Final Storage of Spent Nuclear Fuel – KBS-3

Summary

SKBF/KBS

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PREFACE

The Forsmark 3 and Oskarshamn 3 nuclear power reactors, which are owned by Forsmarks Kraftgrupp AB and OKG AB, are planned to be commissioned during 1984 and at the turn of the year 1984/85, respectively. In order for these plans to be fulfilled, Swedish law requires a special permission from the Government before charging the two reactors with nuclear fuel. The condition for granting such permission is that the reactor owners shall have demonstrated that the spent nuclear fuel can be handled and finally disposed of in a safe manner. The means of achieving this have been investigated within the Swedish Nuclear Fuel Supply Company, Division KBS. The results have been presented in the report "Final storage of spent nuclear fuel - KBS-3", which is a supporting document for the application for permission to charge the Forsmark 3 and Oskarshamn 3 reactors with fuel.

A summary of the handling procedure and the design of the final repository, as described in KBS-3, is given here. The emphasis has been laid on the repository and an evaluation of its long-term safety. Section 22 at the end of the summary presents the general safety conclusions.

Stockholm, May 1983
SWEDISH NUCLEAR FUEL SUPPLY COMPANY (SKBF)
Division KBS

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FINAL STORAGE OF SPENT NUCLEAR FUEL–KBS-3

SUMMARY

1 INTRODUCTION

Swedish legislation prescribes that a new power reactor may only be charged with nuclear fuel after special permission has been received from the Government. In order for such permission to be given, the reactor owner must have demonstrated that the spent nuclear fuel or radioactive waste from this fuel can be finally disposed of in a manner that fulfills very high safety requirements.

Within the KBS project, the Swedish nuclear power utilities have investigated how the legal requirements could be met. The results have been presented in two reports, KBS-1 (November 1977) concerning vitrified high-level reprocessing waste and KBS-2 (September 1978) concerning unreprocessed spent nuclear fuel. On the basis of KBS-1 and a reprocessing contract with Cogema of France, the Government has granted fuelling permission for four reactors. At the request of the Swedish Government, KBS-1 as well as KBS-2 has been produced by Swedish and foreign experts. The Government has, however, not made any statement on the acceptability of the method presented in KBS-2. The forthcoming commissioning of the reactors Forsmark 3 (1984) and Oskarshamn 3 (turn of the year 1984/85) also require special fuelling permits. Applications for the permits are based on principles described in KBS-2 for final storage of spent nuclear fuel without reprocessing. Since 4-5 years have passed since KBS-2 was published, it has, however, been deemed warranted to compile a new report, KBS-3, in which the development during recent years is taken into consideration.

The account in KBS-3 is based on the following generally accepted basic principles:

- A very high level of safety is required, in both the short and long term.

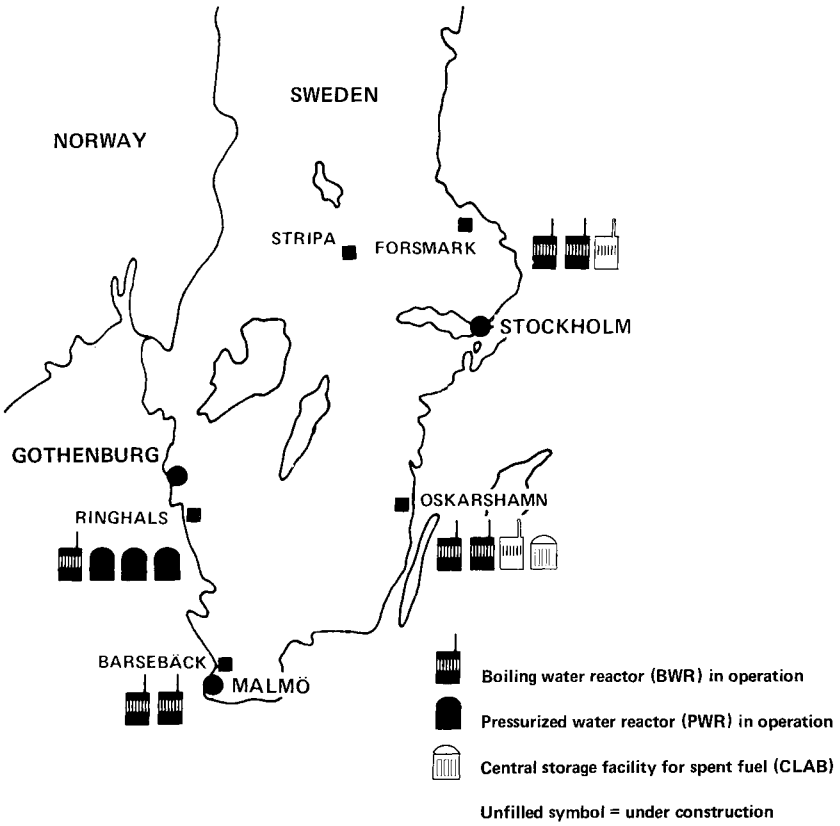


Figure 1. Location of Swedish nuclear power facilities.

- Burdens on future generations shall be avoided wherever possible.

- It shall be possible to carry out the necessary measures with the highest possible degree of national independence.

Different conceptual methods for the final disposal of radioactive waste have been discussed internationally. Efforts have been concentrated more and more on final disposal in deep and stable geologic formations. In Sweden, as in many other countries with similar geologic conditions, final storage in crystalline bedrock represents a realistic solution.

KBS-3 describes how a system for safe final disposal of spent nuclear fuel can be designed on the basis of the present-day state of knowledge. The intention is not to define exactly how and where a final repository for spent fuel will be built. According to current plans, the final repository is to be built during the

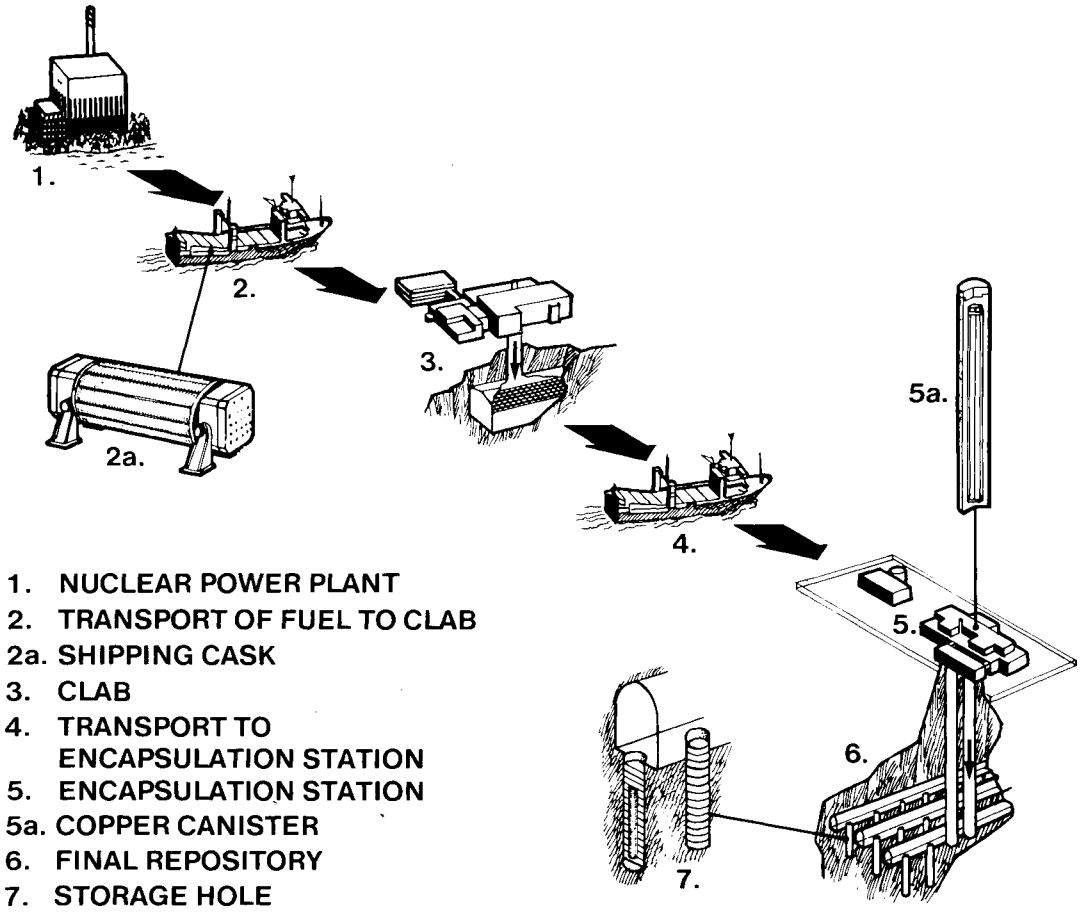


Figure 2. Handling sequence for spent nuclear fuel.

period 2010-2020. In the intervening period up to this time, the extensive research and development work being pursued in many countries will provide further data on which to base the final design.

The report deals with all necessary handling steps, but the main emphasis has been laid on the final repository and related long-range safety assessments.

The location of the Swedish nuclear power facilities is shown in figure 1.

2 HANDLING SEQUENCE AND FUNCTION OF THE FINAL REPOSITORY

General premises

Most of the equipment and operations that are employed in the different facilities are based on experience from nuclear power plants and other industrial activities.

A fundamental principle in the system presented here is that the long-term safety of the repository shall not be dependant upon supervision after the final repository has been sealed.

In order to meet the high safety requirements, the multiple barrier principle is applied in the final repository. This means that safety shall not be dependent upon a single barrier, but rather shall be based on the function of a number of barriers that are independent of each other to as great an extent as possible.

Handling sequence

The handling sequence for the spent nuclear fuel is illustrated schematically in figure 2.

1. The spent nuclear fuel is stored in the storage pools at the nuclear power plants for at least 6 months.

2. The fuel is transported in specially-designed casks (2a) from the power plants to a central intermediate storage facility.

3. The fuel is stored in the intermediate storage facility, CLAB (which is used for the fuel from all Swedish reactors), in water-filled pools for 40 years.

4. The fuel is transported from the CLAB to an encapsulation station situated above ground in connection with the final repository.

5. In the encapsulation station, the fuel is enclosed in copper canisters (5a).

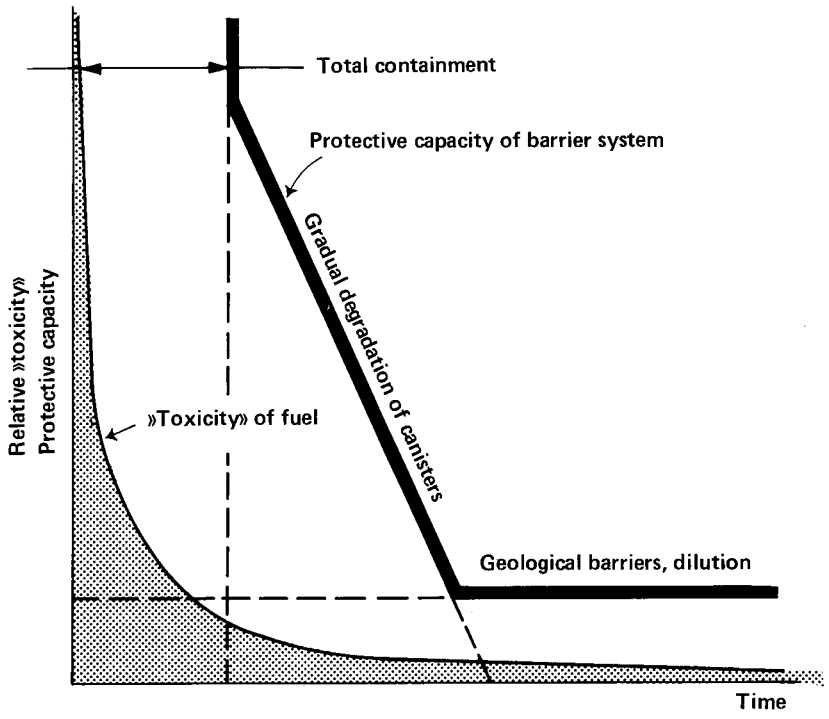


Figure 3. Schematic function of the barrier system.

6. The copper canisters with the fuel are transferred to a final repository in rock at a depth of about 500 m.

7. In the final repository, the canisters are deposited singly in deposition holes, where they are surrounded by a buffer material consisting of highly compacted bentonite clay.

After all canisters have been deposited, the final repository is sealed by filling all tunnels and shafts with a mixture of sand and bentonite clay.

Function of the final repository

When it is deposited in the final repository, the spent fuel has very high radioactivity and thereby high potential toxicity. This radioactivity declines relatively rapidly to begin with, but increasingly slower with time. Activity after deposition declines at approximately the following rate (see also figure 6).

after	100 years	to	1/10th
"	1 000 years	"	1/100th
"	10 000 years	"	1/400th
"	100 000 years	"	1/3 000th
"	1 000 000 years	"	1/8 000th
"	10 000 000 years	"	1/40 000th

The harmful effects on the biosphere of the radioactive substances in the fuel can be prevented in two ways: total containment and/or dispersal at a slow rate and with high dilution so that the concentrations that can reach the biosphere with the groundwater will be acceptably low. It cannot be assumed that total containment will last forever. Therefore, protection in the very long term must be based on slow dissolution, slow dispersal, high dilution and radioactive decay.

The barriers in the system described here consist of:

- The fuel itself, which has very low solubility in water.

- The canister, which isolates the spent fuel completely from the environment for a very long period of time.

- The buffer material - the highly compacted bentonite clay - see figure 11, which prevents flowing groundwater from coming into contact with the canister or, after it has been penetrated, with the spent fuel.

- The rock that surrounds the final repository has been chosen so that the flow of groundwater in it is very low. A strong retardation of most radioactive substances also takes place in the rock through chemical processes between the minerals and the radioactive substances. In this manner, a very large portion of the radioactivity will have time to decay during its transport in the rock.

The basic function of the barriers is illustrated schematically in figure 3.

After deposition and in connection with the sealing of tunnels and shafts, drainage of the repository is stopped. All remaining cavities and pores will then slowly fill with water. When the groundwater seeps in, the bentonite clay in the buffer and backfill material will absorb water and swell. After voids in the mass are filled up and no further swelling can take place, a swelling pressure is instead built up. When this process has achieved equilibrium, the buffer material will be at least as impervious as the surrounding rock. No significant water flow can then take place. Substances dissolved in the water will therefore only be able to be transported in the clay or the clay/sand mixture by diffusion.

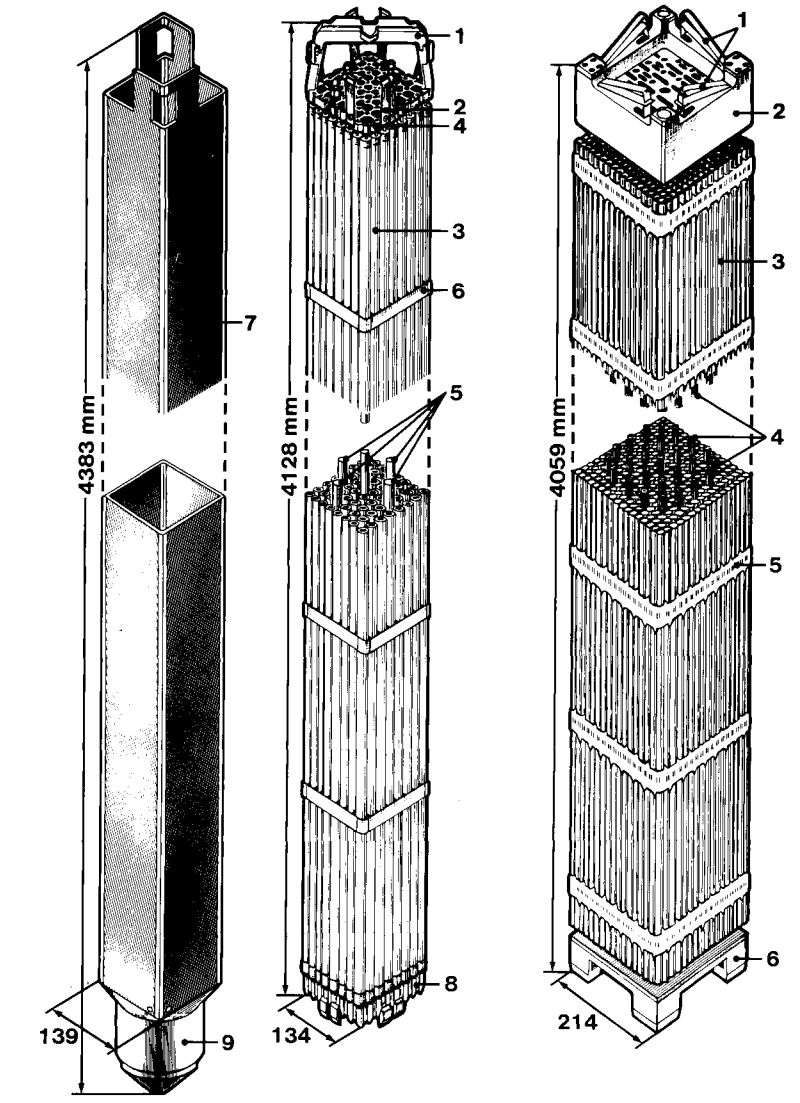
Substances in the groundwater that can attack copper will reach the canister surface in small quantities but over a long period of time and cause corrosion. After a very long time, the corrosion can reach the enclosed fuel. A leaching of the radioactive substances incorporated in the fuel can then begin. Due to the low rate of water flow and the low solubility of the substances, leaching will proceed extremely slowly.

