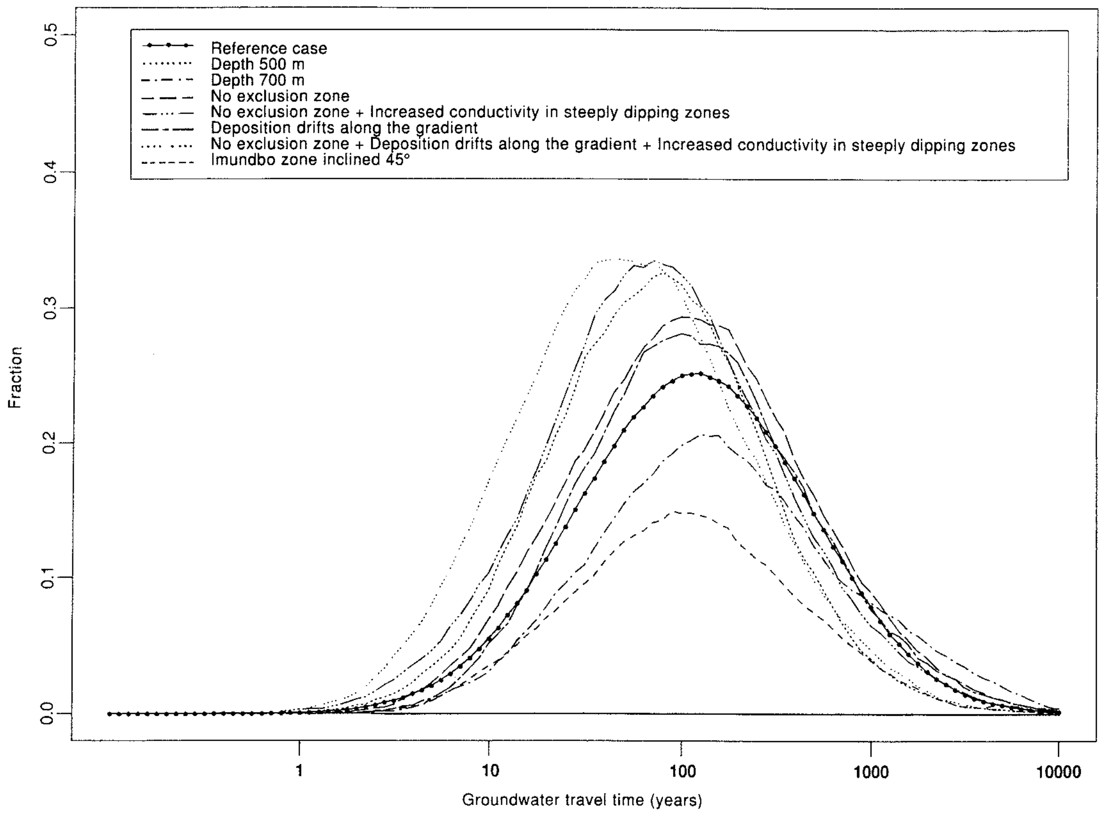



***Figure 9-45.** Floating histogram of travel times for water from the repository to the surface for a number of variations.*

# 10 CONCLUSIONS

*The chapter summarizes the important results of the analyses with reference to the purpose of SKB 91 and presents the conclusions.*

## 10.1 GENERAL

A safety assessment has been carried out for an assumed repository for spent nuclear fuel situated on SKB's geological investigation site at Finnsjön. The repository is assumed to be designed in accordance with the principles arrived at in the KBS studies. This entails a rock repository at a depth of 300 – 700 m where the fuel, encapsulated in copper, is deposited so that the temperature increase in the buffer remains well below 100°C.

The SKB 91 safety assessment differs in certain respects from previous assessments. A larger body of knowledge has made it possible to take into account factors that were previously dealt with in a simplified fashion. Examples are the resistance to leakage from an initially defective canister offered by the hole in the canister wall and the transport of radionuclides in fracture zones. Further, the higher computing capacity of modern computers and new models have made it possible to take into account the variability in the hydraulic conductivity of the rock, as well as the actual geometry of the repository.

Aside from the fact that initially defective canisters are assumed to have been deposited, the new models make the assessments more realistic than before. At the same time, the results are also more strongly affected by the features of the repository site, i.e. the results are site-specific to a greater degree than before. This is necessary in order for it to be possible to examine the impact of the rock barrier on safety, but also means that great caution must be exercised in applying the results to other sites.

## 10.2 REPOSITORY SAFETY

### 10.2.1 Probable conditions

The engineered barriers in the repository have been designed to provide long-term isolation of the radioactive materials from surrounding groundwater. The fuel is encapsulated and deposited in a controlled manner so that in all probability the repository will not contain any defective canisters.

The materials in the canister and the buffer have been chosen so that the barriers are not sensitive to reasonable changes in groundwater chemistry or temperatures. The chemical environment in deep granitic bedrock is such that the copper walls of the canisters will not be penetrated by corrosive substances until possibly after several tens of millions of years.

The lead-filled canisters will act as solid bodies in the rock and will withstand prevailing pressures, including those that are expected to arise in connection with a future glaciation. Rock movements in conjunction with the relief of pressure following a glaciation will be released in the regional fracture zones that surround the repository. Rock movements of such magnitude that the canister would be sheared off will only occur in fracture zones with a length of 10 km or more. Such structures can be identified during the construction of a repository and no canisters will be deposited there.

One possible reason for the canisters losing their integrity is that an inner helium pressure is built up in the canister by $\alpha$-decay in the fuel. This pressure will not reach the level of the yield limit of the copper canister until some 10 million years or so after encapsulation.

Thus, the copper canister will isolate the spent fuel for a very long time, considerably longer than the 100,000 years-plus that are required for the toxicity of the radioactive materials to decline to a level equivalent to that of rich uranium ores.

### 10.2.2 Reference scenario

To substantiate the safety assessment, the repository's impact on the environment has also been studied for less probable cases. One assumption is thereby that faulty canisters have been deposited owing to the fact that defects during manufacture have not been detected by the quality control procedures. A reference scenario has been defined where 0.1% of the deposited canisters have initial defects. Fuel dissolution, transport of radionuclides from the barriers in the near field, through the bedrock and the biosphere, and dose to man are calculated for this scenario.

The release of radionuclides from a damaged canister is limited strongly by the slow dissolution of the fuel and by the maximum possible size of an initial defect. The calculations show that if the radionuclides escaping from a damaged canister travel directly up to the biosphere, the dose would be no more than 0.001 mSv/y for all nuclides except Cs-135, see Figure 10-1.

It is assumed that 5% of the inventory of the isotope Cs-135 has been released from the fuel matrix and is thus available for outward transport as soon as the groundwater comes into contact with the fuel. With the above assumption that this amount of cesium from a damaged canister would reach the biosphere directly, it can give rise to a dose of about 0.03 mSv. In reality it takes about 10 years before the maximum release rate from the near field is reached, which reduces the annual dose from cesium to a few percent of the values given in Figure 10-1.

In other words, the barriers in the near field limit the releases to levels that lie below the suggested dose limit of 0.1 mSv/y.

Thus, the principal safety-related requirement on the rock around the repository is that it shall preserve a chemically and mechanically stable environment around the repository, so that the performance of the engineered barriers is ensured.

In order to determine the safety-related importance of the rock barrier at Finnsjön, a geohydrological modelling of the area has been performed. Water flow and travel times up to the biosphere in different parts of the repository have been calculated.

Sampling in the Finnsjön area has shown that water under Zone 2 has a much higher salinity than shallower water. This stratification of the groundwater's density reduces the groundwater flux under Zone 2. Studies indicate a groundwater travel time

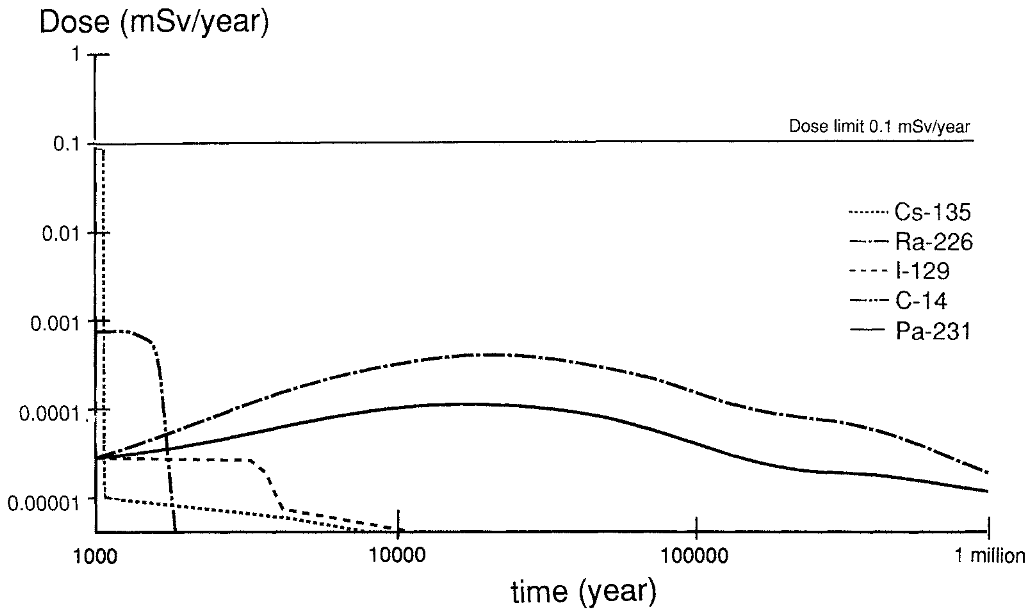



***Figure 10-1.*** *Annual dose to individual under the assumption that the release from an initially defective canister takes place directly to the biosphere.*

between repository depth and ground surface that is between 10 and 100 times longer at existing salinities, compared with a pure fresh water case. The calculations in SKB 91 are based on the less favourable fresh water case, since the prevailing situation may change during the span of time that must be considered, and since the excavation work may disturb the balance. A release to salt water normally gives a considerably lower dose than one to potable water.

The analysis of the radionuclide release rates in the event of an initial canister defect shows that the release from the near field is only slightly affected by the water flow around the deposition hole.

The groundwater fluxes in the model block have been calculated with both stochastic and deterministic hydrology models. The flow patterns that are generated are in good agreement with each other. The results show that the flow is mainly determined by topographical conditions and the flat-lying Zone 2 above the repository. Other fracture zones only affect the flow pattern to a small extent. The principal discharge of groundwater from the repository area takes place to Lake Skålsjön, or to the surface water that runs down towards Lake Skålsjön along the valley of the Imundbo zone, see the fold-out map at the back of the report.

The travel times for water up to the ground surface have been calculated for pathlines that start in different parts of the repository. For nearly half of the pathlines, the travel time is longer than 10,000 years, see Figure 10-2. For the pathlines that reach the ground surface before 10,000 years, the median value of the groundwater travel time in the reference case has been calculated to be 110 years. Groundwater travel times shorter than 10 years are generated in the northeast corner of the repository, with a probability of 5-10%.