Substances that have been dissolved from the fuel will diffuse out through the buffer material and can then be transported further with the groundwater. Most substances are highly retarded as a consequence of various chemical and physical processes, and a large portion of the radioactive substances will decay and convert into stable substances before they reach the biosphere.

However, certain very long-lived radioactive substances might under unfavourable circumstances reach the biosphere after a very long period of time. Since they accompany the groundwater, their outflow can take place in a well, in a water course or in the ocean. It must then be required that their concentrations is so low that they do not alter the natural radiation environment to any significant extent.

Siting aspects

A final repository can only be built at a site where there is a sufficiently large rock formation with suitable geological, hydrological and geochemical properties. The siting of the repository is



1 HANDLE
2 SPRING CLIPS
3 FUEL ROD BUNDLE
4 TOP TIE PLATE
5 TIE ROD
6 SPACER GRID
7 FUEL CHANNEL
8 BOTTOM TIE PLATE
9 TRANSITION PIECE

Figure 4. BWR fuel.

1 SPRING CLIPS
2 TOP TIE PLATE
3 FUEL ROD
4 CONTROL ROD GUIDE TUBE
5 SPACER GRID
6 BOTTOM TIE PLATE

Figure 5. PWR fuel.

only secondarily determined by economic and social factors. Today's plans assume that a siting decision will be reached towards the end of the 1990s.

The treatment facility where the spent fuel is to be encapsulated should, for practical reasons, be co-sited with the final repository.

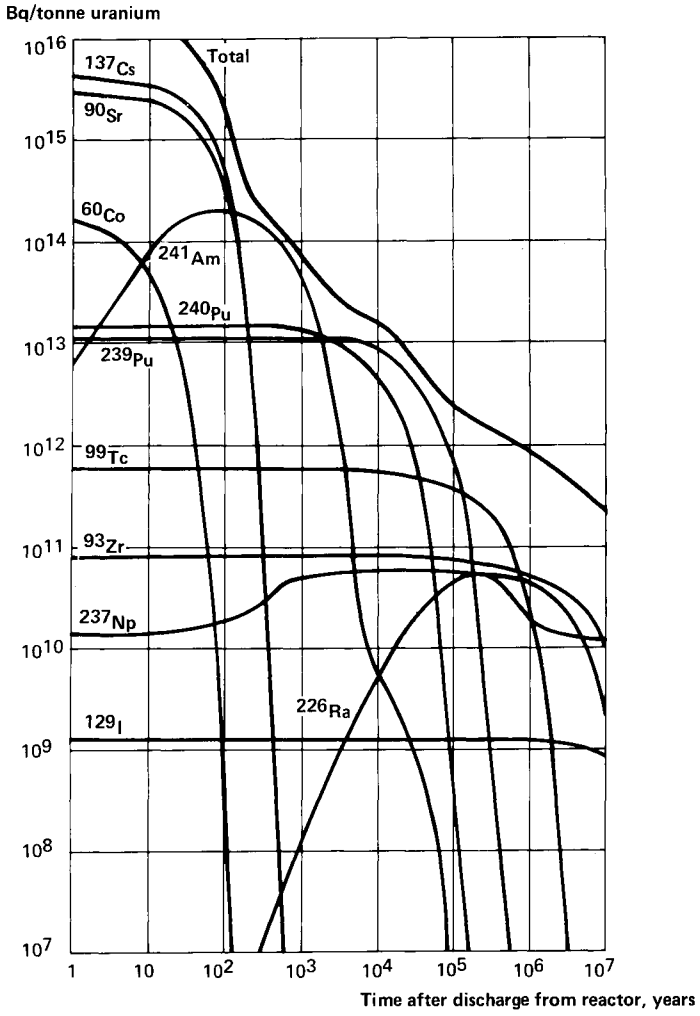


Figure 6. Radioactivity in spent fuel.

Repository depth

A final repository must be located deep enough so that it will not be affected in the long run by events on the surface such as erosion (e.g. resulting from glaciations), well drilling, underground construction etc. A certain depth is also required in order for hydraulic conductivity to be sufficiently low and chemical conditions favourable. On the other hand, the repository must not be located so deep that high rock stresses jeopardize the stability of the bedrock or the temperatures are too high. At very great depths, it is also more difficult to perform investigations from the surface. In good Swedish bedrock, the safety requirements can be met at a repository depth of 400-500 m. However, repository depths of up to about 1 000 m should not pose any major technical problems.

Figure 7. Vehicle, transport cask and ship for transport of spent nuclear fuel.

3 SPENT NUCLEAR FUEL

Premises

According to a resolution adopted by the Swedish Parliament, no Swedish reactor shall be in operation after the year 2010. The total quantity of spent nuclear fuel that will be disposed of will be dependent upon how long the individual reactors are in operation. A report submitted 1982 by SKBF to the National Board for Spent Nuclear Fuel - Plan 82 - for the purpose of determining a waste fee was based on an operating period for each reactor of 25 years.

This calculation premise, which was determined so that the fee per produced kWh will not be underestimated, gives a total quantity of spent fuel equivalent to about 6 000 tonnes of uranium. If all reactors are in operation up to and including the year 2010, the total quantity of fuel will be slightly over 7 000 tonnes. Variations within the range 6 000-7 500 tonnes are without importance for the fundamental systems or the safety assessments reported here.

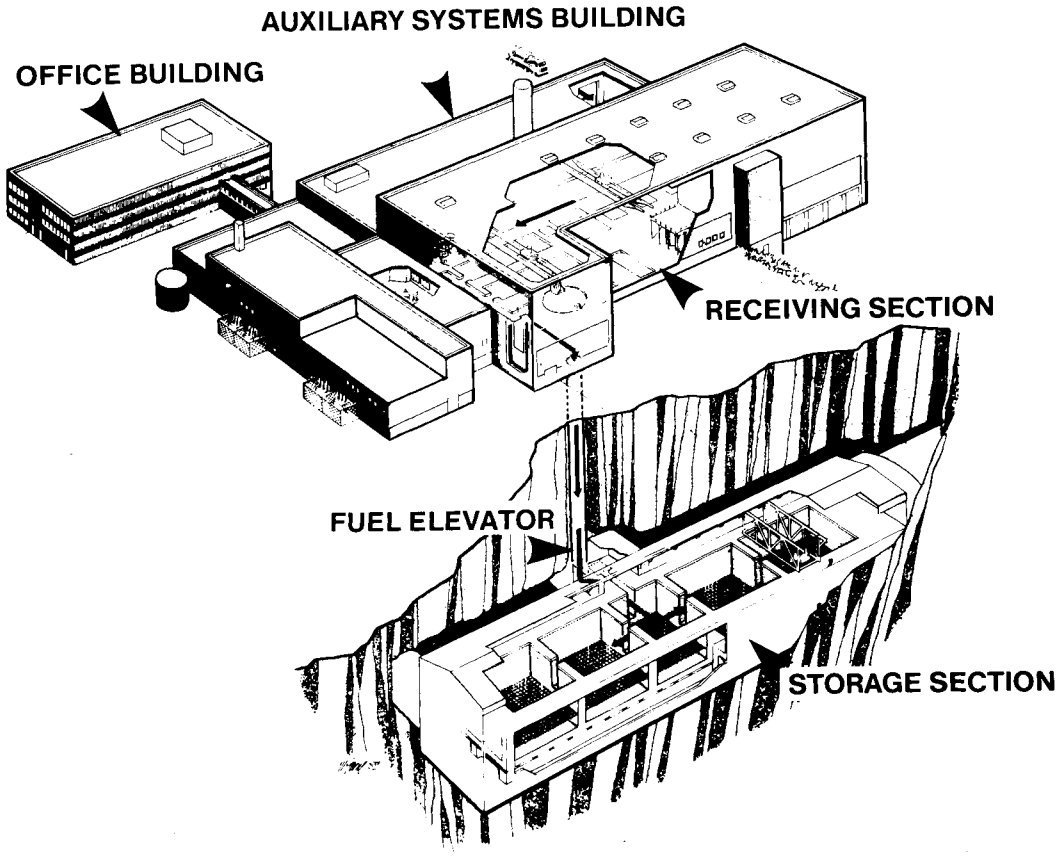


Figure 8. Perspective drawing of the CLAB.

Figs. 4 and 5 show the fuel types that are used in Swedish reactors. The fuel assemblies are slightly over 4 m long. The BWR assemblies contain 63 fuel rods, have a side of 139 mm and weigh about 300 kg. The PWR assemblies contain 264 fuel rods, have a side of 214 mm and weigh about 700 kg.

The spent fuel consists of 95% uranium dioxide, 3-4% fission products and about 1% plutonium and other actinides.

Radioactivity and residual heat in spent nuclear fuel

Figure 6 shows how the radioactivity of various elements in the spent fuel decline with time. The residual heat flux declines during the first thousand years to approximately one tenth of what it was at the time of deposition.

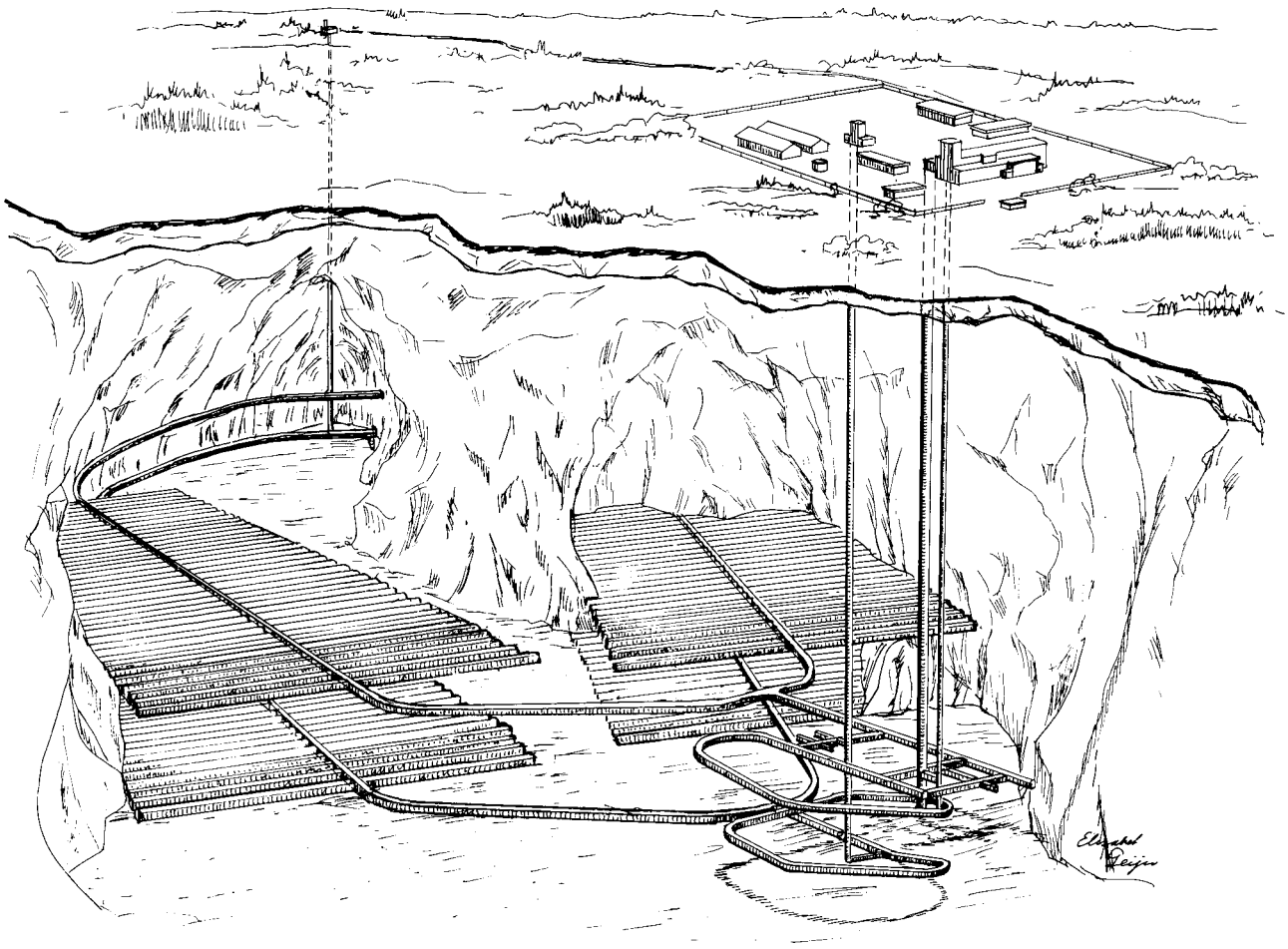


Figure 9. Perspective drawing of final repository.

4 FACILITIES AND EQUIPMENT

General

The facilities that are required for final storage and associated activities are illustrated schematically in figure 2.

Transport system

A transport system for radioactive waste products has been developed under the auspices of SKBF. Since all Swedish nuclear reactors are located on the coast, the system has been based on sea transport. The main components are a specially designed transport ship, transport casks for spent fuel and terminal vehicle, see figure 7. The transport system, which was taken into operation during 1982, will later be augmented with transport casks for other types of radioactive waste as well.

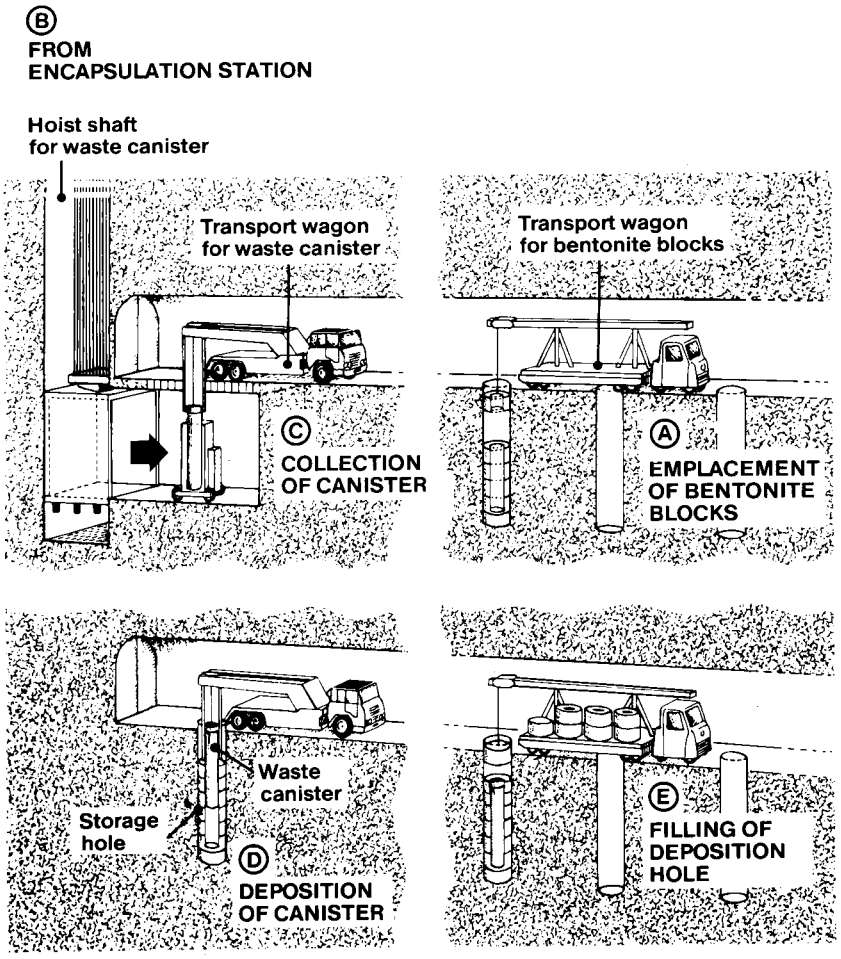


Figure 10. Canister deposition in final repository.

Central storage facility for spent fuel, CLAB

A central storage facility for spent fuel for all Swedish nuclear reactors is under construction at the Oskarshamn Nuclear Power Station. The plant, which is called CLAB and is shown in figure 8, will be ready to receive spent fuel in 1985.

The CLAB is being built in a first stage for the storage of 3 000 tonnes of fuel. The facility is prepared for expansion with additional storage capacity.

Encapsulation station

Before final disposal, the fuel is enclosed in copper canisters. This takes place in the encapsulation station, which is built in connection with the repository.

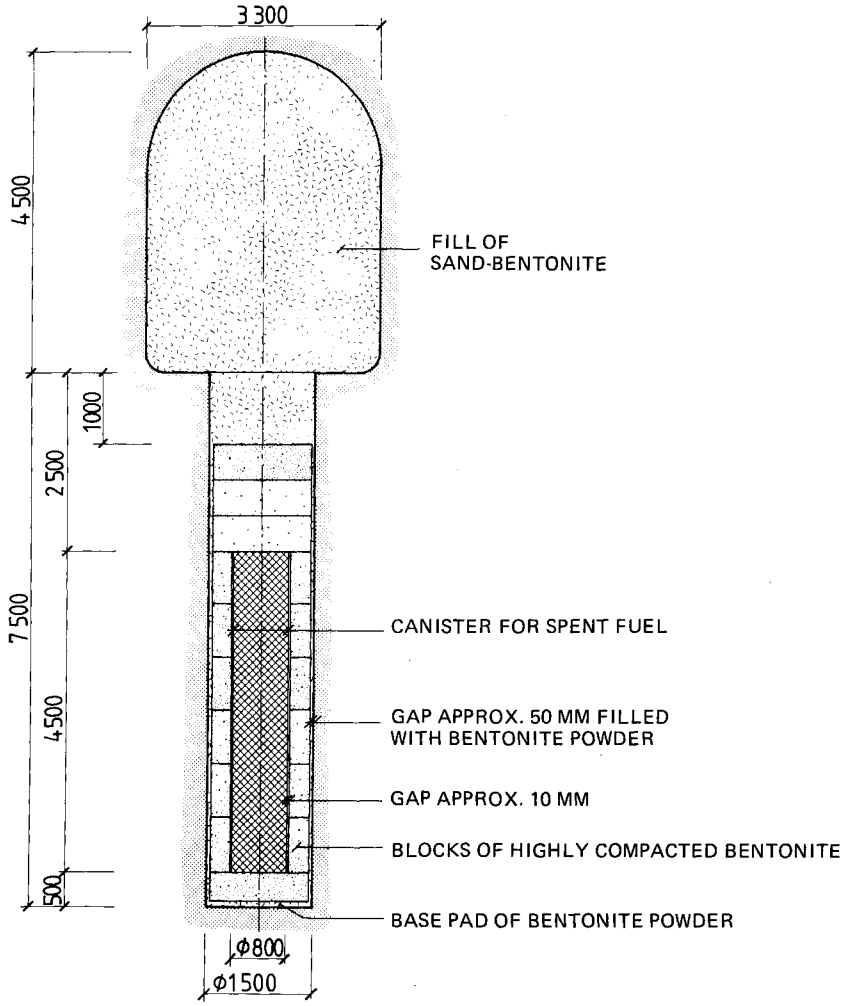


Figure 11. Deposition hole with canister, buffer material and backfill.

Two different methods for fabricating copper canisters have been studied, see section 10.

The BWR fuel's boxes and the PWR fuel's boron glass rods are also treated in the encapsulation station. They are cast in concrete and then transported to a special final repository.

Final repository for spent fuel

The encapsulated fuel is finally disposed of by deposition in a selected rock formation. The location and geometry of the final repository will be adapted to the local geological properties of the bedrock. Figure 9 shows an example of how a final repository can be designed in two levels.

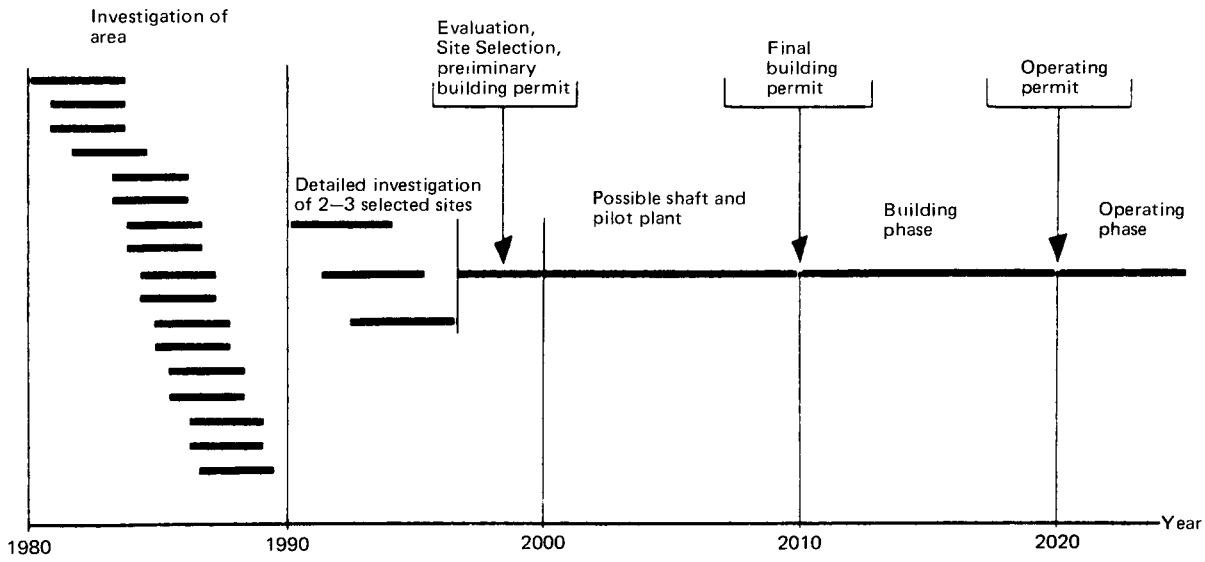


Figure 12. General timetable for final repository.

The final repository consists of a system of parallel tunnels with vertical deposition holes, figure 10. In the deposition holes, the canisters are surrounded by buffer material of highly compacted bentonite clay, see figure 11. When deposition has been concluded, the tunnels and shafts are backfilled with a mixture of bentonite and sand.

The spacing between the storage tunnels - 25 m in the case of a one-level repository and 33 m in the case of a two-level repository - and between the individual deposition holes - 6 m - are chosen so that the temperature in the final repository will be well below 100°C everywhere.

This temperature limit has been included to ensure that the bentonite clay does not undergo chemical changes that could affect its function in the long term. At the same time, the temperature limit keeps the heat-induced stresses in the rock mass to a moderate level.

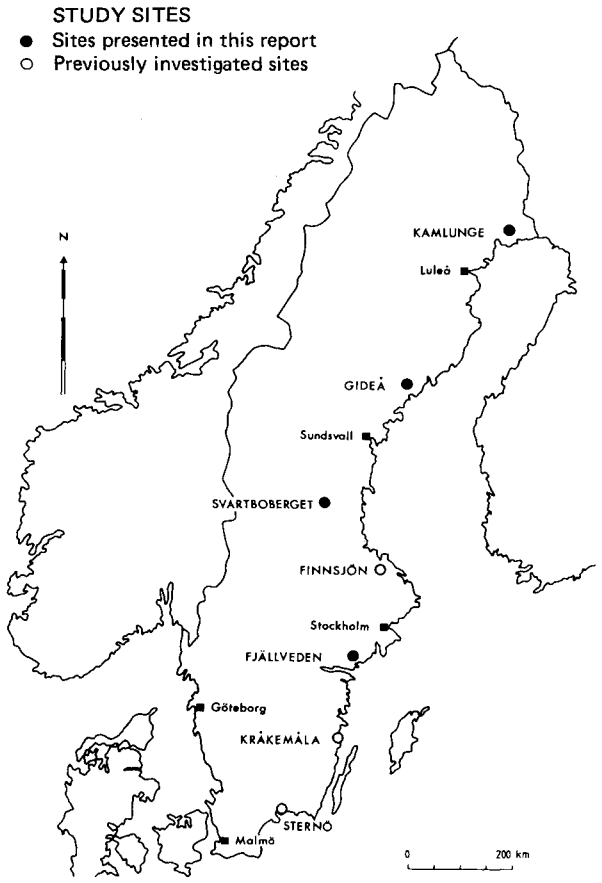


Figure 13. Investigated sites.

5 SITE INVESTIGATIONS

In order to be able to carry out calculations in the safety analysis for a final repository on a given site, it is necessary to have knowledge of the hydrological properties of the bedrock, existing crushed and fracture zones and the chemistry of the groundwater. Considerable efforts have been made in recent years to improve methods and equipment for measuring various parameters in the field.

A final decision on the siting of the final repository is expected to be made towards the end of the 1990s. In order to ensure that a broad and reliable body of data is available for this decision, a relatively large number of sites will be investigated during the 1980s, see figure 12. The results from the study sites at Fjällveden, Gideå, Kamlunge and Svartboberget, which have been investigated in recent years, are presented in this report, see figure 13.

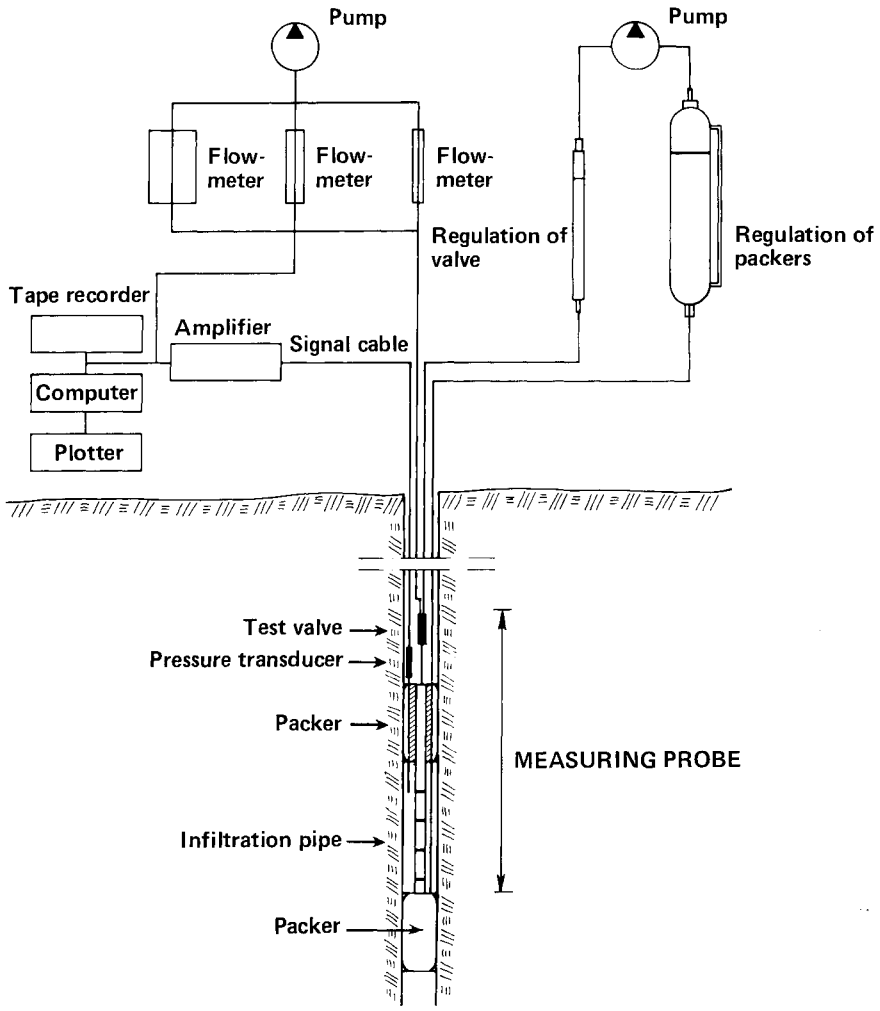


Figure 14. Equipment for measurement of hydraulic conductivity of the rock.

The investigations have been based on a standard programme adapted to local conditions. The programme is divided into four phases:

1. Reconnaissance for choice of study sites
2. Investigations from the ground surface
3. Investigations in boreholes
4. Evaluation and model work

In choosing study sites, such factors as topography, the presence of major fracture zones, rock type distribution and structure of the rock mass, occurrence of ores and groundwater capacity in nearby wells drilled in the rock are taken into consideration.

The reconnaissance phase includes drilling of one deep reconnaissance borehole within the sites deemed to be of interest.

The sites that are selected for further investigation cover an area of 4-5 km^2. There, surface investigations are carried out including logging of rock types, fractures and fracture zones. At the same time, geophysical ground surveys are carried out employing different methods in order to obtain an indication of, for example, possible fracture zones underneath soil-covered sections and the slope of these zones.

Both hammer-drilled boreholes and diamond boreholes are included in the depth investigations. The hammer boreholes, which are relatively shallow (down to 200 m), are aimed primarily at determining the character and orientation of fracture zones.

Deeper boreholes down to 500-700 m have been drilled in the form of core boreholes with a diameter of 56 mm. Up to 15 such holes have been drilled within each site. The core boreholes have been located and directed in such a manner as to obtain the best possible information on the geological and hydrological properties of the deep rock mass and on the character and water content of fracture zones.

The hydraulic conductivity of the rock has been determined by means of water injection tests, where water is injected into sealed-off sections in the boreholes. The sections are sealed off by expanding rubber packers against the walls of the borehole, see figure 14.

In connection with the water injection tests, the natural water pressure is also measured at different levels in the boreholes.

In order to obtain information on the chemical properties of the groundwater and their variations, water samples from different depths in certain boreholes have been analyzed. The sampling is done by pumping from sections in the boreholes sealed off by a packer arrangement similar to that used in the water injection tests.

6 GROUNDWATER MOVEMENTS IN THE ROCK MASS

The bedrock as a water-conducting medium

Groundwater movements in the rock are dependent on characteristics of

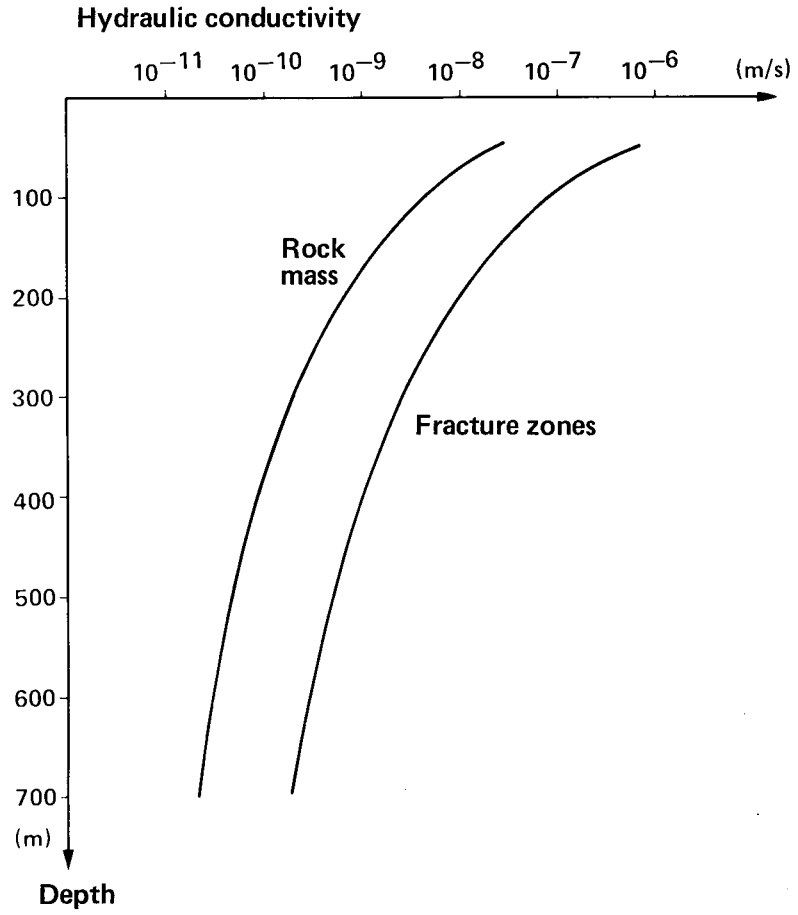


Figure 15. Example of variation of hydraulic conductivity with depth.

fracture system. The width of the fractures, and thereby the hydraulic conductivity of the rock, normally decreases with increasing depth due to the increasing load exerted by the overlying rock.