The calculations show that the size of the release of nuclides to the biosphere is affected to some extent by the groundwater travel time. If the nuclides released from

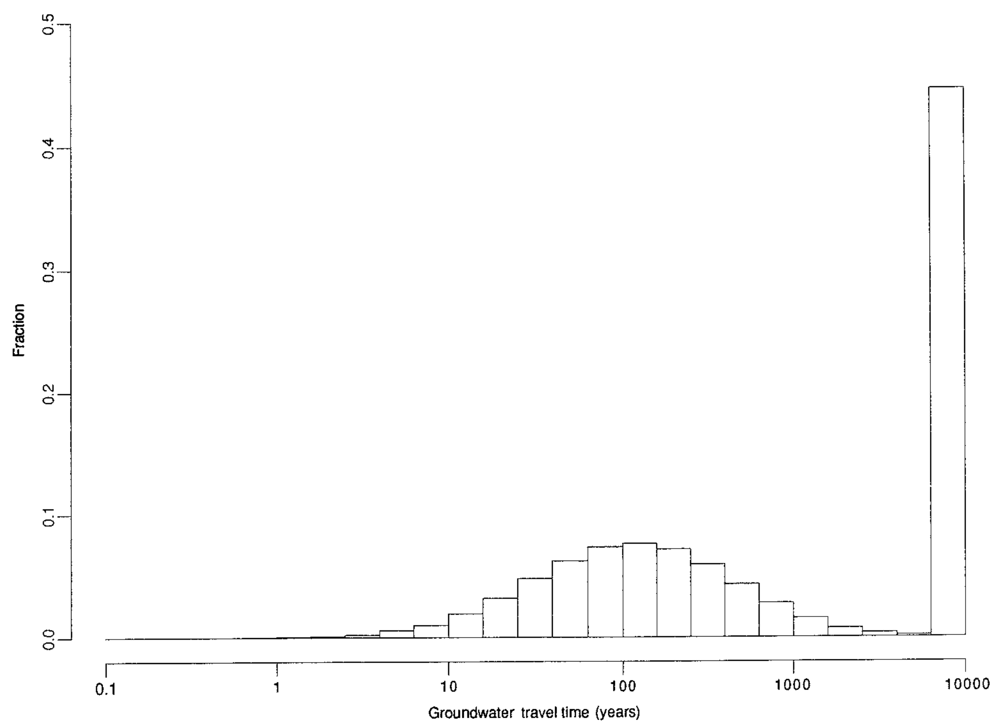



***Figure 10-2.*** *Histogram of travel time for water from different parts of the repository to the ground surface for 500 realizations of the reference case.*

the near field reach the biosphere via a pathline with a groundwater travel time of less than 10 years, the calculations give a dose approximately 10 times higher than if the release had taken place via a pathline with a travel time of 100 years. At a groundwater travel time of 1,000 years or longer, the doses are much lower, see Figure 10-3.

The entire chain of calculations from release from the fuel to dose in the biosphere has been carried out for the reference case. The results show that the repository's impact on the environment is more than a factor of 1,000 less than the individual dose limit suggested by the authorities, and that the result is relatively insensitive to the random variability in the hydraulic conditions, see Figure 10-4.

The importance of the way in which radioactive materials enter the biosphere has been studied with a biosphere model. Compared to a leakage to the standard biosphere used in the reference case, the same release to the Baltic Sea would give doses that are about 100 times lower. If a well should be so extremely positioned that it manages to collect all the radionuclides that are released from a repository, an individual who fills his entire water need with water from this well alone would receive a dose up to 100 times higher.

**In summary**, the assessments show that the barriers in the near field isolate the radioactive materials in the spent fuel very effectively. Radioactive fission products and all actinides with high initial inventory and with the potential to give high individual doses are retained in the near field. Thus, cesium-137 and strontium-90 decay before the water comes into contact with the fuel in a defective canister. Solubility limits and sorption in the bentonite clay prevent other materials with high initial activity – such as the actinides plutonium, neptunium and americium and the