Regarded on a large scale, the crystalline bedrock can be considered to be a porous medium, where the relationship between groundwater flow (q) and pressure gradient (i) can be expressed by Darcy's law:

$$q = K \quad i$$

The coefficient K is a measure of the rock's hydraulic conductivity.

Only a portion of the fractures found in drill cores are water-conducting. Measurements within the investigated sites have shown that 15-30% of the fractures are water-conducting. The reason why certain fractures do not conduct water may be that fracture-filling materials have sealed the fracture, the width of the fracture is too small or that the fracture is not connected to the rest of the fracture system.

Hydraulic units

Different hydraulic elements are used in studies of the groundwater movements on the study sites.

1. Regional fracture zones of great extent and bounding large blocks of more solid rock.

2. Fracture zones of limited extent.

3. Rock mass, including normally occurring fracturing.

In order to characterize the hydraulic properties of the different elements, an "effective" hydraulic conductivity is used, which constitutes a mean value of individual conductivity values measured in the boreholes and is plotted as a function of depth below the ground surface, see figure 15.

Hydraulic gradient

The driving force for the groundwater is the pressure differences that exist between different points in the rock: the hydraulic gradient. In a wet climate, the hydraulic gradient is primarily determined by the topography, i.e. the groundwater table is close to the ground surface. The differences in groundwater head (i.e. pressure) are greatly levelled with depth, and the hydraulic gradients at the level of the repository are much lower than near the surface of the ground.

Model calculations

On the basis of the geometry of the main fracture systems and measured conductivities and gradients, a descriptive model has been drawn up for each site. For calculation of the size and direction of the groundwater flow, the site is divided into a number of three-dimensional elements to which defined properties are ascribed. By means of computerized calculations based on known relationships, a picture can be obtained of the variations of the groundwater head within the site. Groundwater flows, flow directions and transport paths can then be calculated from these results.

7 CHEMISTRY OF THE GROUNDWATER AND THE FRACTURE SYSTEMS

The rock repository is a chemical system with a solid stationary phase (the minerals in the rock, fracture fillings, buffer and backfill) and a liquid mobile phase (the groundwater).

Of special importance for the corrosion of the copper canister and the dissolution and dispersal of species in the fuel are the groundwater's pH and redox conditions as well as its content of corrosive substances and complexing agents.

The site investigations have included chemical groundwater analysis from a total of some 80 sampling points in boreholes at depths varying between about 100 and 700 m. The analyses have yielded the groundwater data given in the table below (the majority of all measured values lie within the given intervals).

pH	7-9
Eh	0-(-0.45)V
HCO_3^-	90-275 mg/l
SO_4^{2-}	0.5-15 mg/l
Cl^-	4-15 mg/l
HS^-	0-0.5 mg/l
Ca^{2+}	10-40 mg/l
Na^+	10-100 mg/l
Fe^{2+}	0.02-5 mg/l

In a few cases, considerably higher salt contents (NaCl) have been observed. The presence of water of both high and low salinity within limited areas indicates that the water exchange between nearby aquifers may be very slow.

Fracture minerals have been studied on drill cores from the investigated sites. This is of interest to shed light on the history of the fracture formation and to determine the sorption capacity in the fractures. The fracture minerals may have either higher or lower sorption capacity than the mother rock. In general, the capacity of the fracture minerals is higher.

8 CHANGES IN THE BEDROCK

The bedrock generally contains radioactive substances, which are characterized by the fact that they disintegrate with time at a mathematically defined rate at the same time as other substances are formed. These relationships can be utilized to determine how much time has passed since a certain rock or mineralization was formed or altered, and thus serve as a basis for a general geological history. It has been found that the oldest Swedish crystalline basement rocks are around 2 000 million years old and the youngest around 900 million years old.

Up to around 650 million years ago, a general denudation of the high-lying parts of the bedrock took place, and the decomposition products were deposited in depressions where sandstones sometimes formed.

During the period 650-300 million years ago, conditions in the Swedish basement were relatively stable, despite the fact that strong bedrock movements and deformations took place in the nearby Scandinavian mountain chain during a portion of this time.

During the period 300-50 million years ago, bedrock movements seemed to have increased at first and volcanism occurred at a number of places in Scandinavia. During the subsequent period up to 3 million years ago, only minor bedrock movements seem to have occurred and volcanism seems to have existed primarily in Northern Skåne and on the Norwegian coast. A number of land uplift periods can be distinguished, however.

From 3 million years ago to the present, traces exist of up to 11 different glaciations. The thickness of the most recent continental ice sheet is estimated to have been between 2 and 3 kilometres. It left the Stockholm region about 10 000 years ago. The land rebound - uplift - is still in progress. At certain places, specially in upper Norrbotten County, local bedrock movements that seem to be associated with the retreat of the ice have been observed.

The present-day Swedish bedrock presents a concentrated picture of all the changes that have occurred since it was formed between 1

and 2 billion years ago. On the basis of this picture and the time scale it represents, it is possible to make an assessment of how similar events can be expected to affect the bedrock during the next 1 million years.

The Swedish crystalline basement is characterized by the fact that it contains "blocks" of sound rock that are bounded by more or less pronounced fracture zones. These fracture zones have arisen during geologically more dramatic periods, the majority more than 650 million years ago. The possibility that the general fracture pattern in the bedrock will be altered to any great extent during the next million years can therefore be regarded as negligible. On the other hand, the possibility of occasional local displacements, which have been found to have occurred even during recent time in geological terms, cannot be excluded. Naturally enough, such movements tend to follow previously fractured and therefore weakened belts, which are of course avoided when selecting the site for a final repository.

The risk that a future rock displacement might intersect a deposition hole and damage a canister has been examined by studies of former fracture displacements on exposed outcrops. A statistical analysis of these observations reveals that, at the most, only one deposition hole in the final repository can be expected to be affected by a minor displacement over 1 million years. Minor displacements will not damage the canisters, as they are protected by the plastic buffer material. The consequences of a single canister being damaged and starting to leak at an early stage have been examined in the safety analysis.

9 BUFFER AND BACKFILL MATERIAL

The buffer material of highly compacted bentonite in the deposition holes, see figure 11, constitutes a mechanical and chemical zone of protection around the canister and limits the inward transport of corrosive substances from the groundwater to the canister surface. In a later stage, it limits the outward leakage of radioactive substances from a penetrated canister to the surrounding rock.

The backfill in tunnels and shafts, which consists of a mixture of bentonite and sand, lends mechanical stability to the excavated spaces and restores the hydrological conditions in the area.

The compacted bentonite clay possesses

- good bearing capacity, so that the canister is held in its position in the deposition hole
- good thermal conductivity
- good long-term chemical stability.

Compacted bentonite swells greatly when it absorbs water. If swelling is restrained, a high swelling pressure is instead created. This property gives the bentonite a self-sealing capacity and prevents water-bearing passages from being created in the material. The swelling pressure also forces the bentonite into any small fractures that may exist in the walls of the deposition hole, thereby sealing the fractures.

Extensive studies have been conducted of the properties of bentonite. Among other things, it has been found that pure bentonite with a density of about 2 t/m^3 has a hydraulic conductivity of 10^{-13} - 10^{-14} m/s, which means that the bentonite is less permeable to water than the surrounding rock. This means that the groundwater in the rock fractures does not flow through the filled deposition hole, but rather around it. The transport of various substances through the buffer takes place solely through diffusion. The hydraulic conductivity of a sand-bentonite mixture, which is used for backfill material in tunnels and shafts, is 10^{-9} m/s at the most, which is equivalent to "normal" low conductivity rock.

The swelling pressure of pure bentonite at a density of 2.0 - 2.1 t/m^3 has been measured when saturated with water to be about 10 MPa, both in the laboratory and in large-scale experiements within the Stripa project.

Observations in nature have shown that bentonite in the environment that prevails in the final repository remains chemically stable for

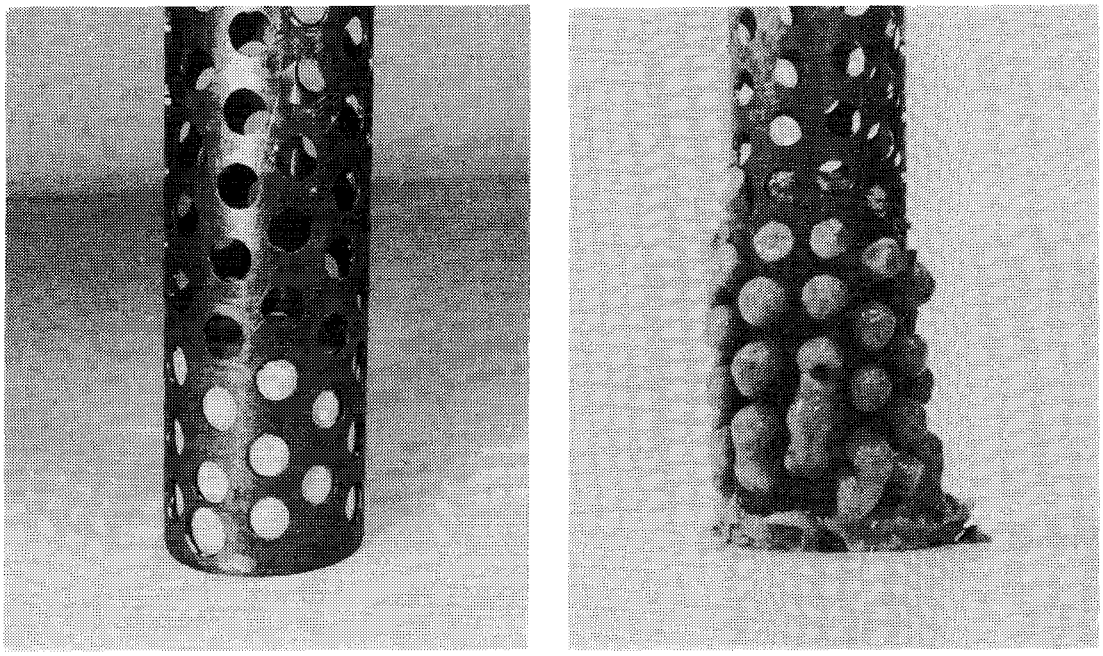
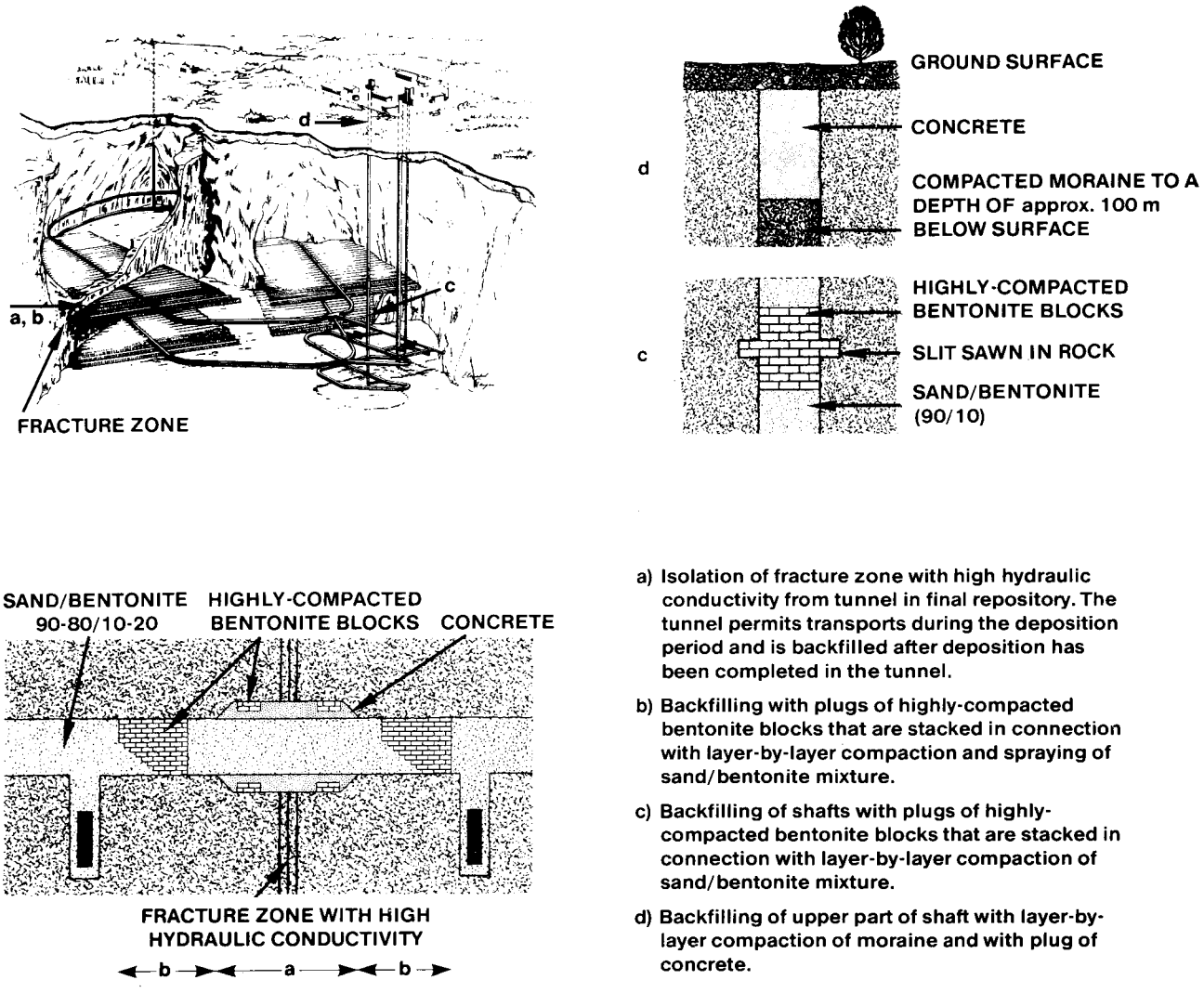


Figure 16. Perforated tube with pressed bentonite pellets for sealing of boreholes.



a) Isolation of fracture zone with high hydraulic conductivity from tunnel in final repository. The tunnel permits transports during the deposition period and is backfilled after deposition has been completed in the tunnel.

b) Backfilling with plugs of highly-compacted bentonite blocks that are stacked in connection with layer-by-layer compaction and spraying of sand/bentonite mixture.

c) Backfilling of shafts with plugs of highly-compacted bentonite blocks that are stacked in connection with layer-by-layer compaction of sand/bentonite mixture.

d) Backfilling of upper part of shaft with layer-by-layer compaction of moraine and with plug of concrete.

Figure 17. Plugs of highly-compacted bentonite for sealing of tunnels and shafts.

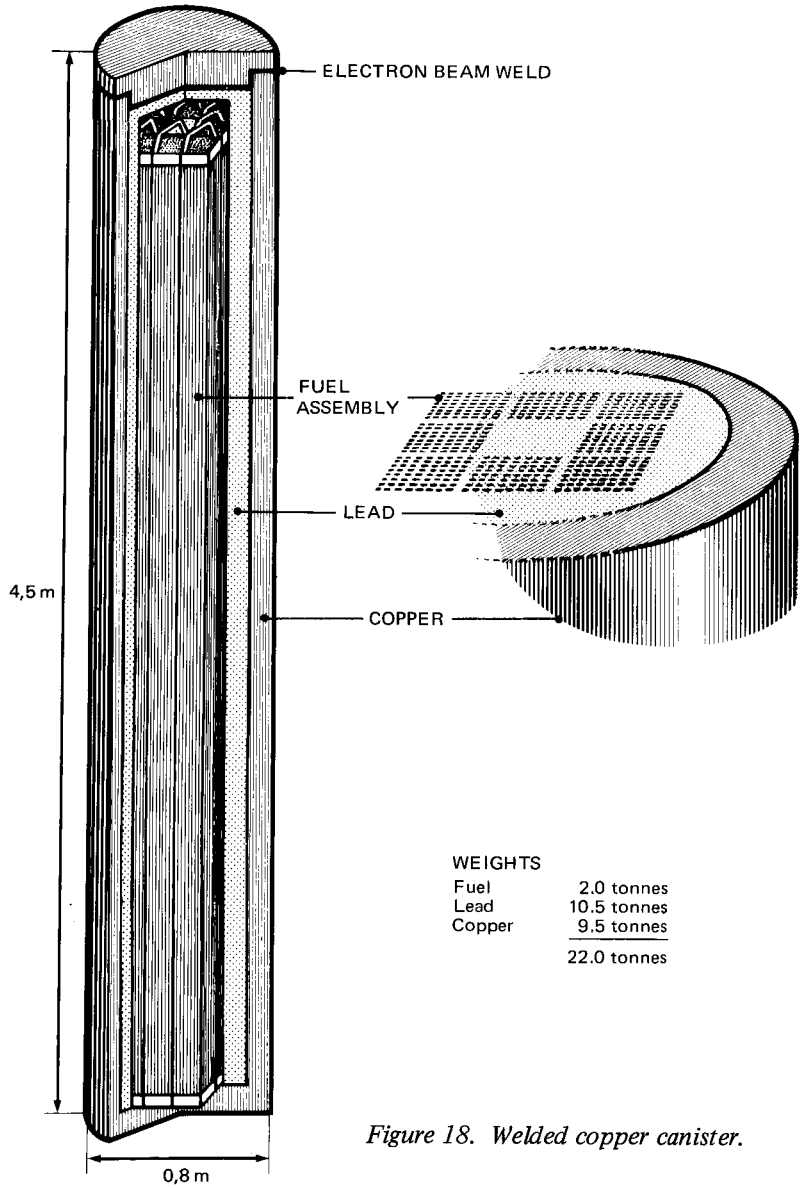


Figure 18. Welded copper canister.