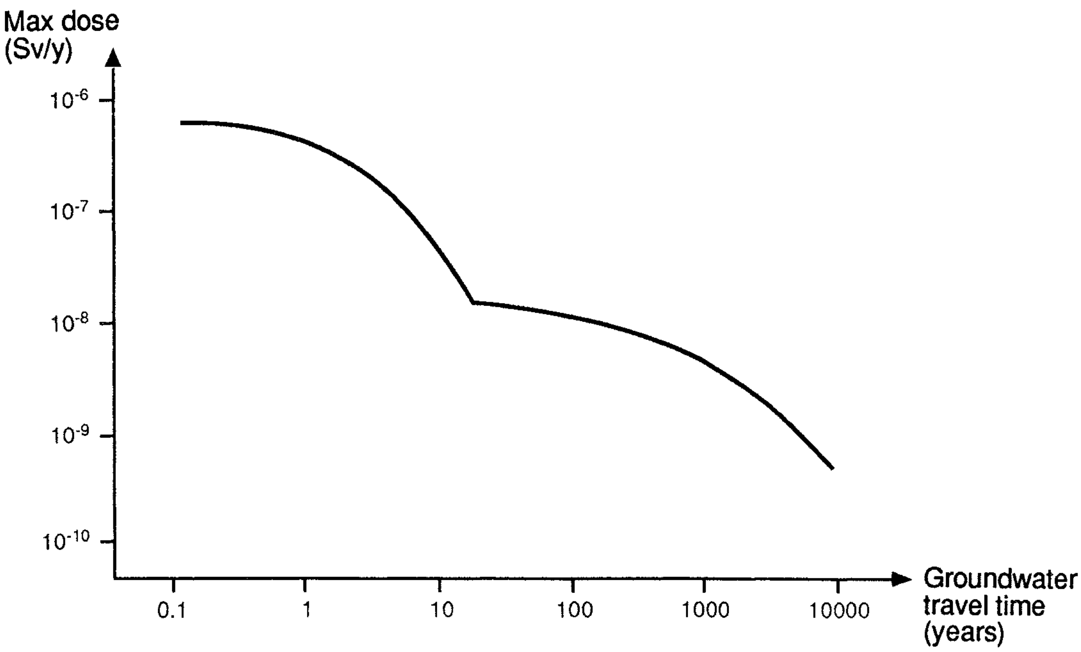



***Figure 10-3.*** *Maximum annual dose commitment for release from an initially defective canister at different travel times for groundwater from canister to biosphere.*

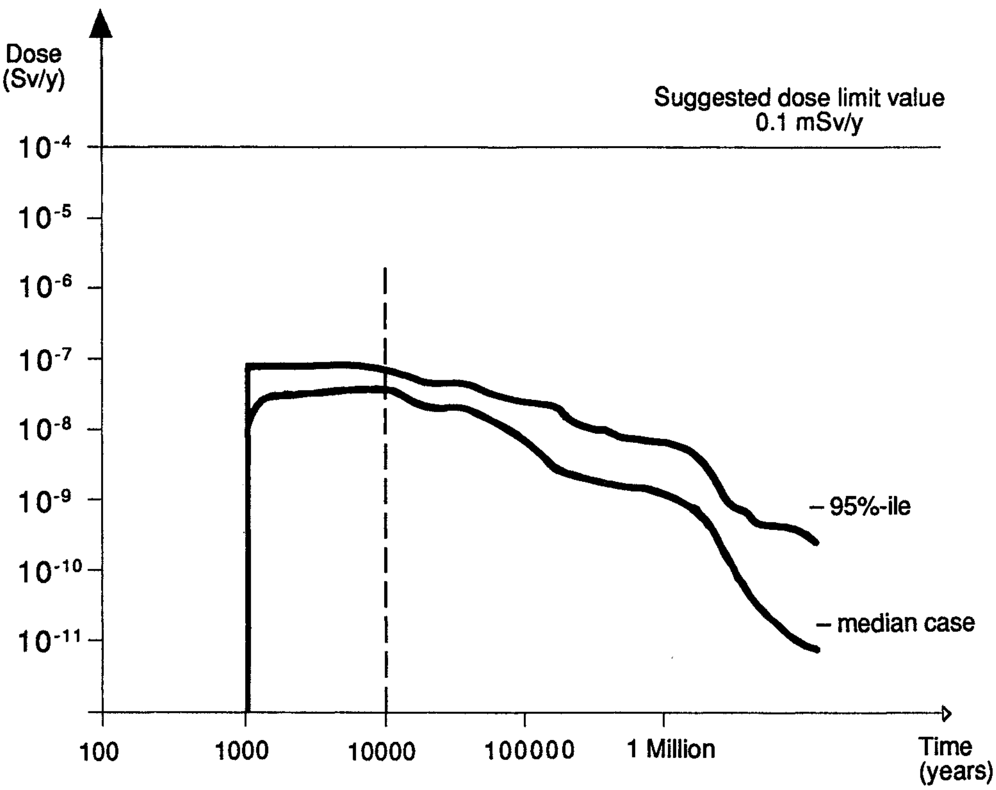



***Figure 10-4.*** *The reference case – Dose commitment for individuals at different times after closure of the repository. The curves show a typical case and an unfavourable case.*

long-lived fission products zirconium-93, palladium-107 and tin-126 – from escaping into the rock even if the canister has an initial defect.

In practice, only the highly soluble and long-lived nuclides carbon-14, iodine-129 and cesium-135, plus the long-lived uranium daughters radium-226 and protactinium-231, can escape from the near field. This limits the release (even with a damaged canister) to such a low level that the safety-related importance of the rock as a barrier to radionuclide transport is very limited. The principal safety-related requirement on the rock is therefore that it should provide a mechanically stable environment where canisters can be emplaced without landing in the middle of potential zones of movement, and that it should provide a chemically stable reducing environment for the near field.

## 10.3 THE ROCK AS A BARRIER – VARIATION CALCULATIONS

The safety requirements on a repository are intended to ensure that the safety of the final disposal system is based on several passive barriers. Thus, even if it is not necessary from a dose point of view to find the geologically absolutely most favourable site for a repository in Sweden, it is reasonable to attempt to utilize optimally the potential of the rock on the chosen site to act as a barrier against radionuclide migration.

The chemical environment in the Swedish bedrock, and the stability that rock blocks being considered for the repository can be credited with, differ very little from place to place. The factor that most readily summarizes the barrier potential of a given rock volume is the distribution of groundwater travel times from the repository to the biosphere. To shed light on how this property is affected by different site-specific characteristics and parameters, some fifteen or so variations of the geohydrologic features of the site have been carried out in the reference case.

The variations cover

- properties of the rock mass in the repository area;
- influence of steeply dipping fracture zones;
- influence of flat-lying fracture zones;
- regional and local hydraulic gradients.

Other variations have been performed to demonstrate the importance of contact area between flowing groundwater and rock, dispersion and matrix diffusion, or the importance of salinity stratification in the groundwater.