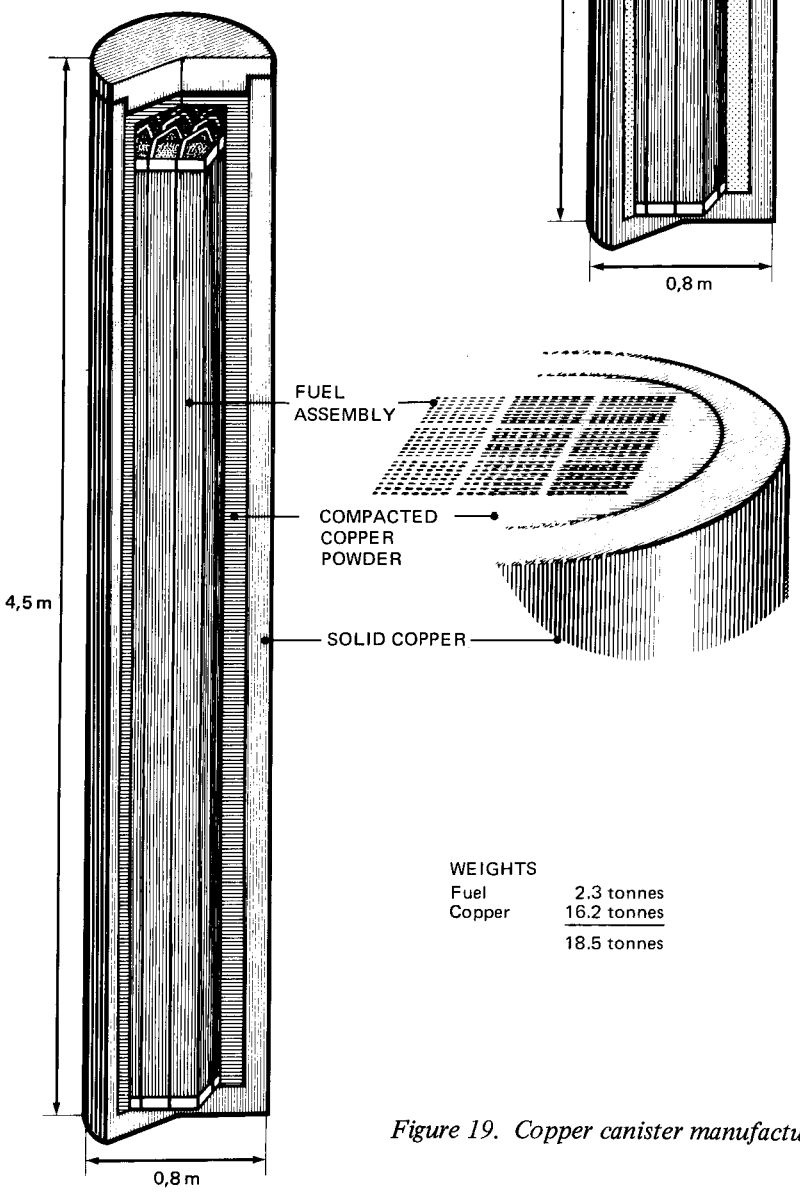


Figure 19. Copper canister manufactured by hot isostatic pressing.

more than 1 million years if the temperature does not exceed about 100°C. The final repository has therefore been designed to keep the temperature in the bentonite below 80°C.

Compacted bentonite is also planned to be used to plug investigation holes and as sealing bulkheads in tunnels and shafts, see figures 16 and 17.

10 THE CANISTER AND CANISTER CORROSION

The purpose of the canister is to contain the spent fuel completely and thereby prevent the dispersal of radioactive substances.

The canister described in KBS-3 is made of copper and has a wall thickness of 10 cm. Copper is not attacked by pure water, but only by corrosive substances that may be dissolved in the water.

Two different manufacturing methods for the copper canister have been studied. In the first method, see figure 18, the spent fuel is placed in a prefabricated canister, where the voids are filled with molten lead. A lid is then welded on by means of electron beam welding. In the second method, see figure 19, the voids in the canister are filled with copper powder, after which a lid is applied and the entire unit is pressed in a special furnace at high pressure (150 MPa) and high temperature (500°C) to a homogeneous body (hot isostatic pressing, HIP). Full-scale tests have been carried out with both methods with good results.

The main substances that can attack the copper canisters in a final repository are oxygen and sulphides. These substances may be present in the buffer material and the tunnel backfill as well as in the groundwater. Moreover, the radiation at thin-walled or penetrated canisters can split the water trough radiolysis, whereby corrosive substances are formed. The total quantities of corrosive substances that can come into contact with the canister can be calculated when their concentrations and the water flow rate are known. From these data, it is then possible to calculate the maximum quantities of copper that can corrode.

However, it cannot be assumed that corrosion of the copper canister will take place uniformly over the entire surface of the canister; here and there, deeper corrosion pits will be created. Studies of a large number of archaeological objects of copper and copper alloys with ages of up to several thousand years as well as earth electrodes for lightning conductors (copper plates) that have lain in the soil for several tens of years have shown that the deepest corrosion pit can be five times deeper than the mean depth of corrosion over the entire object. The same ratio has been observed on a piece of pure copper that had been lying at the place where it was found for at least 8 000 years.

In a foreign study where copper corrosion was studied in different soils, corrosion pits that have been up to 25 times the depth of the mean corrosion have been found. In that case, the chemical environment was probably much less favourable than that in a final repository. However, in order to examine the consequences of an extremely unfavourable case, calculations have also been carried out with a pitting factor of 25.

The expert group that has investigated canister corrosion has calculated the service life of copper canisters of varying wall thickness. No protective effect was attributed to the filling of lead or copper powder in the canisters in these calculations.

The conclusion of the group is that with a probable pitting factor of 5, a canister with a wall thickness of about 1 cm will remain intact for more than 1 million years. With a pitting factor of 25, the service life of the same canister is found to be at least 100 000 years. With a pitting factor of 25, a canister with a wall thickness of 6 cm will have a service life of more than 1 million years.

In order not to overestimate the service life of the canisters, the calculations have been based on values for groundwater flow, water chemistry etc. that are considerably less favourable than those that can be counted on to exist within the investigated sites.

Owing to, among other things, the fact that the flows and the groundwater's content of corrosive substances vary within a reposi-

tory site, corrosion penetration of the canisters will not take place simultaneously, but will be distributed over a very long period of time.

11 FUEL AND FUEL DISSOLUTION

The spent fuel itself constitutes the innermost of the barriers included in the final repository's barrier system. When the copper canister is penetrated by corrosion in the distant future, dissolution of the fuel can begin. Owing to their low solubility and the low rate of groundwater flow in the repository, the remaining long-lived radioactive substances will be dissolved and dispersed at a very slow rate.

Laboratory experiments have been conducted in Sweden, Canada and the United States to determine the dissolution rate of the spent fuel. The results of these experiments are difficult to interpret, however, and certain results point toward an extremely slowly dissolution; the entire quantity of fuel in a final repository can be estimated to have been dissolved only after hundreds of millions of years. Other results indicate dissolution times of a few tens of thousands of years. The safety evaluations have therefore been based on data for the water flow rate in the final repository and known solubility limits for different substances in the chemical environment prevailing there.

12 RADIONUCLIDE CHEMISTRY IN THE GROUNDWATER ENVIRONMENT

Radioactive isotopes of thorium, protactinium, uranium, neptunium and americium with long half-lives are present in the spent fuel. They are of dominant importance for the long-range safety evaluation. These nuclides belong to a group of elements called actinides and have similar chemical properties. The actinides can occur in different oxidation states and have a strong tendency to form complexes.

The groundwater's redox conditions, pH and carbonate content largely determine the chemical behaviour of the actinides in the repository environment.

The solubility of the actinides in the deep groundwaters in Sweden is low (less than 10 mg/l for all actinides) and their tendency to be sorbed on mineral surfaces in the rock is high. The solubility of uranium, which makes up the fuel matrix itself in the form of uranium dioxide, is of particular importance since the release of substances contained in the uranium is related to the dissolution rate of the uranium.

Both experiments and investigations of uranium concentrations in natural waters show that uranium has a very low solubility under the reducing conditions that prevail at deep levels in the rock.

In the immediate vicinity of the spent fuel, oxidizing conditions can arise due to radiolysis of the water. The solubility of the uranium then increases markedly and the concentration of carbonate in the groundwater will then determine how much uranium can go into solution. The solubility of neptunium then also increases sharply, while plutonium becomes less soluble and the other actinides have the same or lower solubility.

The radioactive fission and decay products in the spent fuel consist of a large number of different elements. Some of these are members of the lanthanide series and, like the actinides, form hydroxide and carbonate complex in the groundwater. Several of the metallic elements will be present in the form of free cations, e.g. cesium (Cs^{+}) and strontium (Sr^{2+}). Iodine will largely go into solution in the form of negative iodide ion (I^{-}).

Iodide ions are sorbed virtually not at all on the mineral surfaces. However, like other dissolved radionuclides, iodide can be retarded through diffusion into the micropores in the rock.

Technetium has high solubility under oxidizing conditions and a very low tendency to be sorbed on mineral surfaces. In reducing groundwater, technetium has low solubility and is sorbed to the same degree as e.g. cesium.

The metal components included in the spent fuel contain active isotopes of zirconium, cobalt, nickel, niobium and carbon. The metal components will be stored cast in concrete, which produces an

environment with a high pH. Both nickel and niobium then have very low solubility.

The formation of organic complexes and colloids incorporating the radioactive elements can lead to more rapid transport in the rock fractures. These effects have been taken into consideration in the safety analysis.

13 NUCLIDE DISPERSAL IN THE NEAR FIELD

By "near field" is meant the area around the canisters where the actual repository and its contents can directly influence the dispersal of radionuclides after the canister has been penetrated. The copper canister described here with a wall thickness of 10 cm has a probable life-time of 1 million years or more. In the study of conditions in the near field, however, it has been assumed that the first canister penetration occurs after 100 000 years. This permits a future simplification of canister design or, alternatively, lower demands on the quality of the bedrock.

The spent fuel consists to 95% of uranium dioxide crystals. Other radionuclides are incorporated in these crystals. Exceptions are certain noble gases, hydrogen, iodine and cesium, which have diffused out and been liberated from the fuel during reactor operation. Other substances are released at the rate at which the uranium dioxide is dissolved. The dissolution rate of the uranium dioxide therefore essentially determines the rate of release of other substances.

The uranium dioxide dissolves to a certain saturation point in water. If the dissolved uranium is not transported away, the dissolution will cease when the saturation limit has been reached. In reality, however, uranium diffuses out through the bentonite buffer and the dissolution process continues. The same applies to other released substances. Some nuclides, including plutonium, are less soluble than uranium and therefore dissolve more slowly.

The time it takes for certain radioactive substances to diffuse through the bentonite buffer is so long that they decay completely

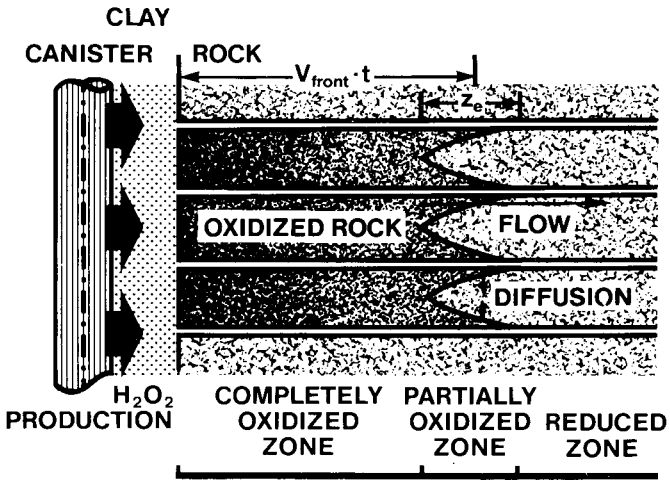


Figure 20. Propagation of the radiolysis front from a penetrated canister.

before they reach the groundwater in the rock fractures. Other very long-lived elements still have a considerable portion of their radioactivity left.

One phenomenon of importance for the processes in the near field is the radiolysis of water. When the canister has been penetrated, radiation from remaining long-lived radionuclides in the fuel splits the water into hydrogen and oxidizing substances. The hydrogen can diffuse out faster, leaving an excess of oxidants near the canister. The environment there then becomes oxidizing and certain long-lived radioactive substances become considerably more soluble in water. As the oxidized groundwater moves away from the deposition holes, the oxidizing agents are consumed by reacting with the bivalent iron present in the minerals. Outside this area the natural reducing conditions are not affected.

The situation is illustrated in figure 20.

It is estimated that the border zone between oxidizing and reducing conditions, called the redox front, will travel no more than 10 m away from a canister over a time span of 1 million years. Studies of conditions around the "natural reactor" discovered at Oklo in Gabon indicate that the effects of radiolysis are much less than these calculations show. At Oklo, uranium dioxide has been accumu-

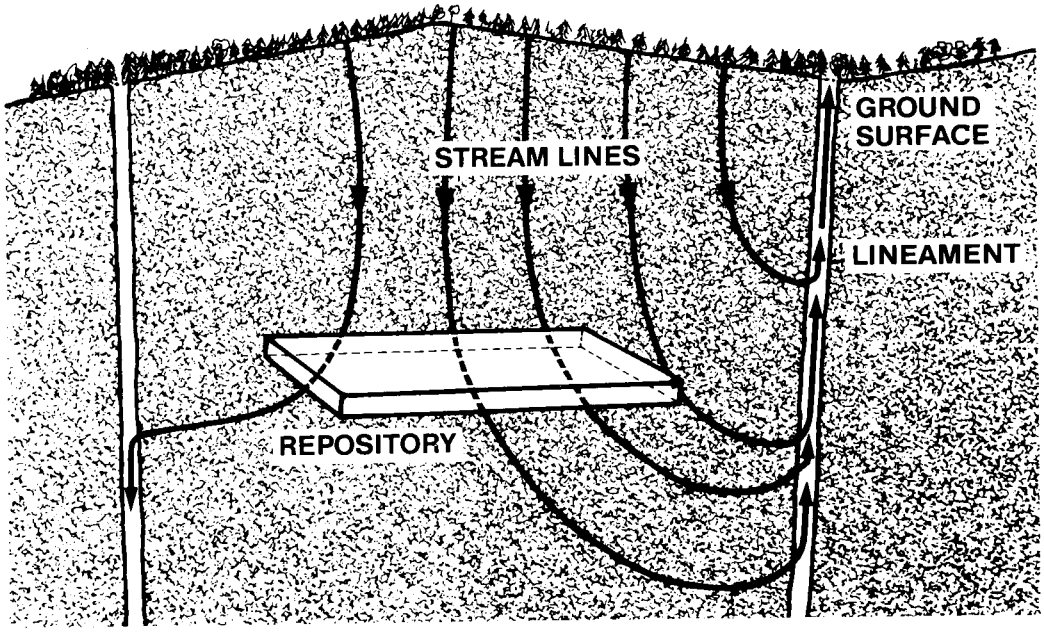


Figure 21. Schematic illustration of groundwater flow.

lated by nature itself in such a manner that a self-sustaining nuclear chain reaction has been brought about. It has been observed there that only a very small portion of the uranium dioxide has moved appreciably from the "near field" over a period of several hundred million years.

Other effects of importance for the dispersal of radioactive substances are the chances of radioactive colloids and organic complexes forming. They can be transported faster with the groundwater than the dissolved radioactive substances.

The near field studies provide information on the quantities and the rate at which radioactive substances are spread to the surrounding rock mass.

14 NUCLIDE DISPERSAL IN THE ROCK MASS

The radionuclides are transported primarily in dissolved form in the groundwater, which moves slowly through the fractures in the rock. The pattern of movement is illustrated by figure 21.

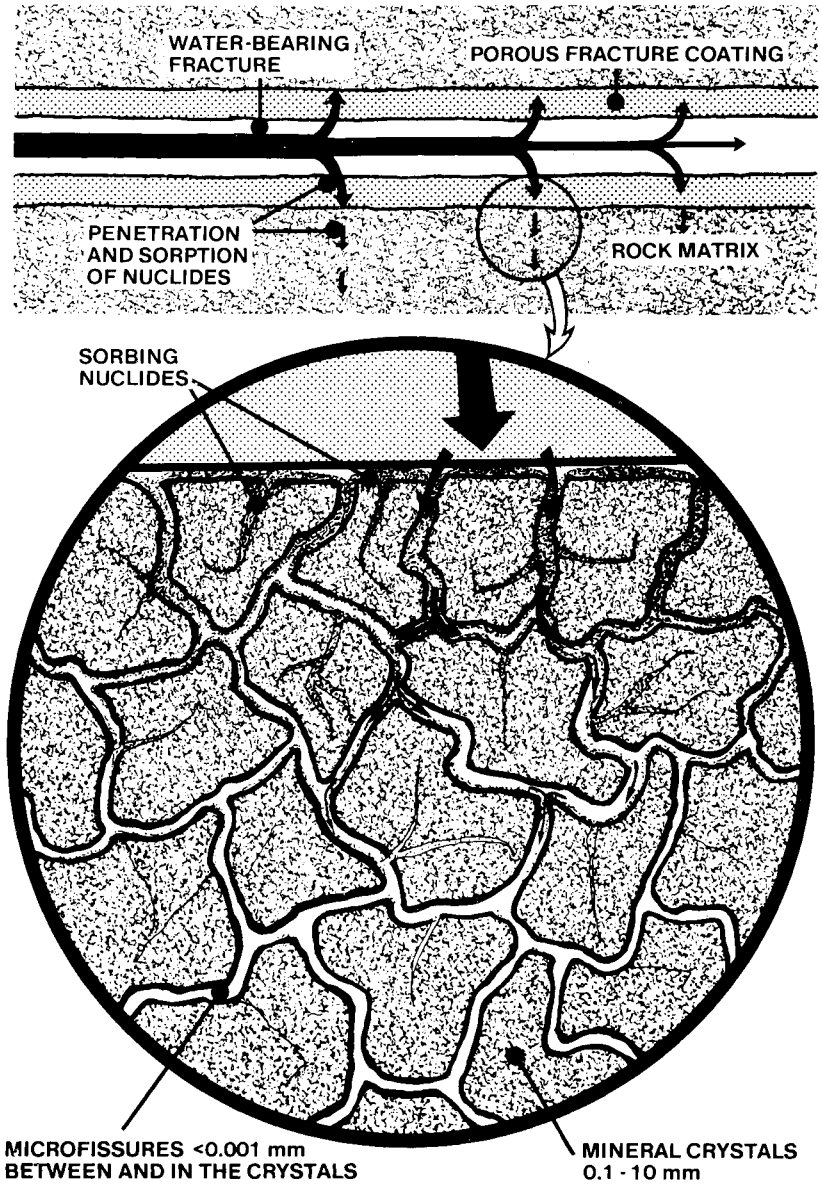


Figure 22. Schematic illustration of sorption and penetration of the radionuclides in the microfissures in the rock.

All important radioactive substances except iodine react chemically and physically with the minerals present on the fracture faces. These reactions, which are collectively referred to as sorption, can be quantified with the aid of equilibrium constants. When we speak of equilibrium, we mean that the ratio between the concentration of a substance in the water and its concentration on the fracture face strive to achieve a state of equilibrium. The substances dissolved in the water will therefore move more slowly than the groundwater itself. This is expressed by means of a "retention

factor", whose value differs for different combinations of radioactive substances and minerals.

The inflow of radioactive substances to the biosphere will not be the same as the outflow that might occur from a final repository. The radioactivity decays on its way as they travel through the rock. The radioactivity that reaches the biosphere is therefore much less than the radioactivity which is released from the final repository.

Another mechanism must also be taken into account, namely dispersion. Dispersion is a phenomenon that derives from the fact that the radioactive substances are transported in different ways in the groundwater volume and in the fracture system. Due to these dispersion effects, which have been studied in various field tests, the "pulse" of radioactive substances that left the final repository arrives at the biosphere spread out over a longer period of time.

Dispersion leads to a reduction of the maximum concentration of radioactive substances in the inflow to the biosphere, but the first traces of radioactivity will reach the biosphere earlier than if there had been no dispersion.

A mathematical model has been developed that describes how different substances are transported in the rock mass. With the aid of this model and known data concerning sorption etc., the quantities of radioactive substances that can reach the biosphere have been calculated. As a result of the interplay between the chemical properties of the radioactive substances - in particular their low solubility, their half-lives and sorption in the rock - only an insignificant fraction of the total radioactivity can reach the biosphere, even under unfavourable circumstances.

In crystalline rock, such as the Swedish bedrock, there are microscopically small fissures between the crystals. These fissures constitute a continuous pore system containing water. The substances (ions) dissolved in the water are much smaller than the width of the microfissures and can therefore diffuse into the pore system, where they are sorbed on the crystal surfaces. The process is illustrated in figure 22.

15 DISPERSAL AND EXPOSURE IN THE BIOSPHERE

If radioactive substances are carried by the groundwater from the final repository to the biosphere, individuals in the environment can be exposed to radiation. The radioactive substances can reach man via consumption of water and foodstuffs.

The dose to which the most highly exposed group of people (the "critical group") may be subjected can be calculated with the aid of different models.

A Swedish model named BIOPATH has been used here. The model describes how radioactive substances are dispersed successively into the various compartments of the biosphere. The data used in the calculations have been taken from a large body of international literature.

The calculations are based on the present-day climate, population structure and dietary habits. We are, however, in conditions that may apply far in the future and present-day conditions may undergo considerable change. Dietary habits and even the human race itself may change in a manner that cannot be predicted now. This leads to unavoidable uncertainties in all long-term dose calculations. However, since the impact of the final repository only constitutes a negligible fraction of natural background radiation, this uncertainty is of little importance.

16 RADIATION DOSES

If individuals or groups of individuals are exposed to radiation, they receive a radiation dose. A differentiation is made between individual doses to the critical group, in the vicinity of the final repository, and the collective dose, which pertains to parts or all of the world population.

The dose conversion factors that are used for converting from activity to dose are based for the most part on data and guidelines recommended by the International Commission on Radiological Protection, ICRP. They take into account the effects of the radioactive

substances on gonads, bone, bone marrow, lungs, thyroid and chest. According to the ICRP's recommendation, the impact on different organs is weighed together to obtain a "weighted whole-body dose".

High radiation doses, 2 Sieverts (Sv) or more, entail serious risks, especially if they are received during a short period of time. For persons in radiological occupations, Swedish radiation protection regulations permit a maximum annual whole-body dose of 0.05 Sv. The natural background radiation in Sweden is equivalent to a dose of between 0.7 and 1.4 mSv/y.

Knowledge of the injuries that may result from very small radiation doses is limited. This is due to the fact that such injuries cannot be distinguished statistically from the very large number of injuries of the same type that have other causes. The ICRP recommends that the risk of radiation injuries be considered to be proportional to the dose received. This assumption is deemed to be cautious, i.e. to lead to an overestimate of the risk of injury resulting from low doses.

The ICRP has also issued risk factors pertaining to genetic damages resulting from irradiation. However, no signs of a higher incidence of genetic damage have been found in the descendents of the large population that survived the bombing of Hiroshima and Nagasaki, receiving high radiation doses. This may also be due to the fact that such damages cannot be distinguished from the very large number of genetic damages that occur in large population groups but have other causes.

17 SAFETY PRINCIPLES

The handling of the spent fuel prior to final disposal is largely of the same kind as the fuel handling that takes place in connection with other nuclear power activities. The fundamental rules, guidelines and limit values that apply for nuclear activities in general can therefore also be applied to the final handling of the spent fuel.

The situation is another one as far as the long-term safety of the final repository is concerned. No established system of criteria and guidelines exists as yet. The possibilities of establishing quantitative acceptance criteria for individual barriers or groups of barriers are being discussed in some countries. It is, for example, possible to stipulate requirements on minimum canister service life, minimum travel time for the groundwater or maximum permissible rate of dispersal of the radioactive substances from the final repository. No such attempt has been made here, since it has been judged that, at this stage, this could put restraints on the future research and development work and counteract an unbiased and comprehensive evaluation of the functions of the different parts of the repository system.

In the light of present knowledge, the best alternative would appear to be to base the assessment of the safety of a final repository on a thorough analysis of a given, defined barrier system applied on a site with known characteristics.

Current standards and guidelines for radiation protection adopt the following standpoints for the issuance of requirements on the radiological safety of a final repository:

- The expected contribution to the radiation dose to the most highly exposed group shall be less than 0.1 mSv/y (the design goal stipulated by the National Institute of Radiation Protection in Sweden for Swedish nuclear power facilities).

- The repository's contribution to the radiation dose to the most highly exposed group shall, even under very unfavourable circumstances, be less than 1 mSv/y (the limit recommended by the ICRP).

Another, more objective way to stipulate radiation protection requirements is to base them on the natural radiation level. Such a requirement could be formulated as follows:

- The contribution to the radiation dose to the most highly exposed group shall constitute only an insignificant portion of the dose from natural background radiation and shall lie within the natural range of variation.

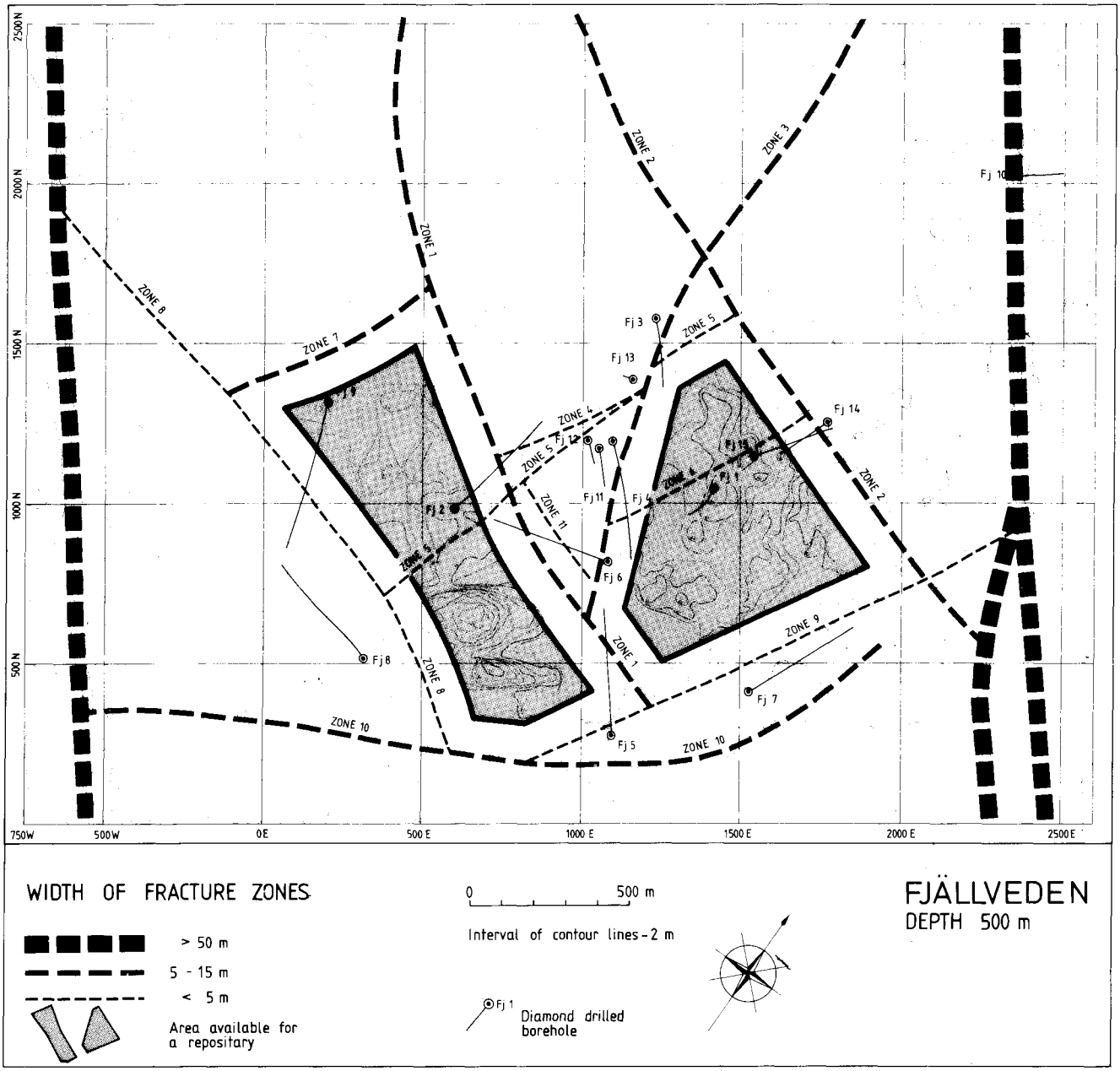


Figure 23. Study site at Fjällveden.

18 SITE-SPECIFIC DATA

Geological, hydrological and geochemical investigations have been carried out in recent years on selected sites at Fjällveden, Svartboberget, Gideå and Kamlunge, see figure 13.

The investigations have included bedrock geology, existing fracture zones, fracturing of the rock mass, hydrological and meteorological conditions, hydraulic conductivity of the rock, groundwater chemis-

try and recipient conditions. The investigation results have been used for an analysis and and evaluation of the safety of conceived repositories on the sites mentioned, with the exception of Svartboberget. The bedrock at Svartboberget has been found to contain fracture zones oriented and distributed in a way that a final repository would have to be split up in several small parts which is not economically feasible. The analyses for this site have therefore not been completed.

Fjällveden

15 core boreholes have been drilled to a maximum depth of 700 m at the site. The total length of the core boreholes is about 7 600 m.

The investigated site is shown on figure 23, where the location of a conceived repository has also been indicated.

The site is characterized by a flat topography. The rock mass, which consists mainly of veined gneiss, generally possesses low hydraulic conductivity, which also applies to the local fracture zones. Approximately 3% of the rock mass consists of vertically oriented layers of granite gneiss with elevated hydraulic conductivity.

The groundwater flow at repository depth has been estimated at between 0.01 and 0.05 $l/(m^2 \cdot year)$, taking into account the presence of the layers of granite gneiss mentioned above.

In view of existing fracture zones, a conceived final repository should be located in two levels at depths of 500 and 600 m, respectively. The areas indicated in figure 23 as being available for a final repository have a total area of 1.85 km^2 and cover the need for 6 000 tonnes of fuel with a surplus margin of about 90%. The influence of the vertical zones with elevated hydraulic conductivity cannot be fully envisaged without further studies. It is therefore unclear at the present time whether the site can be considered suitable for the location of a final repository.