A general observation is that streamline patterns and commonly occurring groundwater travel times in a bedrock such as in the Finnsjön area are relatively little affected by the locations of the steeply dipping fracture zones and their distance from the repository. In order for a clear effect to be apparent, the ratio between the hydraulic conductivity of the fracture zones and that of the rock must be increased from just over a factor of 10 to more than 100, see Figure 10-5.

A stronger effect is obtained from variations in fracture zones with a nearly horizontal orientation. If the Zone 2 lying above the repository is replaced with "normal" rock, the flow pattern is changed and the pathlines become flatter. If a similar flat zone is assumed to lie parallel to Zone 2 but underneath the repository, the change is even

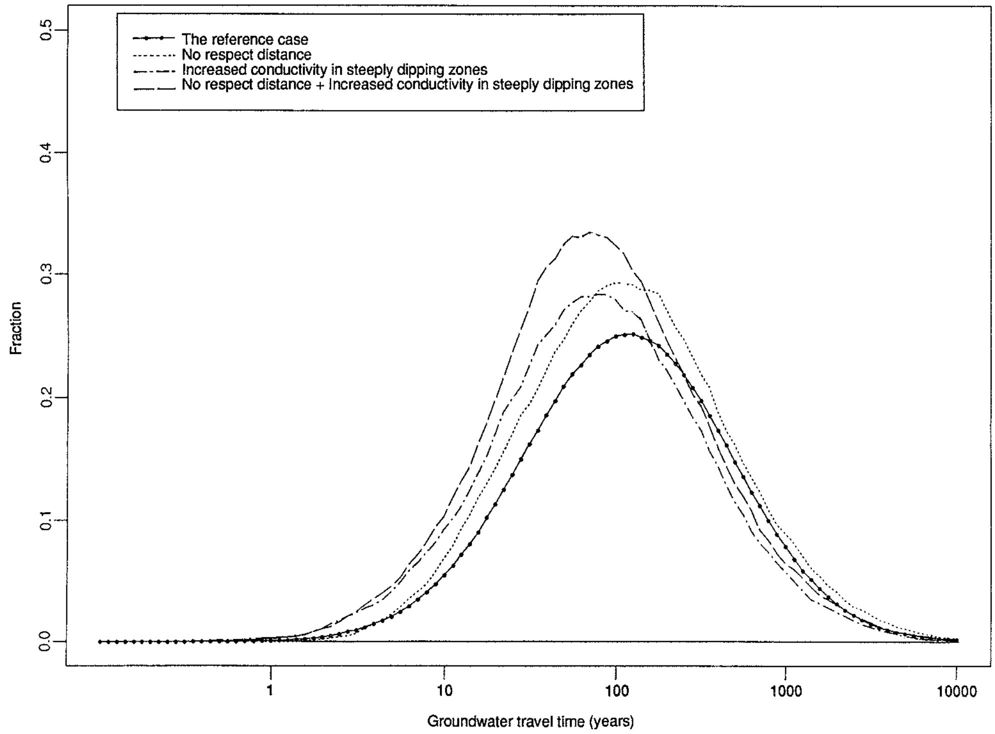



***Figure 10-5.*** *Dependence of groundwater travel times on the distance between repository and fracture zones and on the ratio between the hydraulic conductivity in fracture zones and rock.*

more pronounced, see Figure 10-6. The discharge is conducted to the zone's intersection with the ground surface and the groundwater travel times are 4-5 times shorter. A strongly conductive flat zone underneath the repository should be avoided.

**In summary,** the variations show that the flow pattern and groundwater travel time for water from the repository to the biosphere are changed to a relatively small extent by most of the variations that have been performed. Significant changes are mainly caused by flat-lying, highly conductive zones, which can create both more and less favourable conditions than in the reference case by isolating the repository from groundwater gradients at the ground surface or by routing the water that passes the repository quickly up into a nearby discharge area. However, even in these cases, the effect of the repository's engineered barriers means that the dose is not affected by more than an order of magnitude or so, i.e. less than the margin to the recommended dose limit values.

If a high salinity in the groundwater around the repository persists for a long time, the groundwater flux will be lower through the repository at the same time as certain dispersal pathways to man are eliminated because wells turn saline.

The effect of many of the variations discussed above is naturally dependent to a certain extent on the local conditions that have been chosen for the reference case. Even if there is a great similarity between future candidate sites, caution should therefore by exercised in applying the conclusions drawn from the results for one site to other sites.