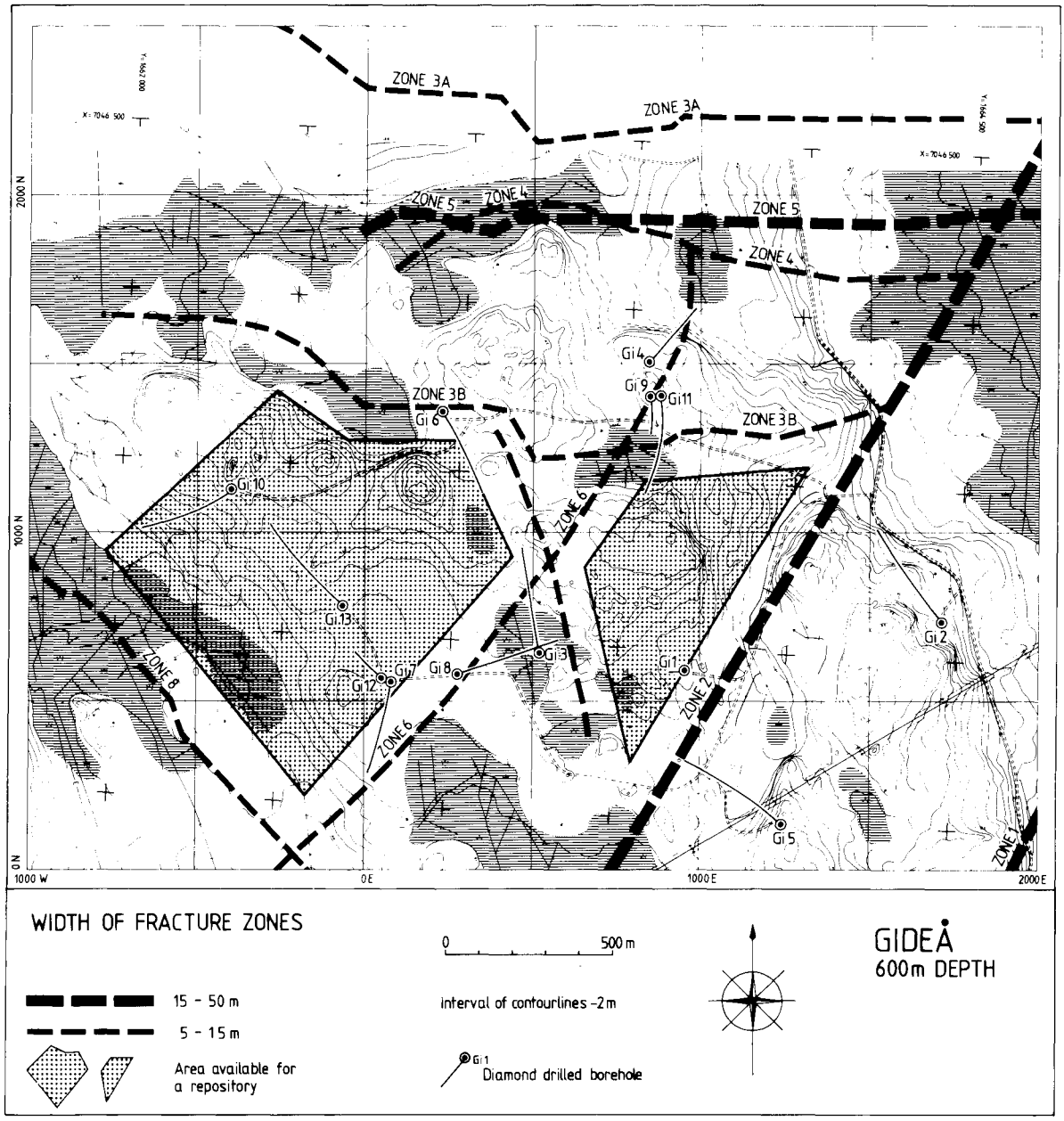


Figure 24. Study site at Gideå.

Gideå

13 core boreholes have been drilled on the site down to a maximum depth of 700 m. The total length of the core boreholes is about 8 250 m.

The investigated site is shown on figure 24, where the location of a conceived final repository has also been indicated.

The site is characterized by a flat topography and the rock mass is dominated by veined gneiss of low hydraulic conductivity. The hydraulic conductivity in the local fracture zones is insignificantly higher than that in the rock mass. As in Fjällveden, granite gneisses of elevated hydraulic conductivity run as layers through the rock mass. In Gideå, however, these layers are oriented horizontally and their hydraulic conductivity differs less from that of the main rock. Diabase dykes in the rock exhibit the same low hydraulic conductivity as the main rock.

The groundwater flow at repository depth in the impervious rock has been estimated at between 0.004 and 0.02 $l/(m^2 \cdot year)$, regardless of whether the influence of the horizontal zones of higher hydraulic conductivity are taken into account or not.

Suitable space should exist for a final repository in one level on the site at Gideå. Further studies would be required to demonstrate this, however. A repository in two levels at 500 and 600 m within the well-investigated area has therefore been illustrated on figure 24. The marked areas have a total area of 2 km^2 and cover the need for 6 000 tonnes of fuel with a surplus margin of about 120%.

Kamlunge

16 core boreholes have been drilled down to a maximum depth of 670 m on the site. The total length of the core boreholes is about 7 800 m.

The investigated site is shown on figure 25, where the location of a conceived final repository has also been indicated.

The site is situated on a plateau with a local relief of about 30 m. The relief to surrounding valleys is about 100 m.

Gneisses and red granite dominate the bedrock. The bedrock also contains amphibolite and granodioritic rock types.

The rock mass possesses low hydraulic conductivity and is intersected by narrow, steeply dipping fracture zones spaced far apart.

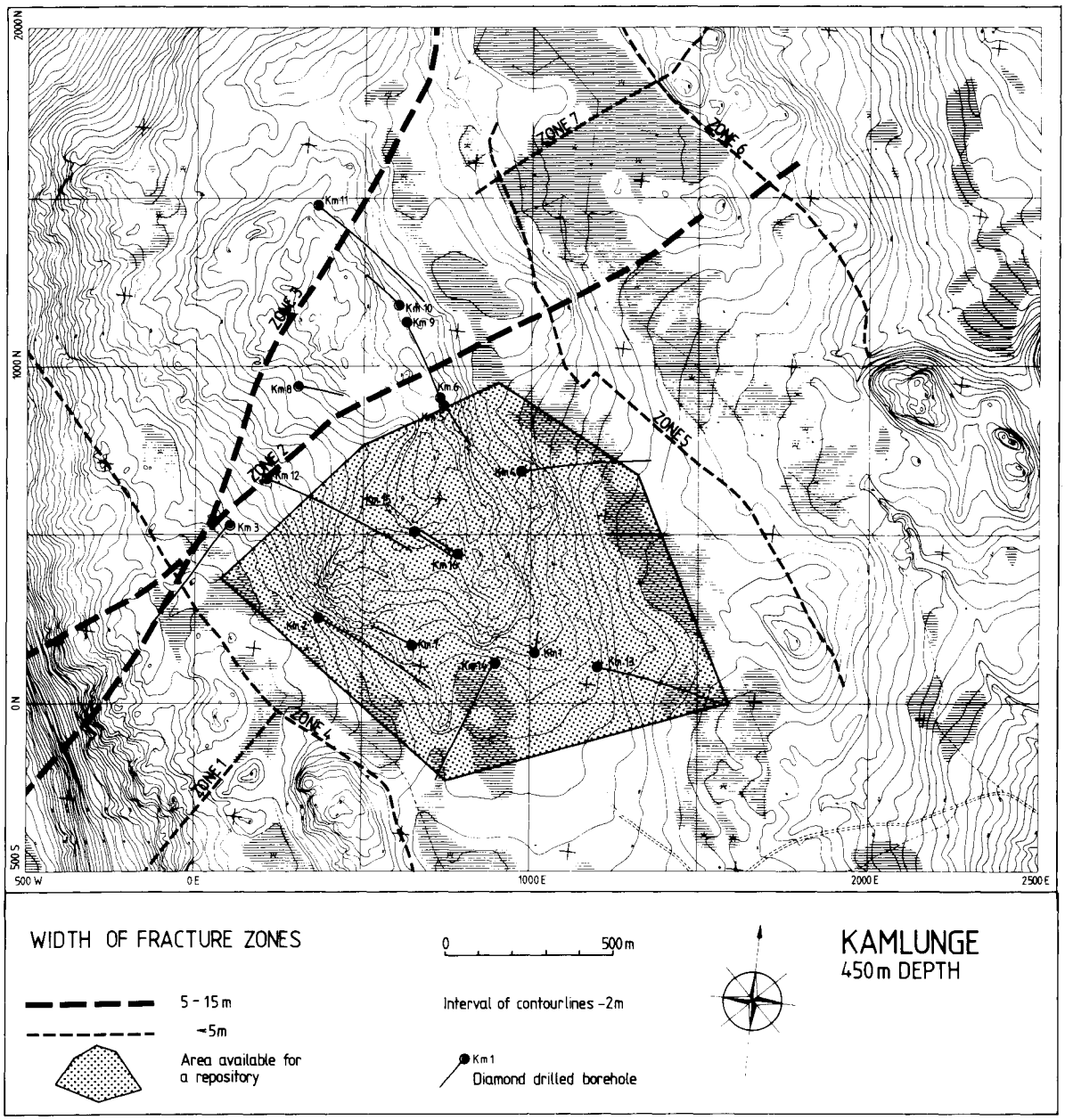


Figure 25. The study site at Kamlunge.

A horizontal fracture zone with elevated hydraulic conductivity has been encountered at a depth of about 550 m below the surface. The zone has been penetrated by four core boreholes, where it has been found to have a thickness of between 4 and 14 m.

The groundwater flow at repository depth, about 450 m, has been estimated to be between 0.003 and 0.06 $1/(m^2 \cdot year)$.

The area marked on figure 25 as being available for a final repository in one level is 1.1 km^2 and gives a surplus margin above and beyond the need for 6 000 tonnes of fuel of about 50%. In view of the horizontal fracture zone found at a depth of 550 m, the repository is conceived as being constructed at a depth of 450 m, i.e. 100 m above the zone.

Svartboberget

A complete analysis has not been carried out of the suitability of Svartboberget for the location of a final repository. Those investigations that have been done have indicated local fracture zones spaced at about 300 m and with a dip of about 45^{o}. This means that a final repository would have to be divided into a large number of small units, which can be regarded as an impractical solution.

19 RADIOLOGICAL SAFETY DURING OPERATION

Various failures and accidents could conceivably occur in connection with the handling and transport of the spent fuel on its way from the power plants to final storage. Various measures must therefore be adopted to limit the risks of such events and the possible consequences.

Detailed safety analyses have been described for activities at the CLAB as well as for the transportation system and the measures have been approved by the authorities in their essential respects. Activities at the encapsulation station and the final repository have, on the other hand, not been reviewed by the supervisory authorities.

The critical steps in the encapsulation and deposition procedures have been examined. With a suitable design of the facilities and a quality surveillance and control of the type and scope that is generally applied in nuclear activities, the risks of significant activity releases can be kept under control.

20 THE SAFETY OF THE SEALED REPOSITORY

General

The main purpose of the report is to demonstrate that a final storage of spent nuclear fuel can be effected in Swedish bedrock and with present-day technology in a manner that meets very high demands on safety over time spans that have not been taken into account in previous technology evaluations.

The account is based on present-day knowledge. Wherever present-day knowledge is incomplete, this has been compensated for by the use of unfavourably chosen premises or by the disregarding of favourable circumstances that cannot yet be completely verified.

Before the site of a final repository is to be selected (around the year 2000), construction started (around the year 2010) and deposition commenced (around the year 2020), considerable further development work will have been carried out. It can therefore be assumed that the solution that is finally chosen will be more optimal than the one presented here.

Probable sequence of events

Site investigations carried out by KBS indicate the existence in Sweden of a number of continuous masses of low-conductivity rock where the groundwater flow at a depth of about 500 m lies between 0.002 and 0.1 litre per m^2 and year. The deep groundwater at these sites has very low concentrations of substances that can attack copper. If the same calculation principles are used as those used by the Corrosion Institute's expert group, but with applying measured values without safety margins, a service life on the order of 100 million years is obtained for a copper canister with a wall thickness of 10 cm. Forecasts over such long periods of time are naturally very uncertain. Nevertheless, the calculations show that most of the canisters will remain intact for several million years and that the penetrations will be distributed over millions of years. After such long periods of isolation, the deposited fuel will have a nuclide composition that is approximately the same as uranium and daughter nuclides occurring in nature.

The Swedish rock contains an average of about 5 mg of uranium per kg. In the rock mass that surrounds the repository, this gives a quantity of uranium of the same order of magnitude as that in the deposited fuel.

The uranium concentration in deep Swedish groundwaters lies in the range 0.1-10 mg per litre. The higher value should correspond to the upper limit for how much uranium can be dissolved in deep groundwaters. The quantity of uranium in the groundwater is thus not dependent on the quantities of uranium present in the rock, but rather on the maximum possible amount that can be dissolved in the water that flows through the bedrock.

The same mechanisms that limit the dissolution of natural uranium from the rock will limit the concentrations that can be derived from uranium in the spent fuel. If all groundwater that flows through the repository (0.1 l per m^2 and year) should dissolve uranium to the saturation limit (10 mg per litre), the time required for all uranium in the final repository to be dissolved will be billions of years.

The most probable sequence of events, based on observations in nature, is therefore that both the possibilities for penetrating the copper canister by corrosion and the natural limits on the solubility of uranium lead to such slow processes that the spent fuel in the final repository will not add at all to the natural radioactivity in the groundwater.

Scenarios

Predictions that cover such long periods of time as those indicated in the preceding section must always be associated with uncertainties. A number of scenarios have therefore been postulated where more unfavourable premises have been chosen for the function of the barriers. Calculations for these scenarios have been carried out according to the scheme shown in figure 26.

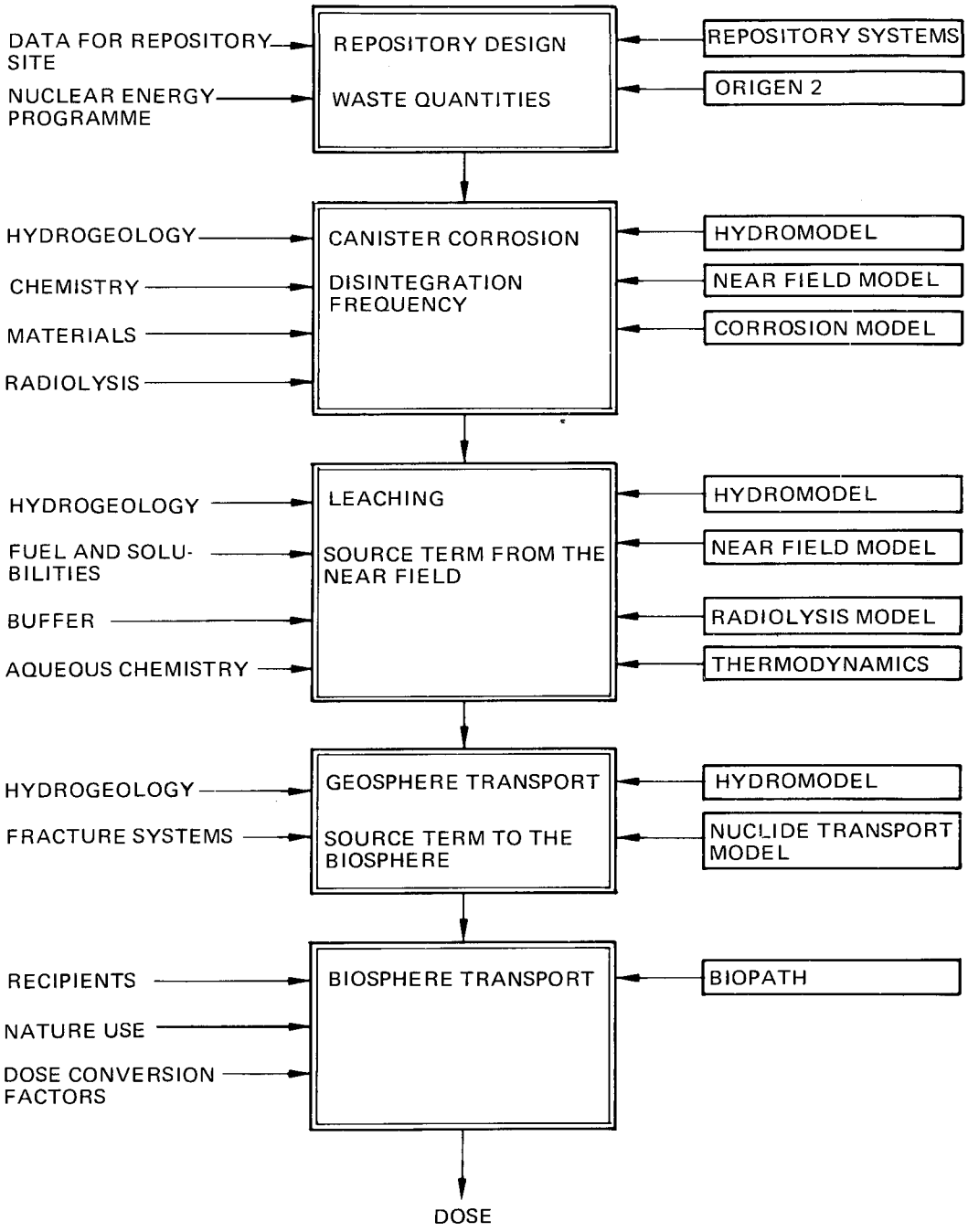


Figure 26. Scheme for scenarios in the safety analysis.

Scenario A

This scenario has been chosen as the "central" one and is based on the following premises:

- The canisters are penetrated successively during the period from 100 000 years to 1 million years.

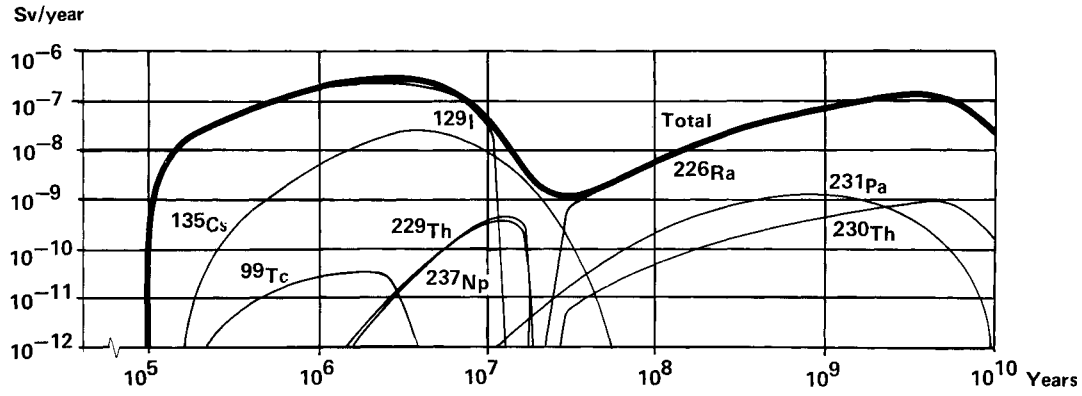


Figure 27. Doses to nearby residents for scenario A.

- The groundwater flow at 500 m depth is 0.1 l per m^2 and year.

- The uranium matrix in the fuel is assumed to be dissolved in the groundwater to a concentration of 360 mg per litre, which is equivalent to the maximum possible solubility under oxidizing conditions and the carbonate concentrations that have been measured in the deep groundwaters.

- Reducing conditions are assumed to prevail in the undisturbed rock, which is of importance for the solubility and sorption properties of certain radioactive substances. Uranium, for example, will then have a solubility of about 10 g per litre.

- The final repository is situated so that the shortest distance to a fracture zone in the rock is 100 m.

The manner in which different variations of the premises given above affect the results is elucidated for the following scenarios.

Scenario B

One canister is assumed to leak from the time of its deposition.

Scenario C

Oxidizing conditions are assumed to prevail in the entire repository area and out to the nearest fracture zone.

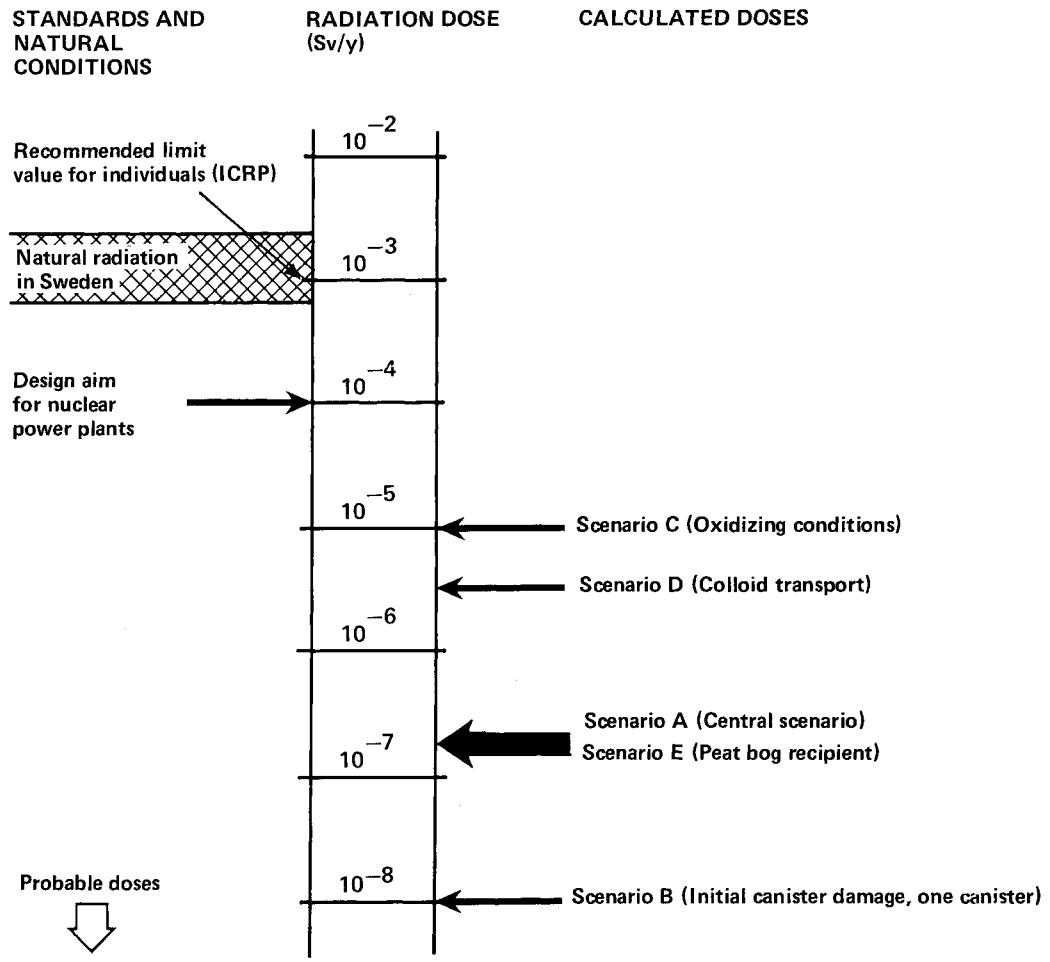


Figure 28. Calculated doses to nearby residents for different scenarios.

Scenario D

It is assumed that part of the radionuclides are transported rapidly to the biosphere with colloids.

Scenario E

Release to the biosphere takes place to a peat bog, where uranium can be highly enriched.

Doses to nearby residents from releases to the biosphere of different radioactive substances have been calculated. As an example, the doses calculated for scenario A at different times are shown in figure 27. The dose values, which are very low, are dominated by iodine-129 and radium-226 during different periods.

The maximum doses to nearby residents obtained for the different scenarios are shown in figure 28.

As mentioned above, the results of the different scenarios are based on unfavourable assumptions. With greater knowledge, it will be possible to perform more realistic analyses, which should result in much lower dose values. This in turn will enable the repository to be designed in a more optimal manner without sacrificing the stringent safety requirements.

The steps in the calculations where the premises have been chosen particularly unfavourably are as follows:

- Canister service life is probably strongly underestimated. Moreover, it has been assumed that the entire barrier function of the canister ceases as soon as it has been penetrated at one point and that the groundwater then comes into contact with all fuel in the canister. In reality, the corrosion products that are formed will limit the possibilities for the groundwater to make contact with most of the fuel.

- The groundwater flow for the central scenario has been assumed to be 0.1 l per m^2 and year. The flows at a depth of 500 m that have been calculated for the investigated sites amount to between 0.003 and 0.1 l per m^2 and year.

21 ACCIDENTS AND EXTREME EVENTS

General

The slow changes that can lead to the dispersal of radioactive substances from a final repository are dealt with in the preceding chapter. It is also conceivable that radioactive substances will escape as a result of extreme or special events that are not covered by the premises that have applied in the preceding analyses. Such events may either have a natural origin or be a consequence of human activities. The former category includes different types of bedrock movements, glaciations and criticality in the final repository. Human activities that can affect the safety of the final

repository can include acts of war and sabotage as well as intentional or unintentional intrusion into the final repository.

Bedrock movements

Bedrock movements could conceivably damage a final repository by creating new paths for groundwater flow or by damaging the canisters.

The Swedish bedrock has an age of between 1 and 2 billion years. The radioactive substances present in the bedrock make it possible to follow the evolution of the bedrock throughout this entire period. The picture obtained in this manner shows that geologically dramatic events have characterized very long periods of time, and that the Swedish bedrock is currently in what can be regarded from a geological point of view as a low-activity phase of its evolution. This does not necessarily mean that bedrock movements will not occur, especially when the load on the bedrock is removed in the final phase of a glaciation. For natural reasons, such movements will preferably take place in already weakened sections, i.e. existing crushed zones. A repository that has been located in a block of sound rock, surrounded by crushed zones, would therefore be protected by these zones.

The conclusion of this geological retrospect is that the likelihood that the hydrological conditions in a repository area will be significantly altered during the next million years is extremely low.

The fracture pattern that can be observed in today's bedrock constitutes the cumulative result of all the stresses and metamorphisms to which the bedrock has thus far been subjected during 1 billion years or more. Even if it is assumed that the number of fractures will double during one-thousandth of this time, i.e. during the next million years, this would not lead to any essential change in the groundwater flows.

The risk that the deposition holes will be intersected by rock displacements that cause the canisters to be subjected to shearing forces has been assessed against the background of observations of

previous displacements and their frequency on exposed outcrops. A statistical analysis of the observations reveals that perhaps one deposition hole could be affected by such a movement during 1 million years. The plastic and elastic properties of the buffer material and the copper will prevent smaller movements from causing damage to the canisters. The consequences of damages to individual canisters have been dealt with in the safety analysis (scenario B).

Criticality in the final repository

Theoretically, it is conceivable that the fissionable isotopes plutonium-239 and uranium-235 that are present in the repository could be separated over a very long period of time and accumulate in such geometrical configurations that a self-sustaining chain reaction results. For physical reasons, such a course of events must be regarded as beyond the realm of reasonable possibility. If it is nevertheless assumed that a critical mass may arise, the consequences will be local only, since the reactions cease when the water boils away.

Acts of war and sabotage

In the long time perspective, it is doubtful whether acts of war can be considered to be "extreme events". On the other hand, the possibility that acts of war might lead to serious damages to a sealed repository in rock at a depth of 500 m must be regarded as extremely remote. Even a ground detonation of a nuclear device of 10-50 megatonnes would not create a crater deeper than 100-200 m. This would weaken but not totally destroy the geological barrier. In such a situation, the release of radioactivity from the repository would only be a fraction of the radioactivity from the bomb and would be of relatively subordinate interest.

The final repository is not judged to be a target of primary interest for saboteurs. Reasonable safety measures are foreseen during the period prior to sealing of the repository.

Intrusion into the repository

It must be assumed that future generations will bear the responsibility for their own conscious actions. What is of importance in this context is to provide them with the best possible information as a basis for their decisions, i.e. to make sure that information on the location, design and function of the final repository is carefully recorded and preserved. If, at some time in the future, people wish to retrieve and recover the copper or the spent fuel present in the final repository, they will then be aware of and able to cope with the radiological risks.

Knowledge of the repository could conceivably be lost, for example as a result of catastrophic events such as a global war of extermination or if the country is rendered uninhabitable during a glaciation period and then repopulated. It is then conceivable that metal deposits could be detected in the repository through e.g. geophysical methods, and that people might enter the area to exploit these metals, unaware of the existence of the repository. However, this would require such advanced technical know-how that such people should also possess the capability to detect the radioactivity and deal with its risks.

It is also conceivable that the thermal energy that will be stored in the rock mass around the repository during the next thousand years or so might become attractive to recover. This is not feasible after a new glaciation, however, since such a period would be of such long duration that the heat generated by the fuel will have been dissipated long before its end.

Since the site of a final repository is selected where there are no workable minerals, there is no risk that the area will be utilized for mineral extraction.

22 GENERAL SAFETY CONCLUSIONS

General

According to Swedish law, the nuclear power producers are responsible for the safe dispoal of radioactive waste from the nuclear

power stations. The nuclear power utilities have contracted the jointly owned Svensk Kärnbränsleförsörjning AB (Swedish Nuclear Fuel Supply Company) to take responsibility for the necessary measures. This is done in accordance with a long-range plan, which is updated annually.

An important part of the work is to develop a system for the final and safe storage of spent nuclear fuel. Under Swedish law, a reactor owner must show that the spent nuclear fuel can be handled and finally disposed of in a safe manner before the reactor can be loaded with fuel for the first time.

The radioactivity in the spent nuclear fuel gradually declines with time. Some radioactive substances in the fuel, however, have such long half-lives that they can be equated in practice with stable toxic substances. As yet, there is no legislation requiring an accounting of how such substances can affect the envrionment over the very long run. It has therefore not been possible to evaluate the safety of a final repository for spent nuclear fuel in this report in the light of what general view society takes of safety problems that affect the environment in the very long run.

The account presented in this report is based on the state of knowledge achieved as of the start of 1983.

Safety in the handling sequence

The handling and treatment steps that precede the final storage of the spent nuclear fuel have their counterparts within industry and nuclear power plant operation. The necessary safety measures can therefore largely be based on experience. No technical difficulties in meeting stringent safety and protection requirements are foreseen.

The long-term safety of the final repository

Time perspective

The radioactivity in the spent fuel declines very rapidly at first. Ten years after discharge from the reactor, the spent fuel contains

only one hundredth of its original radioactivity. In order for the activity in the "ten-year-old" fuel in turn to decline to one hundredth, a period of 10 000 years is required. A further reduction of radioactivity to one hundredth takes place during the period from 10 000 years to 10 million years.

During the long spans of time that must be considered here, many changes will occur in our environment.

- During a period of on the order of 100 years, nature can be altered, for example by the eutrophication of lakes.

- During a period of on the order of 10 000 years, essential climatic changes can take place that could possibly lead to a new glaciation.

- During a period of on the order of one million years, evolution can lead to the origin of new species and the extermination of others.

- During a period of on the order of several tens of millions of years, major geological changes can take place.

Naturally, the uncertainties in forecasts and future assessments are greater the longer the periods of time they are applied to. In order for the safety evaluation of a final repository for spent nuclear fuel to be complete, however, it is necessary to shed light on anticipated conditions very far in the future. The properties of both the rock formation that will be selected for the final repository and the materials included in the engineered barriers are characterized by the fact that they have persisted over long geological periods of time. It is therefore meaningful to carry out evaluations of the barrier functions in the final repository even over a perspective of some million years. In time perspectives beyond some million years, the isotope composition of the spent nuclear fuel will be largely the same as that of the uranium that occurs naturally in the Swedish bedrock.

Storage site

The Swedish crystalline bedrock is very stable geologically and no major changes can be expected in the hydrological or geochemical conditions of the bedrock at a depth of several hundred metres over the next million years or so.

The safety analysis is based on geological, hydrological and geochemical data that have been obtained from extensive investigations at different sites in Sweden. Conditions vary somewhat between the sites, but the safety analysis covers most of the variations that have been observed.

The site investigations and the safety analysis have shown that there are several sites in Sweden where the bedrock is well suited for the construction of a safe final repository. The recently investigated areas at Gideå and Kamlungekölen, and probably also Fjällveden, as well as the previously investigated area at Sternö are examples of such sites. The analyses have shown that even sites such as Finnsjön, with relatively higher groundwater flows than those mentioned above, should be acceptable from the point of view of safety.

Before the site of the final repository is definitely decided on at some time towards the close of the 1990s, additional areas will be investigated so that a sufficient body of data will be available for an optimal site choice.

Safety

The spent fuel is surrounded in the final repository by different barriers. They have been designed and chosen to isolate the fuel completely from the environment over a very long period of time and to retard and dilute the radioactive substances that can eventually leak out from the repository over an even longer period of time.

A canister made of copper with a wall thickness of a few cm is expected to remain intact and leakproof for at least one million years, probably much longer.

The bentonite clay in the storage holes comprises a sealing layer as well as a mechanical and chemical buffer between the canisters and the rock mass. Geological observations show that bentonite is a durable natural product that retains it properties for at least some million years, provided the temperature does not exceed 100°C.

Both geochemical observations in nature and laboratory studies show that uranium and other actinides present in the spent fuel have very low solubility in water. Together with the very low rate of groundwater flow in the final repository, this ensures that the leaching of the radioactive substances that are left in the fuel when the canisters have been penetrated will be extremely slow.

In the chemical environment that prevails in the groundwater in the rock, the radioactive substances will migrate extremely slowly. Sorption in the microfissures in the rock will retard their transport.

An analysis of the function of the described barrier system and knowledge of how naturally occurring uranium moves in the rock indicate that the final repository will not affect the environment at all. However, sufficient knowledge and data have not been gathered to demonstrate this in an absolutely conclusive manner. Dispersal calculations have therefore been carried out for a number of postulated cases.

Unfavourable (pessimistic) premises have been chosen in the various calculation cases, for example with regard to the life of the canisters, the rate of water flow in the rock and the chemical retardation effects. Even then, the calculated doses are insignificant - on the order of between a thousandth and a hundredth of the dose from natural radiation - and they do not arise until a very distant future. Compared to current radiological standards, the repository system described here provides a very large margin of safety.

The analyses show that considerable scope should exist to achieve, through continued research and development, a solution which, without compromising the high safety requirements, is much more favourable with respect to economy and resource utilization.

Conclusion

Spent nuclear fuel from the Swedish nuclear power plants can be handled and finally disposed of in a manner that satisfies very high demands on safety and radiation protection. This handling and final disposal can be carried out using technology currently known and available in Sweden. The bedrock at a number of places in Sweden possesses the quality required for a safe final repository.

The disposal method described here is flexible and can be adapted to local conditions. Continued research is expected to provide a basis for considerable improvements with regard to economy and resource utilization.