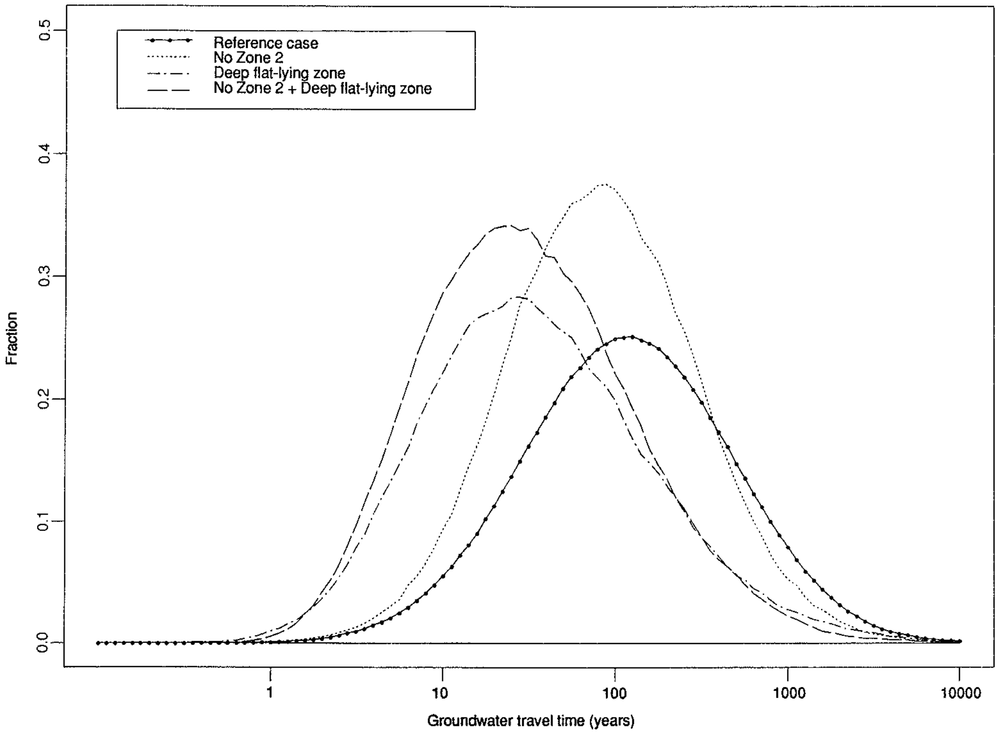



*Figure 10-6. Dependence of groundwater travel times on flat-lying zones with high conductivity.*

## 10.4 REPOSITORY DESIGN – ADAPTATION TO LOCAL CONDITIONS

The excavation of deposition drifts can create a zone with higher hydraulic conductivity parallel to the drift. If the direction of the drift is perpendicular to the hydraulic gradient, no appreciable effects will be obtained. Even when the drifts are oriented maximally unfavourably with respect to the fractures and the hydraulic gradient, the effects are small. Only when the above conditions are combined with large differences in hydraulic conductivity between the rock and nearby fracture zones will an increase in the short travel time fraction be noticeable, see Figure 10-7.

The transport of radionuclides is controlled by the pathlines through the repository. The risk of placing canisters in positions that can give short groundwater travel times can be avoided by adapting the layout of the repository to the groundwater's flow pattern.

Provided that the rock block is sufficiently large, or that several adjacent blocks can be used for deposition, the disposal principle utilized provides a good opportunity to adapt the positions of drifts and deposition holes to progressively obtained information on the local properties of the repository rock. The analyses show that the hydraulic conditions in the evaluated repository block are such that the shortest travel times are always associated with a specific corner in the repository. For an area such as Finnsjön, the value of not depositing in this corner is greater than trying to avoid deposition positions that by chance have been located in unfavourable conditions.

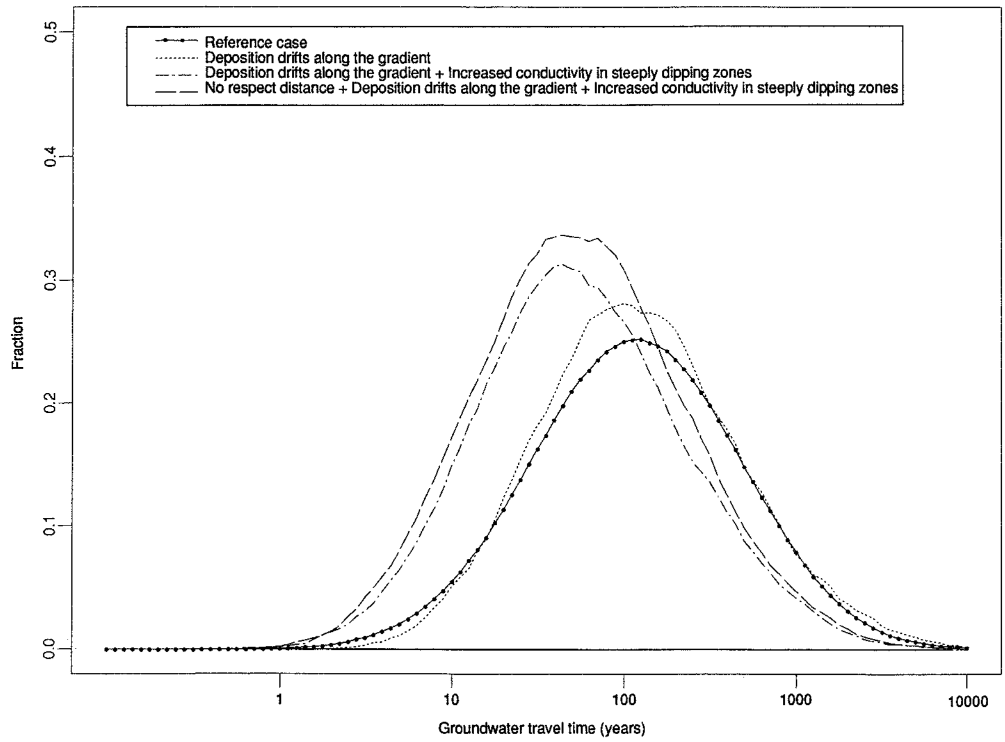



***Figure 10-7.*** *Dependence of groundwater travel times on increased conductivity around the repository drifts.*

The variations covering zones above and below the repository show that an exclusion zone between major flat-lying fracture zones and the nearest canister positions of around 100 m is well warranted. A change in the depth of the repository by 100 m up or down affects the travel times by a factor of two.

**In summary**, it can be concluded that some opportunity exists to exploit the potential of the local bedrock to act as a safety barrier by adapting the geometric configuration of the repository. However, the differences do not normally appear to be of such a magnitude that they would be decisive in determining whether a site is acceptable or not. One main reason for this is that the safety assessment takes into account the fact that the repository is extensive in space. Even if a certain placement of the repository were to bring a number of canister positions into a less favourable location, the safety of the repository as a whole would be affected only marginally.

Qualitative evaluations such as the above are deemed to be valid for all sites studied in Sweden. A quantification of the value of adapting the repository to local conditions is highly site-specific, however. Moreover, only part of the site-related information at Finnsjön has been obtained for the purpose of being used in a safety assessment.

Similar judgements of the importance of various parameters must nevertheless always be made when adapting a repository to a given site. There are great similarities as far as the incompleteness of the body of data is concerned between the premises for SKB 91 and the conditions that will prevail at an early stage of a site evaluation. The essential difference is that the geological investigations on a candidate site can be continuously focused on parameters and structures which are found to be important in the early analyses. Continued analyses based on a larger body of data, interspersed with verifying investigations and a refinement of the body of data, will permit a gradually improved understanding to be obtained of the safety-related performance of the site and a local adaptation of the repository design.

The assessment sequence that has been used for SKB 91 has therefore been built up so that it permits running assessments in parallel with ongoing site characterization and repository design. This enables models to be replaced to match the desired level of detail, and databases and most parameters can be changed in a simple manner, without requiring modifications in models and computer programs.

## 10.5 SUMMARIZING CONCLUSIONS

The SKB 91 safety assessment shows that a repository constructed deep down in Swedish crystalline basement with engineered barriers possessing long-term stability fulfils the safety requirements proposed by the authorities with ample margin. The safety of such a repository is only slightly dependent on the ability of the surrounding rock to retard and sorb leaking radioactive materials. The primary function of the rock is to provide stable mechanical and chemical conditions over a long period of time so that the long-term performance of the engineered barriers is not jeopardized.

SKB 91 has shown that the safety-related requirements on a site where a final repository is to be built are such that they are probably met by most sites SKB has investigated in Sweden. The assessments also show that there are a number of factors that can strongly influence how the bedrock performs as an extra safety barrier. Examples are the presence and location of flat-lying structures and their hydraulic conductivity.

SKB 91 constitutes an example of how performance and safety assessments can be used to shed light on the importance of different geological structures in a potential repository area and to clarify factors that are essential from a safety point of view. The methodology can, in the continued siting work, be utilized to adapt the repository in such a way that the potential of the rock to contribute to the safety of the repository is effectively utilized. However, this requires access to site-specific data and an opportunity to augment these data continuously as the safety assessments progress.

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Ebbe Eriksson[1], Bertil Johansson[2], Margareta Gerlach[3], Stefan Magnusson[2], Ann-Chatrin Nilsson[4], Stefan Sehlstedt[3], Tomas Stark[1]
[1]SGAB, [2]ERGODATA AB, [3]MRM Konsult AB
[4]KTH
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Kaj Ahlbom[1], Jan-Erik Andersson[2], Rune Nordqvist[2], Christer Ljunggren[3], Sven Tirén[2], Clifford Voss[4]
[1]Conterra AB, [2]Geosigma AB, [3]Renco AB,
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Björn Lindbom, Anders Boghammar
Kemakta Consultants Co, Stockholm
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Swedish Institute for Metals Research, Stockholm
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Johan Claesson
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Roland Pusch, Harald Hökmark
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J E Geier, C-L Axelsson, L Hässler,
A Benabderrahmane
Golden Geosystem AB, Uppsala, Sweden
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Sven Norman
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**Description of the transport mechanisms and pathways in the far field of a KBS-3 type repository**
Mark Elert[1], Ivars Neretnieks[2], Nils Kjellbert[3],
Anders Ström[3]
[1]Kemakta Konsult AB
[2]Royal Institute of Technology
[3]Swedish Nuclear Fuel and Waste Management Co
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'Sif Laurent[1], Stefan Magnusson[2],
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[1]IVL, Stockholm
[2]Ergodata AB, Göteborg
[3]Dept. of Inorg. Chemistry, KTH, Stockholm
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Sven Norman
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Jordi Bruno[1], Patrik Sellin[2]
[1]MBT, Barcelona Spain
[2]SKB, Stockholm, Sweden
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Sven Follin
Department of Land and Water Resources,
Royal Institute of Technology
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Vesa Henttonen, Miko Suikki
JP-Engineering Oy, Raisio, Finland
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W Dershowitz[1], K Redus[1], P Wallmann[1], P LaPointe[1], C-L Axelsson[2]
[1]Golder Associates Inc., Seattle, Washington, USA
[2] Golder Associates Geosystem AB, Uppsala, Sweden
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Kung Chen Shan[1], Wen Xian Huan[1], Vladimir Cvetkovic[1], Anders Winberg[2]
[1] Royal Institute of Technology, Stockholm
[2] Conterra AB, Gothenburg
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Mats Skålberg, Jan-Olov Liljenzin
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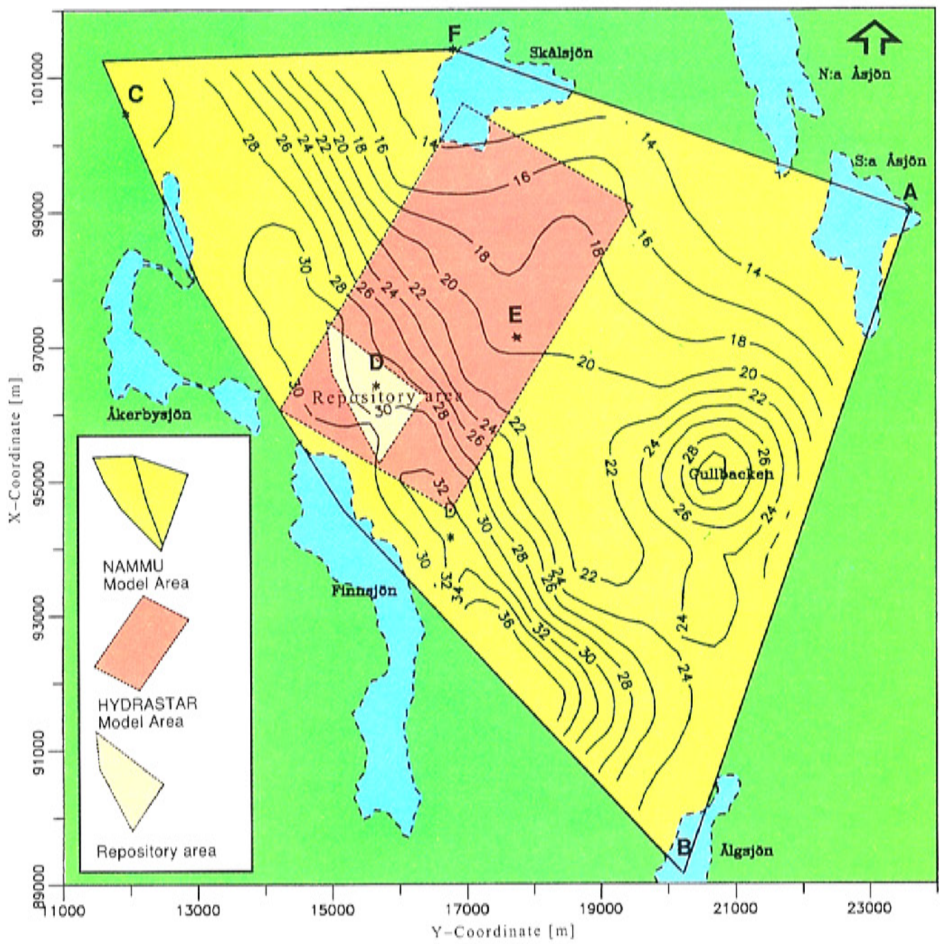
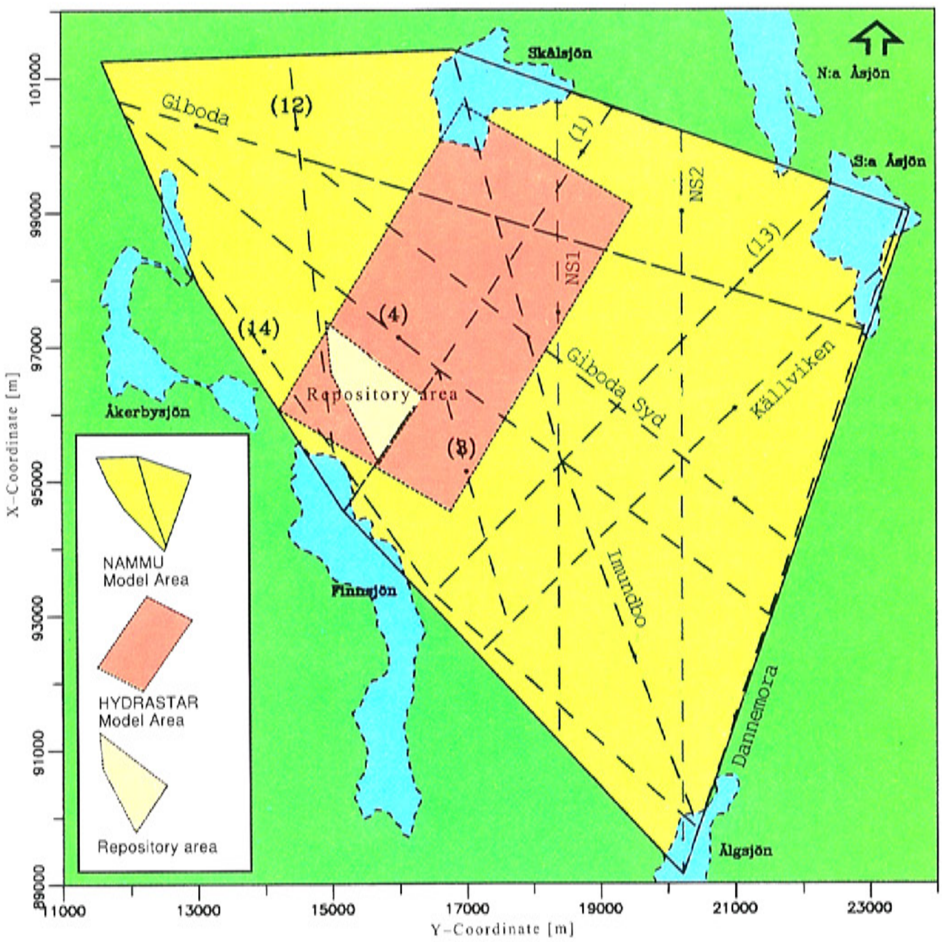


Skålsjön
N:a Åsjön
S:a Åsjön
Åkerbysjön
Finnsjön
Gullbacken
Älgsjön
Repository area
A
B
C
D
E
F
NAMMU Model Area
HYDRASTAR Model Area
Repository area
X-Coordinate [m]
Y-Coordinate [m]

Skålsjön
N:a Åsjön
S:a Åsjön
Åkerbysjön
Finnsjön
Älgsjön
Giboda
Giboda Syd
Källviken
Imundbo
Dannemora
NS1
NS2
(1)
(4)
(5)
(12)
(13)
(14)
Repository area
NAMMU Model Area
HYDRASTAR Model Area
Repository area
X-Coordinate [m]
Y-Coordinate [m]